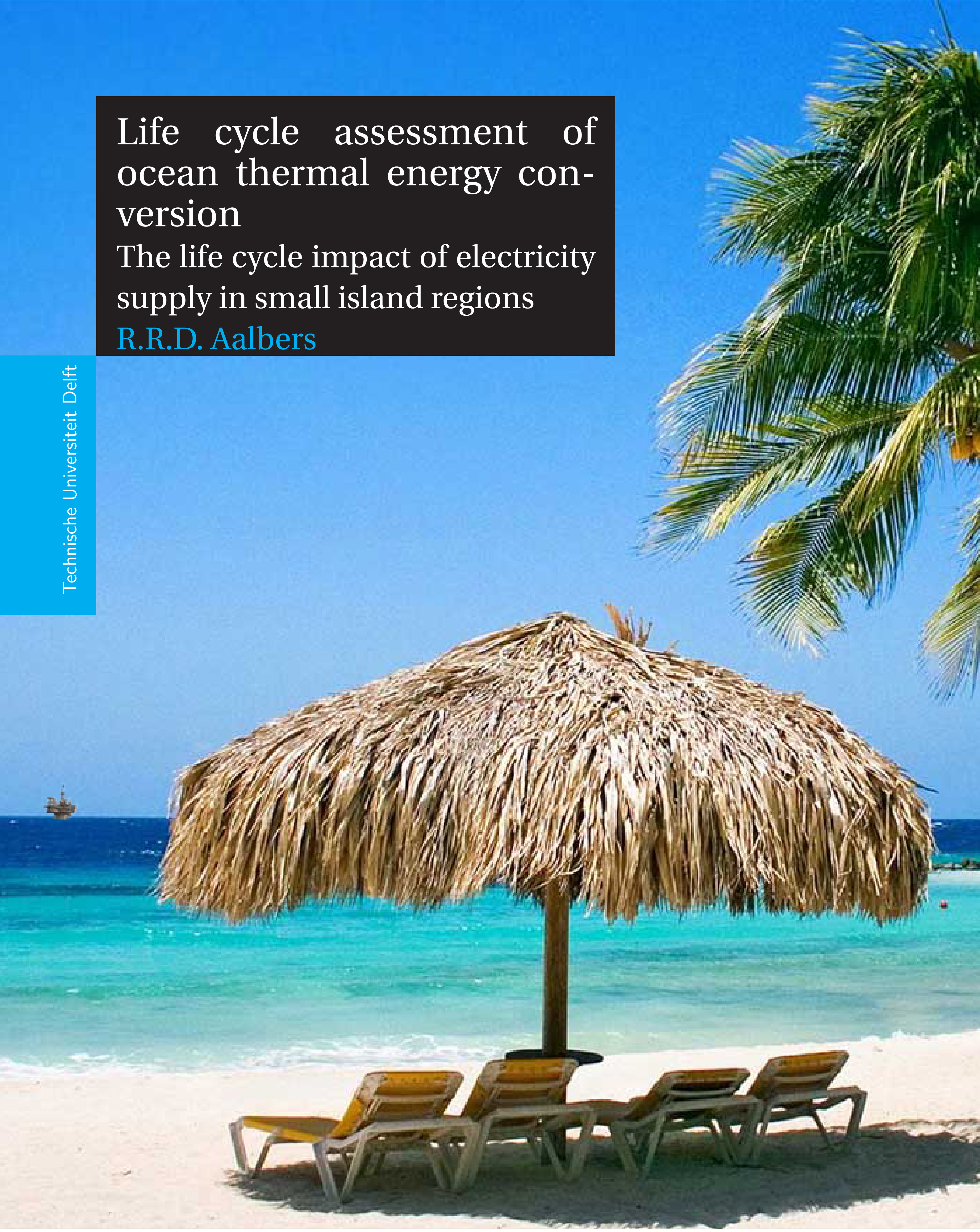

Life cycle assessment of ocean thermal energy conversion

The life cycle impact of electricity supply in small island regions

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Challenge the future

LIFE CYCLE ASSESSMENT OF OCEAN THERMAL ENERGY CONVERSION

THE LIFE CYCLE IMPACT OF ELECTRICITY SUPPLY IN SMALL ISLAND REGIONS

by

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ABSTRACT

The use of renewable energy solutions in generating electricity constitutes an interesting option in small island regions. Current energy supply generally comes from fossil fuels and besides high costs this also contributes to high CO_2 emissions. Ocean thermal energy conversion (OTEC) is a technology that potentially could be implemented. It makes use of the temperature difference of the ocean to generate electricity. However, an OTEC system has a considerable size. The cold water pipe made of composite is 1,000 meters long and has a diameter of 4 meter. Moreover, the large area required for heat exchange implicates large requirements of (energy intensive) titanium. Therefore it is necessary to investigate the environmental impact of the whole life cycle. This thesis is performed to assess the CO_2 emissions associated with OTEC. In order to obtain these results the life cycle assessment method is used. The results for OTEC are compared with diesel, wind and PV technology. Both on a 1 kWh electricity basis and in an energy mix scenario context. It can be concluded that renewable energy impact follows mainly from raw materials, manufacturing and transport, while with diesel the impact is a direct result of the use phase.

The CO_2 emission resulting from 1 kWh of electricity production by a 10 MW OTEC installation on Curacao is 16 times lower than the CO2 emission resulting from 1 kWh of electricity production by diesel generators. In relation to a 3kW peak PV installation the emissions resulting from OTEC are 1.752 lower. The OTEC emissions are 3.9 times higher compared with an 800 kW wind turbine. In an energy mix scenario this slightly changes in favor of OTEC, even despite the favorable wind conditions on Curacao. This thesis shows that OTEC is a very promising technology considering the relatively low CO_2 emissions in combination with base load electricity generation.

ACKNOWLEDGEMENTS

The thesis about the LCA of OTEC is the final product of my Master at Delft University of Technology. Delft is where I started in the year 2007. Yet, a small intermezzo of four years at the Hague University was required. The return at the TU turned out to be more succesful.

Berend Jan Kleute offered me the opportunity to graduate at Bluerise. As a start-up company at YES!Delft they are devoted to implement their OTEC system and I'm very delighted to have been part of this project. I would like to thank you Berend, for your critical look on my work and as well your time and devotion to supervise me.

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To my sister Nina Liza Aalbers I would like to say: Who would have thought I would 'possibly' (caution note) graduate sooner after we were in class together during high school. I'm very grateful for you to be my sister and for your kind words whenever I need them.

Lastly I would like to thank my parents. My mom for her love and support, always. And my dad, for his tremendous support throughout my time of study (and of course before that as well). None of this would have been possible without you and therefore I'm very grateful.

Roman Rubin David Aalbers

LIST OF ABBREVIATIONS

ADP abiotic depletion potential APacidification potential

cf capacity factor

CML Centrum voor Milieukunde

EP eutrophication potential

EPBT Energy payback time

EVR Eco-costs / Value Ratio

FAETP freshwater aquatic ecotoxicity potential

FRP Fiber reinforced plastics

HTP human toxicity potential

GWP Global warming potential

IPCC Intergovernmental panel on climate change

kWh kilowatt hour

kWp kilowatt peak

LCA Life cycle assessment

LCOE Levelised cost of energy

MAETP marine aquatic ecotoxicity potential

mT metric tonnage

MW megawatt ODPozone depletation potential

OTEC Ocean thermal energy conversion

POCP photochemical ozone creation potential

PV photovoltaics

SWAC Sea water air conditioning

TAETP terrestrial aquatic ecotoxicity potential

UCTE Union for the Co-ordination of Transmission of Electricity

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INTRODUCTION

The options for sustainable electricity generation are ample; wind, solar, hydro power, geothermal and biomass are all capable of producing electricity renewably. A less common example makes use of the ocean as an energy source, whose capacity to store thermal energy delivered by the sun can be exploited. The sun warms up the ocean's surface and the temperature in the lower region of the ocean remains more or less constant. The temperature difference of these layers can be big enough to be used to drive a thermodynamic cycle that produces electricity. This system is called ocean thermal energy conversion (OTEC) and it will be thoroughly discussed in this thesis report.

Electricity can thus be produced in a lot of different ways and a combination of the alternatives will be the solution for a growing electricity demand in the future. It is preferred to replace fossil fuel sources by renewable ones. However, sources such as wind and solar energy need back-up systems due to their fluctuating character (caused by absence of wind or shade). Back-up would be supplied by diesel generators or storage systems. Diesel generators have high CO_2 and other emissions, which have an impact on the environment. The rise of CO_2 emissions globally is the cause of climate change. That statement is based on findings in numerous reports of the Intergovernmental Panel on Climate Change or IPCC. So, it is important to find the right balance for electricity generation, preferably with a low share of fossil fuels.

The environmental impact of a typical energy source depends on emissions occurring during the whole life cycle of the system. Examples of life cycle stages are extraction of raw materials, manufacturing, transport, operation and decommissioning. If the whole life cycle of the system is considered, some unexpected outcomes might be found. A system that is supposed to be very sustainable might have huge environmental impact during construction and will not be able to make up for that during the operating phase. Quantification of impact during the whole life cycle is needed in order to be decisive and have conclusions about the performance. A method that is very applicable is life cycle assessment (LCA), which is a tool useful for comparing environmental impact of different systems or for quantifying impact of different stages of a system.

The public opinion about certain renewable energy systems can change significantly when critical views are put forward. The statement that wind energy or solar energy can be harvested without any impact at all is wrong, because then the impact related to manufacturing and demolition of the system are neglected. If this impact are ignored a critical notion is justified. Therefore this thesis will include the whole life cycle of an OTEC power plant and compare this with power generation by alternatives such as diesel, wind or photovoltaics (PV). The thesis will not focus on the decision making process for electricity supply, but instead will make a comparison between the alternatives for electricity production.

At first a short introduction of the life cycle assessment method will be given (chapter 1). The renewable energy technology ocean thermal energy conversion will be introduced next and previous research about the LCA of OTEC is reviewed. After the introduction the structure of LCA will be followed and all four stages will be dealt with (chapter 2, 3, 4 and 5). Chapter 6 will be subjected to a description of the energy mix scenarios and their LCA results. The thesis will end with the conclusion, discussion and recommendations (chapter 7, 8 and 9).

1.1. LCA

Life cycle assessment is a method that is used to determine the environmental impacts of a project. The method consists of an assessment of all the inputs and outputs of a system throughout the life cycle. Four different stages can be identified in the study;

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

In the goal and scope stage the aim of the research is described, as well as the reason for applying the LCA method. The boundaries of the research are indicated, because an LCA study can be infinitely large if not delimited. All the in- and outputs of the system need to be investigated and that requires a lot of data. This information is obtained in the inventory stage and consists of quantification of the flows [1]. The impact assessment follows from linking the inventory quantification of flows with specific impact models. There are several different impact models available and these all have different views on how to relate emissions with their influence on the environment. The LCA concludes with the interpretation stage in which the study is evaluated on the reliability. A discussion of the obtained results is included in this stage [8].

The structure of LCA and how the environmental impacts are calculated is dependent upon the following terms; function, functional unit (FU), reference flows and the unit process. The function is the service that is provided by a certain system (e.g. transport) and the functional unit is a quantification of that service (e.g. 1 person transport of 1 kilometer). The reference flows are the different options to meet that function (e.g. bike, scooter and more). The unit processes are all the separate processes that lead to the fulfillment of the function (all the processes needed to accommodate a car, bike or public transport). The description of the function, FU and reference flows is done in the goal and scope stage. The unit processes and the data that they require are to be found in the inventory analysis. Two examples can be seen in the flow diagrams of transport by bike, figure 1.1 or by scooter, figure 1.2. Traditionally emissions are excluded from flow diagrams.

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[1] The flows in the life cycle assessment are based on goods that 'flow' from one process to another

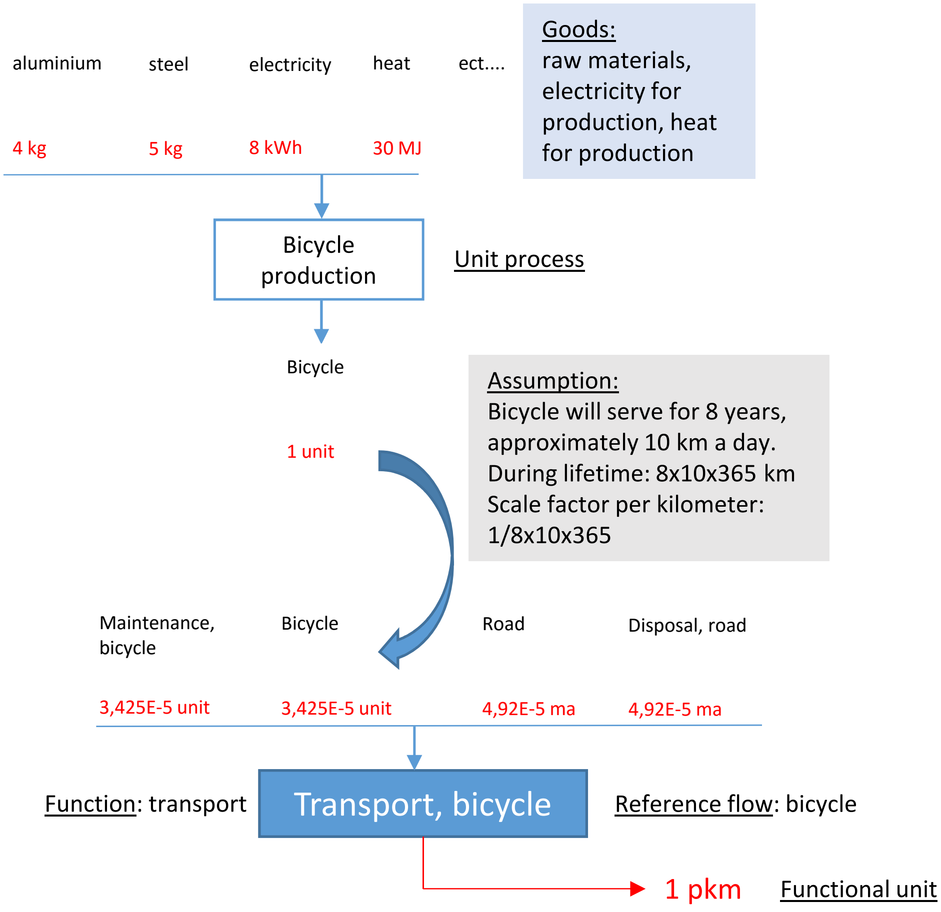

Figure 1.1: Example of flowdiagram with basic LCA terms. Reference flow: bicycle

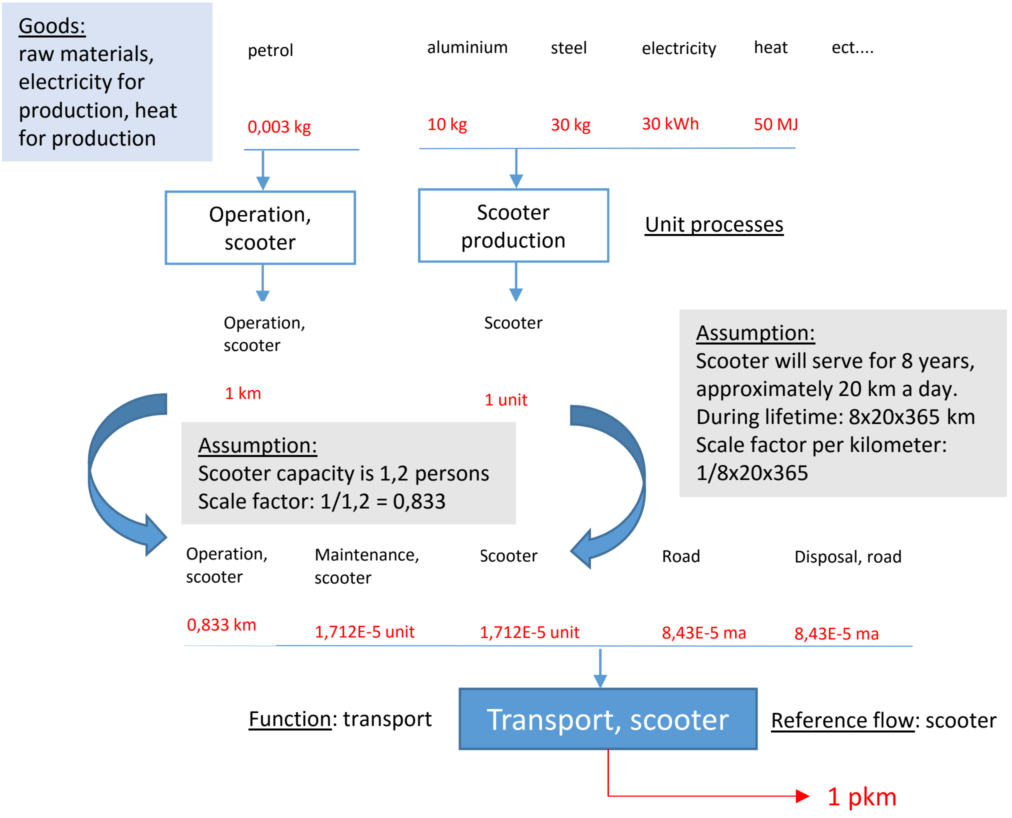

Figure 1.2: Example of flowdiagram with basic LCA terms. Reference flow: scooter

1.1.1. GOAL AND SCOPE

The most important aspect of the goal and scope stage is the description of the aim of the research. Life cycle assessment can have two different purposes. It can give an analysis of the hot spots of a system, or it can be used to compare different systems that perform the same function. The highest contributors can be identified, so called 'hot spots', either per component or for the whole system. Both purposes can be achieved within the same project. With the identification of the hot spots improvements for the system can be addressed. A comparison can be useful in the decision making process, or for marketing purposes. The information that is presented with LCA can be sensitive for some stakeholders, which is why a critical review is mandatory with a comparison study. Thus, all the choices and assumptions that are made have to be well documented in the assessment, because after the study it must be possible to retrieve this information. Another aspect of the goal is to mention everybody that is involved with the research [8].

The scope is a complete description of all the assumptions and boundaries of the study. It gives the most important processes and defines the temporal, geographic, and technology coverage [8]. Temporal coverage is the time that will be needed to complete the study. The location for the LCA or at least the features of that location will be discussed at the geographic coverage. Considerations about the state of the technologies used as a reference flow are also mentioned in the scope. The goal and scope stage concludes with the definition of the function, functional unit and reference flows.

1.1.2. INVENTORY ANALYSIS

The inventory is built up from all the unit processes of a system. These can be seen as all the steps that are needed to provide the function by one of the reference flows. With the functional unit the unit processes can be linked together. To stick with the example that was presented in section 1.1 in order to travel 1 kilometer by bicycle the production of a bike is required. During the lifetime of the bicycle approximately 29,200 km on average will be traveled (as example, no real data). Thus per kilometer of transport 3.425×10^{-5} unit bicycle is required. In order to link unit processes to the functional unit it needs multiplication with scaling factors.

Within the scope it is defined which processes are in the foreground (processes modeled by executor of the LCA study) and which are in the background (from databases, public references, and estimated data). In that way the foreground processes are more specific for the site of the performed LCA study, following from measurements or reports about the specific system. Every unit process has economic and environmental in- and outflows. The unit processes with the economic flows are presented in a flowchart. There is economical flow when there is economic value. For example flue gas from a gas turbine can be discarded by a system, but it can also be used again by a heat exchanger in a steam cycle. If it is used again the economic value is positive and it is defined as a good. With a negative value it is defined as a waste. The discussion about whether a flow has economic value is important in LCA and assumptions should be well described by the practitioner.

The inventory stage is the most time consuming phase of the LCA, because it includes data gathering. The level of detail in which the system is looked at can be chosen as such that the study will not be too extensive; the production of a single nail can be a LCA study on his own. It is possible to exclude processes from your LCA -this is called cut-off- but it is also an option to copy processes from databases. In common life cycle assessment cut-off is introduced for processes that contribute less than 1% to the total system.

Data for the inventory can be obtained in different ways: primary data for the foreground processes and secondary data for the background processes. Primary data consists of field research, reports and common sense estimations and assumptions. Secondary data can be found in databases and previous LCA studies. One of the available databases for this study is Ecoinvent version 2.2. [9]. Some unit processes that occur in the system might be multifunctional (have multiple functional flows). As will be explained later in section 1.1.5, this creates problems when solving the equations in a LCA study.

1.1.3. IMPACT ASSESSMENT

In the impact assessment phase of LCA the inventory results are interpreted and aggregated [10]. Aggregated means that all the emissions from the inventory are appointed to a specific impact category. To explain how this is done the category climate change is used as an example. Climate change is indicated by the influence of greenhouse gas emissions on radiative forcing and these gases all have different potential to contribute to this forcing. Radiative forcing is considered as the characterization indicator and global warming potential or GWP is the characterization factor. The baseline for GWP is 1 kg CO_2 and GWP is thus measured in CO_2-equivalence. Some gases have a different GWP than CO_2 like CH_4, which has a GWP of 21. The Intergovernmental Panel on Climate Change (IPCC) compiled a list of the emissions and there GWP for different time frames; 20, 100 and 500 years. These time frames are introduced due to contribution in radiative forcing of the gases. There is a difference in decay for greenhouse gases. For example CO_2 is a long-lived greenhouse gas, while CH_4 would be considered a short-lived greenhouse gas. Over long time periods the contribution of CH_4 will stay the same, because they decay much faster and do not cause additional forcing after the first couple of years. The contributions of CO_2 on the other hand will increase, because the radiative forcing decays in a much slower pace. Figure 1.3 shows these differences between the two gases. Yet, this discussion about characterization factors is not further needed, because that would imply a change of thesis topic. Different methods for the impact assessment of a LCA use different models in order to characterize all the emissions from the inventory.

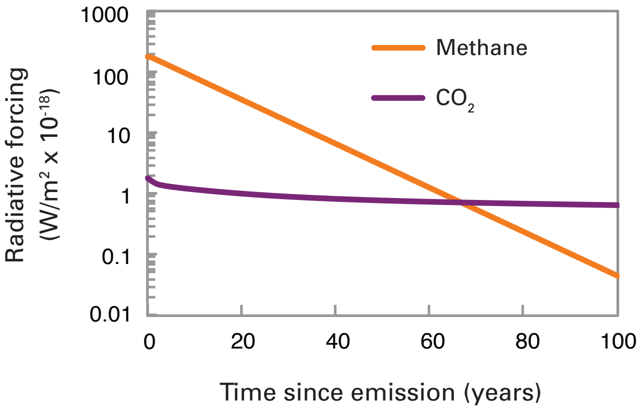

Figure 1.3: Radiative forcing CH_4 and CO_2 over time [1]

Another distinction between the different methods is how the final results can be interpreted.

- Endpoint results give values that represent damage on humans or the environment. Examples of methods that give endpoint results are Eco-indicator 99 [11] and Impact 2002+ [12].

- Midpoint results do not have a verdict about the values that evaluate the damage done on the environment, instead midpoint methods only give the outcomes for the different impact categories. CML2001 [8] is a method that gives midpoint results.

All the impact categories can be divided in three groups; baseline, study-specific, and other categories. The list of all the baseline impact categories can be found in the appendix A.1.

CML2001 is a method that includes characterization factors for all the baseline categories [8]. With the choice for a particular category the data used for the study must contain the emissions linked to this category. In order to include the category climate change a whole list of emissions must be included during the inventory phase. This causes problems with data gathering, because not all emissions can be found all the time. There are a lot of toxic substances that do not really fit in a specific impact category yet, because this is not accounted for by specific impact models. These toxic substances can be mentioned apart from the discussed categories.

1.1.4. INTERPRETATION

The results of the impact assessment need to be interpreted. In the interpretation stage the most significant contributors are identified from the contribution analysis. For studies with reference flows a comparison analysis can be done. It is important to formulate conclusions carefully, because there are always uncertainties that should be mentioned about the obtained results. These uncertainties are mentioned in the interpretation phase. Some analysis can be done that will help the understanding of the results. The sensitivity analysis will

Inconsistency is a risk in life cycle assessments. Examples of inconsistencies would be accuracy of the data that is obtained, the extensiveness of the gathered data and the date of the reference of the data. Databases might change over time, due to changes in production methods or new insights of processes in general.

LCA is a linear method, so with all information that is created as input for the program there will be an option to scale it all up. The downside to this feature is that not everything scales up linearly; the environmental impacts of the energy production of a 100 MW power plant will not be the same as 10 times a 10 MW power plant. This needs to be addressed in the research. The scale of technology will be discussed in section 2.3.

1.1.5. CALCULATIONS AND SOFTWARE

In section 1.1.2 the link between the functional unit and the unit processes is explained by the example of the bicycle. That example is used for simplicity, because with more unit processes the assessment will become a complex network of multiplications. Linear algebra is used to calculate the outcomes of the life cycle assessment and knowledge of linear algebra is required to follow the steps presented by Heijungs [13].

Every unit process exists of a block with economic and environmental flows in and out. The economic outflows of all the processes are included in the A matrix, and the environmental flows in the B matrix. The flows in have a negative value and the flows out are considered positive. Next to the matrices there are three vectors needed to complete the calculation; the $\bar{f}$ for the alternatives (reference flows), the $\bar{s}$ for all the scaling factors and the $\bar{g}$. The $\bar{g}$ is the solution that needs to be found, which are the environmental impacts of all the reference flows. The unknowns in this problem are the scaling factors and the eventual environmental impacts, so $\bar{f}$ and $\bar{g}$. These can be found with the following equations:

$$A\bar{s} = \bar{f} \tag{1.1}$$

The A matrix multiplied with the scaling factors will need to give the reference flows as an output, this is also stated before as; the unit processes linked to the functional unit, as stated in section 1.1.2. The scaling factors are unknown, but A and $\bar{f}$ are known. So equation 1.2 will give the $\bar{s}$:

$$\bar{s} = A^{-1}\bar{f} \tag{1.2}$$

The same applies for B, but now the scaling factors will give the $\bar{g}$ as an outcome. With replacing $\bar{s}$ with formula 1.2 the $\bar{g}$ can be calculated with only known variables, formula 1.4.

$$B\bar{s} = \bar{g} \tag{1.3}$$

$$\bar{g} = BA^{-1}\bar{f} \tag{1.4}$$

These equations can only be solved if the A matrix satisfies the two following conditions: A must be square and A must be non-singular (A^{-1} needs to exist, so determinant $A \neq 0$).

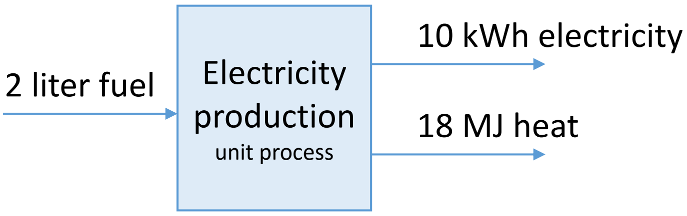

Figure 1.4: Multifunctional process [2]

Table 1.1: Economic flows with rectangular A matrix, example by Heijungs [2]

	Electricity	Fuel
Electricity	10	0
Fuel	-2	100
Heat	18	0

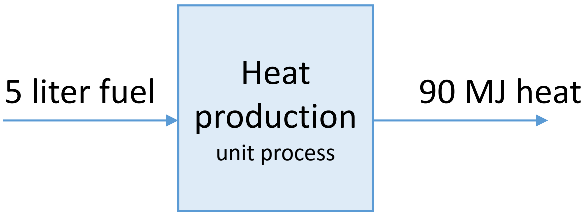

Figure 1.5: Substitutioning [2]

Table 1.2: Allocation by substitution, example by Heijungs [2]

	Electricity	Fuel	Heat
Electricity	10	0	0
Fuel	-2	100	-5
Heat	18	0	90

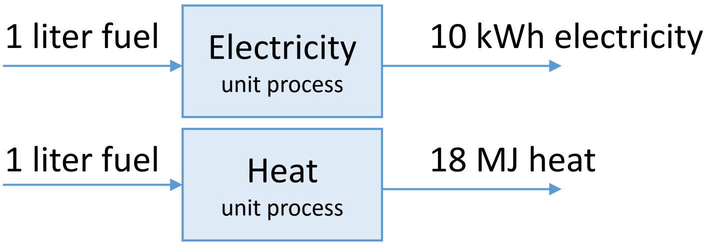

Figure 1.6: Partitioning [2]

Table 1.3: Allocation by partitioning, example by Heijungs [2]

	Only electricity	Fuel	Only heat
Electricity	10	0	0
Fuel	-1	100	-1
Heat	0	0	18

This has implications for the economical flows of the unit processes, because matrix A needs to be a square. Some of the unit processes can be considered multifunctional, which implies that they have multiple functional flows, and this will make A rectangular. Table 1.1 shows an example process that is rectangular. It produces not only electricity, but also heat. Thus, as a result the process becomes multifunctional (function of 'electricity' and 'heat' production, see figure 1.4). Solving such a multifunctional process is called allocation [2] and it can be done in two ways; substitution or partitioning. Substitution is including a new process that can function as a substitute for one of the functional flows 1.2. In this example the heat production process is an additional process that performs one of the same functions of the multifunctional process, see figure 1.5. The multifunctional process delivers electricity and heat, thus the heat production process of figure 1.5 is avoided. Therefore substitution is sometimes referred to as the 'avoided burden method'. The multifunctional process can also be divided into multiple processes that have only one functional flow, also known as partitioning. In table 1.3 the factor for fuel used for electricity or heat is 0.5, the factor that is chosen needs to be supported by arguments. This 0.5 is called the allocation factor. With end of life considerations allocation is specifically interesting for recycling processes [14].

1.2. OTEC

Ocean thermal energy conversion (OTEC) is a technology that makes use of the temperature difference in the ocean. At large depths typically the ocean has a temperature of approximately 5 $^\circ C$ and the temperature at the surface of the ocean can reach temperatures of 28 $^\circ C$, due to heating by the sun. The principle is based on a thermodynamic Rankine Cycle in which a working fluid is used that boils at relatively low temperature. The details about this process are presented at section 1.2.1. At the moment there are not a lot of existing projects, the list of table 1.4 shows all of them.

With rising prices for fossil fuels and more focus on renewable energies OTEC might be able to gain a foothold in the future energy market. Especially interesting are small island regions because of their potential and dependency on fossil fuels. An important advantage compared to other renewable sources is the constant output of energy, OTEC is a baseload technology [15].

Table 1.4: OTEC plants build to date

Year	Location	Initiator	Scale	Type of cycle	Depth [m]	Type of plant
1930	Cuba	Georges Claude	22 kW	Open	<700	Shore
1979	Hawaii	Mini OTEC	53 kW	Closed	670	Floating
1980	Hawaii	OTEC-1	1 MWe	Closed	670	Floating
1982	Nauru	Japanese Consortium	100 kW	Closed	580	Shore
1984	Japan	Saga University	75 kW	Closed		Lab model
1992	Hawaii	NELHA	210 kW	Open	2040	Shore
1995	Japan	Saga University	9 kW	Closed		Lab model
1996	Hawaii	NELHA	50 kW	Closed		Floating
2001	India	NIOT	1 MW	Closed	1100	Floating

1.2.1. WORKING PRINCIPLE

This report is not focused on the technological aspects of the working principle of OTEC, but the basic principles should be clear. OTEC is based on a thermodynamic cycle with a working fluid that evaporates at relatively low temperatures. The working fluid that is used by Bluerise is a mixture of ammonia and water. The mixture is pumped through the evaporator in which the warm ocean water evaporates the mixture. This evaporated mixture drives a turbine and the mixture expands from high enthalpy to low enthalpy. After the turbine the mixture flows through the condensor, which turns the low enthalpy gas into a fluid mixture. This cycle is schematically shown in figure 1.7.

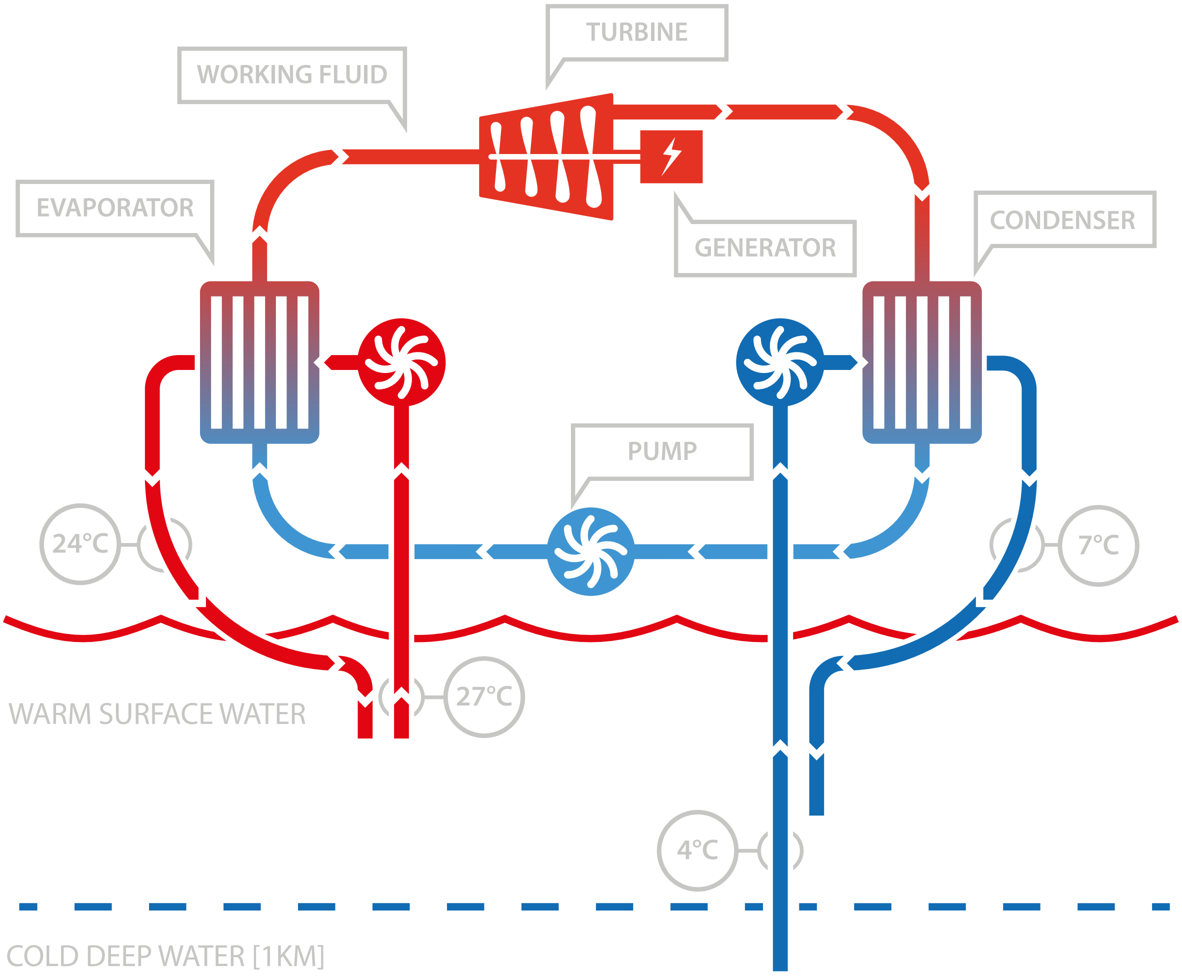

Figure 1.7: Schematic projection of OTEC thermodynamic cycle

The theoretical maximum efficiency of this system can be calculated with the formula based on the Carnot cycle, see equation 1.5. If the thermal energy is transferred into work in the most efficient way OTEC only achieves 7,6% efficiency. Although this efficiency is extremely low, the source of energy is abundant, clean, renewable and free [15].

$$\eta = 1 - \frac{T_C}{T_H} \tag{1.5}$$

The biggest downside of the low temperature difference is the implication for the heat transfer process. Heat transfer is based on a heat transfer coefficient times the surface times the temperature difference. The coefficient is dependent on a specific material and the temperature difference is small, thus increase of area is required to increase heat transfer. The materials that can be used are limited because sea water affects most materials. If for example aluminium would be considered for the heat transfer plates approximately every 10 years these plates would have to be replaced because of corrosion by the seawater. Next to the corrosive seawater the working fluid consisting of a mixture of ammonia and water can have corrosive effects in the long run on materials (steel and aluminium) as well [16].

1.2.2. IMPACT DURING OPERATION

The influence of OTEC on the ocean ecosystem would be important to consider, but there is no consensus yet about the quantification of this impact. In this section the impact of OTEC that is known from literature will be discussed. The impact will be included in the LCA, but only those that can be quantified. The reason is that there is no data available, because of the minimal amount of operational OTEC projects. The following implications on the ocean ecosystem are mentioned;

- High level of nutrients in cold water
- Direct impingement of marine life
- Chlorine use to clean the heat exchangers
- Dissolved CO_2 in cold ocean water is likely to be released due to temperature rise and pressure release [17]

The study of Abbasi poses a critical view on the disadvantages implicated by renewable energy sources [18]. Among others, the OTEC system is reviewed and the downsides are argued. OTEC requires large quantities of water and the influence on marine life could therefore potentially be large. Flows of warm and cold water into the plant may impinge on fish or other forms of life. Harrison performed a study in order to see the influence of an OTEC system on marine life [19]. The most important conclusion of this report was that research on an operating OTEC is needed to be more conclusive about the presented data. The basis of the study was a $40MW_e$ OTEC plant and it discussed the items that are mentioned above. The direct impingement on marine life has its implications but is only of importance for small sea life. There was an increased local mortality rate for some species of plankton. However, as plankton habitats tend to be vast, this increase will be statistically insignificant [19].

The cold water that is pumped up from 1,000 m and eventually discharged at 130 m depth has high nutrient values and that might influence sea life in a harmful way due to eutrophication. Eutrophication can cause a depletion of oxygen in the water due to excessive algae growth and thereby induce high mortality of marine life. However, higher nutrient values could have a positive effect on marine life as well. High nutrient values will enhance some fish populations due to higher availability of food. Makai Ocean Engineering performed a study in order to predict implications of discharge plumes of OTEC at different depths [20]. The study published by Rocheleau and Grandelli concludes that below 130 m the higher nutrient values will not cause significant growth of phytoplankton, because this growth is light-limited. The higher levels of nutrients can also be used in ecoparks, but the combination of OTEC with ecoparks is beyond the scope for this assessment.

The chlorine is required to protect heat exchangers from biofouling. With the discharge of the warm and cold water mixture the chlorine will end up in the ocean [18]. Biofouling is the accumulation of microorganisms on wet surfaces and this will eventually affect the efficiency of the heat exchange. The chlorine indeed might be toxic for the marine environment; especially near the plumes the concentrations might be too high [19]. However, Bluerise will use plate heat exchangers that are cleaned without the use of chlorine.

The cold water flow has CO_2 gas dissolved in the water and some of the gas will be released due to elevated temperatures and pressure release. The temperature of the water will rise in the condenser and the pressure is released because of the pressure difference between 1,000 m depth and atmospheric pressure. For closed cycle OTEC design the CO_2 emission during operation is 0.0008kgCO_2/kWh [17]. The emission during operation is incorporated within the LCA model.

1.2.3. PREVIOUS LCA STUDIES OF OTEC

Previous studies related to the CO_2 emissions and energy payback time of ocean thermal energy conversion are conducted in Japan [2]. Uchiyama performed a life cycle assessment of wind and solar energy in and a table with the energy payback time of 4,58 years for OTEC was included [21], the actual assessment of the OTEC system was not found. The study by Tahara performed an inventory of the materials required for 100 MW OTEC, based on a study by Uchiyama of a 2500 kW OTEC plant [22]. The scaling factor that is used is approximately 0,56, which can be obtained from a follow-up study by Tahara [23]. It is said that production of the system is taken into account, but background information about the manufacturing processes or assumptions for transportation and installation are not mentioned. Data is obtained from the Resources counsil, Science and Technology agency, this data is from the year 1983, related to processes in Japan and presumably related to embodied energy for materials and manufacturing processes. The energy payback time for 100 MW was calculated to be 0,46 years, but there was a mistake made with the estimation of yearly electricity production. The energy produced per year by 100 MW OTEC was estimated to be 5,66E6 GJ, but should be 2,018E6 GJ [3] based on the assumption of 0,8 capacity factor and 20 % energy consumed by pumps and other equipment. If the calculation was performed correctly they would have obtained an energy payback time of 1,31 year.

Nomura et al. investigated the life cycle emission of oxidic gases for different power generating systems [24]. The same database is used as by Tahara and presumably both are based on the same research. The study also considered a 2500 kW OTEC system. It mentions that the largest fraction of emission, around half of the total emissions, comes from material production for the generating equipment (heat exchangers). This is due to the requirement of large amounts of titanium and manufacturing.

Banerjee et al. estimated the emissions and energy payback time of 100 MW OTEC and they based there values on the study by Tahara and is not much different [17]. They do however mentioned the emissions during operation which is included in this study. For the energy payback time of 100 MW OTEC they estimated 1,33 years and for the emissions 0,0124 kg CO_2/kWh.

1.2.4. BASELINE LCA OF OTEC

This research is not very specific in the sense that an actual OTEC system could be investigated, because as shown previously not a lot of OTEC systems are build to date. OTEC is not yet realized by Bluerise and there were no resources to explore one of the existing projects.

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[2] Some of these were not available in English, so unfortunately these could not be included in this study.

[3] $100 \cdot 10^6 \cdot 0,8 \cdot 0,8 \cdot 3600 \cdot 24 \cdot 365 = 2,018 \mathrm{GJ/year}$

Instead it is chosen to use the experience of Bluerise to make a reasonable estimation of one configuration. For now 10 MW offshore OTEC is considered. This scale is based on the feasibility report of Bluerise and will be a logical next step for them after proving concept. For typical island regions 10 MW would be a scale that can significantly contribute to renewable electricity production. Curacao has 195 MW installed capacity for electricity and the peak load is approximately 105 MW according to Aqualectra [25]. Implementation of 10 MW OTEC would then increase the electricity produced by renewable energy with almost 10%. Another consideration is that 10 MW is approximately the point at which offshore will be more suitable than onshore. With larger OTEC energy production the cold water pipe that starts onshore will face more complexity with installation and requires significantly more material. The life cycle assessment of 10 MW OTEC offshore could add new information to this discussion. It is expected that the offshore design will be leading when large scale electricity production by OTEC will be implemented in the future.

2

GOAL AND SCOPE

2.1. GOAL

In this thesis the environmental impact of an ocean thermal energy conversion system is investigated. The emissions related to the whole life cycle from raw materials till end of life are considered. Results will be used to identify the components that have the largest contribution, which is called 'hot spot' or contribution analysis. A few scenario's for different heat transfer plate materials will be compared. Next to this there will be a comparison between OTEC and other options to produce electricity. The final aim is to see how different energy mix scenarios will perform for small island regions.

From this aim the main question of this thesis can be described as followed:

What is the life cycle impact of electricity supplied by 10 MW ocean thermal energy conversion compared to reference flows and how would it perform in an energy mix scenario in small island regions?

This question will be answered by first carrying out a life cycle assessment of an ocean thermal energy conversion system. The results of the impact assessment will be used in combination with a few scenario's possible for electricity supply on small islands. So the sub questions are:

- What is the life cycle assessment of OTEC?
- What is the life cycle assessment of diesel, wind and PV?
- What are realistic energy scenarios for small islands regions suitable for OTEC?

The study is a master thesis project and is accommodated by Bluerise, which is a start-up at YES!Delft. They are devoted to implement OTEC in the near future and are doing a lot of research in this field. The supervision is done by the following commission:

Supervision:	Dr. W. de Jong,	TU Delft	Experience with commissioning LCA projects
	G.A. Tsalidis,	TU Delft	LCA of co-firing biomass
Committee:	Prof. dr. ir. J. C. Brezet,	TU Delft	Several publications in the field of LCA
	Dr. G. Korevaar,	TU Delft	Experience with commissioning LCA projects
	Ir. B. J. Kleute,	Bluerise	No experience with LCA

Theoretical background about LCA for conducting this study is gathered during the course Advanced Course on Life Cycle Assessment at the Faculty of Science Institute of Environmental Sciences at the University of Leiden. The TU Delft has the ambition to include more LCA related courses and studies in their program as well and this project illustrates that.

This study will provide interesting information for Bluerise about their system and its unanticipated implications. Moreover, political organizations could make use of this study for energy management purposes. Some stakeholders might disagree with the presented results and therefore it is needed to get an expert review, which is obligatory for comparison LCA studies.

From the goal description and the final aim it can be concluded that LCA is the right method to be used. Two main reasons are the hot spots that need to be found for the OTEC design and the comparison between the different reference flows to fulfill the need for electricity. As stated in 1.1.1 LCA is suited for both purposes.

2.2. SCOPE

The timescale of the study is nine months, this includes; three months of literature review, five months of data gathering and verification and one month of finalizing the report and preparation for the final presentation.

The areas of interest are small island regions that have enough OTEC potential [15]. As a case study Curacao is an interesting option, because of Bluerise's experience with the island. In Curacao the project for implementation of small scale OTEC is closest to realization. The most important aspect of the location is the transport that is needed. Other local influences as for example specific efficiencies of the Curacao harbor are neglected, because there were no opportunities to visit Curacao and investigate the local conditions.

The reference flows should be feasible for energy generation at this location, which implies that some competitive energy sources can be excluded from this study. With 105 MW peak load coal and nuclear are no viable options for Curacao and can therefore be excluded from this study. Electricity in Curacao is currently supplied by diesel generators 79% and wind turbines 21%, so these are important reference flows [26]. Photovoltaic energy could be implemented and is therefore suitable as well.

The environmental impacts of OTEC during construction will be allocated to the input of raw materials, production processes of the components, transport to the site, and assembly processes at the site. The baseline impact categories from table A.1 are seen in most LCA studies, yet the practitioner is free to choose categories. Climate change is the category that can be seen as most relevant for this LCA study, because attention for renewable energy sources are there due to their lower contribution to climate change. Other baseline categories retrieve less attention by those who are unfamiliar with LCA, therefore it will have less priority. The wishes of Bluerise are to address at least climate change and energy payback time [1]. Other emissions like CO, SO_2, NO_x, but also water (as waste) could be interesting additions. Another suggested topic was to look into future scarcity of materials and how it will influence the LCA, but there is no time constraint in LCA which makes it linear and not dynamic. On the other hand it should be possible to adept the LCA model every year and change the conditions.

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[1] Energy payback time is not an impact category, but it can be estimated from all the gathered data

In this thesis the preference is given on midpoint results, as discussed in section 1.1.3, because it should be prevented to end up in a debate about the definition of damage on the environment. Another reason is that climate change is the most interesting category and this is only given as a midpoint result. Whatever the consequences are of climate change are thus not discussed in this study.

Data collection was mostly done based on literature and databases. In this thesis the CMLCA software was used to import the Ecoinvent database. In Ecoinvent most of the processes are linked together. As an example in order to produce the good *'G7, steel'*, steel itself is required (e.g. for mining equipment). This is useful, because it can be seen what the unit processes are to produce a certain good. It is also possible to import everything in Excel, yet this would be a cumbersome method because the data provided by Ecoinvent is very extensive. Models for inventory (databases) and impact assessment (CML2001) can be imported into CMLCA without any delay. The downside of the program is that there is no real function to make graphs and figures, but there is an adequate function to copy results to Excel. Other software like Gabi and Simapro were also considered, but these were not available at all time and have no clear advantage over CMLCA other than a better interface.

Before the data is used most of the time the processes need modification in the form of scaling, addition or reduction of information. An important issue with the use of Ecoinvent is that some processes are not sufficiently documented, which is the case for a small part of the database. Another issue is that some data is only applicable to a certain location. The database is specialized in the area of energy, which makes it very applicable to this thesis. The LCA is already uncertain due to the uncertainties within the OTEC design. Average values of the database will therefore represent a sufficient approximation for this study. Another positive side effect from making use of Ecoinvent is that all known emissions are included, thus with the impact assessment all baseline categories give an output.

In the case of OTEC it is sure that the contributions to the environmental impact are mostly related to the raw materials and construction phase of the life cycle. The environmental impacts on marine life are possibly negligible and also outside of the scope of this study. It is excluded from the study because of the lack of data that is available. During operation no emissions are expected other than the CO_2 emission due to the condition changes of the cold water, which is 0.0008 kg CO_2/kWh [17]. Other emissions during operation are related to maintenance and these will be neglected. The reason is that OTEC has a very high capacity factor [15]. In order to perform maintenance only small contributions can be expected for transport.

With contributions are mostly related to the raw materials and construction of the OTEC system, it is essential to look at the processes that will produce the required components. Another aspect that will have great influence on the LCA is the recycling rate that is considered and how recycling is modeled. The assumption is that all the recycling processes are closed loop recycling, because for the considered materials (steel and titanium) there is no significant loss of quality after the recycling process. Material that is not recycled is either considered to be incinerated or ends up in a landfill. Closed loop recycling is based on formula 2.1, with E_p = energy for production, E_r = energy for recycling and E_D = energy for disposal [27].

$$E = (1 - R) \cdot E_p + R \cdot E_r + (1 - R) \cdot E_D \tag{2.1}$$

2.3. FUNCTION, FUNCTIONAL UNIT, ALTERNATIVES AND REFERENCE FLOWS

The function of electricity production can be fulfilled by different power generation options, these are the reference flows of the study. These flows can be compared in the LCA study and will give useful information for the future discussion of energy supply.

In table 2.1 the function, functional unit and reference flows are given. From the glossary of terms of the LCA handbook: the function is the service that is provided by a product or system, the functional unit is the quantified function provided by the system that is under study, and the reference flow is the representation of one specific way of obtaining the functional unit [8]. In other words; 1 kWh of electricity can be supplied by reference flows; OTEC, wind energy, PV and diesel.

Table 2.1: Function, functional unit and reference flows

Function:	Production of electricity in Curacao
Functional unit:	1 kWh of electricity
Reference flows:	Production of 1 kWh electricity by 800 kW Wind Turbine
	Production of 1 kWh electricity by 3kWp PV
	Production of 1 kWh electricity by 10 MW OTEC
	Production of 1 kWh electricity by 10 MW Diesel generator

The reason that the functional unit is introduced is that the function can be quantified in many different ways, so in order to be consistent throughout the study the same quantification is needed for all the reference flows. The output of power plants is usually given in megawatts, but this is not the best option for the FU. Installed wind power in megawatts is the rate at which the turbine can produce energy (power), not the amount of energy that it generates in a certain time period. The function; 'production of electricity' is measured in the amount of energy that is produced, not the rate at which this energy is produced. To conclude, a better option would be to see the output in the energy form rather than the power form, so in [MWh] or [kWh]. Another discussion is that OTEC is a base load energy source and wind energy is a fluctuating source, OTEC delivers a constant output of energy (day and night) and wind energy is dependent on occurrence of wind. This problem is partly solved when the capacity factor is included in the calculation. The capacity factor is the actual output of energy divided by the maximum possible output of energy, so this also implies [kWh]. However only considering the capacity factor is not enough, as will be explained in chapter 6. The influence of scale on the life cycle assessment is discussed for the reference flows. The scale for diesel is not important, because the emissions are related to the use phase, as will be shown in section 5.2.2. However the efficiency of the burned diesel will, to a large extent, determine the impact (with lower efficiencies more fuel is burned). The efficiency for different systems and scales will diverge. In this thesis it is assumed that variance between efficiencies is negligible. For PV technology the scale would not influence the life cycle impact results under the condition that more of the same type of PV panels are installed. Yet the inverter and electric installation [2] could be different

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[2] Approximately 10% of the CO_2 emissions are related to inverter and electric installation [28]

for different scales of PV installation, this is not incorporated in this thesis. For wind energy there is also no relation to be found between the scale and changes of the life cycle assessment. Yet a small advantage on larger turbines is expected due to scaling factors that might decrease the relative amount of material per installed capacity. Manufacturing processes could potentially be better optimised for larger scale of wind turbines or PV installations. For OTEC the influence of scale will be shown in chapter 5. The improvement of PV and wind technology will reduce the environmental impact of the technologies as well. Several wind turbine manufacturers, such as Siemens [3], Enercon [29] and Gamesa [30], are performing life cycle assessments in order to reduce the emissions of the life cycle stages of their turbines. Next to the capacity factor the lifetime of the technology (not for diesel) is very important for the outcome of the life cycle assessment. The lifetime of the plant will determine eventually how much energy is produced and thus directly influences the impact score. For OTEC the lifetime of the plant is considered to be 30 years. The lifetime for PV is between 20 and 30 years [28]. The lifetime considered for the wind turbine is 20 year for moving parts and 40 years for fixed parts [31].

2.4. SYSTEM BOUNDARY

Figure 2.1 shows the flow diagram of the system boundaries of this study for 10 MW OTEC. In this diagram the considered foreground processes (blue) and background processes are distinguished. It can be seen that the titanium production is more extensively focused on than the other processes, because new unit processes are constructed with the goods required for titanium production. Most other goods are chosen from Ecoinvent without a lot of adaptation, such as *'G103, transport'* or *'G1629, disposal'*. It can be seen that the following are all within the system boundary; raw materials, transport and end of life. The included processes for equipment and manufacturing are not really visible, but are included as goods for the unit processes. Examples are *G3452, G3457* for manufacturing and *G2095, G2099* for equipment (respectively metal working factory and metal working machine). Excluded from the system boundary are; onshore grid connection and other impacts during operation besides CO_2 emissions, as discussed in section 1.2.2.

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[3] http://www.energy.siemens.com/

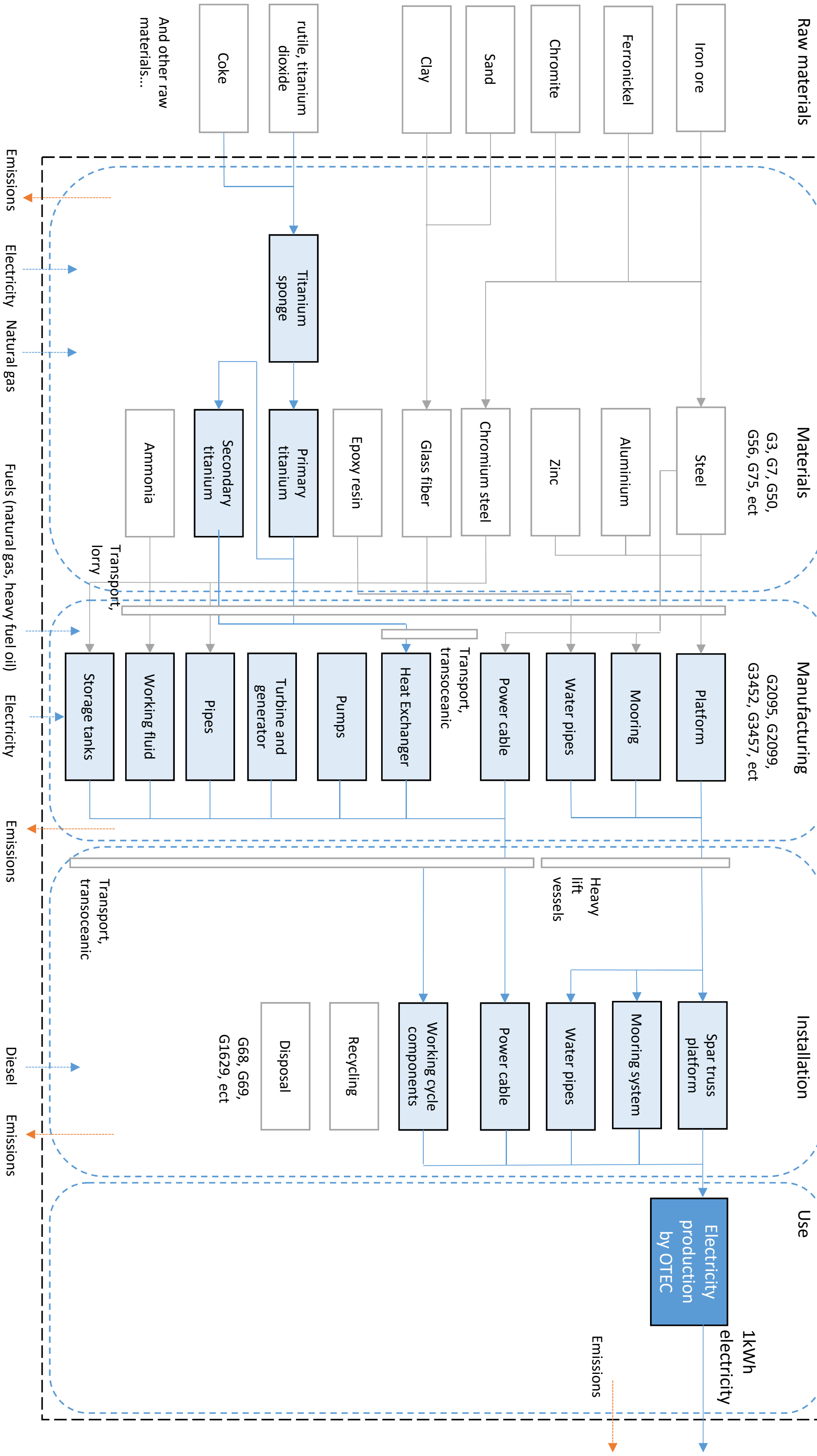

Figure 2.1: Flow diagram of the system boundaries for 10 MW OTEC

The system boundaries for wind energy (figure 2.2) and PV (figure 2.3) are obtained from the studies of Ecoinvent [3].

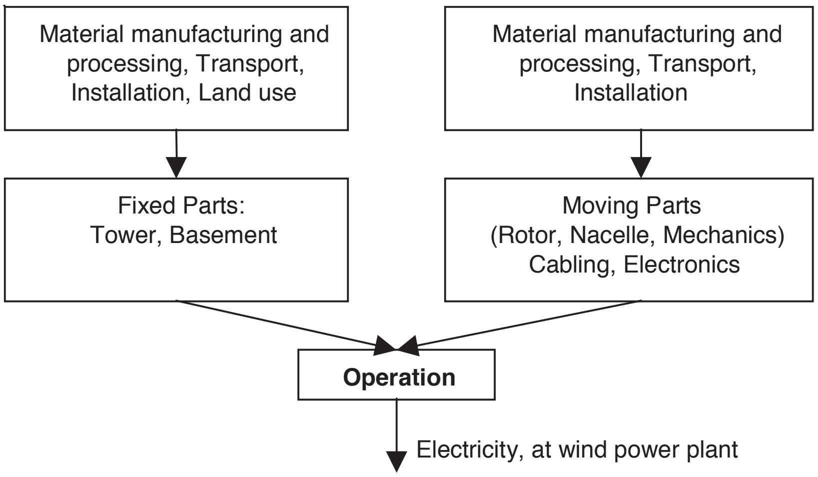

Figure 2.2: Flow diagram of the system boundaries for wind [3]

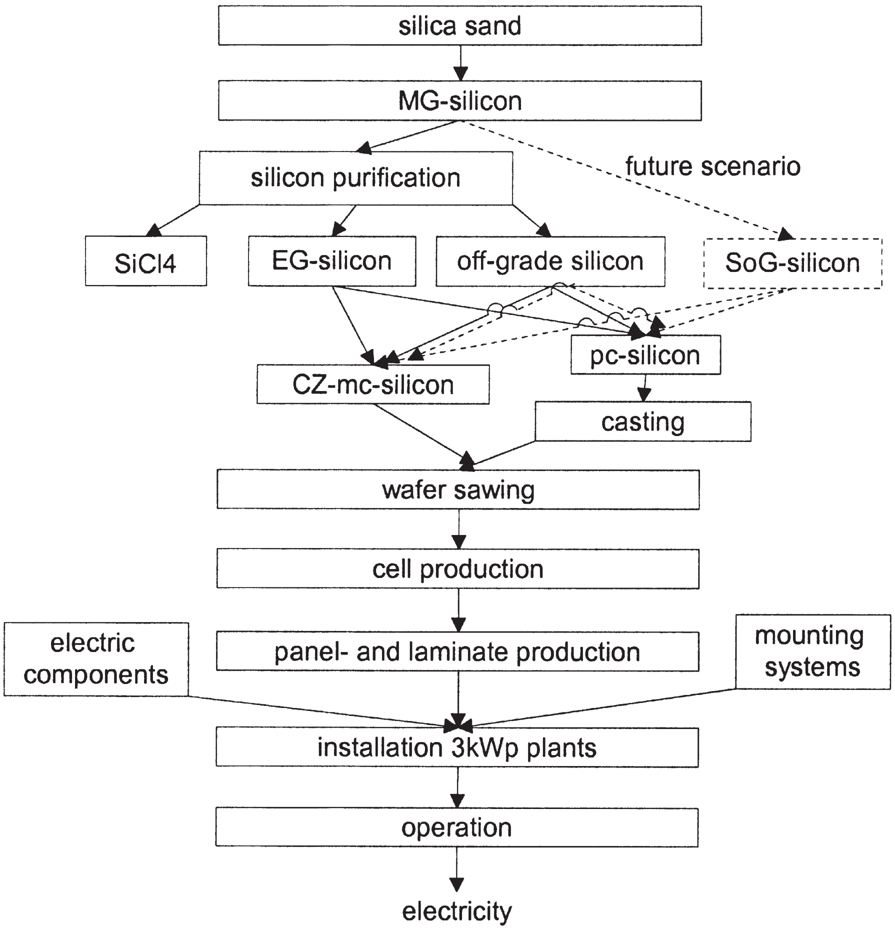

Figure 2.3: Flow diagram of the system boundaries for PV [3]

3

INVENTORY ANALYSIS

3.1. INTRODUCTION

In this chapter the inventory analysis is presented. The inventory includes all the data that is required to construct the unit processes for the 10 MW OTEC system. In table 3.1 the components of OTEC and their estimated mass are shown.

Table 3.1: Table of 10 MW OTEC components

Component	**Part**	**Material**	**Mass (kg)**
Working cycle	Heat Exchanger	Titanium grade 1	3.07×10^5
		Stainless steel (AISI316Ti)	3.13×10^5
	Working fluid	Ammonia	1.55×10^5
	Storage tanks	Stainless steel (AISI316Ti)	2.57×10^5
	Piping	Stainless steel (AISI316Ti)	9.00×10^4
Water pipes	CWP	Composite	1.66×10^6
	Discharge pipe	Composite	3.55×10^5
	WWP	Composite	1.66×10^4
Platform	Structure	Steel	1.05×10^7
Mooring	Chains	Steel	7.8×10^5
	Wire	Steel	2.56×10^5
	Anchor	Steel	2.00×10^5
Power distribution	Cable	Copper	1.78×10^4
	Cable	Steel	1.64×10^5

The components and their related processes will be discussed in this chapter. The different stages of the life cycle of an OTEC system are acquiring raw materials, manufacturing, transport and decommissioning. All the stages require energy and contribute to the impact of the system. The use phase is also included as mentioned in section 1.2.2. Downtime due to maintenance is accounted for by the capacity factor and other aspects of maintenance are assumed to have negligible contributions [1]. The cut off criteria for life cycle assessment would be around 1% of contribution. The cut off in this inventory is based on engineering insight in the order of magnitude of the processes. The processes used from Ecoinvent did not require a cut off criteria. With the total inventory a model is configured in CMLCA. The related flow diagrams are shown in appendix A.2. Throughout the whole inventory data from Ecoinvent is used and the goods will be indicated by their number of the Ecoinvent database.

Some of the assumptions are valid for most of the components. These general assumptions are;

- Average production processes from Ecoinvent are used, no data from manufacturers. The goods considered are *'G3452 metal working factory operation'* and *'G3457 metal working machine operation'*.
- On land transportation is assumed to be 100 km by *'G132 lorry, >28 t, fleet average'* for all materials. Calculations for the service of transport are based on the unit tkm, which stands for ton kilometers (thus 1,000 kg of good is transported 1 kilometer).
- Offshore transportation is either by *'G103 transoceanic, freight ship'* or *'G593 transoceanic, tanker'*.
- If there is no mention about lifetime it surpasses the 30 years lifetime of the system.
- Recycling rate of steel (and chromium steel) is 0.37 [32].

3.2. SPAR TRUSS PLATFORM FOR 10 MW OTEC

Offshore OTEC is built on an offshore platform comparable with platforms used in the oil industry. Several different configurations are possible and it is hard to reduce the options to just one design. The best possible design for OTEC is not yet known to date, but the spar truss platform is one of the configurations that shows a lot of potential. For now the spar design is the one elaborated on, because this design is adopted by Bluerise. The spar is well applicable for OTEC as can be seen by a feasibility study [15]. It is a floating device, which floats vertically in the water. The construction does not tilt because of an high ballast mass approximately 135 meter below sea-level, while it floats because of buoyancy, achieved by enough volume of air under water. Eq. 3.1 gives the buoyancy force as a result of the difference in density between water and air. The spar has a diameter of 20 meter and it has a length of 145 meters in total, figure 3.1 illustrates the design of the platform.

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[1] In order to perform maintenance only small contributions can be expected for transport. With the use of the calculation fro transport in section 3.2.1 1.5×10^6 tkm is obtained which is a factor 1×10^3 smaller than transportation of the platform. The replacement of equipment is accounted for in the assessment by lifetime estimations.

Figure 3.1: Total overview platform with numbered components used to construct table 3.2 [4]

It consists of a hard tank that creates the acquired buoyancy and stores OTEC components, the truss section with heave plates and the keel tank or ballast [33]. The heave plates will provide damping of vertical movements of the platform. The mass and materials required for the platform can be estimated from different sources. Data is estimated from pictures [4], sketches [33], sheets from the offshore course: 'Bottom Founded Structures', web-based information [34] and the Offshore Handbook by S.K. Chakrabarti [35]. The pictures and are made of the Medusa platform which is a project of Mc Dermott International. The Medusa platform is produced in Jebel Ali, Dubai, has a 30 m diameter and weighs 12,800 ton (excluding topsides and mooring). Topside and mooring have a combined weight of 5,600 ton. The size of the Medusa platform is used as a reference. With the information of the mass and sizes of the platform in combination with figures 3.1 and 3.2 an estimation could be made for an OTEC platform design.

$$B = (\rho_f - \rho_a) \cdot V_{disp} \cdot g \tag{3.1}$$

Figure 3.2: Platform ring with numbered components used to construct table 3.2 [4]

Table 3.2: Platform structure volume estimations (all units are in meter), r=radius

nr.	component	N	width	length	height	r_{out}	r_{in}	V [m^3]
1	Outer circle	1			50	10	9.95	157
2	Inner structure	148	0.05	0.25	50			93
3	Circle structure inside	160						250
4	Truss large tubes	4			85	1	0.9	203
5	Truss small tubes	32			23	0,25	0.2	52
6	Truss plates	3	25	25	0.1			188
7	Truss ballast	1	25	25	10			
	Total							942

The different components and numbering of the spar truss platform can be seen in table 3.2. The volume of the components are calculated from the figures 3.1 and 3.2. The aim was to determine the volume of the steel for the whole structure. The risk with estimations based on pictures is that not the whole structure is visible and therefore it might not be possible to distinguish hollow from solid parts. All pipes are assumed to be hollow, due to structural advantages. The resistance against bending with same amount of material will be larger with hollow pipes in comparison with a solid rod. The ballast as can be seen in the photograph 3.1 resembles a solid block of steel. However, that would imply that the weight of the ballast is more than 3.6 times the weight that can be kept afloat by the buoyancy force. In other words the platform would sink. Thus it is more likely that the ballast weight consists of different hollow modules welded together, the volume of the steel required is estimated by the force balance shown by equation 3.2. The remaining force will be the force implied by the ballast. It should be noted that the hollow structure itself would add buoyancy. Yet, during installation it will fill itself with water, which was also mentioned in a movie from Technip [34]. Buoyancy in the ballast is not beneficial, because the function was to create stability. In table 3.3 masses and implied forces are shown, resulting in an equilibrium situation for the platform.

Table 3.3: Platform mass estimations and implied forces

Component	**Mass [kg]**	**Force [N]**
Structure (platform: hard tank and truss)	7.34×10^6	7.21×10^7
Load	2.05×10^6	2.01×10^7
Buoyancy		1.23×10^8
Ballast	3.17×10^6	3.11×10^7

$$\begin{gathered}\sum F = 0\\ F_{buoyancy} - F_{structure} - F_{load} - F_{ballast,max} = 0\\ F_{buoyancy} - F_{structure} - F_{load} = F_{ballast,max}\end{gathered} \tag{3.2}$$

Another approximation for a spar truss platform is given by the offshore handbook and comes down to 1.1×10^6 kg deck steel, 1.87×10^7 kg steel for column steel and 2.0×10^6 kg mooring steel [35]. These values are for a 3,000 ton payload, 1,000 ton more than required for the OTEC equipment.

Other parts that can be seen from the figures are the silver-colored parts on the side, which are the zinc anodes used as cathodic protection. The zinc anodes will corrode instead of the iron. At the top of the structure it can be seen that there is a supplemental coating layer. The topside of the platform consists of docking facilities, a helicopter pad and OTEC components that could not be positioned in the hard tank. The topside consists of a steel frame with concrete and the mass is included in the mass of the load, which is defined in the feasibility study [15].

To conclude, for the spar truss platform of OTEC the required mass of the specific materials is estimated and the different manufacturing methods for the parts are known. The masses for the OTEC platform of table 3.3 are compared with the spar truss platform in the Offshore Handbook, which is shown in table 3.4. The ratio of payload and structure weight gives that the structure of the OTEC platform is slightly underestimated, while the mooring steel is overestimated. This will be addressed at section 5.2.1.

Another option is to check the mass of the platform with key figures from the offshore for floating devices. These were also used by Bluerise to estimate the weight of a vessel and are based on volume of submerged or dry construction. With the diameter (20 m) and the length of the platform (145 m) these volumes can be estimated, approximately 115 meter will be submerged. Key figure for submerged volume is 0.25 mT/m^3 and for for dry volume is 0.15 mT/m^3 (mT = metric tonnage). The total mass will then come down to 10,000 ton of steel, which is comparable to the other estimations.

Table 3.4: Offshore Handbook compared with OTEC platform estimation

	Offshore Handbook tons steel	**OTEC platform** tons steel
Payload	3,000	2,050
Deck steel	1,100	not considered
Column steel	18,700	10,510
Mooring steel	2,200	3,330

3.2.1. PLATFORM IN CMLCA

In Ecoinvent there is a process for an offshore platform produced in Europe *'P1552 platform, crude oil, offshore'* [36]. This platform is in some regards the same as the platform that is going to be used for OTEC, but it is not a floating platform. No data could be gathered from the offshore industry, therefore the data of Ecoinvent is used and supplemented with the information obtained of the Medusa platform, section 3.2. The most important inputs for the Ecoinvent platform considering manufacturing are *'G146: electricity, medium voltage, production UCTE'* (UCTE = the average electricity in Europe, the location in the model is changed to Finland) and *'G156: diesel, burned in building machine'*. The CO_2 emissions of these goods are high, but there is an uncertainty about these numbers. In the supporting documents of Ecoinvent the electricity required for the construction of the structure and the module could be found. The diesel was required for the building machines and for transportation over sea [36]. The platform for Ecoinvent is estimated to be around 2,500 ton and that implies an electricity requirement of 3.8 kWh/kg of manufactured mass, in comparison, for the production of a wind turbine this number is only 0.5 kWh/kg [31]. Other references for energy requirement of large offshore structures in Ecoinvent are the transoceanic freight ship or tanker. For the building of these ships an interesting relation is found. The energy for production of the ship is 50 % of the cumulative energy of the used materials (10 % electricity and 90 % heavy fuel). This relation is better applicable for the model, because it shows a direct relation between material and manufacturing. Yet for platform production the proportion of electricity and diesel are estimated to be equal to *P1552*, which is respectively 66 % and 34 %. The heavy fuel required for transportation is excluded from this.

Important to include in the OTEC platform process is the amount of steel that is acquired, which consists of 1.99×10^6 kg steel tubes and $8{,}52 \times 10^6$ kg of steel plates. Steel can be found in the Ecoinvent database in a lot of different forms, *'G7 steel, low alloyed, at plant'* is the process for common steel and includes primary and secondary production of steel (basic oxygen furnace or electric furnaces), plus the hot rolling process. With distinguishing primary and secondary steel *G7* includes closed loop recycling and the standard recycling rate of steel by Ecoinvent is 0.37. Steel tubes need the additional welding process *'P1143 welding, arc, steel'*. The welding process is actually a service that is done on the steel and is measured in meters. For the structure 1,000 m of steel tubes are needed, estimated from table 3.2. However the welding of the steel structure is neglected, because it is assumed that it is accounted for by the electricity that was needed for production.

It is assumed that the platform production is done by the company Technip at their yard in Pori, Finland. Technip, specifically their location in Finland, is specialised in the manufacturing of spar truss platforms. The number of kilometers between Pori and Willemstad, Curacao is 9,660 km [37]. The Technip workshop in Finland is found to be 3.55×10^5 m^2, this value can be used to adjust *'G2095, metal working factory'*. One unit of G2095 is described by Ecoinvent as 2.74×10^5 *'G188, building hall (m^2)'* combined with 1.62×10^7 *'G1255, roads, company, internal (m^2a)'*. When this good is used for a general metal working process 4.37×10^4 ton of metals is processed anually. For a lifetime of 50 years this implies $4{,}58\times10^{-10}$ unit per kg of metal [38]. During the lifetime of the yard in Pori approximately 70-100 platforms can be produced, which means between 0.0143 and 0.01 factory unit per production of a spar truss platform.

Transport and installation of the platform and the sea water pipes are treated differently then the conventional transoceanic transport processes in Ecoinvent, because these components have to be transported by heavy lifting vessels. A typical vessel that is capable for transportation of the platform is 'Mighty Servant 1'. It is estimated how much heavy fuel it consumes from the engine capacity, which is 13,000 kW [39]. The specific fuel consumption of ships can be found in literature and for low speeds is estimated to be 195 gr/kWh [40]. The distance from Finland to Curacao is 9,660 km and this takes 21 days. During the transportation the engine will not run on full capacity, but rather an average engine load of 0.7 is expected [40], which means the engine runs on 0.7 times the installed capacity. Combining the data will result in 1.79×10^6 kg of heavy fuel. 1 tkm of *'G593, transoceanic tanker'* equals 0.0013 kg of heavy fuel, thus 1.79×10^6 kg equals 1.38×10^9 tkm. *G593* is preferred to use, because then the vessel is accounted for in the form of a transoceanic tanker. This estimation can be made, because in this process the burned heavy fuel is significantly more important than the other economic flows of the process. The flow diagram of the platform modeled in CMLCA is shown in appendix A.2.

3.2.2. OTEC VESSEL

An alternative for the offshore platform would be an OTEC vessel, as also mentioned in the feasibility report by Bluerise [15]. With the key figures for offshore floating devices the required mass of the vessel can be calculated. The surface of the vessel is approximately 1,500 m^2, with 4 meter above and 3.2 meter beneath the water line. With values of 0.25 mT/m^3 for submerged volume and 0.15 mT/m^3 for dry volume. The mass of the vessel will therefore approach 2,100 mT. The vessel is modeled in CMLCA based on good *'G2217, barge'* which is a 300 mT barge. 300 mT multiplied by 7 gives a 2,100 mT vessel. The number of tkm for the OTEC vessel can be estimated based on 7 days of travel with a typical engine capacity for 2,000 mT tankers, which is approximately between 800 and 900 kW. Disadvantages of the vessel compared to other alternative structures are; higher pumping requirements and lower availability in rough water conditions [15].

3.3. MOORING

To keep the platform stational it is moored onto the ocean floor. This is done with anchors, chains and wire ropes. Normally every 5-7 years the mooring lines have to be replaced [35]. Yet the wire rope that is used for mooring in this project is 'sheated spiral strand wire rope' and has an estimated lifetime beyond 20 years [41]. A schematic overview of a mooring line can be seen in figure 3.3. The documentation of the mooring system of the Neptunes spar [5] and the quotation of Vryhof [42] show a different ratio for the chain length and the strand wire rope length. This is an important ratio because the chain of the mooring system contributes significantly as will be seen in the interpretation phase. It also explains the overestimation discussed at section 3.2.

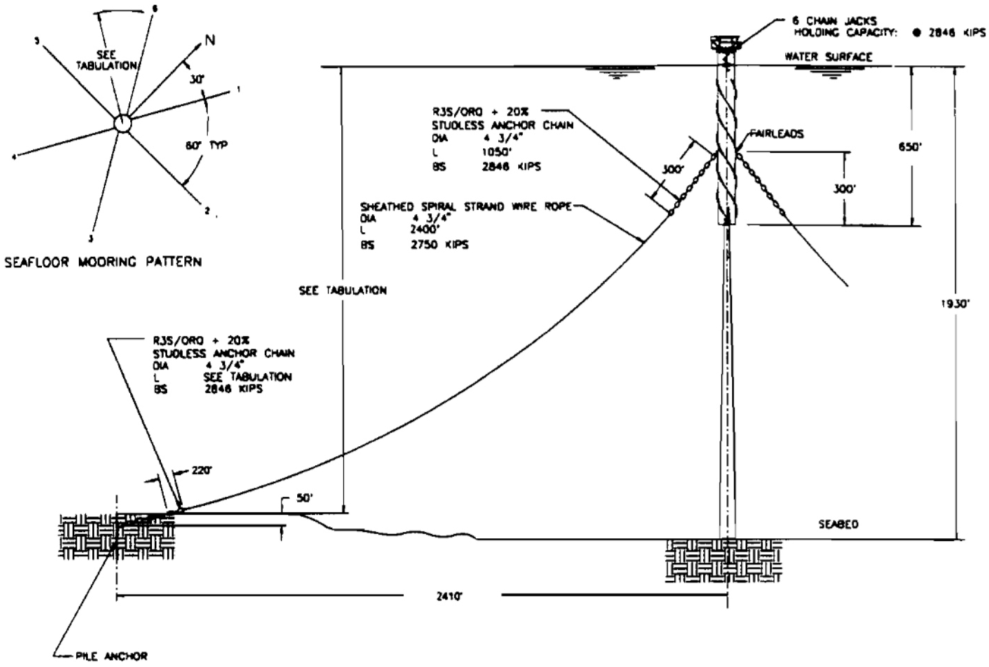

Figure 3.3: Schematic overview mooring system [5]

In order to calculate the length of the mooring line the shape of the line can be approximated by the integral in equation 3.3. Limits are set to zero and 1,200 meter ocean depth and function 3.4. The function is found by assuming a quadratic function with x = 1,200 and y = 2,000 [2]. With f(x), from eq.3.4 the length of the mooring line becomes approximately 2,400 meter.

$$S = \int_0^{1200} \sqrt{1 + [f'(x)]^2} dx \tag{3.3}$$

$$f(x) = 0,00138 \cdot x^2 \tag{3.4}$$

3.3.1. MOORING IN CMLCA

There are three different components associated with the mooring system; sheated spiral strand wire rope, studless chains and anchors. These are all assumed to be made out

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[2] Value for y is assumed to be the perpendicular distance between anchor and platform

of steel. In Ecoinvent the service of *'P1130, drawing of pipes'* and *'P1146, wire drawing'* are present to account for the processes required for the production of the wire ropes and chains. From the quotation the quantity of the required materials could be estimated [42];

- Chains; the volume of the link of a chain could be estimated based on the thickness of 90 mm diameter, figure 3.4 shows the other sizes. Based on these numbers the volume is 0.01091 m^3. The effective length of each link is 368 mm, thus 1,500 m ground chain [42] divided by 0.3675 m gives 4,082 links, and for 50 meter top chain 136 links. This comes down to 44.5 m^3 or 347,100 kg of steel. There are eight ground and top chains, which comes down to 367.9 m^3 of steel in total.
- Sheated spiral strand wire rope, the diameter of the strand wire rope is 82 mm and the mass of the wire is given in a catalogue of Bridon, which is 37.7 kg/m [43]. The total length of one mooring line is approximately 2,400 meter, thus with 1,500 meter ground chain and 50 meter top chain leaves a length of 850 meter for the strand wire rope.
- Anchors, the mass of the anchor is 25 mT of steel.

For installation of the mooring system a heavy lift vessel will be required and some tug boats. It is assumed that the heavy lift vessel will already be available at the site due to transportation of the platform and sea water pipes. The installation is estimated to take 7 days, and as before the average engine load and capacity are assumed to be 0.1 and 13,000 kW respectively. The capacity of the tug boats is 1,000 kW and they have an engine load of 0,5. All this combined will add up to 6.05×10^7 tkm for *'G593 transport, transoceanic'*. The flow diagram of the mooring modeled in CMLCA is shown in appendix A.1.

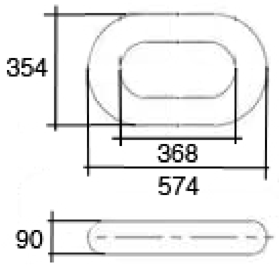

Figure 3.4: Schematic representation of one link, values in [mm]

3.4. SEA WATER PIPES

The cold water pipe (CWP) consists of a composite of glass fiber and epoxy resin. It is made by the filament winding process. The glass fiber wires get pulled trough a bath of resin and get turned around on a tube. The diameter of this tube determinates the diameter of the pipe. The desired diameter of the pipe is 4 meters. This is quite large for the filament winding process, however the assumption is that this will not be an issue. When enough material is wrapped around the tube, curing is induced by heat and an infrared lamp. Once the tube is gelled it is placed in an oven for further cure [44]. It is assumed that the CWP will operate the entire OTEC lifetime even without maintenance [15]. The discharge pipe and warm water pipe are produced in the same way. For end of life it should be considered that composites from fiber reinforced plastics do usually end up in landfills. Yet after service the reuse of the sea water pipes should not be excluded, because the lifetime of the pipe easily surpasses the lifetime of the OTEC system.

3.4.1. SEA WATER PIPES IN CMLCA

Both materials for the sea water pipes *'G50, glass fiber, at plant'* and *'G75, epoxy resin, liquid, at plant'* can be taken from Ecoinvent. The composite Epoxy/S-glass fiber is found in CES Edupack, which has a fraction of fibers in the composite of 0.675. Energy required for the filament winding process is found to be 2.7 MJ/kg [45]. Furthermore it is assumed that the energy required in the process is the usage of electricity, because energy is mainly required to power electric motors. The factory needed to produce a CWP can be estimated following the same principles for G2095 as done in section 3.2.1. It is assumed that since the mass of the CWP is 6 times smaller than the platform 420-600 CWP's can be produced in the same metal working factory. Off course it should be noted that there is a difference between factories that either produce metal or composite, but considering only the building hall area these differences can be neglected. The transportation and installation of the of the CWP and discharge pipe can not be estimated by ordinary transoceanic transport, because especially the CWP with a length of 1,000 meter will require special transport. It is estimated that the transportation will be done with 4 heavy lift vessels from Big Lift, each with a engine capacity of 7,800 kW [46]. Production of the pipes can be done on multiple locations, for now the United States is appointed. This location is preferable over Europe, due to a smaller travel distance. The distance is assumed to be 2300 km from New York to Willemstad. As a consequence 7 days of transport is accounted for with 0.7 engine load, 7 days of installation with a small engine load of 0.1 and 5 days of return, with again 0.7 load [40]. Installation of the CWP is considered to be slowly drafting of the pipe and putting it vertically with the heavy lift equipment. Just as in section 3.2.1 combining the data results in 1.332×10^6 kg of heavy fuel and 1.025×10^9 tkm. Disposal is accounted for by goods *'G68, disposal, glass'* and *'G69, disposal, plastics mixture'*. This procedure is also followed for the fiber glass reinforced plastics used for the wind turbine production [31]. Ecoinvent has no processes that are directly related to fiber reinforced plastics disposal, so this method can be considered as the best available option. The flow diagram of the cold water pipe modeled in CMLCA is shown in appendix A.6.

3.5. WORKING CYCLE

The working cycle of OTEC consists of heat exchangers, working fluid, storage of the working fluid, turbine, generator, and pumps. Each component is elaborated on in this section.

3.5.1. HEAT EXCHANGER

Energy conversion by OTEC originates from the temperature difference between the ocean surface water and the ocean water at 1 km depth. The heat that is transferred is dependent on the heat transfer coefficient, the area of heat transfer and the temperature difference. Due to the fact that there is a small temperature difference the heat transfer requires a large area. Plate heat exchangers are the most obvious design for OTEC due to large available area. The concept is based on compressed plates with a gasket in between, (for a sketch) see figure 3.5. On one side of the plate there is the warm water flow and on the other side there is the ammonia-water flow. The gaskets prevent leakage, so the two streams will not be able to mix. The most important components of the heat exchanger are the fixed plate, movable plate and the heat transfer plates because these acquire a lot of material. Stainless steel for the fixed and movable plate and titanium for the heat transfer plates. As titanium is crucial for the LCA the data that is acquired needs to be verified. This can be done by reviewing the process of titanium production. Per heat exchanger 2,280 kg of titanium (heat transfer plates) is required and 2,400 kg of stainless steel (fixed and movable plates) [47]. Titanium is produced in a couple of locations around the world. Alfa Laval said that their titanium for the heat transfer plates is originated from Japan. Transport will then be from Japan to Denmark (as titanium plates) and from Denmark to Curacao (as final product).

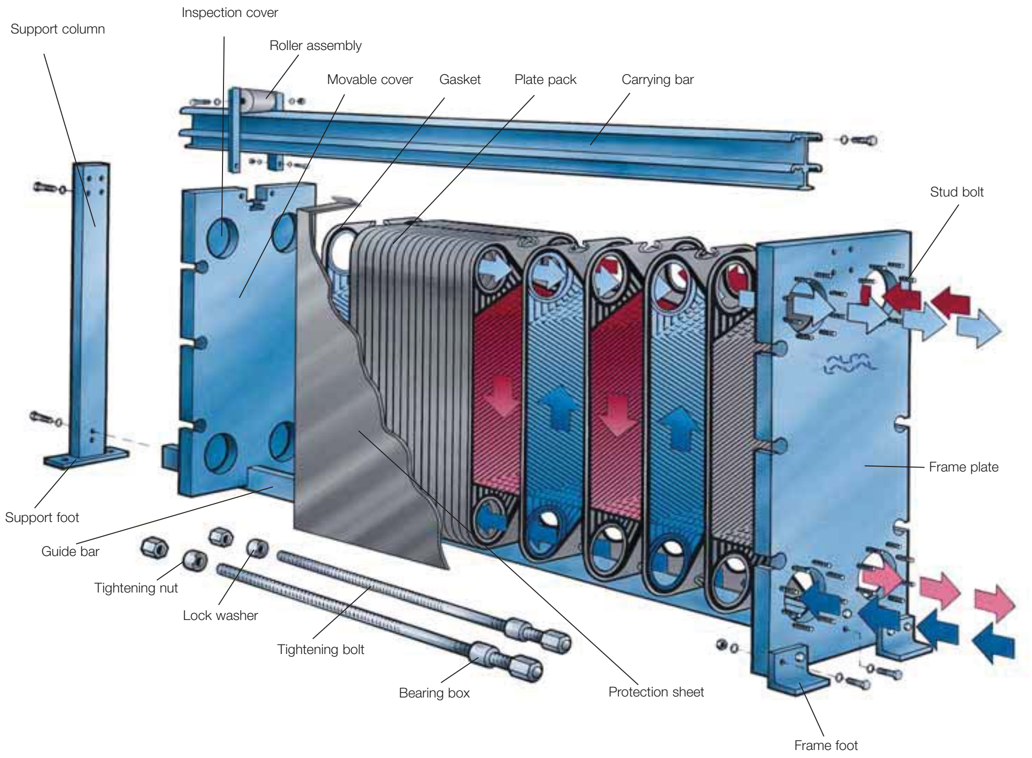

Figure 3.5: Overview of typical plate heat exchanger [6]

TITANIUM PRODUCTION PROCESS

For titanium production it is important to make a distinction between titanium sponge and titanium as a final product. The general opinion about titanium products are that these are very expensive and that is mainly due to the very energy intensive production route. High costs are not related to the element titanium itself, because it is the seventh most abundant metallic element on Earth [48]. Yet the abundance of the element is no guaranty for high availability. In order to produce titanium plates the Kroll process is needed to create titanium sponge out of rutile (TiO_2) or ilmenite ($FeTiO_3$). After that Vacuum Arc Remelting and more fabrication processes are needed to produce the plates, these processes are shown in figure 3.6. The Kroll process needs 30 kWh to produce 1 kg of titanium sponge [49] and it consists of three succeeding steps;

- Chlorination of rutile or ilmenite ore, see equation 3.5
- Fractional distillation to remove impurities
- Reduction of titaniumtetrachloride with magnesium, see equation 3.6.

After the Kroll process electrolysis of magnesiumchloride 3.7 is necessary to reuse magnesium and chloride.

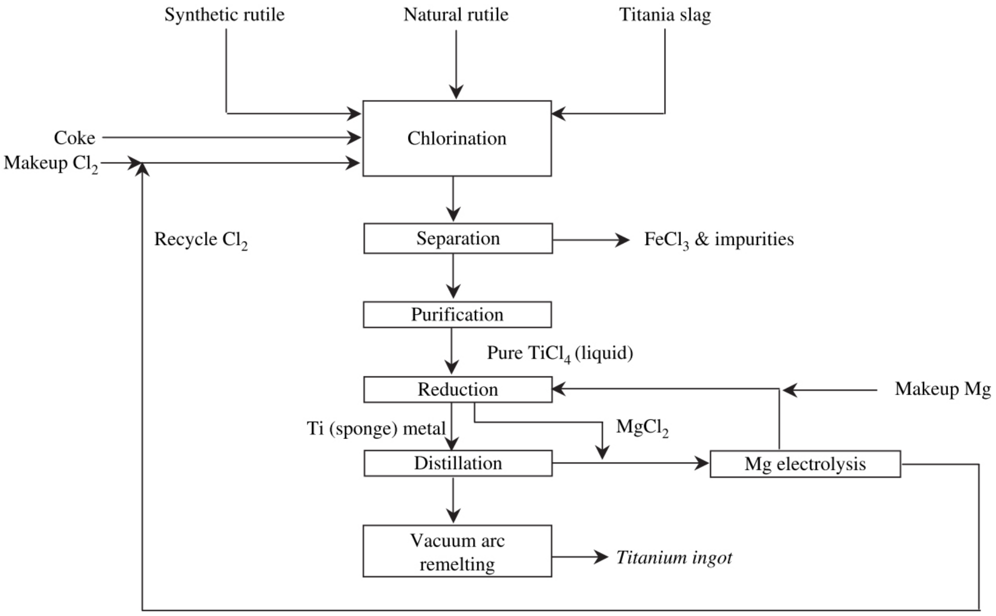

Figure 3.6: Overview of titanium production process [7]

$$TiO_2 + C + Cl_2 \rightarrow TiCl_4 + 2CO \tag{3.5}$$

$$TiCl_4 + 2Mg \rightarrow Ti + 2MgCl_2 \tag{3.6}$$

$$MgCl_2 \rightarrow Mg + Cl_2 \tag{3.7}$$

The chlorination of the rutile ore process in the presence of carbon is done in a fluidized bed reactor at 900°C. From a temperature of 600°C no extra heat is required to get the reaction going. After the chlorination step the titaniumtetrachloride requires some cleaning procedures to remove volatiles [49]. These volatiles are insoluble and soluble metal chlorides and none of them could be found in the emission database of Ecoinvent. The theoretical energy requirement for the electrolysis of magnesiumchloride is 7 kWh/kg[3] and common practical values vary from 12 to 18 kWh/kg. Another consideration is that titanium sponge cannot be entirely converted into titanium ingot, which makes the titanium production process less efficient than considered here. From 1.3 kg titanium sponge that is available only 0.4 kg finished titanium end product can be produced [50]. As a consequence the impact of 1 kg of titanium end product grows substantially with a factor 3.25. As will be seen in the next section 3.5.2 the embodied energy of titanium in this model is 443.5 MJ/kg. In the life cycle assessment the mass balances and emissions are more important than the embodied energy. However from the embodied energy of titanium it can be concluded that titanium is indeed an important aspect, it is approximately 18 times as high as for instance plain carbon steel (AISI1030).

3.5.2. HEAT EXCHANGER IN CMLCA

The heat exchangers contain large amounts of chromium steel plates and titanium grade 1 sheets. Chromium steel is well defined in Ecoinvent by the good *'G56, chromium steel 18/8'* and needs no adaptations. Regarding fabrication everything should be included, for instance the building where it is produced, but also the lights and so on. Due to the fact that no information is gathered from the suppliers the standardized processes from Ecoinvent were used. If if the impact of these kind of processes are considered it is seen that they will have no significant effect on the total impact and therefore does not prejudice the investigation. Examples of these processes are *'G2095, metal working factory (unit)'*, *'G2099, metal working machine (kg)'*, *'G3452, metal working factory operation (kg)'* and *'G3457, metal working machine operation (kg)'*. The last two goods are services for the metal and depend on the amount of material that is worked on and the first two goods are average values for a metal factory and working machine [38].

It is expected that the production of titanium is a large contributor to the life cycle of OTEC, because it requires large amounts of energy. The energy requirement for titanium grade 1 is estimated by CES Edupack between 550 MJ/kg and 609 MJ/kg, the linked CO_2 emissions are between 37.3 kg and 41.2 kg. This grade of titanium is suited for heat exchangers [51], [47]. These numbers will be used as a reference for the titanium production process that is configured in CMLCA. This production process is discussed in section 3.5.1 and in this section estimations and assumptions will be shown.

Due to the fact that there is data missing to complete the missing gaps in the flow diagram of titanium production it is unavoidable to simplify the model. From Ullmann encyclopedia it was possible to gather the essential information to make a viable estimation [49]. The overall energy demand for titanium sponge is given, which is 30 kWh/kg [4]. Other valuable information is the mass input of $TiCl_2$, Mg and mass output of $MgCl_2$ per kg of titanium sponge. Next to that it is given that most reduction reactors are gas heated [49]. Combined with the information of the study by Sibum and the stoichiometric balance, all the masses of input can be found [50]. Electricity is required as well to perform the elec-

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[3] The voltage of process is equal to 3.07 V calculated with $\frac{\Delta g}{nF}$ and the current is 2,204 A calculated with I=φ nF (φ comes from 1 kg of Mg in 1 hour = 41.14 mol/h = 0.0114 mol/s of Mg), this results in 6,766 W (thus almost 7 kWh/kg)

[4] 30 kWh/kg is considered only for production of sponge, not for electrolysis of $MgCl_2$

trolysis of magnesiumchloride, this is estimated to be 10 kWh [5]. It is assumed that all the chloride and magnesium is completely reused in the process. This cannot be true, but it is not known how much chloride or magnesium is lost in the process and therefore it is estimated to be insignificant. In order to estimate the energy that is required from burning natural gas, the heating value of petroleum needs to be subtracted from the overall required energy. This results in 22.5 kWh [6] per 1.3 kg titanium sponge and that is 81 MJ/kg of energy supplied by *'G99; natural gas, burned in industrial furnace'*. It is assumed that all the heat as input is wasted, because this heat will not produce any energy, only titanium sponge. Next to waste heat also carbon monooxide is emitted. All the estimations together result in 443.5 MJ/kg embodied energy for titanium. This is lower than the values from CES Edupack, but the related CO_2 emissions (43 kg/kg) are higher than assumed by CES Edupack.

Titanium is produced in a furnace and it is assumed that this furnace is comparable with a blast furnace, yet an important difference is that titanium is produced in batches. Possible output of titanium per furnace is 500 ton titanium per month [49]. The use of Ecoinvent good *'G1468, blast furnace'* for steel production is based upon 1.5×10^9 kg production annually with a lifetime of 50 years. Per furnace for titanium only 6.0×10^6 kg can be produced annually, thus instead of 1.33×10^{-11} *G1468* the titanium production requires 3.33×10^{-9} *G1468*. The complete flowdiagram of primary titanium production is shown in figure 3.7.

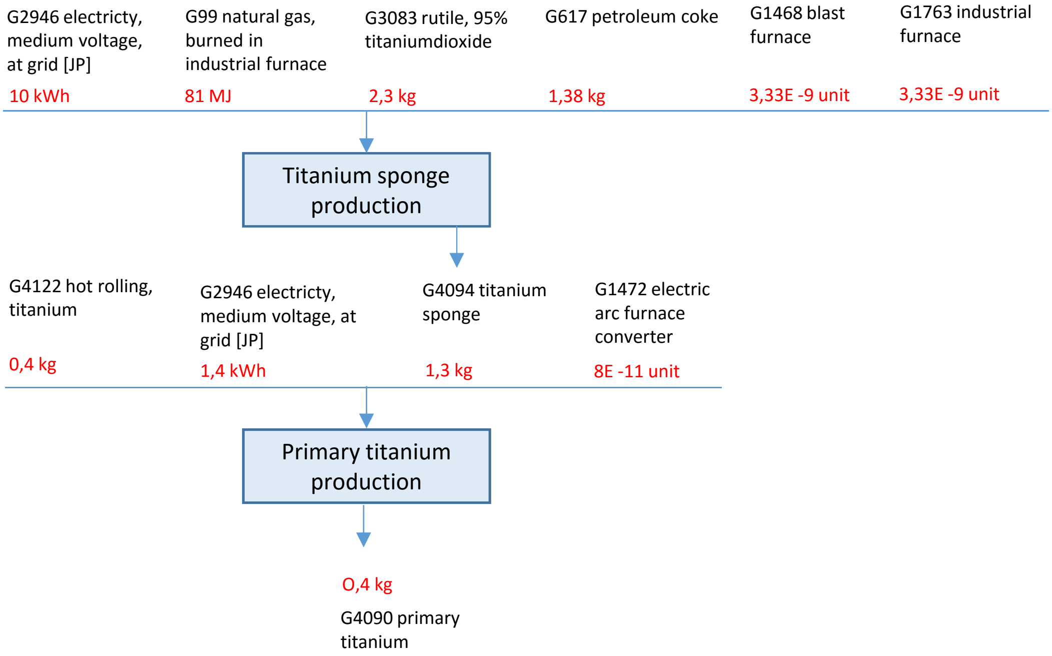

Figure 3.7: Flowdiagram of titanium production in CMLCA

Part of the titanium that is used for heat exchanger production is secondary titanium, or recycled titanium. From CES Edupack 2014 it can be concluded that 21% of the titanium may be considered as secondary titanium [51]. The recycling process of titanium consumes significantly less energy than primary titanium production. Primary production

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[5] 1 kg sponge produces 3.975 kg of $MgCl_2$, electrolysis of 7.835 kg of $MgCl_2$ produces 1 kg of Mg, thus 1,3 kg of sponge requires 0.66 kg of Mg, which results in 8-12 kWh electricity

[6] 30 kWh/kg times 1.3 subtracted by 12 kWh (43 MJ/kg) times 1.38 kg C

was estimated at 550 MJ/kg and recycling is estimated at 72.8 MJ/kg, thus the fraction of energy needed compared to primary production is 0.132. Yet the form of energy required for secondary production is different as well, because the electrolysis process is not needed. Recycling is assumed to require 51.3 MJ of G99. The flow diagram of the heat exchanger modeled in CMLCA is shown in appendix A.5.

ALUMINUM HEAT EXCHANGER

Aluminum as a heat exchanger material could be interesting for OTEC as well, because in comparison with titanium the heat transfer coefficient is ten times better. A clear disadvantage of aluminum is the corrosion in sea water. Metal loss due to corrosion can be estimated at 0.51 mm in 30 years [**?**]. Another consequence of corrosion is that the heat exchange process is deteriorating over the years. Thus the advantage of aluminum having a better heat transfer coefficient might cancel out over the years. Aluminum that is considered for heat exchangers is the '3003 alloy' and the strength is approximately 95-135 MPa. The strength of titanium grade 1 is approximately 172-240 MPa. Therefore it is assumed that aluminum heat exchanger plates should at least be 1.3 time thicker than the titanium plates. For the model in CMLCA it is estimated that the surface required for heat exchange is 1.31 times less than the titanium option [52]. A lifetime of 10 years is expected [53]. Per heat exchanger 2,400 kg of chromium steel and 1,345 kg of aluminum is required.

COMPOSITE HEAT EXCHANGER

For sufficient heat exchange with a composite heat exchanger reinforcement of epoxy is required by carbon fibers [54]. The process for carbon fiber is not in Ecoinvent, but the process for glass fiber is. Due to the time frame of the study it is chosen to use the glass fiber process. This is a rough assumption, but the LCA about the process of producing carbon fiber could be a research on itself. With the comparison between glass and carbon fiber reinforced epoxy resin in CES Edupack the values for primary energy and CO_2 emission are approximately even. For the model in CMLCA it is estimated that the surface required for heat exchange is 1.24 times more than the titanium option [52]. The same lifetime of 30 years for the OTEC system is expected or more. Per heat exchanger 2,400 kg of chromium steel and 1,120 kg of composite is required. In the impact assessment (section 4) the aluminum and composite heat exchangers are compared with the titanium heat exchanger option.

3.5.3. TURBINE AND GENERATOR

The turbine and generator combination for OTEC is comparable with systems that produce energy from excessive heat of flue gasses. This implies a single stage turbine. The lifetime of the turbine and generator is estimated to be 15 years, next to the relatively short lifetime also technological progress will stimulate the replacement of this component. With ammonia as a working fluid materials like titanium and nickel are necessary to cope with the corrosive environment.

TURBINE AND GENERATOR IN CMLCA

The mass of the turbine and generator is estimated from turbo-expander and generator data of general electronics [55]. The different materials of the components are estimated from typical materials used in turbines and generators; steel, cast iron, copper and aluminum [56]. As stated before steel is not able to deal with the corrosive character of the ammonia, so this is replaced by titanium. Yet titanium is lighter than steel and thus less mass is required. The density of titanium divided by the density of steel is 0.58. The stiffness-to-weight ratio is comparable for both materials, so the initial mass of steel times 0.58 gives the required mass of titanium. For the same reason as for steel aluminum, cast iron and copper are replaced by nickel. The metal working processes are composed in the same way as in section 3.5.2. During the OTEC lifetime the components have to be replaced 1 or 2 times.

3.5.4. WORKING FLUID AND STORAGE

Ammonia is the working fluid of the OTEC system and in the working cycle it has a volume of 150 m^3 [15]. Storage of ammonia is done in six vessels of stainless steel each having a volume of 32 m^3 and weighing 42.9 mT. The vessels are 50% filled with ammonia, the total amount of ammonia is then approximately 250 m^3. Additionally there is 2.57×10^5 kg of stainless steel for six storage vessels, 9.0×10^4 kg for piping and 5 mT of instrumentation and control.

WORKING FLUID AND STORAGE IN CMLCA

Ammonia can be found in the Ecoinvent database as good *'G148, ammonia'*. Stainless steel is already introduced in section 3.5.2. The flow diagrams of the working cycle equipment modeled in CMLCA is shown in appendix A.3 and A.4.

3.6. POWER DISTRIBUTION

For power distribution only the cable from platform to shore is considered, thus the electric infrastructure on land is neglected. This connection with the grid can be neglected, because it will be neglected for the other reference flows as well. The length is considered to be 5,000-7,000 meter from platform to shore, that will result in a power cable length of approximately 8,000-10,000 meter. It is assumed that the power cable can operate the entire lifetime of OTEC.

3.6.1. POWER DISTRIBUTION IN CMLCA

The power cable consists of copper wires *'G5, copper'*, insulation XLPE *'G1364, polyethylene, LDPE'* and a steel *'G7'* armour. In figure 3.8 the area's of the specific parts of the cable are shown. Copper is transformed into wires with the process *'P1145, wire drawing, copper'*. Other goods and processes are neglected due to low contribution of this component. The flow diagram of the power cable modeled in CMLCA is shown in appendix A.7.

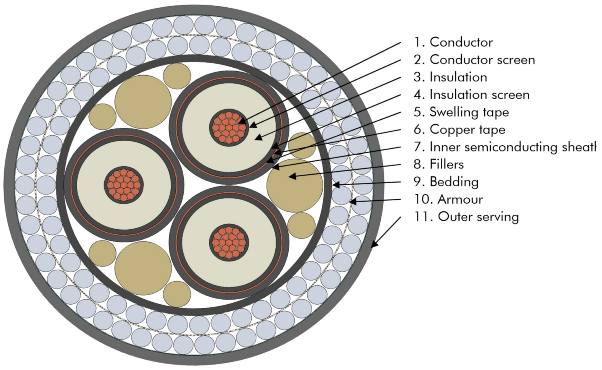

Figure 3.8: Schematic cross-sectional view of the power cable

3.6.2. POWER PRODUCTION OF 10 MW OTEC

The functional unit of this study is 1 kWh of electricity generated by one of the reference flows. In order to obtain this functional unit for an OTEC system the produced kWh during the lifetime of the plant must be calculated. Eq. 3.8 gives the energy produced by OTEC over a lifetime of 30 years. The energy produced [kWh] = Installed capacity (10,000 kW) x lifetime (30 years) x system efficiency (pumps) x capacity factor.

$$\mathrm{E} = 10000 \cdot 30 \cdot 0,8 \cdot 365 \cdot 24 = 2,1 \times 10^{9}\,[kWh] \tag{3.8}$$

3.7. REFERENCE FLOWS

Life cycle assessment is a method that is able to make a comparison between different reference flows. The comparison is based upon the results of the impact assessment for 1 kWh of electricity by the different technologies. The reference flows considered are OTEC, diesel, wind energy and photovoltaic panels. In this section the remaining reference flows will be analyzed, all are based upon processes from the Ecoinvent database with some minor adjustments.

3.7.1. DIESEL

The process considered from the Ecoinvent database is *’P1440 diesel, burned in diesel-electric generating set’*. This process generates an output of 1 MJ *’G1819 diesel, burned in diesel-electric generating set’*. The efficiency of the process is not included, so a new process was created that transformed 7.94 MJ of *G1819* in 1 kWh of *’G4093 electricity from diesel generator’*.

3.7.2. WIND ENERGY

There are several references found for life cycle assessments performed for wind turbines. The scale of the turbines varies a bit, also because of the accelerating pace at which the turbines developed from 1995 till 2005 (0.5 MW to 5 MW respectively[57]). For wind energy several LCA studies can be considered. However the model for electricity by wind energy available in the Ecoinvent database is sufficient. *’P2138 electricity, at wind power plant 800 kW’* is the considered process and all the assumptions are documented by Burger and Scherrer [31]. An interesting number is electricity per kg of production which is estimated based on the costs of a specific combined heat power unit and the energy intensity per

Swiss franc. It can be seen that this approximation is established in a fairly random manner, because no information was available. For transport the turbines are shipped from Europe to Curacao with *'G103 transport, transoceanic, freight ship'*.

3.7.3. SOLAR ENERGY (PHOTOVOLTAIC PANELS)

The reference used for photovoltaic energy is also found in Ecoinvent [58]. With process *'P1640 electricity, PV, at 3kWp facade, single-Si, laminated, integrated'* a common Si PV module is chosen. The kWp stands for kilowatt peak, which would be the maximum output of the solar panels under optimal conditions. For transport it is considered that the panels are shipped from Europe to Curacao with *'G103 transport, transoceanic, freight ship'*. It should be noted that it is a bit conservative to choose a silicon solar panel, since PV technology is constantly improving. Yet this applies to all renewable technologies.

4

IMPACT ASSESSMENT

Table 4.1 shows the results for the different impact categories obtained from CMLCA. The impact assessment is dependent upon the model that is used. In this case the model CML2001 is used, which is created by CML at Leiden University [8]. The values in the table are difficult to quantify in the sense of actual impact on the environment or day to day life, because most of the impact categories do not have units that directly present their influence.

4.1. SELECTION OF THE IMPACT CATEGORIES

Impact category climate change is considered the most important one, mainly because of the attention it receives from all over the globe. From the showed results it is clear that diesel stands out compared to electricity from OTEC, wind and PV. The other impact categories can be looked at as well, but it should be noted that with data gathering no specific attention was given to other than climate change. Especially for the titanium production process it can be expected that vital emissions for some categories might be missing [49]. The Kroll process had some volatiles that could not be found in the emission database of Ecoinvent and estimated emissions for NO_x and SO_x by CES Edupack do not match with the emissions from 1 kg of primary titanium [51].

Table 4.1: Results obtained from CMLCA

	OTEC	Wind	PV	Diesel	Unit
Eutrophication	8.10×10^{-5}	2.68×10^{-5}	0.00023	0.0016	kg PO4-Eq
Depletion abiotic resources	3.13×10^{-4}	8.19×10^{-5}	0.00053	0.0045	kg antimony-Eq
Acidification potential	3.27×10^{-4}	5.14×10^{-5}	0.00036	0.0072	kg SO2-Eq
Photochemical oxidation	2.15×10^{-5}	3.61×10^{-6}	2.22×10^{-5}	2.34×10^{-4}	kg ethylene-Eq
Climate change, GWP100a	**0.0428**	**0.0113**	**0.0748**	**0.7**	**kg CO2-Eq**
Terrestrial ecotoxicity	0.00039	0.00016	0.00055	0.00073	kg 1,4-DCB-Eq
Marine ecotoxicity	48.2	22.8	176	84	kg 1,4-DCB-Eq
Freshwater ecotoxicity	0.0243	0.0147	0.054	0.0173	kg 1,4-DCB-Eq
Ozone depletion	3.15×10^{-9}	6.79×10^{-10}	1.48×10^{-8}	8.63×10^{-8}	kg CFC-11-Eq
Human toxicity	0.0931	0.0624	0.175	0.0961	kg 1,4-DCB-Eq

For wind energy the values can be compared with the study by Martinez that also shows CML2001 results [30]. On all categories the model of Ecoinvent scores significantly higher and this can be explained by the key assumptions for recycling in the Martinez model. The biggest contribution is from glass fiber, but after that steel and chromium steel together account for more than 40% of the contribution. If 90% of recycling is considered this will influence the results a lot. This effect is even more exploited due to the different sizes of the two considered turbines of 800 kW and 2 MW. The 2 MW turbine uses approximately 2.5 times more material (yet 90% is recycled), but also produces 4 times more energy. It should therefore be noted that the considered recycling rate of the used materials has major implications on the life cycle assessment, especially for renewable energy sources.

In table 4.2 the impact assessment is shown for different OTEC scenario's. It clearly shows that an higher recycling rate and increasing the scale significantly reduces the impact. In the interpretation phase the background of the scenario's is explained.

Table 4.2: Results for different OTEC scenario's

	OTEC 10 MW	OTEC 90%	OTEC best case	OTEC 100 MW
Eutrophication	8.10×10^{-5}	6.27×10^{-5}	3.19×10^{-5}	1.95×10^{-5}
Depletion of abiotic resources	3.13×10^{-4}	2.27×10^{-4}	1.27×10^{-4}	9.09×10^{-5}
Acidification potential	3.27×10^{-4}	2.89×10^{-4}	1.56×10^{-4}	6.49×10^{-5}
Photochemical oxidation	2.15×10^{-5}	1.28×10^{-5}	7.42×10^{-6}	6.60×10^{-6}
Climate change, GWP100a	**0.0428**	**0.0331**	**0.0184**	**0.0124**
Terrestrial ecotoxicity	0.000393	0.000547	0.000237	0.000107
Marine aquatic ecotoxicity	48.2	36.9	19.8	14.1
Freshwater aquatic ecotoxicity	0.0243	0.0192	0.0110	0.00743
Stratospheric ozone depletion	3.15×10^{-9}	2.58×10^{-9}	1.33×10^{-9}	9.10×10^{-10}
Human toxicity	0.0931	0.0594	0.0456	0.0318

In table 4.3 the results for the impact of the different options for the heat exchangers for 10 MW OTEC can be seen.

Table 4.3: Results for different heat exchanger options

	Aluminum	Composite	Titanium	Unit
Eutrophication	1.19×10^{-5}	1.74×10^{-6}	8.29×10^{-6}	kg PO4-Eq
Depletion of abiotic resources	4.15×10^{-5}	7.85×10^{-6}	5.68×10^{-5}	kg antimony-Eq
Acidification potential	3.23×10^{-5}	6.01×10^{-6}	2.48×10^{-5}	kg SO2-Eq
Photochemical oxidation	1.95×10^{-6}	2.97×10^{-7}	6.09×10^{-6}	kg ethylene-Eq
Climate change, GWP100a	$\mathbf{6.18}\times10^{-3}$	$\mathbf{1.09}\times10^{-3}$	$\mathbf{6.37}\times10^{-3}$	**kg CO2-Eq**
Terrestrial ecotoxicity	9.12×10^{-5}	2.00×10^{-5}	3.73×10^{-5}	kg 1,4-DCB-Eq
Marine aquatic ecotoxicity	16.2	2.49	6.73	kg 1,4-DCB-Eq
Freshwater aquatic ecotoxicity	8.72×10^{-3}	2.16×10^{-3}	3.22×10^{-3}	kg 1,4-DCB-Eq
Stratospheric ozone depletion	4.12×10^{-10}	5.18×10^{-11}	6.94×10^{-10}	kg CFC-11-Eq
Human toxicity	0.0478	0.0125	0.0141	kg 1,4-DCB-Eq

5

INTERPRETATION

The results from the impact assessment will be interpreted in this chapter. Based on the analysis of the results the conclusions and recommendations can be obtained. At first the information of the previous stages will be reviewed and the most significant issues will be identified. This is done with a contribution analysis for the different life cycle stages and the different components of OTEC. Only the data of the most significant processes will be evaluated.

5.1. CONSISTENCY CHECK

Possible reasons of inconsistency of the results could be due to the use of different data, for example use of primary data that is measured and secondary data that comes from literature. Different sources of data might be inconsistent, because of accuracy, temporal aspects (year of execution or time invested in the study) and the location dependency. With the comparison of the reference flows in this study it must be noted that there are some differences in the level of the extensiveness of the LCA models. Especially for the PV model the production steps to produce PV cells out of silicon are very elaborately conducted. This does not imply that the PV model is more accurate, but it seems more rigid. Another issue with both the PV and wind model of Ecoinvent is that the technologies are significantly improved over the years, this can be seen for example by studies done by Martinez that show a climate change impact of 0.00658 kg CO_2/kWh for wind energy [30]. This number is almost two times lower than considered in this study, yet for the study of Martinez there was an assumption for 90% recycling for most of the materials.

5.2. CONTRIBUTION ANALYSIS

It is interesting to see which components of OTEC contribute the most to the obtained LCA results, because then possible improvements can be applied in the right sections. Two different analysis are done for OTEC;

- The OTEC components analysis will show the contributions of all the different components.
- The life cycle stages contributions for raw materials, production, use, transport and end of life can be seen.

5.2.1. OTEC COMPONENTS

The components of OTEC were mentioned already in the inventory phase and their contributions can be seen in figure 5.1. In order to keep it clear only the category climate change is considered here. It shows that the platform is the biggest contributor of the life cycle assessment. This is mainly due to the large amount of steel that is required and large amount of energy for production. In section 3.2 the assumptions for the platform are underpinned. Contribution of the heat exchangers and the sea water pipes are almost equal and certainly interesting to investigate to a larger extent. The contribution of the mooring system stands out as well and that has to do with the estimation of the required mass of steel for the chains. As stated in section the length of the chains seems to be overestimated in the quotation of Vryhof, if compared with the mooring system of the Neptune spar [42],[35]. The total mass of steel required for mooring was therefore reduced from 3,300 ton to 1,577 ton. In figure 5.1 the contribution of 1,577 ton mooring is shown. The contribution of the processes for the platform, heat exchangers and cold water pipe are shown next. The rest can be found in appendix A.3.

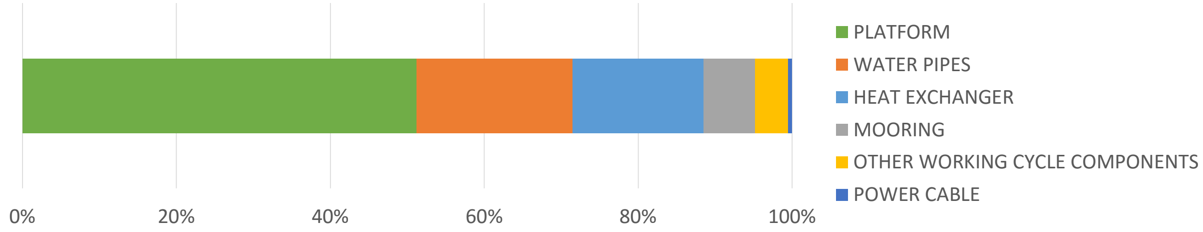

Figure 5.1: Contribution of 10 MW OTEC components for climate change, GWP100a

PLATFORM

The steel platform structure accounts for more than 50 % of the OTEC contributions and it could therefore be very interesting to look into other platform options or configurations. In figure it is shown which processes of the platform contribute the most. Steel is the main contributor. More than 75% of the impact is related to steel and energy (electricity and diesel) required to produce the steel platform structure. It can also be seen that transport by a heavy lift vessel, as described in section 3.2.1, should not be neglected.

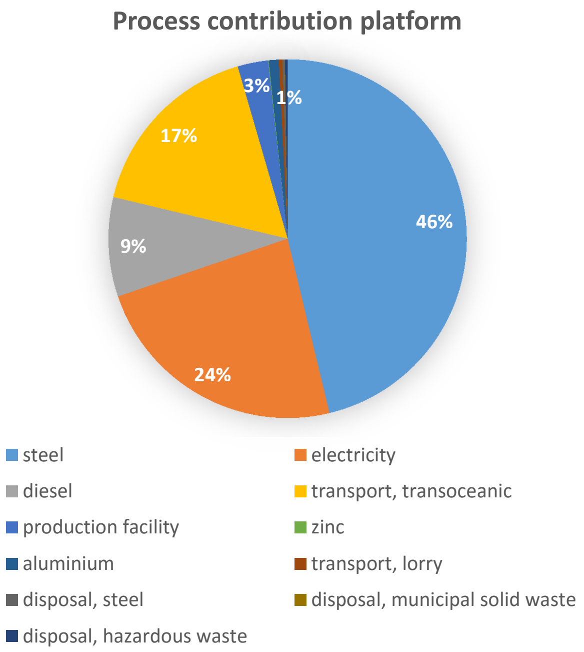

Figure 5.2: Contribution of platform processes for climate change, GWP100a

HEAT EXCHANGERS

In figure 5.3 the contribution of the processes related to the heat exchangers is shown. Titanium is responsible for the largest contribution. It can be seen that more than 90% of the impact is due to the required raw materials (titanium and chromium steel). Considering the results for the heat exchangers from section 4 it can be seen that the alternative aluminum heat exchanger has a similar impact as the titanium option. In the long term titanium will have the preference over aluminum (from an LCA perspective) due to corrosion. The titanium heat exchanger plates will not deteriorate during the lifetime of OTEC. The composite heat exchanger is definitely the best option, but regarding implementation a lot of challenges remain. More discussion about the composite option in section 5.5.

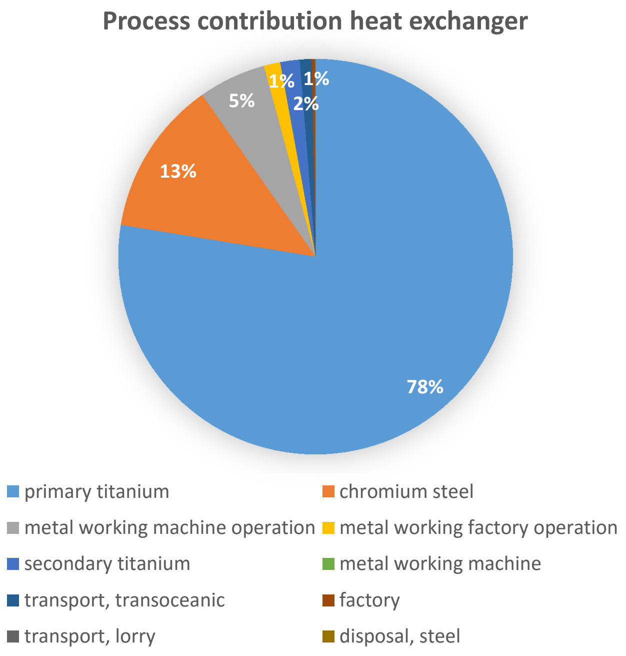

Figure 5.3: Contribution of heat exchanger processes for climate change, GWP100a

COLD WATER PIPE

In figure 5.4 the cold water pipe processes are shown. The contribution of transoceanic transport is very significant, due to heavy lift vessels required for transport and installation. Other options for installation can be found in the feasibility report of Bluerise, these are not considered in this study mostly due to uncertainties of the associated processes. The cold water pipe is the only component where disposal relatively contributes to a large extent. Disposal of plastics is responsible for this contribution.

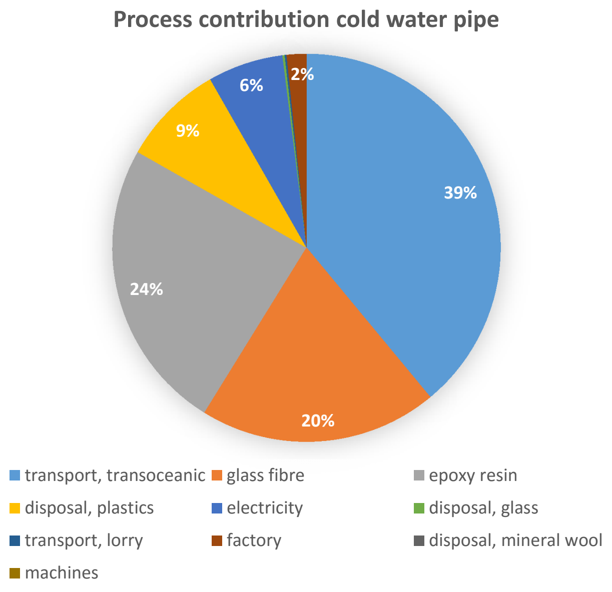

Figure 5.4: Contribution of cold water pipe processes for climate change, GWP100a

5.2.2. LIFE CYCLE STAGES

From figure 5.5 it can clearly be seen that the three most important phases are raw materials, manufacturing and transport. For the life cycle assessment of the reference flows wind and solar it can be seen that transport does not contribute as much as for OTEC. This has to do with the assumption that transoceanic transport is possible. Raw materials are an important factor due to the large amount of materials that are required and the high embodied energy of these materials. The manufacturing phase comes from assumptions for the manufacturing of the platform and the goods; *G3452* and *G3457*, which are average metal working operations for the factory and machines. With the platform and sea water pipes heavy lift vessels were required and explain the result for transportation. End of life is mostly related to the disposal processes related to the sea water pipes and these can not be considered as very accurate because it is considered as glass and plastics being separate. With fiber reinforced plastics it is not easy to get the raw materials apart and they mostly end up in landfills [45].

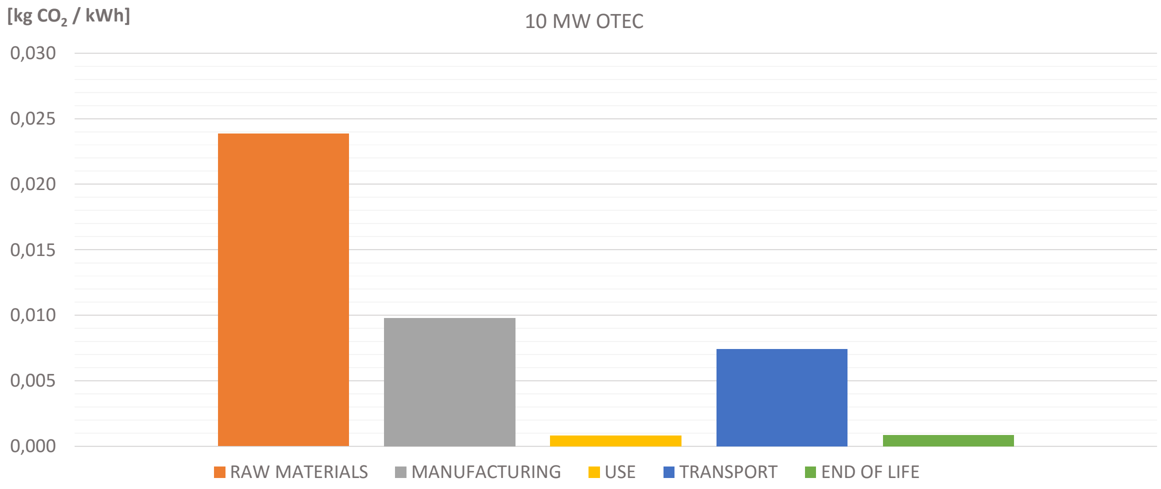

Figure 5.5: Contribution of life cycle phases of OTEC on climate change, GWP100a

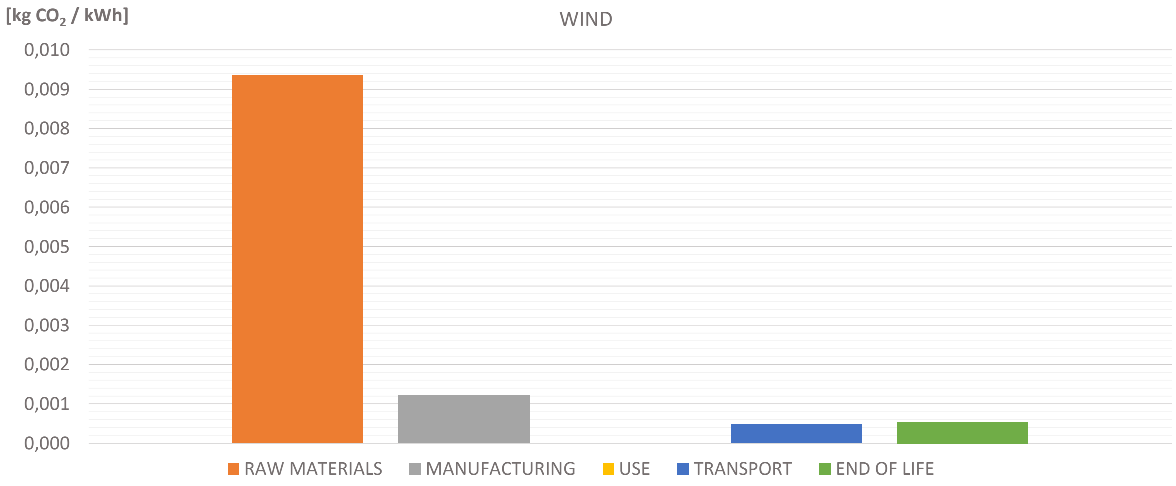

Figure 5.6: Contribution of life cycle phases of wind energy on climate change, GWP100a

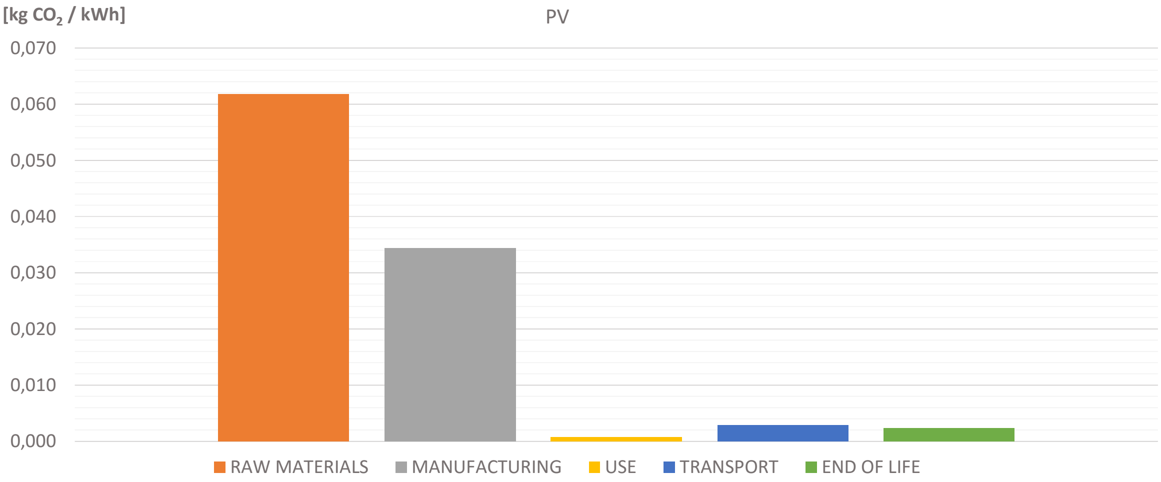

Figure 5.7: Contribution of life cycle phases of PV on climate change, GWP100a

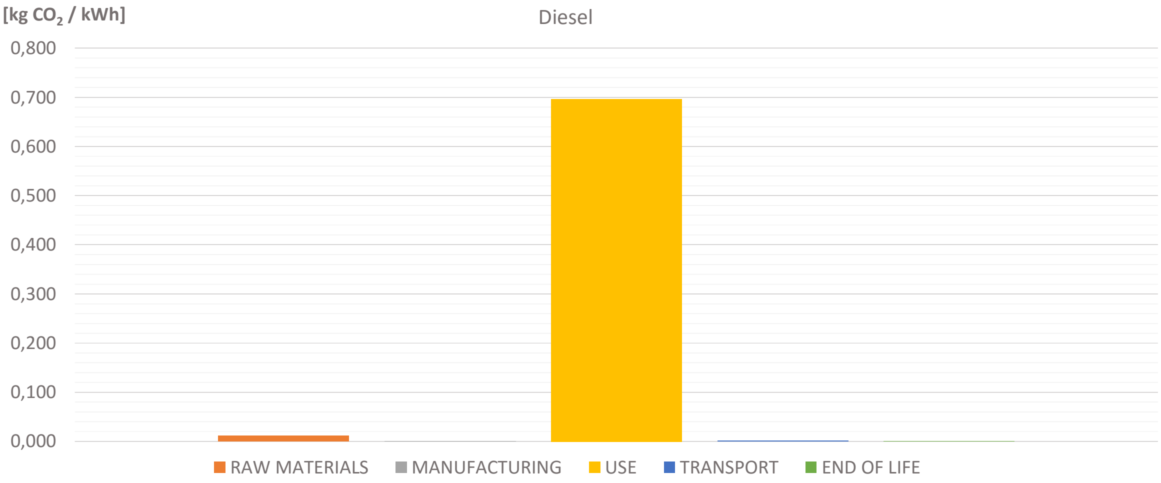

Figure 5.8: Contribution of life cycle phases of diesel on climate change, GWP100a

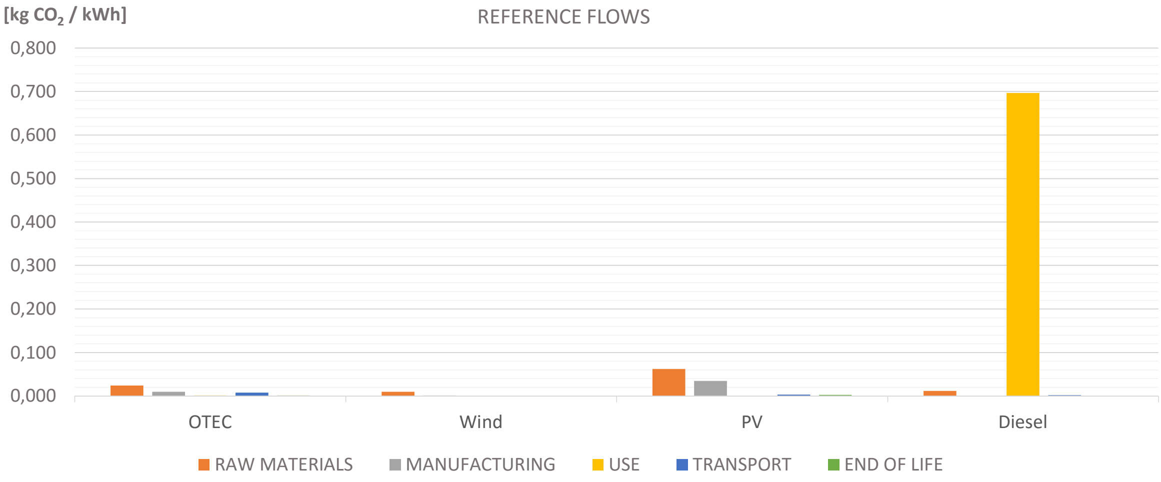

Figure 5.9: Life cycle contributions for all reference flows

In figure 5.6 the contribution of the life cycle phases of a wind turbine are shown. This graph is constructed based on information obtained from the processes required for wind electricity production in Ecoinvent [31]. Figures 5.7 and 5.8 show how the life phases of PV and diesel contribute, also based upon data from ecoinvent [28]. Thus emissions from renewable energy sources are mainly contributed by raw materials and manufacturing, while diesel solely emits during the use phase. In figure 5.9 the difference in impact between the reference flows is shown. It shows the immense difference between diesel and the renewable alternatives. If decisions were only based on cutting CO_2 emission as much as possible supply by diesel would definitely be omitted. Especially because OTEC as base load technology would generate the same output. The differences between fluctuating and base load technologies will be discussed in chapter 6.

The life cycle stages for the different 10 MW OTEC components can be found in the appendix A.4.

5.3. SENSITIVITY ANALYSIS

In the inventory analysis there were a couple assumptions that are uncertain. Examples are;

- Production of primary titanium is uncertain in the range of embodied energy between 551 and 609 MJ/kg. Most of the emissions related to the production could not be found in the Ecoinvent database, yet these are not emissions that have a climate change potential. As titanium is modeled right now the embodied energy is approximately 444 MJ/kg and the related CO_2 emissions are 43 kg/kg (value obtained as output of CMLCA model). With increasing the embodied energy to 609 MJ/kg the CO_2 emissions increase to 54.5 kg/kg. Implication for the overall LCA score of 10 MW OTEC is a 3.3% increase from 0.0428 to 0.0442 kg CO_2/kWh.

- Energy required for platform production is estimated to be 50% of the mass of the platform, as described in section 3.2.1. Another option to approximate the required energy is to scale up the 2500 ton ’G1816, platform’ from Ecoinvent. The required electricity will then increase by 71% and diesel with 55%. As a result the climate change score for 10 MW OTEC is increased by 11%, from 0.0428 to 0.0475 kg CO_2/kWh. This increase is quite significant and therefor it must be noted that more research is required to address this uncertainty.

- Heavy lift vessel for cold water pipe installation. Transport and installation for the cold water pipe is an uncertain process, because the number of heavy lift vessels that are required is not known. The whole process might be more complicated than assumed in the inventory. If the number of vessels is doubled the score for 10 MW OTEC is increased by 6.3%. To double the required vessels is speculation, it does show the significance of the uncertainty. More research is needed and more should be said in a later stage of the OTEC development.

5.4. OTEC 90% RECYCLING

For 10 MW OTEC recycling rates of 0.37 for steel and 0.21 for titanium are assumed. As said in section 2.2 closed loop recycling is considered for this study, thus the processes related to primary materials decrease and for secondary materials increase. It can clearly be seen that 90 % recycling reduces the CO_2 impact significantly for the components that are dependent on steel, chromium steel and titanium. As can be seen in appendix A.5 the contribution related to raw materials significantly decreases compared to 10 MW OTEC. Especially for the heat exchanger components it should be possible to achieve high recycling rates or even reuse.

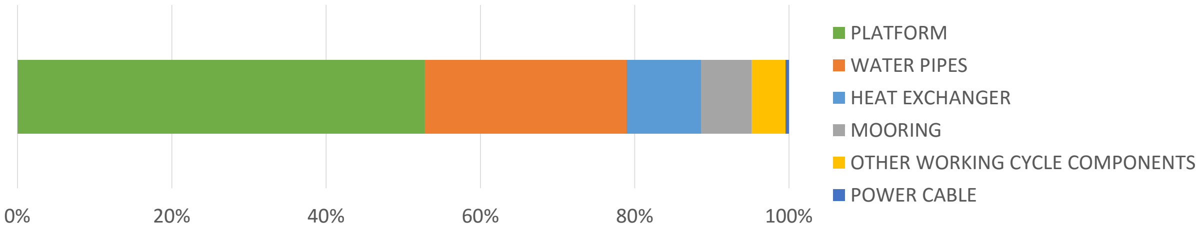

Figure 5.10: Contribution of 10 MW OTEC components with 90 % recycling

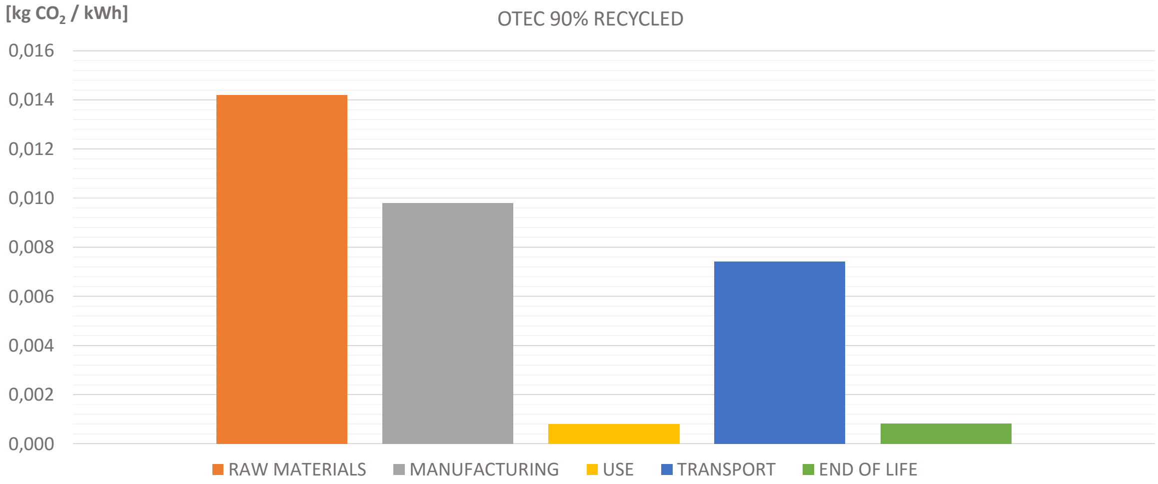

Figure 5.11: Contribution of life cycle phases of OTEC with 90 % recycling

5.5. BEST/WORST- CASE SCENARIO

Several OTEC configurations are suggested in the feasibility report by Bluerise and the current considerations have let to the inventory analysis as it is. It would be interesting to see what happens if other design options would be possible to reduce the impact. In this section the best and worst case scenarios are discussed.

The current design can be seen as the worst case scenario, because with the platform as such a large contributor most other options will likely reduce the impacts. In addition, the recycling rates for steel and titanium can be expected to be higher than currently adopted in the model [1].

The best case scenario should give an alternative for the spar truss platform. It would be possible to look into reduction of the use of materials or consider different materials. Another option is to make use of a vessel, which is described in section 3.2.2. Disadvantages of a vessel are motions of the ship and higher pumping requirements [15]. The use

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[1] Recycling rates for iron and titanium are estimated to be above 50% according to an UNEP status report [59]

of polymer heat exchangers is not included in the best case scenario, because this is not an immediately applicable option. Several companies perform research on this topic, but the tests for example on the mechanical strength of the polymers are not yet finalised.

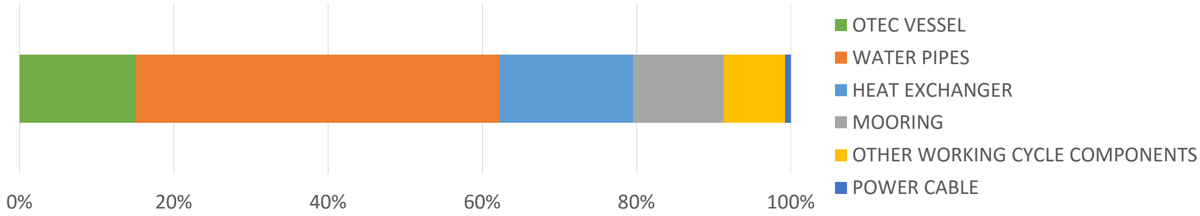

Figure 5.12: Contribution of 10 MW OTEC components best case scenario

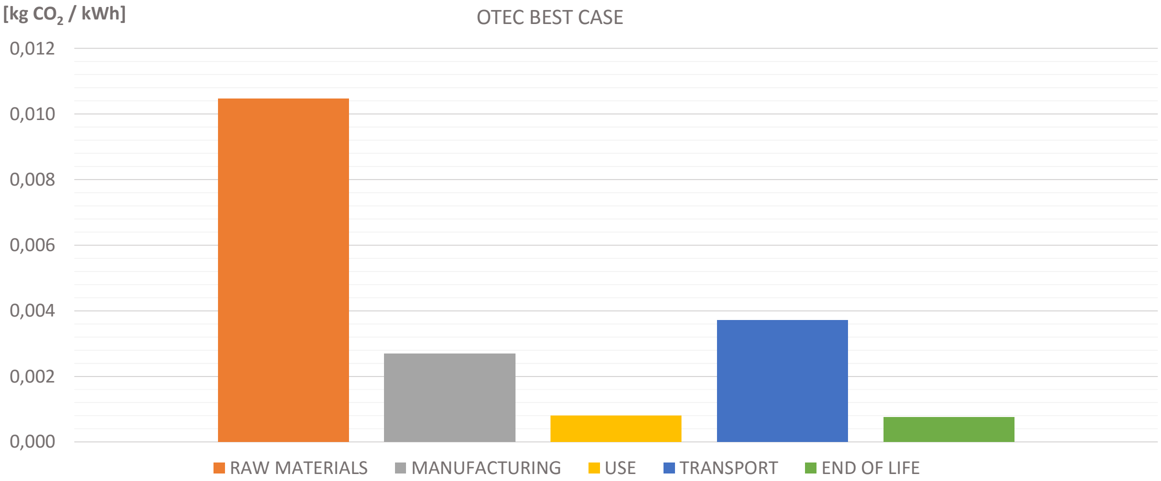

Figure 5.13: Contribution of life cycle phases of OTEC best case

5.6. 100 MW OTEC

From previous sections it could be concluded that the platform is a major contributor for the LCA of OTEC, so it is interesting to see what happens with a larger scale of production. If the production facilities would be scaled up from 10 MW to 100 MW the scaling factors of the components are defined by Bluerise and can be seen in table 5.1.

Table 5.1: Scale factors for 10 MW to 100 MW OTEC

	10MW		scale factor	**100MW**	
Ballast load hull (seawater)	300	mT	0.6	1,194	mT
Mooring vertical loads	491	mT	0.6	1,954	mT
Cycle equipment	1,384	mT	0.8	8,731	mT
Seawater pumps	60	mT	0.7	301	mT
Bulk/piping weight	30	mT	0.6	119	mT
Auxiliary systems	100	mT	0.5	316	mT
Power cable vertical load	55	mT	0.6	221	mT
Mooring winches	8	mT	0.6	32	mT
Mixed discharge pipe vertical	16	mT	0.6	64	mT
Total	**2,444**	**mT**		**12,932**	**mT**

Most interesting is to see what happens with the platform configuration and how it scales up. From several sources it can be concluded that for much higher payloads than considered in section 3.2 the mass of the structure does not have to be much larger, as can be seen in table 5.2. This either means that the payload was underestimated before or that with approximately the same mass different payloads are possible. This can be the case, because with changing the diameter of the platform the buoyancy can be increased a lot, without significantly changing the mass. In the offshore handbook it is noted that decks weighing from 3,000 to more than 20,000 tons have been installed on spars, thus 10,000 ton should not be an issue [35].

Table 5.2: Offshore spar platform comparison

	Offshore Handbook [35]	**Lucius** [60]	**Constitution**	**OTEC platform**
	tons steel	tons steel	tons steel	tons steel
Payload	3,000	16,500	10,770	2,050
Deck steel	1,100			not considered
Column steel	18,700	20,000	14,800	10,510
Mooring steel	2,200			1,577

The 'Lucius' platform is defined by T. Ayers as a conventional spar truss platform with a diameter of 33 meter, height of 198 meter and 20,000 ton structure that can support a 16,500 ton topside [60]. With these values for a conventional spar truss platform the LCA of 100 MW OTEC changes a lot. The contribution of the platform together with the mooring will be much smaller than with 10 MW OTEC and the overall impact will decrease as well.

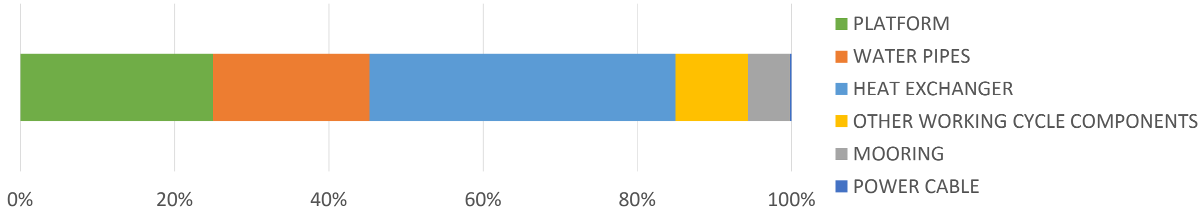

Figure 5.14: Contribution of 100 MW OTEC components

As can be seen in figure 5.14 the platform contribution is reduced from more than 50% for 10 MW to approximately 25% for the 100 MW system. The fact that the offshore spar truss platform is capable of carrying different payloads without significant change in mass implies that the platform design still needs some optimisation for OTEC.

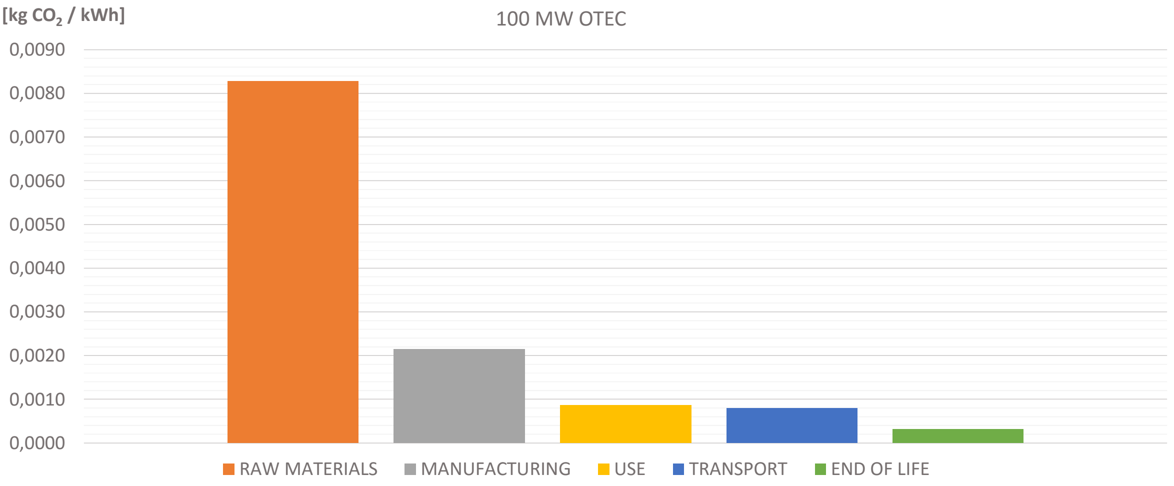

Figure 5.15: Contribution of life cycle phases of 100 MW OTEC

5.7. ENERGY PAYBACK TIME

The energy payback time can be calculated from the results of the life cycle assessment, because all required data is already assembled. The embodied energies of the materials are adopted from CES Edupack [51]. From contact with mister M.J. Ashby it can be assumed that the results from Edupack will mostly match the data from Ecoinvent. Energy for manufacturing, transport and disposal can be obtained from the model in CMLCA. All the results summed is the energy that is required for the 10 MW OTEC system and the energy payback time in years is this sum divided by the yearly production of energy by the system. The results can be seen in table 5.3 and they show that the energy payback time of a 10 MW OTEC system comes down to 3.76 years. In table 5.4 the EPT of the other OTEC systems are shown as well.

Table 5.3: Energy payback time

		Mass	[MJ/kg]	Energy [MJ]
Materials	Steel	7,718,004	25	192,950,100
	Recycled steel	4,532,796	7.5	33,995,970
	Chromium steel	493,857	82	40,496,274
	Recycled chromium	290,043	18	5,220,774
	Primary titanium	262,587	550	144,423,125
	Secondary Titanium	66,050	51.3	3,388,365
	Copper	17,760	60	1,065,600
	Aluminium	136,000	200	27,200,000
	Zink	7,200	45	324,000
	Glass fiber	1,370,200	70	95,914,000
	Epoxy resin	658,380	135	88,881,300
	Polymeres	12,774	90	1,149,696
	Nickel	6,405	170	1,088,850
	Secondary nickel	2,490	30	74,700
	Ammonia	155,000	23.4	3,627,000
	Cast iron	108,000	30	3,240,000
Manufacturing	Diesel			62,149,215
	Electricity			104,892,785
Transport	Diesel	3,256,288	42	136,764,134
Disposal	Diesel			1,152,906
	Electricity			700,446
Total				**948,699,241**
Energy production [MJ/year]				252,288,000
EPT [year]				**3.76**

Table 5.4: Energy payback time for OTEC systems

	10 MW OTEC	90% Recycled	Best case	100 MW OTEC
CO_2 [kg/kWh]	0.0427	0.0329	0.0184	0.0124
EPT	3.76	2.74	1.85	1.14

6

ENERGY MIX SCENARIOS

6.1. INTRODUCTION

First of all it should be noted that from the life cycle assessment point of view renewable energy sources clearly have a preference over fossil fuels (in this case diesel) when considering climate change. Therefore this section is not about a competition between available renewable energy options, but more about viable scenario's that will be capable of replacing diesel. In comparing the reference flows a discussion is needed about the capacity factor (cf) and base load versus fluctuating energy delivery systems. The capacity factor of the different energy systems is available, yet for an acceptable comparison only the cf is not enough. Fluctuating energy delivery systems like wind energy or PV need some kind of storage in order to function in the same way as a base load technology does. Even if the installed capacity of wind energy would be sufficient to supply energy during peak loads and taking into account the cf, there will be times without wind and a backup energy supply is needed. That is why wind and solar energy as reference flows will need adaptions in the LCA in order to be comparable to base load technology. Addition of backup options could be storage or diesel generators. In this study the LCA was obtained for 1 kWh of electricity produced by different technologies. The second stage of the study will focus on different energy mixes as electricity supply for a small island. The goal of the proposed energy mix will be to fulfill the need for electricity on Curacao. The suggested scenarios will give an output of energy per examined source and from these values their share in the total electricity supply can be determined. With slight adaptation the LCA-score obtained in section 4 will be multiplied by the percentages of each energy source in the mixture and this will give the LCA of the specific energy mix scenario.

6.2. CURRENT POWER SUPPLY

The current power supply is based on diesel generators combined with wind turbines. Practical information about wind energy in Curacao is presented by Aqualectra, this company is responsible for 90 % of the electricity production in Curacao [25]. The date of the presentation was 2006 and at that time two windfarms were installed; at Tera Kora 12 windturbines with 250 kW capacity each and Playa Kanoa 18 windturbines with 500 kW capacity each. The capacity factors of the farms were 0,34 and 0.583 respectively. Aqualectra states that wind speeds are practically constant throughout the whole year [25]. They range between 8 - 9 m/s (figure 6.1 shows the windspeed profile at Curacao for one week) and for 95 % of the time come from the same direction. From the statement of Aqualectra it can be concluded that the wind profile would be favorable. However, constant wind speeds throughout the year is not true as can be seen by figure 6.1. Future wind energy plans were to replace the old windturbines with 1 MW windturbines in Tera Kora. But it eventually resulted in 2 wind farms in Tera Kora and Playa Kanao of 5 windturbines with 3 MW capacity (Vestas) installed by Nu Capital [26]. The capacity factors of the current situation is not known, but approximately 20 % of the energy is accounted for by wind energy. Both scenarios were modeled in Matlab, the results are shown in table 6.1.

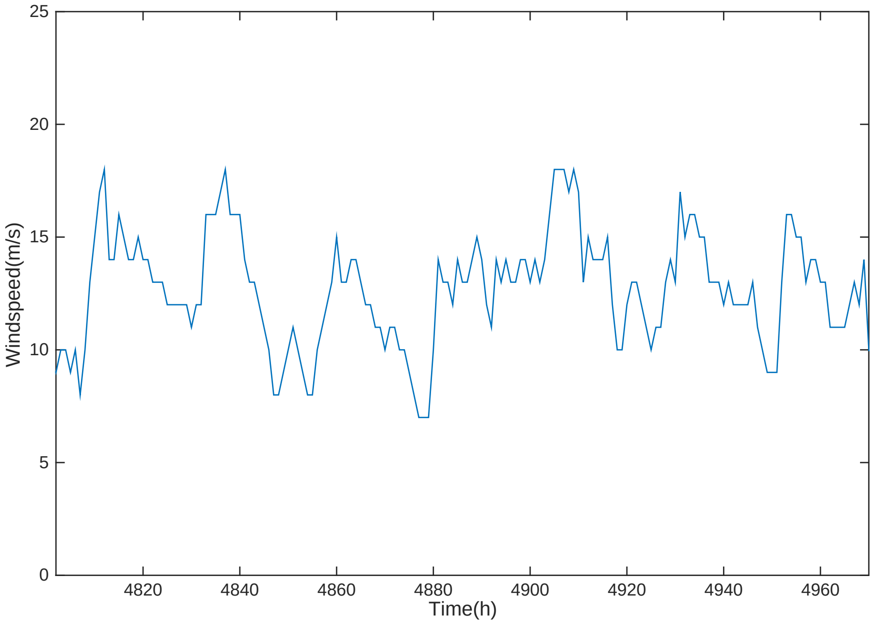

Figure 6.1: One week profile of windspeeds in Curacao obtained from Meteorological Service Curaçao

Table 6.1: Current situation, energy on yearly basis

	Situation 2006 [25]	Current situation
Energy [kWh]		
Diesel	4.42×10^8	3.94×10^8
Wind	5.49×10^7	1.04×10^8
OTEC	0	0
PV	0	0
Capacity factor		
$\text{cf}_{windTeraKora}$	0.340	0.395
$\text{cf}_{windPlayaKanoa}$	0.583	0.395
cf_{OTEC}	0	0
cf_{PV}	0	0

The scenario's are modeled in Matlab and the code can be found in appendix A.8. The energy mix scenario's will include diesel and wind, but for the future energy mix scenario's solar energy and OTEC are considered as well. Inputs are the load, wind speed (figure 6.1), insolation and ocean water temperatures (all specific for Curacao). The goal of the model is to predict how much energy is produced per energy source. It should be noted that the model is an oversimplification of reality, due to varying complexities such as the start-up time. All the renewable energy that is produced is subtracted from the load, the remaining load is accounted for by diesel. The energy that is produced while there is no load is discarded.

For the energy produced by the wind turbines eq. 6.1 is used to simulate the power output of the turbine. With η = the system efficiency (that can be tuned to achieve the right capacity factor), ρ = the density of air, N = number of wind turbines and A = the cross sectional area. The power curve for the 250 kW wind turbine is shown in figure 6.2, for 500 kW in figure 6.3 and for 3 MW in figure 6.4.

$$P = \eta \cdot 0.5 \cdot \rho \cdot v_{wind}^{3} \cdot N \cdot A \cdot \times 10^{6} \tag{6.1}$$

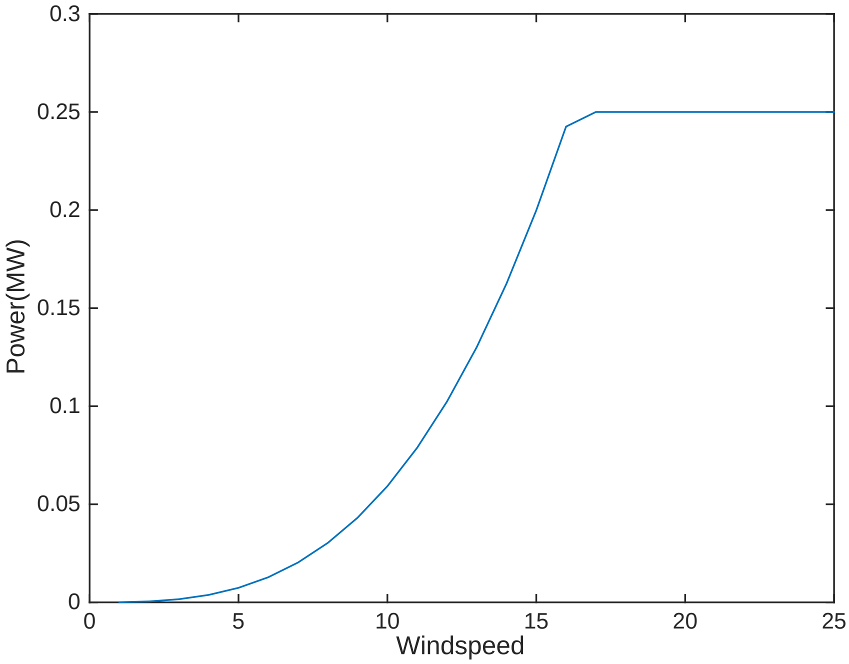

Figure 6.2: Power curve of 250 kW wind turbine

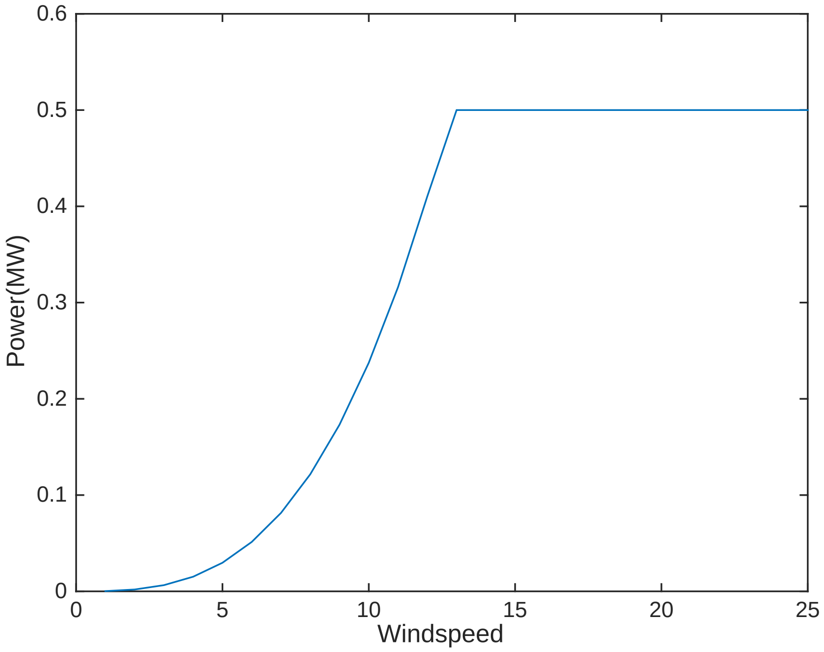

Figure 6.3: Power curve of 500 kW wind turbine

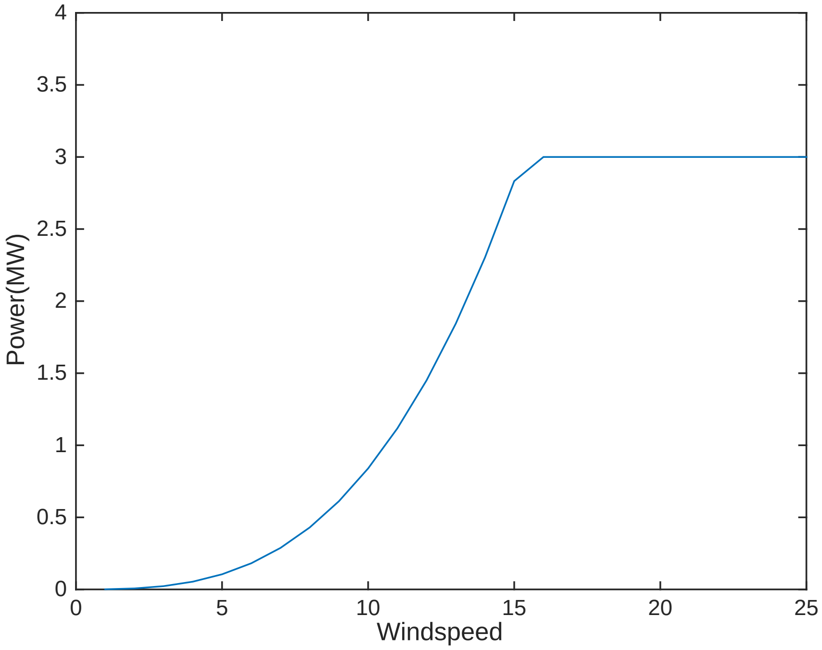

Figure 6.4: Power curve of 3 MW wind turbine

From figures 6.5 and 6.6 it can be seen that the share of diesel decreases due to larger capacity of the wind turbines. With the percentage of energy generated per source the LCA score could be obtained. Yet the conditions in the model should be the same as the assumptions made in the life cycle assessment. Especially the capacity factor should be similar. In table 6.2 the LCA score for wind energy with different capacity factors is shown. The inventory of the wind turbine remains the same, yet the amount of generated electricity increases (with increasing cf).

Table 6.2: CO_2 emissions per kWh for different capacity factors for wind energy

Capacity factor	0.2	0.34	0.395	0.583	
800 kW [51], [31]	0.0104	0.00609	0.0052	0.0036	kg CO_2 /kWh
2 MW [51], [30]	0.0134	0.00786	0.0068	0.0046	kg CO_2 /kWh

The results of table 6.2 are calculated with a quick LCA performed for a 800 kW wind turbine and 2 MW wind turbine. The data is obtained from Ecoinvent [31], the study by Martinez [30] and CES Edupack 2014 [51].

With the percentage of electricity that is generated per source and the emissions related to different capacity factors the LCA score for the current situation can be calculated. The LCA score for the situation in 2006 is not looked at, because the range of 250 kW wind turbine is not close enough to the 800 kW turbine. For the current situation the 3 MW turbines are assumed to have approximately the same value for the CO_2 emissions per kWh as the 2 MW turbine from table 6.2. The LCA score for the current situation is shown in table 6.4.

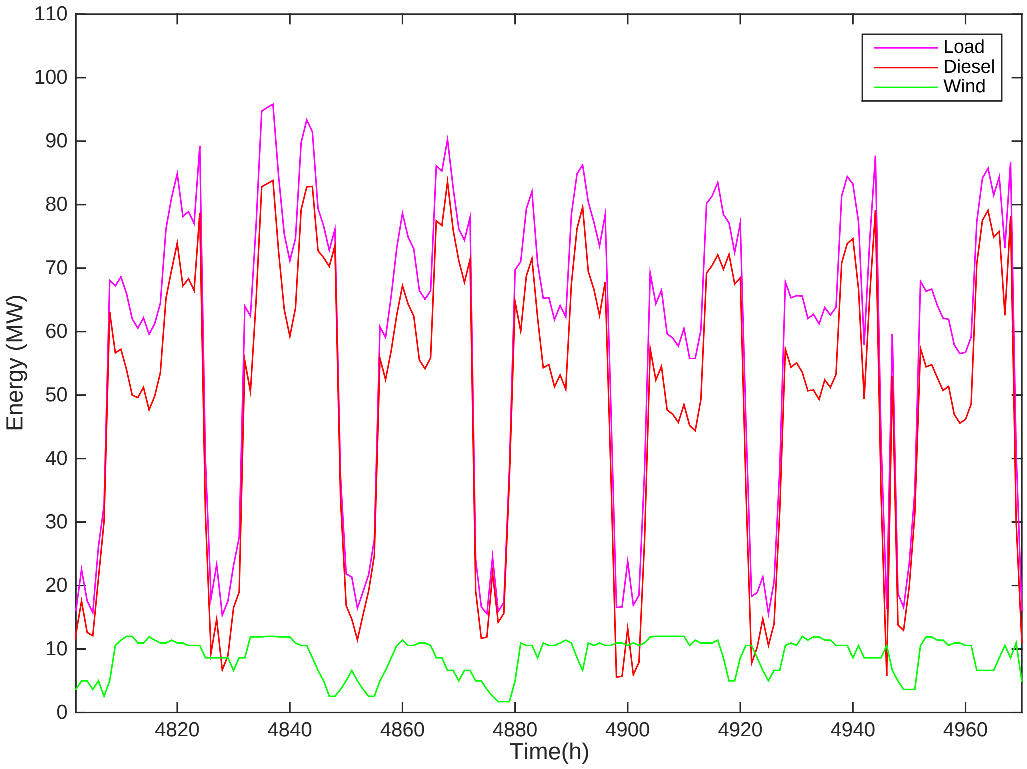

Figure 6.5: Energy generation; in 2006

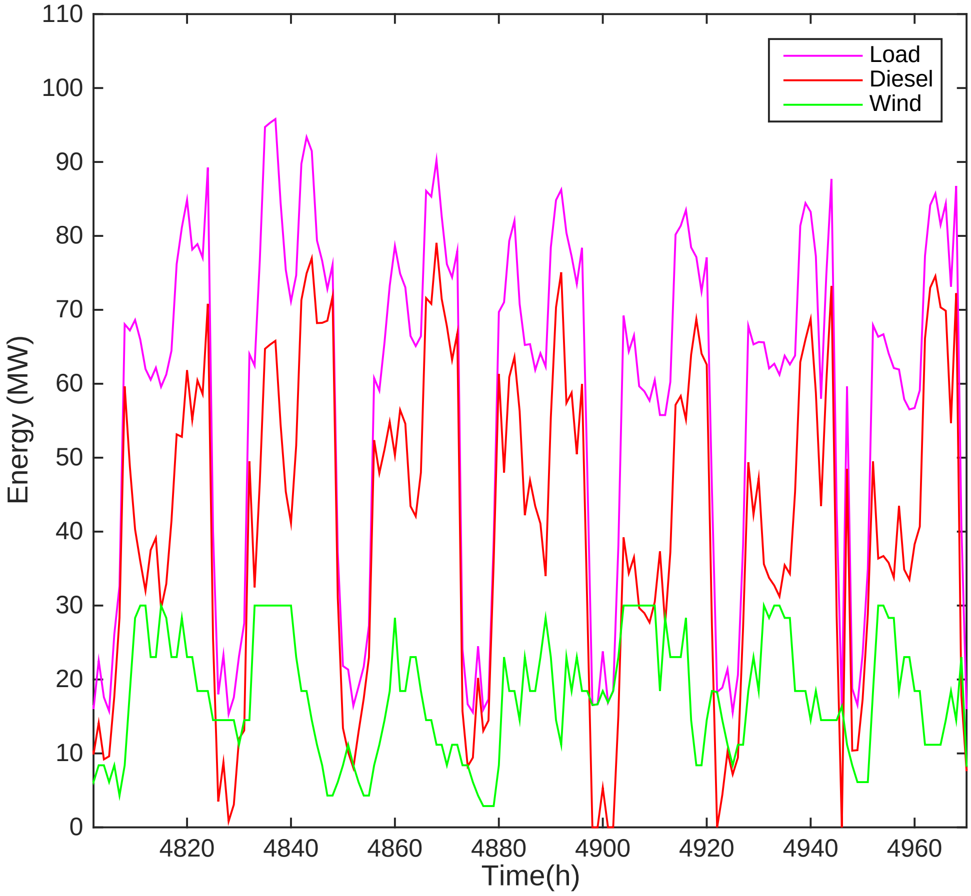

Figure 6.6: Energy generation; current situation

6.3. FUTURE SCENARIOS OF POWER SUPPLY

For future energy scenarios it would be interesting to see what would happen if a 10 MW OTEC system would be installed on Curacao, or several 10 MW OTEC installations. Next to OTEC the influence of increasing other renewable sources is considered as well. In table 6.3 the following scenario's are to be found;

- 10 MW OTEC; next to the 30 MW of wind energy 10 MW of OTEC is installed on Curacao. This scenario is chosen, because this scale is investigated in this research.
- 30 MW all; 30 MW of OTEC, wind and solar energy is installed. This scenario will show the output of the different technologies together and their characteristics.
- 60 MW wind; the capacity of wind is expanded to 60 MW. This would be the maximum installed capacity of wind energy on Curacao according to van Engelen [61]. It is assumed that a large capacity factor of 0.595 is reached for the newly installed wind turbines, based on the earlier achieved cf for the situation in 2006 6.1.
- 60 MW OTEC; the 30 MW of wind energy is omitted and 60 MW of OTEC is installed. It is interesting to see what will happen with extreme scenario's. The implications of large scale OTEC is one of them. The 30 MW wind is omitted, because then the

comparison of OTEC and wind will be better. The 60 MW is due to the limit of 60 MW of wind capacity that can be installed.

In the model there is a loop that could cause a decrease of the capacity factor of wind and solar, because energy produced by OTEC overrides the energy produced by other sources. This issue does not occur in any of the scenarios. It can be seen that in the 60 MW scenario the cf of OTEC is reduced, that is a consequence of OTEC energy that is discarded when there is no load. The decrease of the capacity factor of OTEC will affect the LCA score of OTEC. With a cf of 0.707 the LCA score of OTEC becomes 0.048 kg CO_2/kWh.

Table 6.3: Future energy mix scenario's, on a yearly basis

	10 MW OTEC	30 MW all	60 MW OTEC	60 MW wind
Energy [kWh]				
Diesel	3.21×10^8	1.63×10^8	1.25×10^8	3.01×10^8
Wind	1.04×10^8	8.82×10^7	0	2.08×10^8
OTEC	7.30×10^7	2.07×10^8	3.72×10^8	0
PV	0	4.70×10^7	0	0
Capacity factor				
$cf_{windTeraKora}$	0.395	0.336	0	0.591
$cf_{windPlayaKanoa}$	0.395	0.336	0	0.591
cf_{OTEC}	0.833	0.788	0.707	0
cf_{PV}	0	0.179	0	0

6.4. LCA FOR DIFFERENT SCENARIOS

The LCA is largely dependent on the amount of diesel that is annually used for electricity generation. As seen earlier the emissions for electricity by wind or OTEC are much lower compared with emissions from diesel generators. With the results from table 6.3 it can be seen that 60 MW of wind results in less reduction of use of diesel than 60 MW of OTEC. This is due to the fluctuating character of wind energy as mentioned before in section 6.1. In the scenario with 60 MW of OTEC installed it can be seen that only 25% of the electricity is produced by the diesel generators. In table 6.4 the LCA scores for the different scenarios are shown. It shows that OTEC has a clear advantage due to highest reduction of diesel. However this is only valid if besides CO_2 emissions no other factors (such as levelised costs of energy) would be considered.

Table 6.4: LCA scores for the scenarios, percentage is the share of electricity supplied per source over a year

	Current situation	10 MW OTEC	30 MW all	60 MW OTEC	60 MW wind
Diesel	79%	64%	32%	25%	59%
Wind	21%	21%	17%	0%	41%
OTEC	0%	15%	41%	75%	0%
PV	0%	0%	9%	0%	0%
CO_2 [kg/kWh]	**0.555**	**0.460**	**0.252**	**0.212**	**0.416**

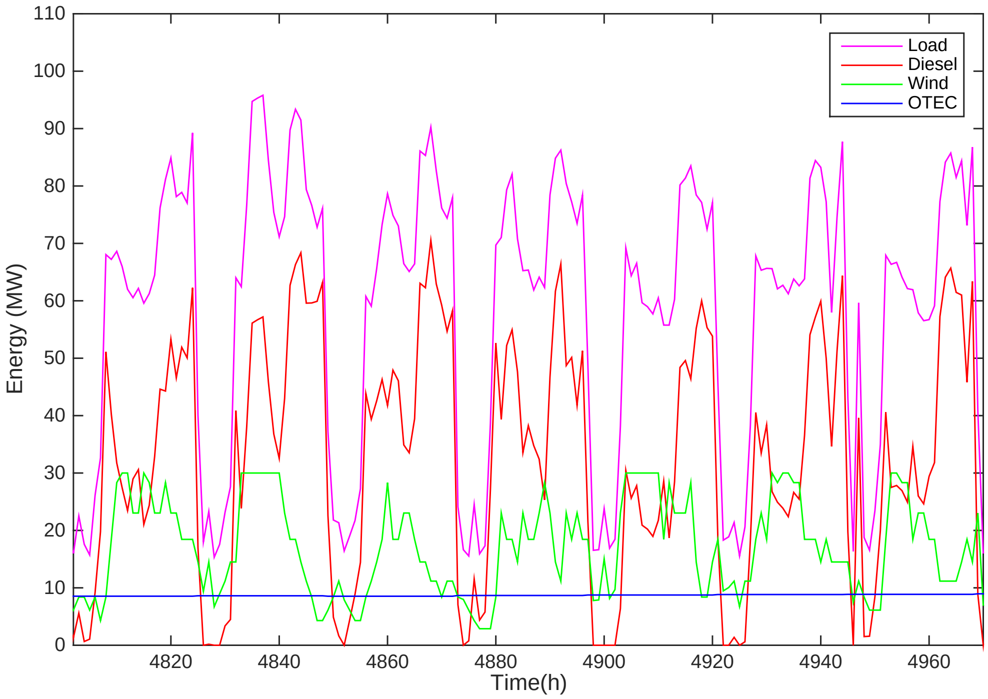

Figure 6.7: Energy generation; 10 MW OTEC

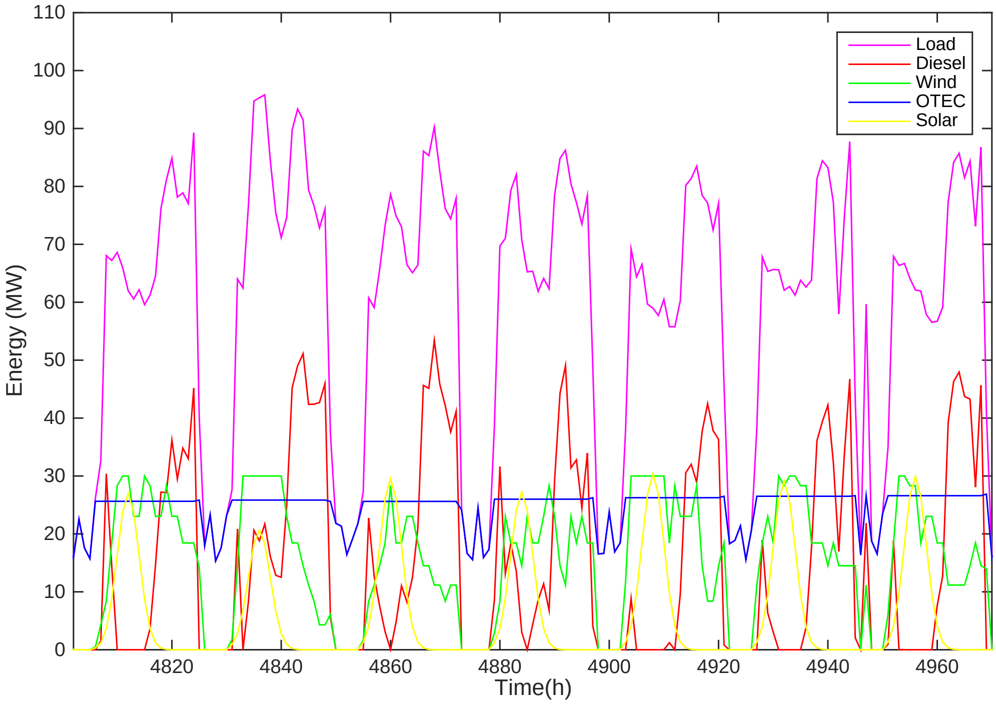

Figure 6.8: Energy generation; 30 MW OTEC, solar and wind

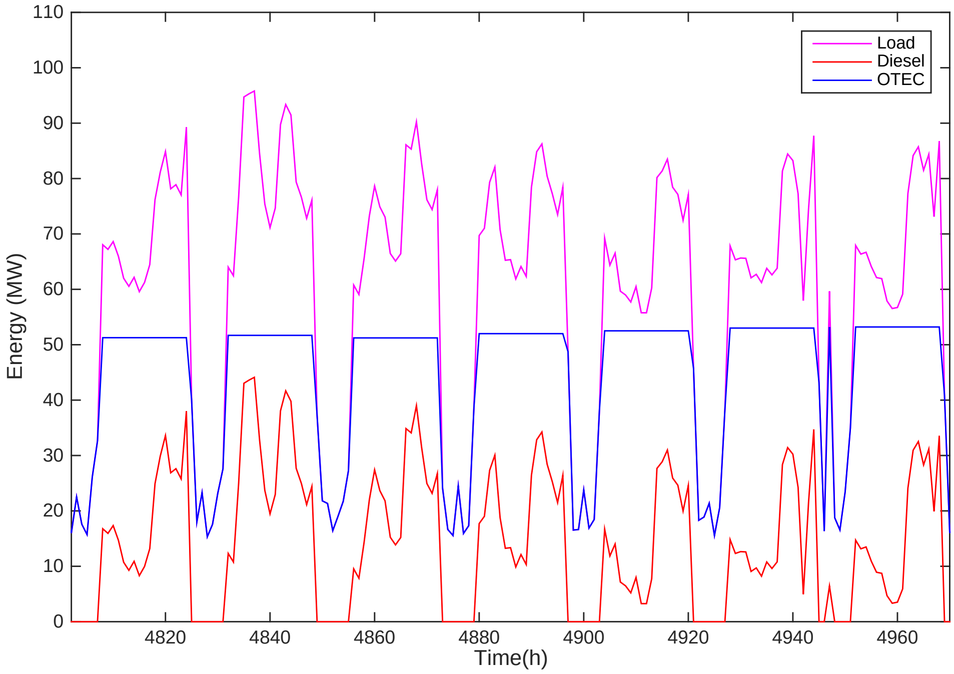

Figure 6.9: Energy generation; 60 MW OTEC

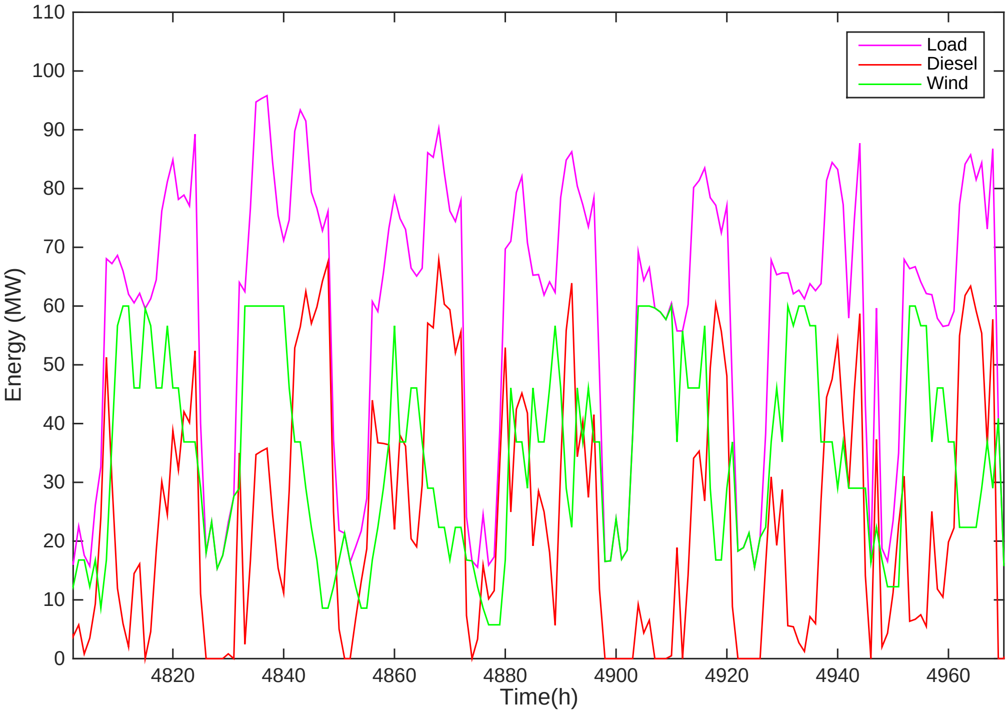

Figure 6.10: Energy generation; 60 MW wind

6.5. OPTIMAL SCENARIO FOR ELECTRICITY SUPPLY ON CURACAO

As seen in the previous sections with large scale implementation of OTEC the capacity factor is reduced. With large scale implementation of wind energy the share in electricity supply by diesel was still 59 %. Thus both scenarios are not optimal. An optimal scenario for Curacao considering the LCA of the reference flows would include both OTEC, wind energy and PV. OTEC could supply the base load requirements for the island, while wind energy in combination with storage should handle the peak loads. However the base load on Curacao is not very high, therefore not a very large capacity of OTEC would be installed (between 20 and 30 MW, considering the graph of the load). Then the issue with the fluctuating source of wind energy remains. An optimum situation should be investigated for the combination of OTEC, wind energy, PV and storage [1]. In this investigation the specific requirements for electricity in Curacao should be mapped. For instance it might be possible that a significant percentage of the peak load electricity is required due to air conditioning. If this is the case the discarded cold water flow of the OTEC system could be used for seawater air conditioning (SWAC). The use of cold water other then for OTEC is not incorporated in this study. Next to the score of impact it would be interesting to include the levelised costs of energy for the reference flows.

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[1] An additional idea was mentioned by van Engelen, to store energy in electric vehicles [61].

7

CONCLUSION

Based on information of the feasibility report of ocean thermal energy conversion by Bluerise the life cycle assessment of a 10 MW OTEC system on Curacao was obtained. The whole life cycle of OTEC was considered from raw materials till end of life. Results of the study are focused on the impact category climate change and the energy payback time. The climate change potential of 10 MW OTEC is 0.0428 kg CO_2/kWh and with a 90% recycling rate this might be reduced to 0.0331 kg CO_2/kWh. Even more reduction is possible if the spar truss platform is replaced by an OTEC vessel, this option would result in 0.0184 kg CO_2/kWh. The energy payback times are respectively 3.76 years, 2.74 years and 1.85 years. With the contribution analysis in the interpretation phase it is shown which components of OTEC contribute the most. For every component it is shown which processes are the most significant as well. This information is valuable in order to see which changes in the design are most important to improve.

The CO_2 emission resulting from 1 kWh of electricity production by a 10 MW OTEC installation is 16 times lower than the CO_2 emission resulting from 1 kWh of electricity production by diesel generators. In relation to a 3kWp PV installation the emissions resulting from OTEC are 1.752 lower. The OTEC emissions are 3.9 times higher compared with an 800 kW wind turbine. This means that at first glance OTEC is less preferable than wind energy. Yet, when taking into account the fluctuating character of wind in an energy mix scenario, the opposite is true. For the same installed capacity (60 MW) OTEC reduced the share of diesel to 25%, while wind reduced it to 59%. Thus, it can be concluded that OTEC as a base load technology and with relatively low CO_2 emissions is a promising technology.

8

DISCUSSION

8.1. ENVIRONMENTAL PERFORMANCE OF OTEC

Previous studies related to life cycle assessment of ocean thermal energy conversion are discussed in 1.2.3. The first estimation of the energy payback time was done by Uchiyama [21], which was 4.58 years for a 2,500 kW OTEC system. The study of Uchiyama was used by Tahara to estimate the CO_2 emissions and energy payback time of 100 MW OTEC. This thesis differs with the study of Tahara on the following issues [23];

- The flow diagrams and considered unit processes are included and can be found in appendix A.2.
- Processes for manufacturing are described in the inventory, see chapter 3. The required assumptions are documented.
- The system boundaries are shown in section 2.4
- Estimations of materials and their embodied energy. The mass of titanium that is required in comparison Tahara is two times lower. However, the CO_2 emissions related to titanium production are estimated 4 times higher. The assumptions for titanium production are obtained from recent databases [51].
- The required amount of electricity for construction is two times higher than found by Tahara.
- There is an extensive contribution analysis performed, see chapter 5.

Considering the results of the thesis and the study of Tahara the CO_2 emissions per kWh and energy payback time of 100 MW do look quite similar. Tahara et. al. obtained an energy payback time of 1.31 year and emissions of 0.0136 kg CO_2/kWh. The estimated energy for materials and construction by Tahara [22] are comparable with this study, yet the data which it is based on is different.

The study of Banerjee et. al. found the emissions of OTEC to be 0.01146 kg CO_2/kWh [17] and they based their inventory on the study by Tahara [22]. The data of Banerjee et. al. only includes the materials steel, copper, iron, plastics and cement, so they did not consider titanium. Furthermore there is no mention about manufacturing, transport or end of life considerations.

Another study performed by Nomura et. al. shows 0.111 kg CO_2/kWh and this study does include titanium and manufacturing processes [24]. The scale for this study is 2,500 kW OTEC and it is said that titanium and thus the heat exchangers account for a large part of the LCA. It does not give the percentages of the different contributions. Considering the OTEC scale the study might be based on the previous study by Uchiyama. As with the study by Tahara, the background information about manufacturing and transport is missing and end of life processes are excluded.

This thesis shows that the major contribution to CO_2 emissions are related to the transport and steel construction of the platform, transport and installation of the cold water pipe and the production of titanium for the heat exchangers, see chapter 5. Two of them (steel construction and titanium production) are mentioned by previous studies. The estimations for transport of the platform and cold water pipe are not mentioned/neglected. In the study by Nomura et. al. [24] the share of the manufacturing of heat exchangers is considered to be a large one, yet the percentage is not mentioned. In this thesis the energy needed for the manufacturing processes of the heat exchangers accounts for only 6 %. This is mainly due to the high contribution of the raw materials. For primary titanium the emission of CO_2 is assumed to be 43 kg/kg, i.e. 4 times higher than is mentioned in previous studies.

8.2. DESIGN OPTIMALISATION FOR 10 MW OTEC

The interpretation phase has shown the biggest contributors to the impact on climate change as a consequence of electricity generation by OTEC. The platform is one of the biggest contributors and considering the weight to payload ratio it seems that the spar truss platform is not the best option for 10 MW OTEC. Yet it should be possible to make an alternative platform design optimised for the application of OTEC. As discussed in the interpretation an OTEC vessel would be a more direct approach to reduce the emissions of 10 MW OTEC.

The titanium heat exchangers are the most important aspect related to the CO_2 impact, considering the working cycle of OTEC. This is due to the large energy intensive titanium surface required for heat transfer. Reducing this impact theoretically can be achieved by reducing the impact of titanium or searching for alternative heat exchanger materials. The reduction of impact of titanium is possible by looking into alternative ways of production. However, this thesis did not investigate these alternatives. Alternative heat exchanger materials are aluminum and somposites. Especially composites seem promising. Bluerise is focusing on this field of research [52]. From the LCA perspective, composites have a significant lower impact than the titanium heat exchangers. With high recycling rates this difference becomes smaller. For large scale implementation of OTEC systems in combination with reuse of materials, titanium therefore might still perform better than composites.

The use of heavy lift vessels for transport and installation increases the impact of the cold water pipe significantly. Specific information for installation of the cold water pipe is still uncertain, but the length of the CWP will make it a complex process. Other options such as part by part installation on site could be an alternative, but that requires more research.

8.3. PERFORMANCE IN AN ENERGY MIX SCENARIO

With the energy mix scenarios it is shown that large implementation of renewable energy will reduce the CO_2 emissions. An ideal scenario for Curacao would be OTEC as source for the base load electricity in combination with preferably wind and storage for the peak loads. Wind is preferred over solar due to a lower impact score. Yet, in order to install enough capacity for the island PV should be considered as well (60 MW would be the maximum installed capacity for wind). The amount of storage that is required could be reduced with larger installed capacities of OTEC. Specific requirements of the electricity in Curacao are not investigated.

9

RECOMMENDATIONS

9.1. REDUCTION OF THE IMPACT OF OTEC

For a 10 MW OTEC installation the spar truss platform is not optimal. The design should be adapted for OTEC or omitted and the alternative of an OTEC vessel should be considered. With installed capacities of 100 MW the spar truss platform is better applicable. Investigation of composite heat exchangers is very interesting. Implementation of the heat exchangers could reduce the CO_2 emissions of OTEC significantly. Other recommendations would be to look into the recycling possibilities of the components. With high recycling rates the impact is severely reduced. Most of the materials used for OTEC are suitable for recycling, with the sea water pipes as exception. Disposal of the sea water pipes could have more impact than currently assumed in this study. Fiber reinforced plastics mostly end up at landfills. It is therefore recommended to consider reuse of the sea water pipes and take that into account at the design stage.

9.2. IMPROVEMENT OF THE LIFE CYCLE ASSESSMENT MODEL

The life cycle assessment could have been improved with better availability of data. This issue is very common for LCA studies. Better cooperation of related industries would have led to less required assumptions and thus uncertainties.

Only climate change is considered to be an important impact category. Yet other categories could be addressed in future research, then it will be essential to look better into the titanium production process. Some volatiles during the Kroll process are neglected and the emissions from primary titanium production have too low values for NO_x and SO_x.

The influence of OTEC on the ocean ecosystem is neglected in this thesis. More research is required on this topic. As mentioned earlier (section 1.2.2) the best approach would be to measure the impact from operational OTEC systems.

9.3. FUTURE WORK

Research into an optimal energy mix scenario including the specific energy requirements of the island Curacao and levelised costs of energy would form a complete picture for policymakers. Minimum impact with a low levelised cost of energy seems achievable. The technologies are there and the increased installed capacity of wind energy on Curacao has reduced the price of electricity by more than 50% already [61].

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A

APPENDIX

A.1. IMPACT CATEGORIES

Table A.1: Impact categories from Guinee, baseline categories [8]

Impact category	Interpretation	Factor and Unit
Depletion of abiotic resources	Natural resources regarded as non-living (energy, iron ore, crude oil), focused on extraction and depletion	ADP, kg (antimony eq)
Impacts of land use land competition	Land occupation, land temporarily unavailable	$m^2 \cdot yr$
Climate Change	**Impact of human emissions on the radiative forcing of the atmosphere**	**GWP_{100}, kg(CO_2 eq)**
Stratospheric ozone depletion	Thinning of the stratospheric ozone layer as a result of anthropogenic emissions, implicates more UV-B solar radiation	ODP_{∞}, kg (CFC-11 eq)
Human toxicity	Impacts on human health of toxic substances present in the environment	$HTP_{\infty,global}$, kg (1,4-dichlorobenzene eq)
Ecotoxicity; freshwater aquatic ecotoxicity	Impacts of toxic substances on freshwater aquatic ecosystems	$FAETP_{\infty,global}$, kg (1,4-dichlorobenzene eq)
Ecotoxicity; marine aquatic ecotoxicity	Impacts of toxic substances on marine aquatic ecosystems	$MAETP_{\infty,global}$, kg (1,4-dichlorobenzene eq)
Ecotoxicity; terrestrial ecotoxicity	Impacts of toxic substances on terrestrial ecosystems	$TAETP_{\infty,global}$, kg (1,4-dichlorobenzene eq)
Photo-oxidant formation	Formation of reactive chemical compounds such as ozone by the action of sunlight on certain primary air pollutants (VOCs and CO in presence of NO_x)	POCP, kg (ethylene eq)
Acidification	Acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials	AP, kg (SO_2 eq)
Eutrophication	Impacts of excessively high environmental levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P)	EP, kg (PO_4)

A.2. FLOW DIAGRAMS

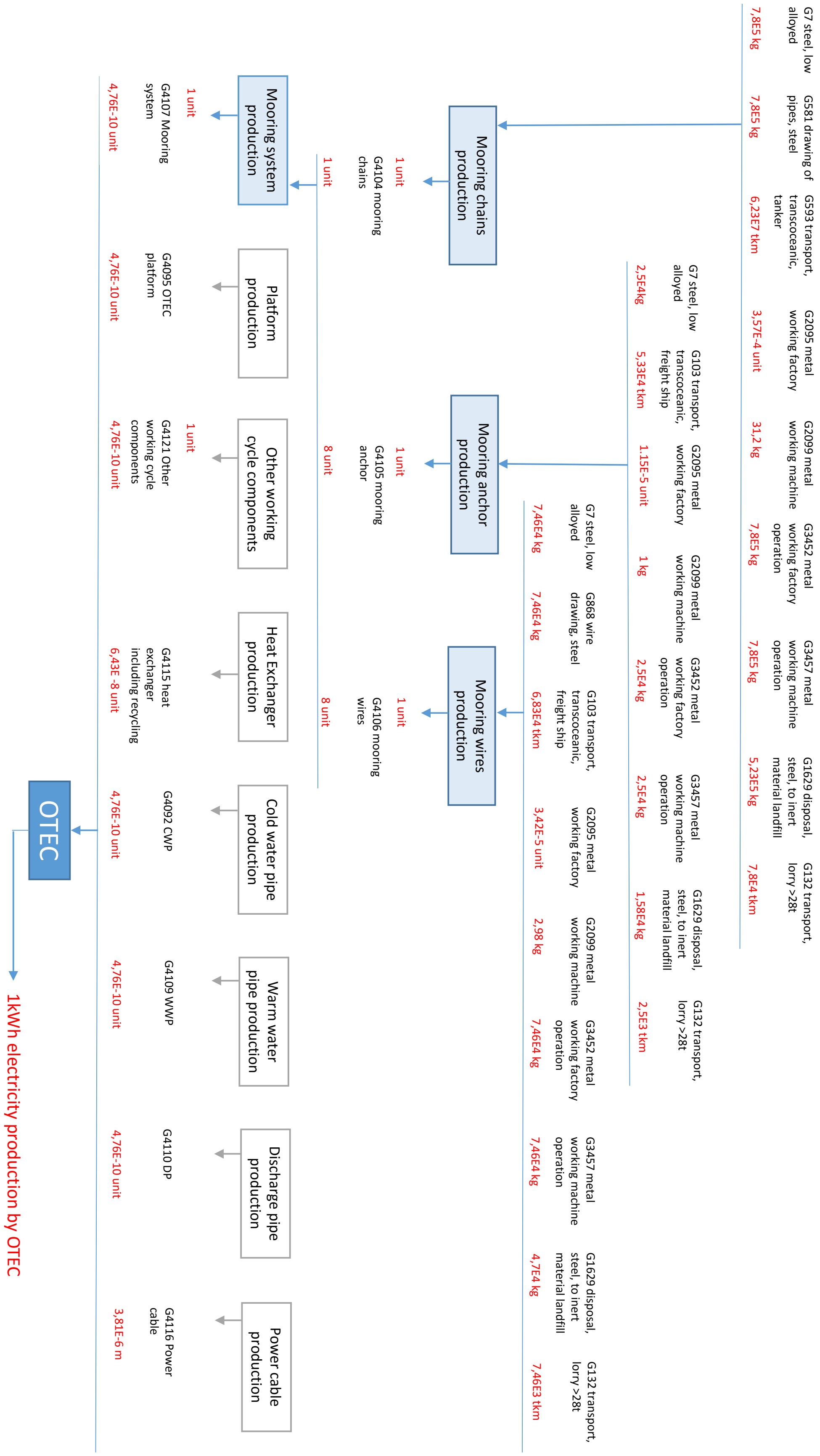

Figure A.1: Flowdiagram unit processes of the mooring system

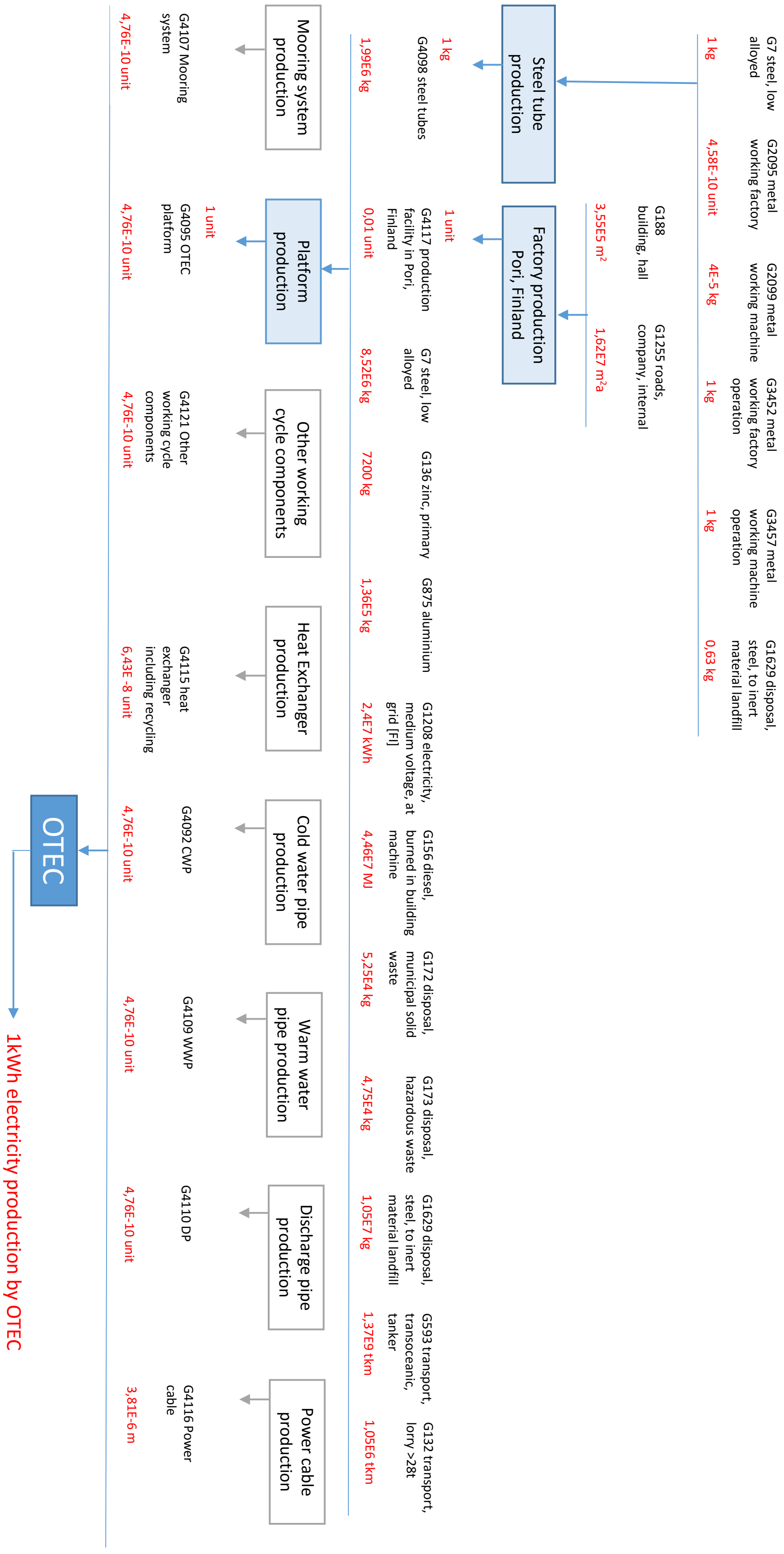

Figure A.2: Flowdiagram unit processes OTEC platform

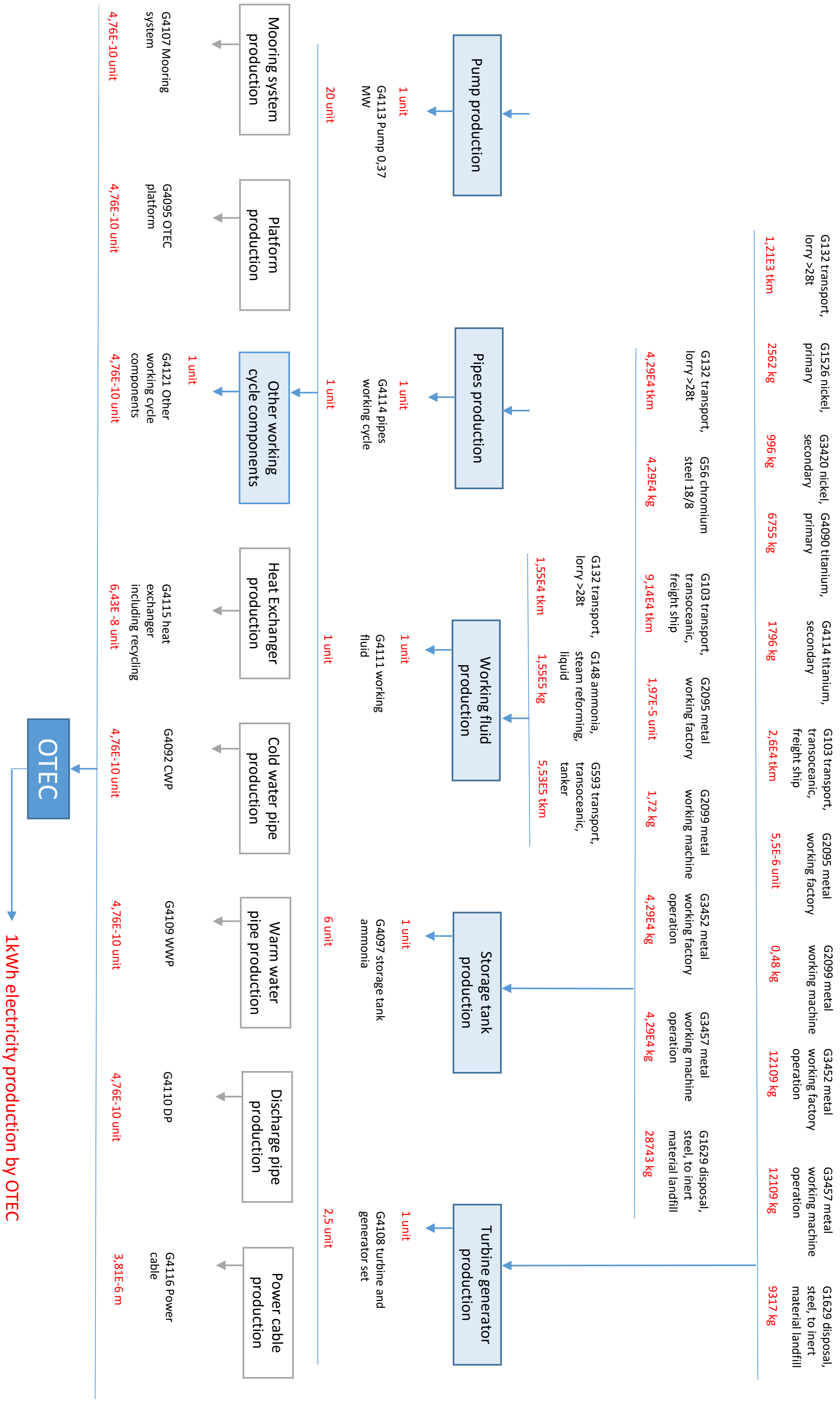

Figure A.3: Flowdiagram unit processes of working cycle components part 1

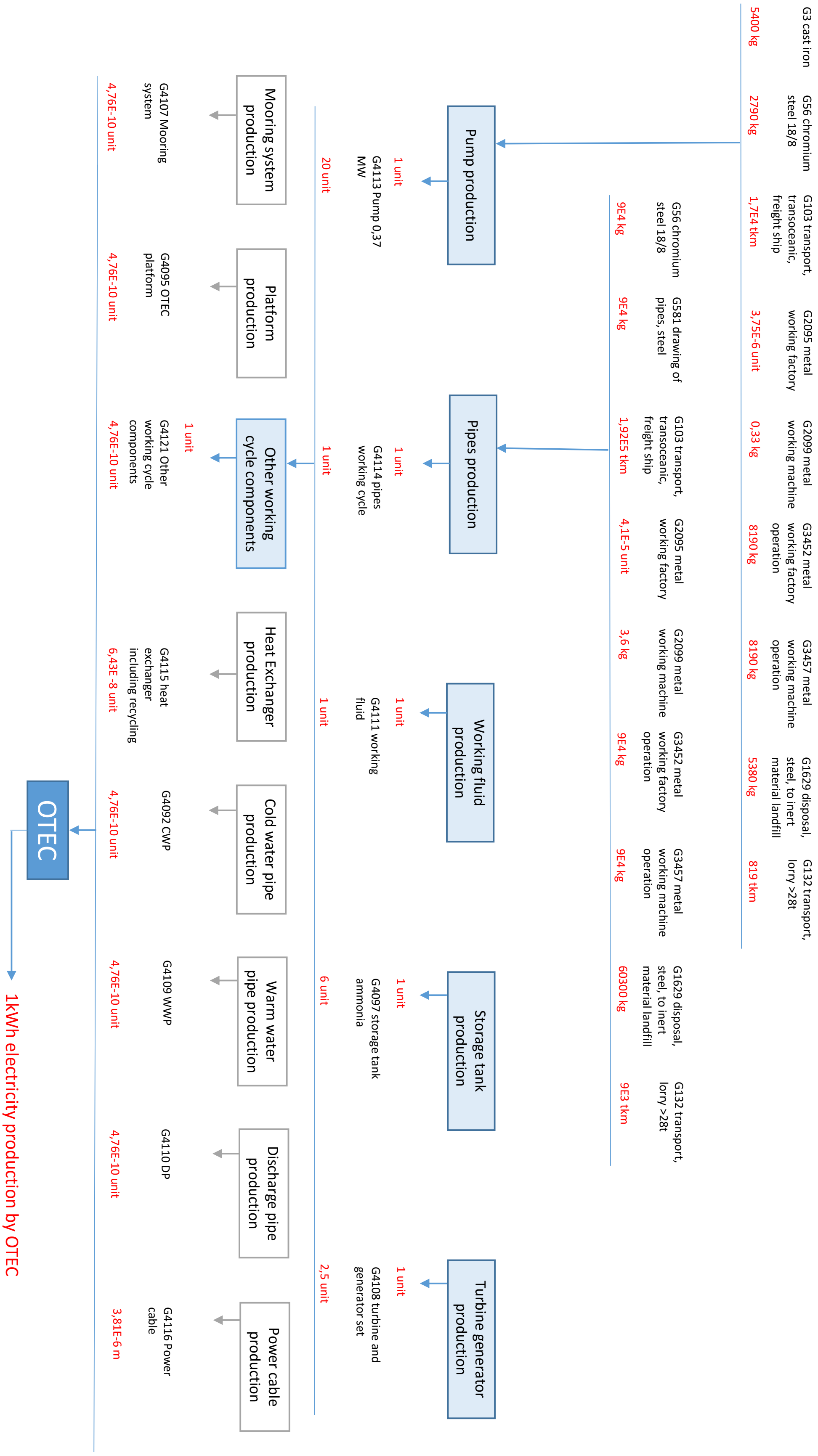

Figure A.4: Flowdiagram unit processes of working cycle components part 2

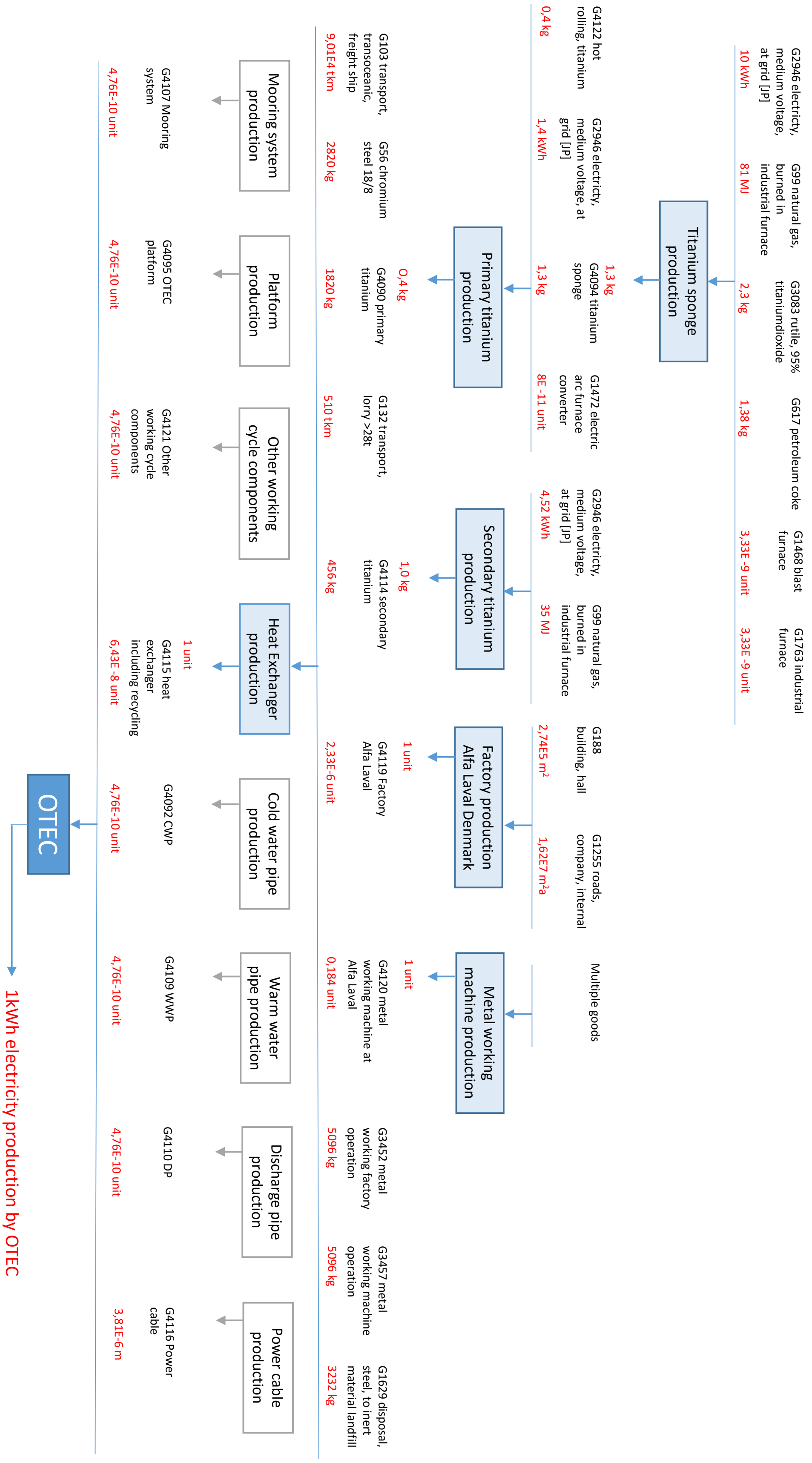

Figure A.5: Flowdiagram unit processes of the heat exchanger

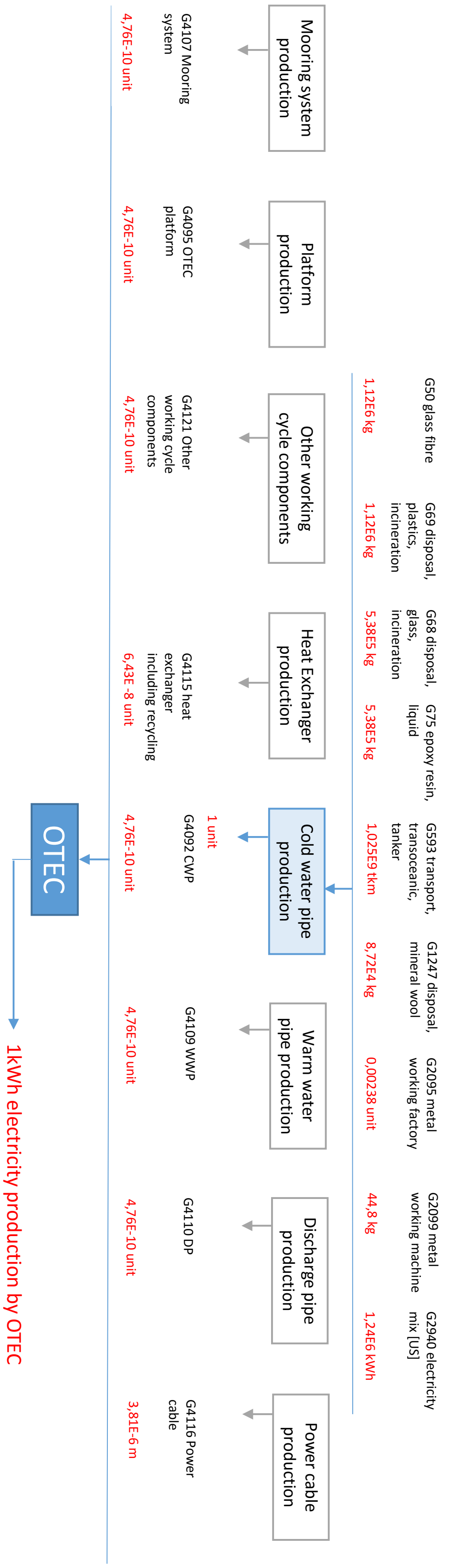

Figure A.6: Flowdiagram unit processes of the cold water pipe

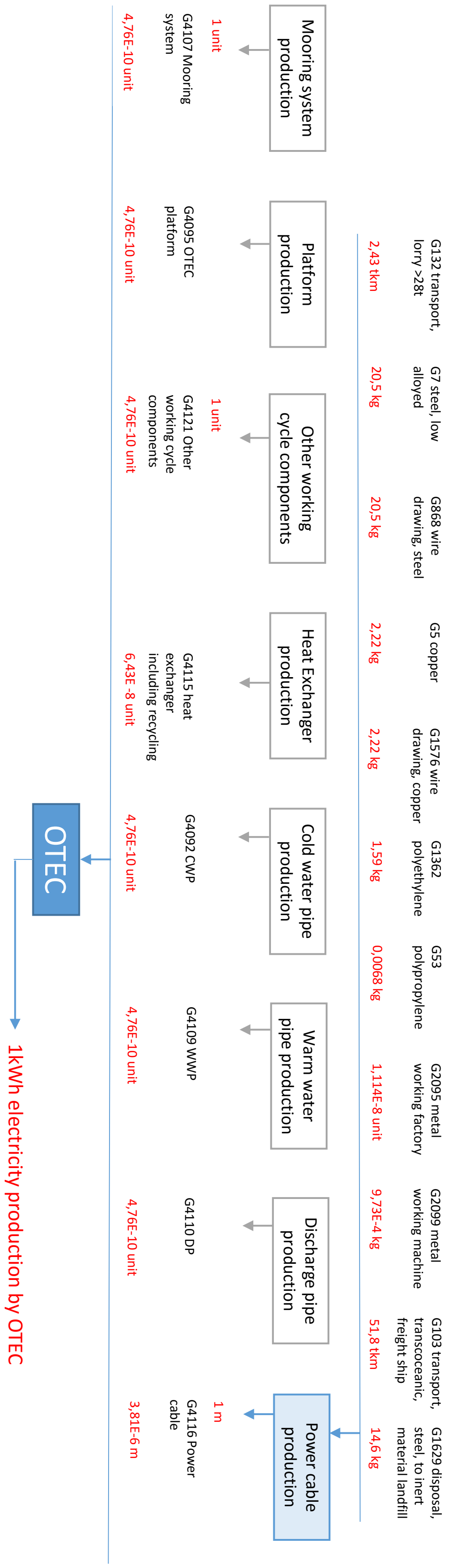

Figure A.7: Flowdiagram unit processes of the power cable

A.3. CONTRIBUTIONS OF PROCESSES FOR REMAINING COMPONENTS

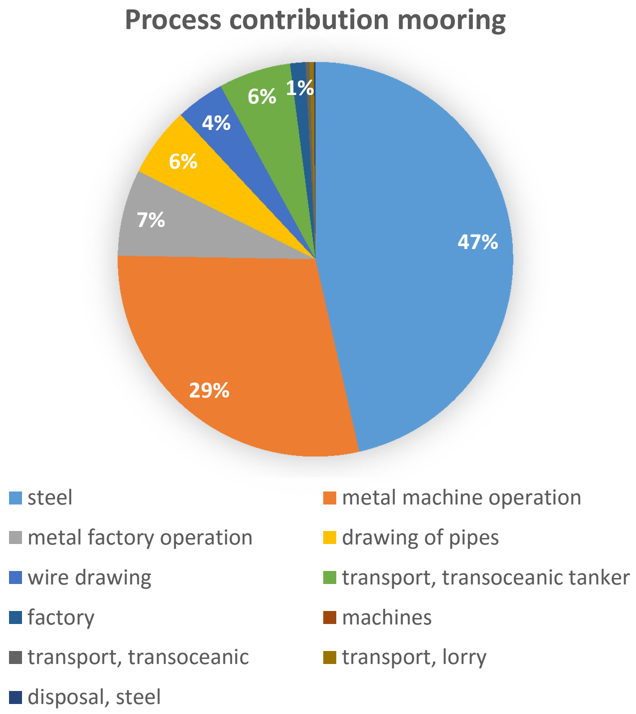

Figure A.8: Contribution of mooring processes for climate change, GWP100a [kg CO_2]

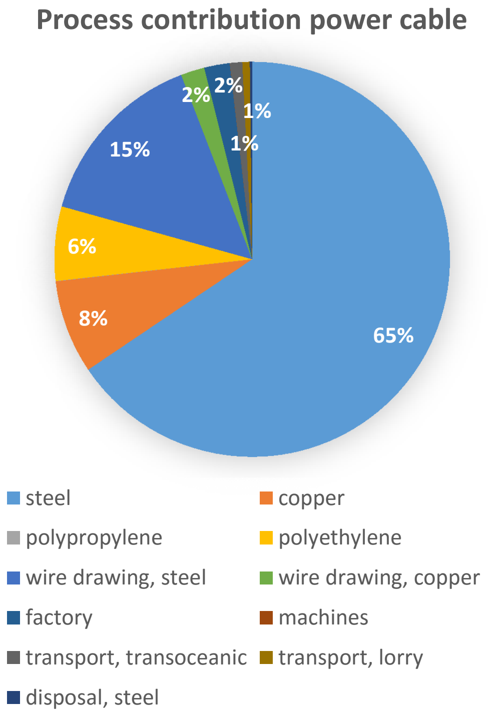

Figure A.9: Contribution of power cable processes for climate change, GWP100a [kg CO_2]

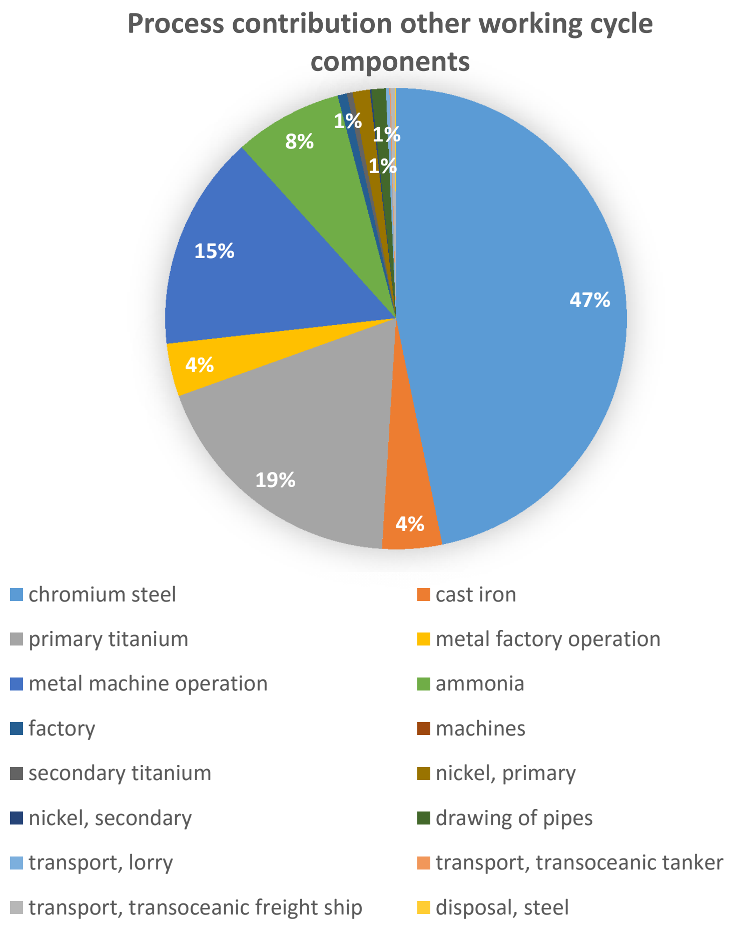

Figure A.10: Contribution of other working cycle components processes for climate change, GWP100a [kg CO_2]

A.4. LIFE CYCLE STAGES COMPONENTS OF 10 MW OTEC

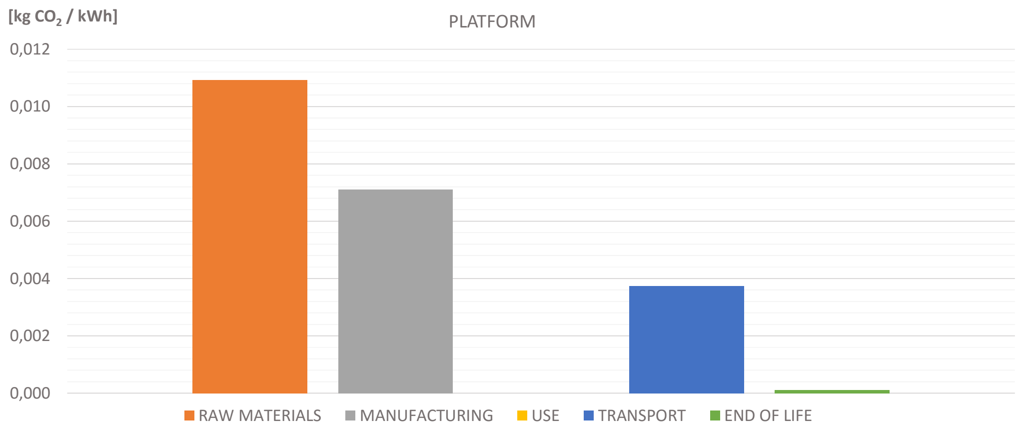

Figure A.11: Contribution of life cycle phases of platform

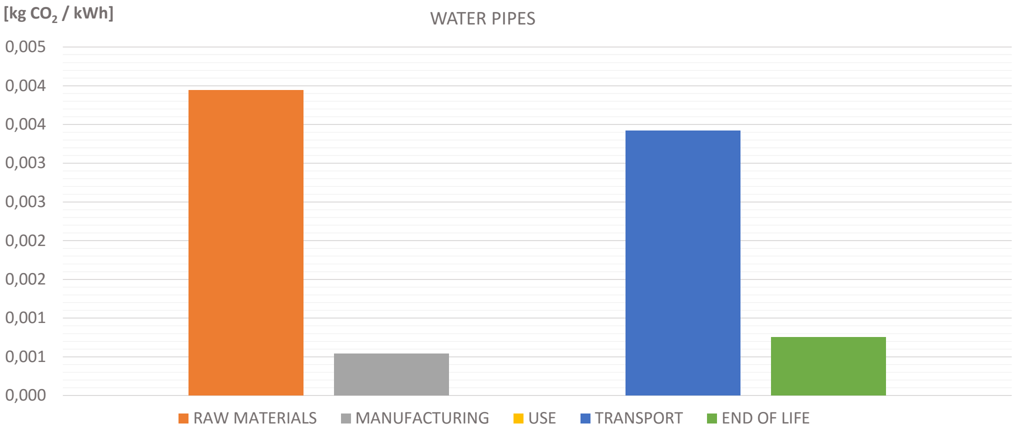

Figure A.12: Contribution of life cycle phases of water pipes

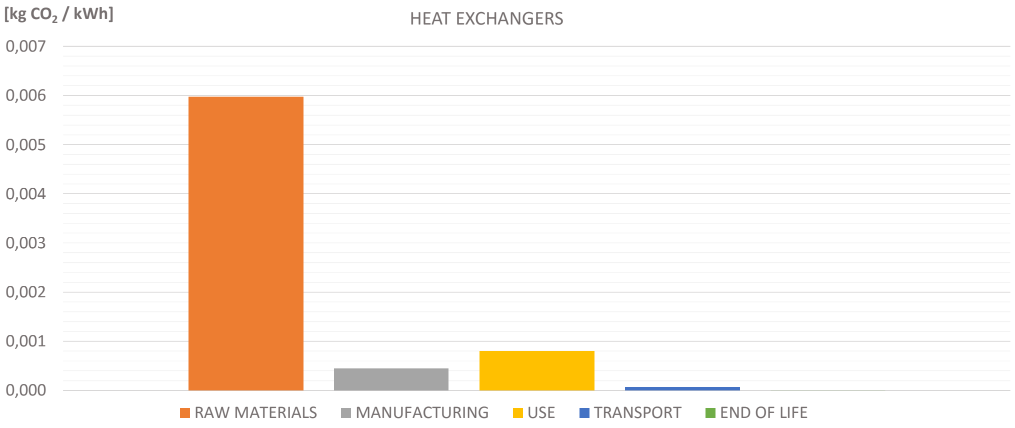

Figure A.13: Contribution of life cycle phases of heat exchanger

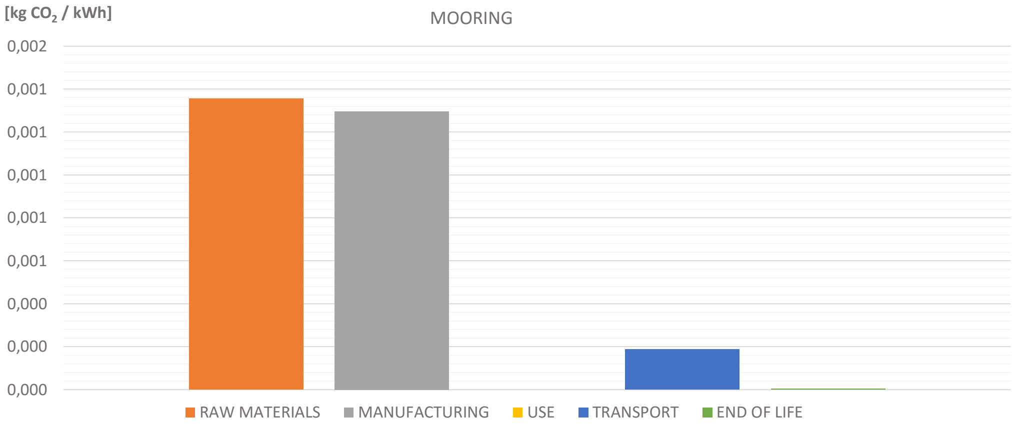

Figure A.14: Contribution of life cycle phases of mooring

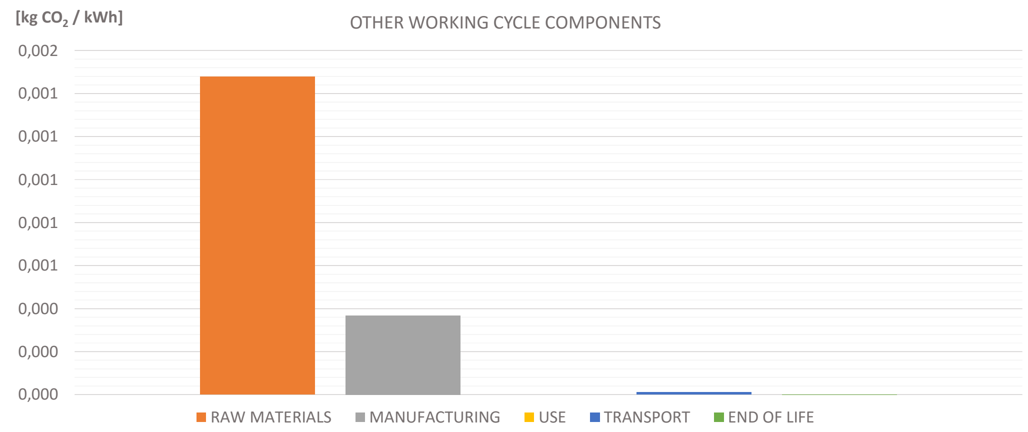

Figure A.15: Contribution of life cycle phases of other working cycle components

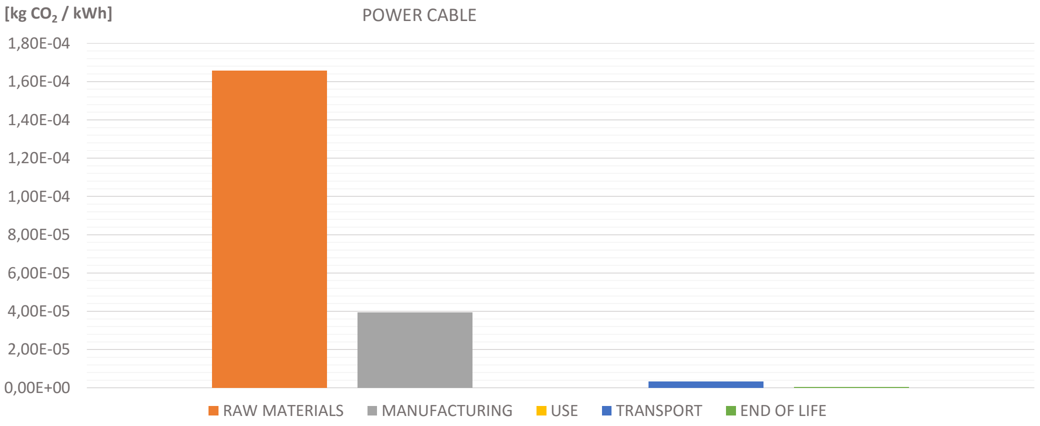

Figure A.16: Contribution of life cycle phases of power cable

A.5. LIFE CYCLE STAGES COMPONENTS OF 10 MW OTEC WITH 90% RECYCLING

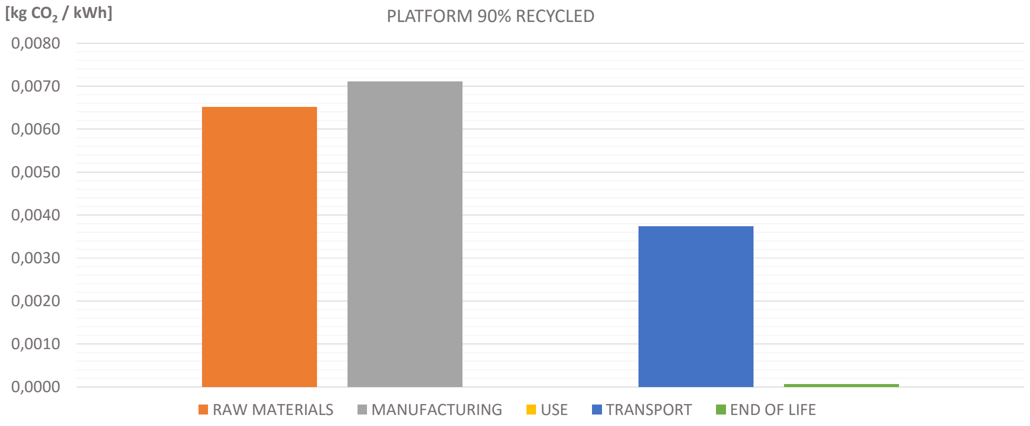

Figure A.17: Contribution of life cycle phases of platform with 90% recycling

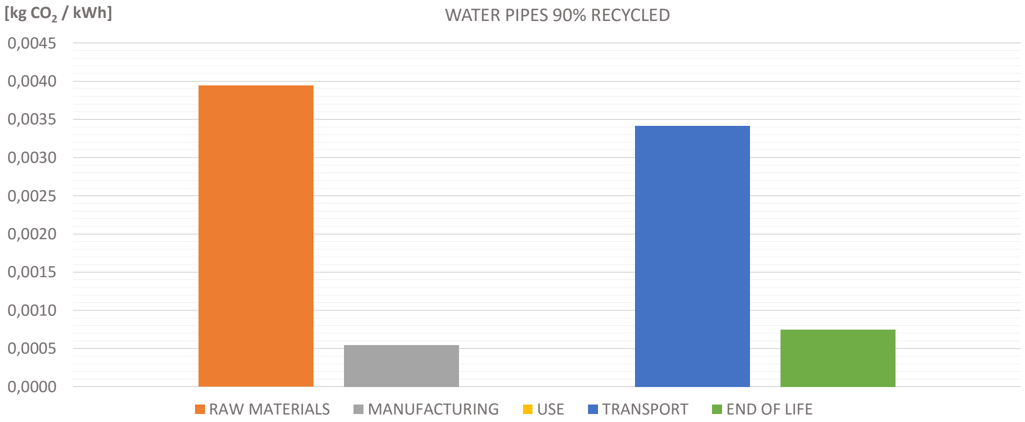

Figure A.18: Contribution of life cycle phases of water pipes with 90% recycling

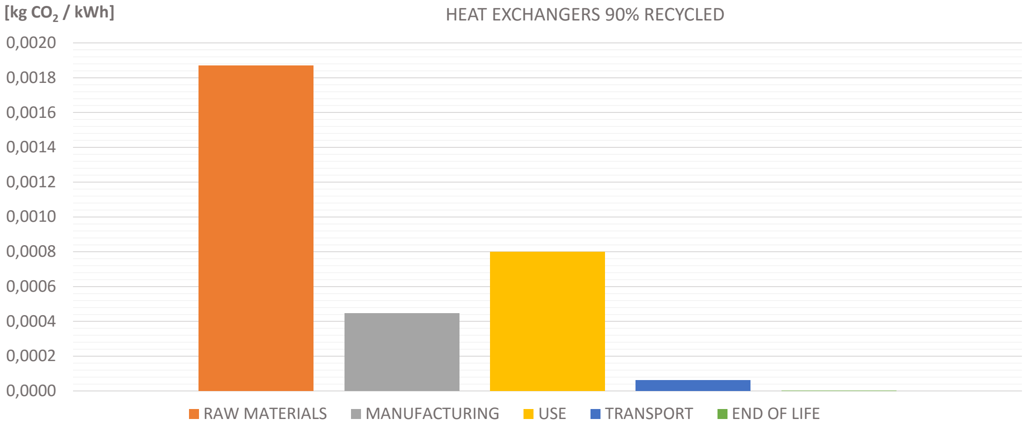

Figure A.19: Contribution of life cycle phases of heat exchanger with 90% recycling

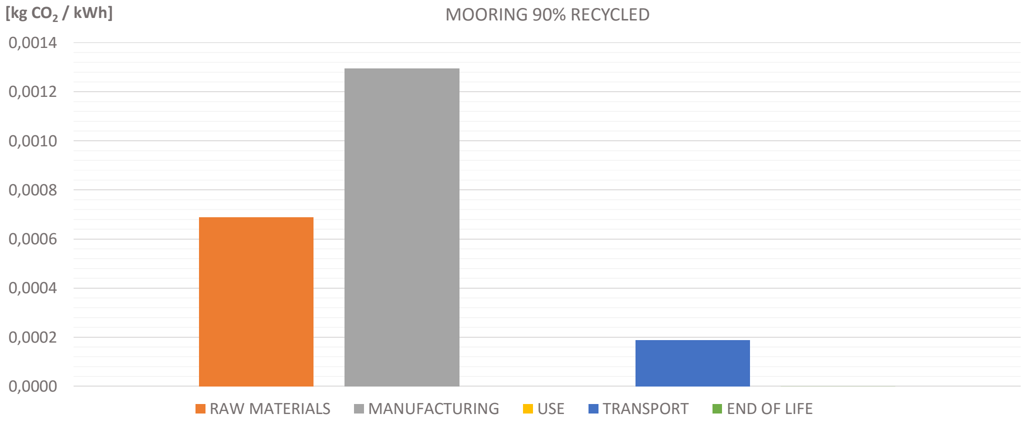

Figure A.20: Contribution of life cycle phases of mooring with 90% recycling

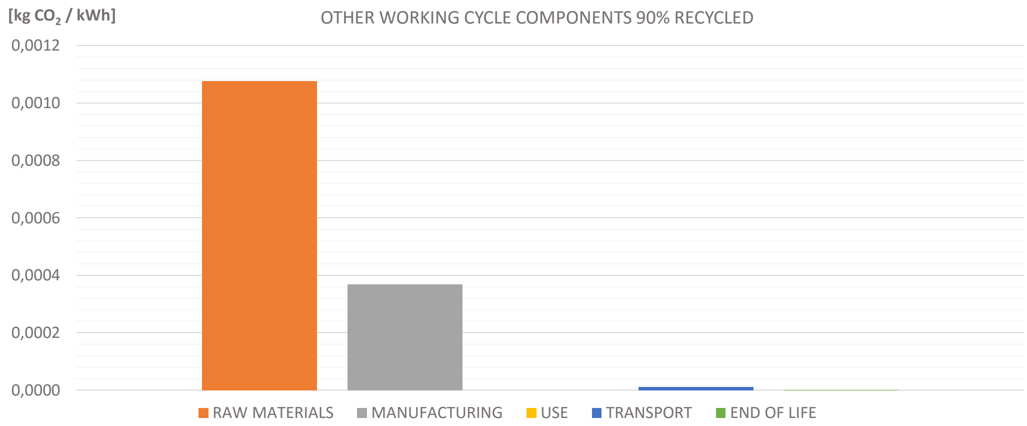

Figure A.21: Contribution of life cycle phases of other working cycle components with 90% recycling

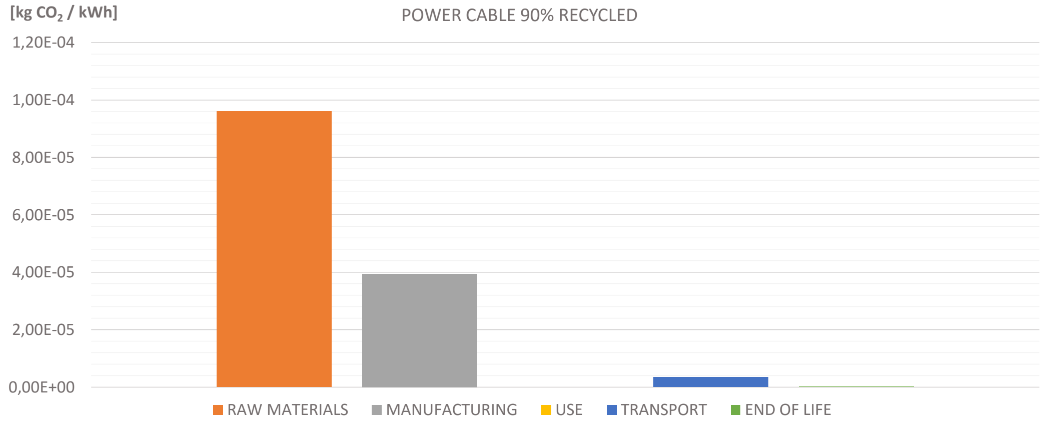

Figure A.22: Contribution of life cycle phases of power cable with 90% recycling

A.6. LIFE CYCLE STAGES COMPONENTS OF 10 MW OTEC BEST CASE SCENARIO

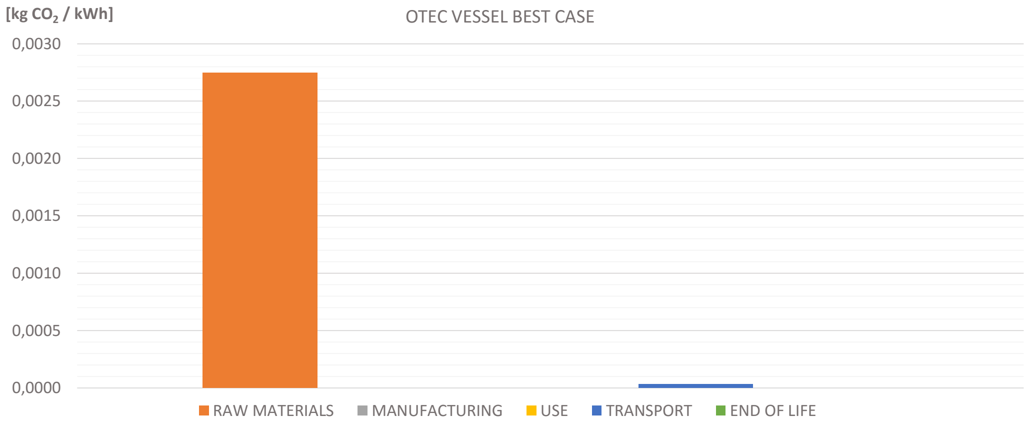

Figure A.23: Contribution of life cycle phases of OTEC vessel

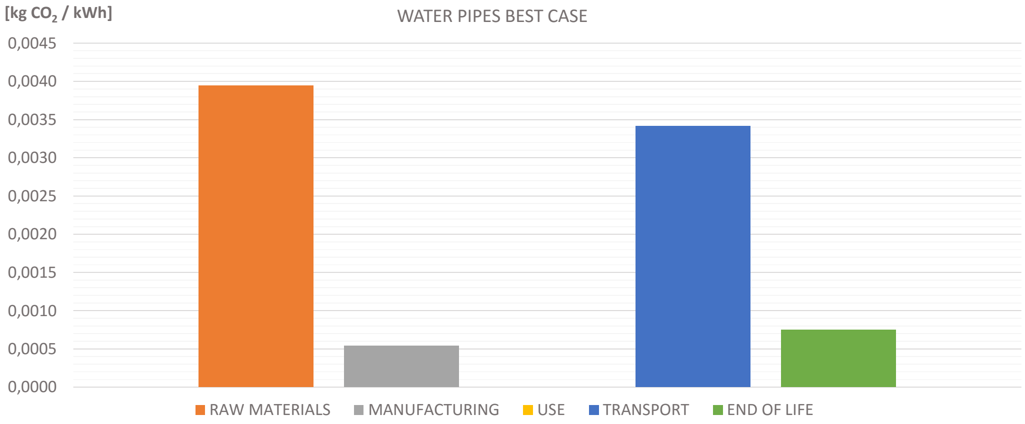

Figure A.24: Contribution of life cycle phases of water pipes with for best case scenario

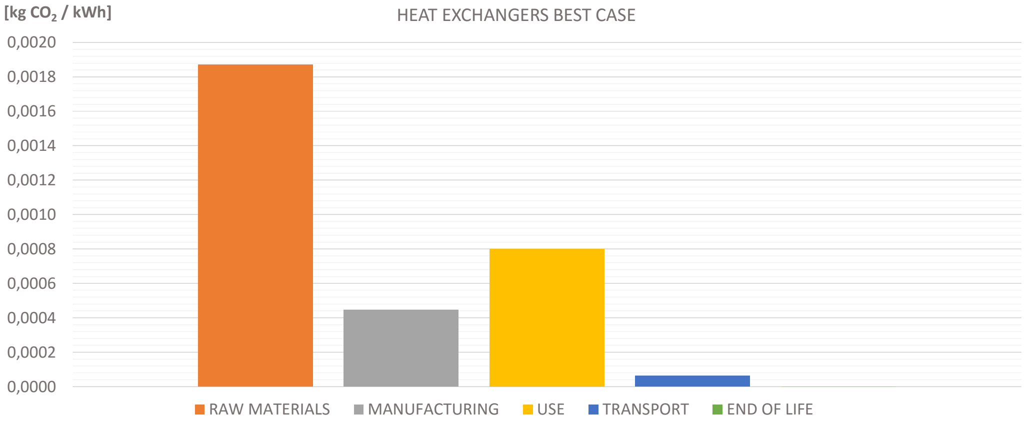

Figure A.25: Contribution of life cycle phases of heat exchanger for best case scenario

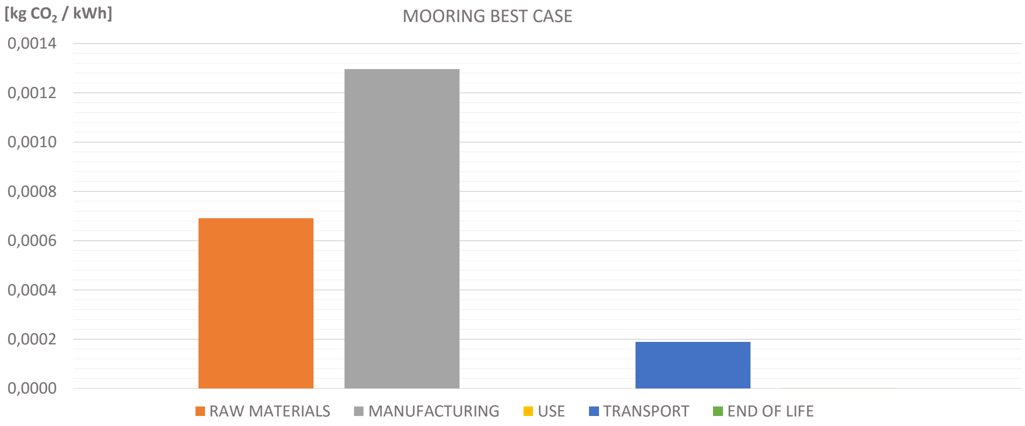

Figure A.26: Contribution of life cycle phases of mooring for best case scenario

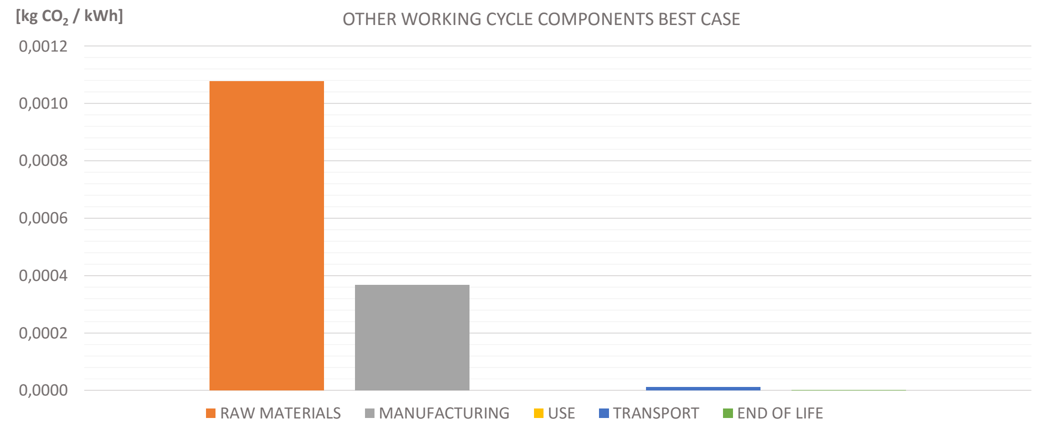

Figure A.27: Contribution of life cycle phases of other working cycle components for best case scenario

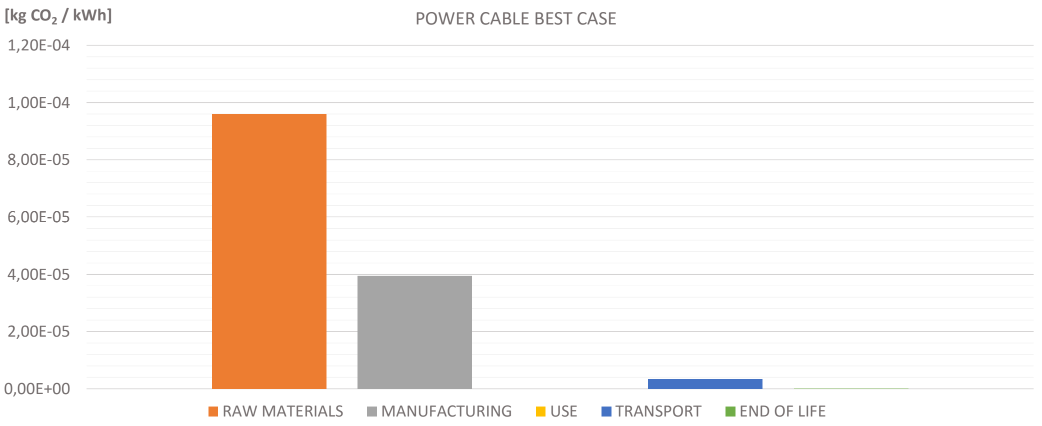

Figure A.28: Contribution of life cycle phases of power cable for best case scenario

A.7. LIFE CYCLE STAGES COMPONENTS OF 100 MW OTEC

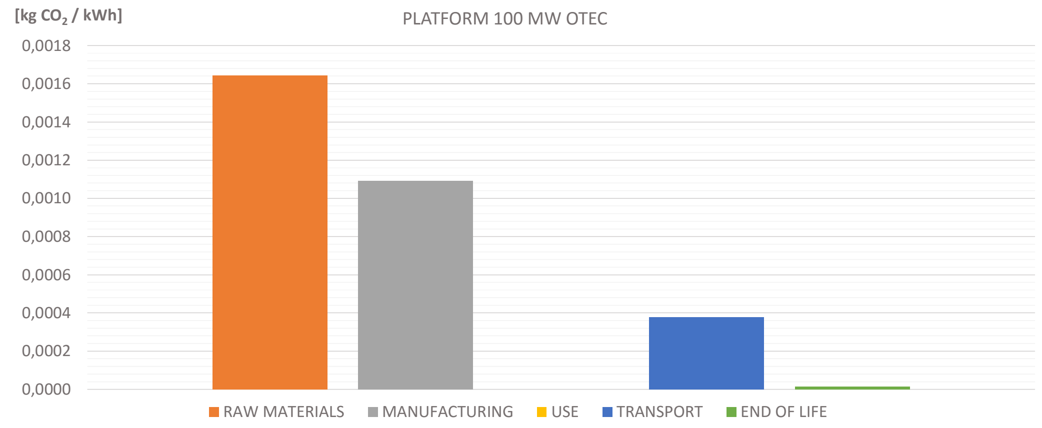

Figure A.29: Contribution of life cycle phases of platform for 100 MW OTEC

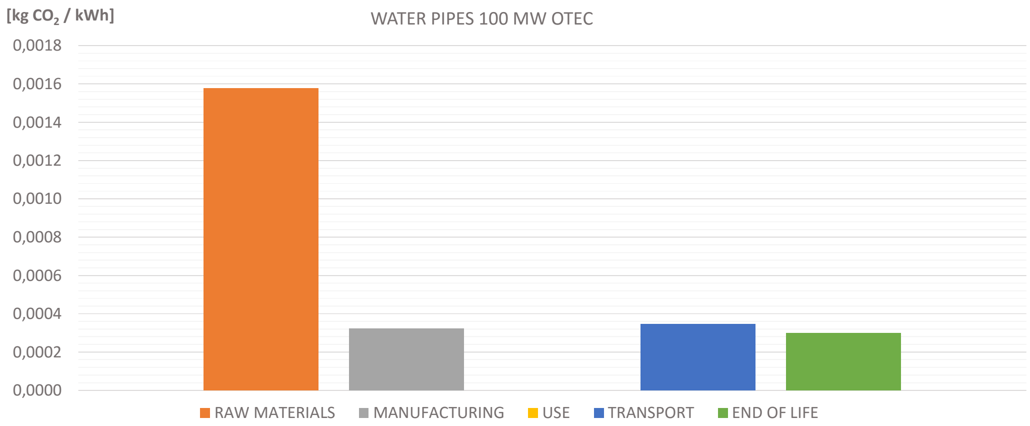

Figure A.30: Contribution of life cycle phases of water pipes for 100 MW OTEC

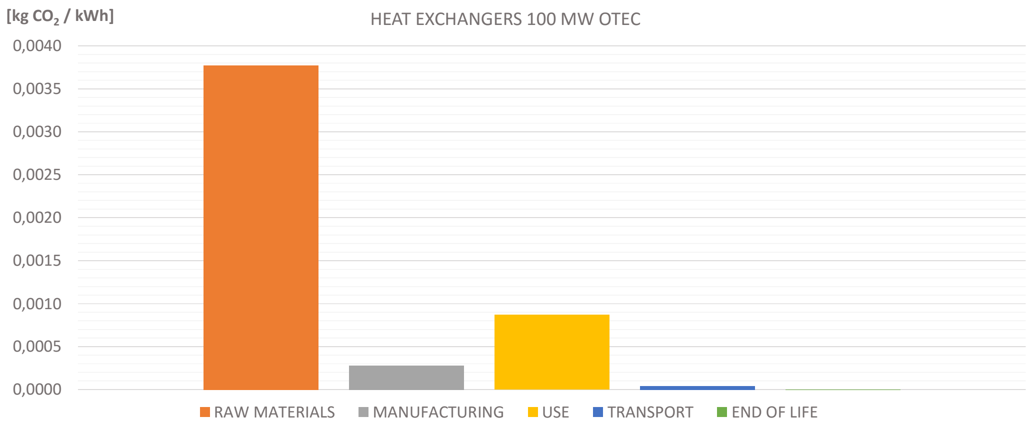

Figure A.31: Contribution of life cycle phases of heat exchanger for 100 MW OTEC

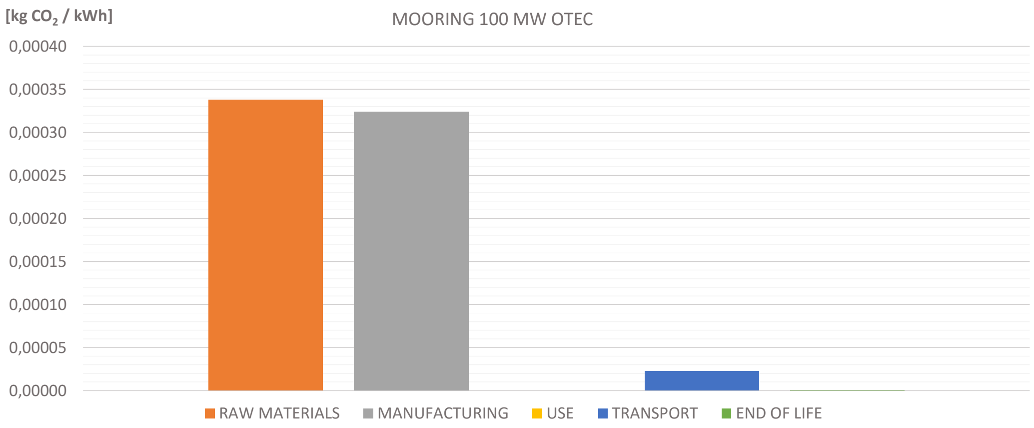

Figure A.32: Contribution of life cycle phases of mooring for 100 MW OTEC

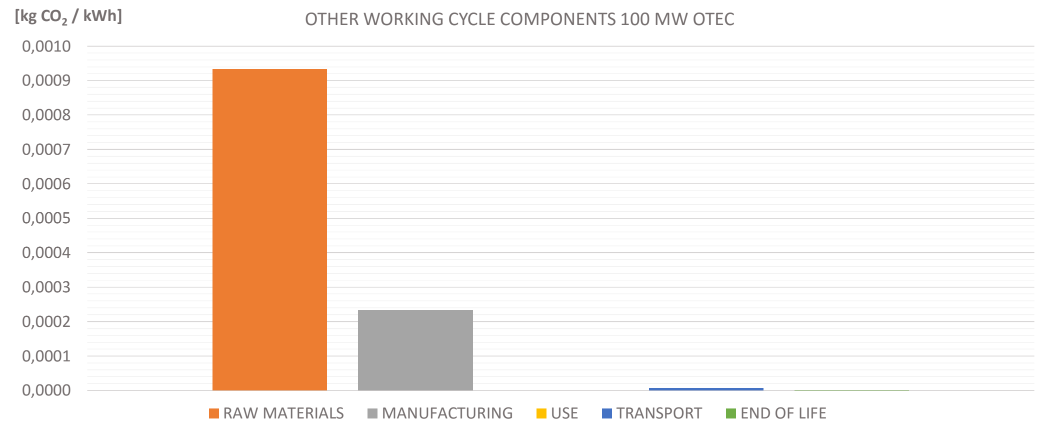

Figure A.33: Contribution of life cycle phases of other working cycle components for 100 MW OTEC

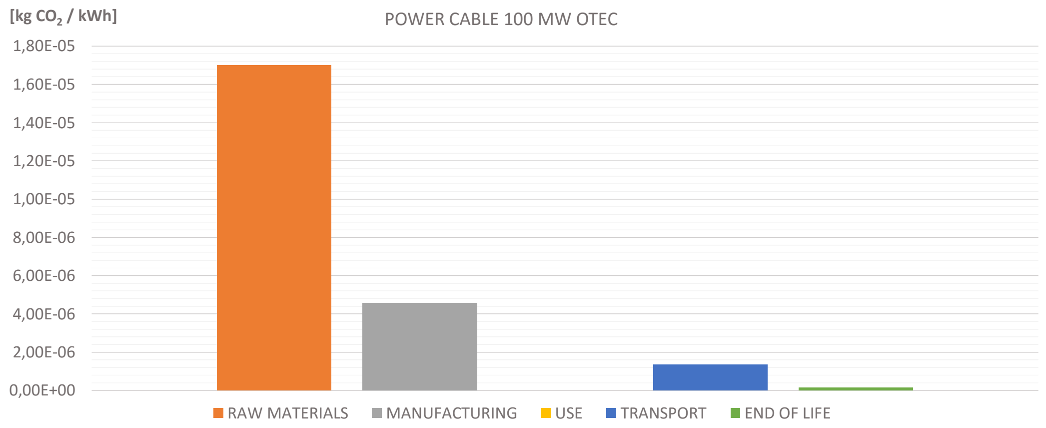

Figure A.34: Contribution of life cycle phases of power cable for 100 MW OTEC

A.8. MATLAB CODE ENERGY MIX SCENARIO

```
clc; clear all;close all;

%%%% INPUTS %%%%
%Energy sources penetration as a percent of the maximum demand.
otec_pen=1;
solar_pen=0;
area_wind=491; %area of 3MW wind turbine
wind_turb_no=12; %number of windturbines
wind_capacity =3; %installed wind capacity in MW
wind_capacity_matrix = wind_capacity(ones(8760, 1)); %capacity matrix
area_wind_2=1670; %area of 0.5MW wind turbine
wind_turb_no_2=18; %number of windturbines
wind_capacity_2=9; %installed wind capacity in MW
wind_capacity_matrix_2= wind_capacity_2(ones(8760, 1)); %capacity matrix
```

```
%%% DEMAND DATA %%%
%data were taken by multiplying given data so that a maximum demand of
%around 105MW could happen.
load=0.001*(xlsread('Load','Dataset','J2:J8761'));  % data in MW
year_hours=xlsread('Load','Dataset','E2:E8761'); % 1..8760 hours (all year)
peak_load=max(load); % maximum demand

%%% SOLAR INSOLATION INPUTS %%%

 eff_solar=0.135; % Solar panel efficiency
 insolation=xlsread('solar_data','Sheet1','G45:G409'); % data for a year-1998,
                                                       %average for every day in kWh/m^2
hours=1:24;
hours_year=1:8760;
insolation_hours = (insolation./0.2)*normpdf(hours,12,2);
insolation_hours1=insolation_hours';
insolation_hours_new=insolation_hours1(:);

%%% WIND SPEED DATA %%%

windspeed=xlsread('windspeed','Sheet1','H493:H9252');

%%% WATER TEMPERATURE DIFFERENCE DATA %%%

Th = xlsread('OTEC_temperatures','Sheet1','E1283:E1647'); % Temperature hot
Tc = xlsread('OTEC_temperatures','Sheet1','G1283:G1647'); % Temperature cold

%Generator of temperatures to extend the values of temperatures to hours
%per year and not only in days as the original data was

for i=1:length(Th)
    for j=1:24
    Th_new(j,i) = Th(i);
    Tc_new(j,i) = Tc(i);
    end
end

%Create 1D matrix instead of 2D
hours_year1=1:8760;
Th_n=Th_new(:);
Tc_n=Tc_new(:);


%%% ENERGY GENERATION %%%

%%% Solar power generation %%%
```

```
solar_capacity=solar_pen*peak_load;   %in MW
%following data were retrieved from market values
peak_panel_power=300; %% in Wp
area_solar_panel=1.6; %in m2
%Number of solar panels
solar_panels_no=1000000*(solar_capacity/peak_panel_power);
area_solar=solar_panels_no*area_solar_panel; %( in m^2)
eff_pvsystem=0.36; % pv system efficiency
prod_solar=0.0005*(eff_pvsystem*eff_solar*insolation_hours_new*area_solar);
%(production in MWh)
solar_percent=(prod_solar./load)*100;


%%% OTEC generation %%%

%OTEC input parameters

DT=Th_n-Tc_n;
otec_capacity=otec_pen*peak_load;
prod_otec=(otec_capacity/10)*0.07*(12.5.*DT-149.71);

%%% Wind power production %%%

prod_wind=0.201*wind_turb_no*(windspeed.^3)*area_wind*0.5*1.2*(1E-6);
prod_wind_2=0.237*wind_turb_no_2*(windspeed.^3)*area_wind_2*0.5*1.2*(1E-6);

for i=1:8760
    if prod_wind(i)>=wind_capacity_matrix(i);
    prod_wind(i)=wind_capacity_matrix(i);
    end
end

for i=1:8760
    if prod_otec(i)>=load(i);
    prod_wind(i)=0;
    end
end

for i=1:8760
    if prod_wind_2(i)>=wind_capacity_matrix_2(i);
    prod_wind_2(i)=wind_capacity_matrix_2(i);
    end
end

for i=1:8760
```

```
    if prod_otec(i)>=load(i);
    prod_wind_2(i)=0;
    end
end

prod_wind_tot = prod_wind+prod_wind_2;

% production by renewables can not be more than load

for i=1:8760
    if prod_otec(i) > load(i);
        prod_otec(i) =load(i);
    end
end

for i=1:8760
    if prod_wind_tot(i) > load(i)-prod_otec(i);
        prod_wind_tot(i) =load(i)-prod_otec(i);
    end
end

for i=1:8760
    if prod_otec(i)>=load(i)-prod_otec(i);
        prod_solar(i)=load(i)-prod_otec(i);
    end
end


%%%%%%%%%%%%% ENERGY MIX%%%%%%%%%%%%%%%%%%%

load_max=max(load);
load_min=min(load);
load_new_max=max(load);

prod_renewable=prod_otec+prod_solar+prod_wind_tot;
fuel=load-prod_renewable;

for i=1:8760
    if load (i)<= prod_otec(i);
    fuel(i)=0;
    elseif load (i) > prod_otec(i);
    fuel(i)=load(i)-prod_renewable(i);
    end
end

for i=1:8760
```

```
      if fuel(i)< 0;
      fuel(i)=0;
      end
end

   %Rated power of otec plant
q_otec=1000*otec_capacity;   %% (kW)
mean_otec=mean(prod_otec);
sum_otec=sum(prod_otec);
E_otec=1000*sum_otec;   %%IN kwh

   %Wind energy power capacity and energy produced
q_wind=1000*wind_capacity;   %% (kW)
mean_wind=mean(prod_wind);
sum_wind=sum(prod_wind)+sum(prod_wind_2);
E_wind=1000*sum_wind;   %%IN kWh

  %Solar energy power capacity and energy produced
q_solar=1000*solar_capacity;   %% (kW)
mean_solar=mean(prod_solar);
sum_solar=sum(prod_solar);
E_solar=1000*sum_solar; %%IN kWh

%%%%Capacity factors for each source
%otec capacity factor

cap_otec=100*(mean(prod_otec)/(otec_capacity));

%solar capacity factor

cap_solar=100*(mean(prod_solar))/(solar_capacity);

%wind capacity factor

cap_wind=100*(mean(prod_wind))/(wind_capacity);
cap_wind_2=100*(mean(prod_wind_2))/(wind_capacity_2);

%Calculating how much fuel is needed

E_fuel=1000*sum(fuel);

%figure
%plot(hours_year,fuel,'r',hours_year,load,'m',hours_year,prod_wind_tot,'g',
%hours_year,prod_otec,'b',hours_year,prod_solar,'y')
%xlabel('Time(h)')
%ylabel('Energy (MW)')
```

```
%ylim([0 110])
```

A.9. Eco-costs / Value Ratio

Table A.2: Eco-costs / Value Ratio calculation

		Mass [kg]	Costs [€/kg]	Costs [€]
Materials	Steel	7718004	0,68	€ 5.248.243
	Recycled steel	4532796	0,13	€ 589.263
	Chromium steel	493857	4,85	€ 2.395.206
	Recycled chromium steel	290043	0,29	€ 84.112
	Primary titanium	262588	28,3	€ 7.431.226
	Secondary Titanium	66050	2,99	€ 197.490
	Copper	17760	6,49	€ 115.262
	Aluminium	136000	6,82	€ 927.520
	Zink	7200	3,27	€ 23.544
	Glass fiber	1370200	1,12	€ 1.534.624
	Epoxy resin	658380	2,27	€ 1.494.523
	Polymeres	12774	1,9	€ 24.271
	Nickel	6405	26,08	€ 167.042
	Secondary nickel	2490	0,29	€ 722
	Ammonia	155000	0,66	€ 102.300
	Cast iron	108000	0,23	€ 24.840
Manufacturing	Diesel			€ 1.338.000
	Electricity			€ 2.388.532
	Processes			€ 1.342.844
	Labour			€ 2.470.665
Transport	Diesel	3256289	1,28	€ 4.168.050
Disposal				€ 8.002
				€ 4.413
Eco-costs				**€ 32.080.696**
kWh produced (30 years)				**$2{,}1 \times 10^9$**
Eco-costs / Value ratio				**0,0153 €/kWh**
EVR onshore wind				**0,0025 €/kWh**
EVR PV				**0,0062 €/kWh**
EVR diesel				**0,2382 €/kWh**

A.10. GWP TIMESCALES

Table A.3: Results for different climate change timescales, obtained from CMLCA

	10 MW OTEC	Wind	PV	Diesel	Unit
GWP 20a	0.0468	0.0127	0.11	0.716	kg CO2-Eq
GWP 100a	0.0428	0.0113	0.0989	0.7	kg CO2-Eq
GWP 500a	0.0411	0.0107	0.0955	0.687	kg CO2-Eq
upper limit of net GWP	0.0438	0.0114	0.099	0.764	kg CO2-Eq
lower limit of net GWP	0.0431	0.0113	0.0985	0.752	kg CO2-Eq