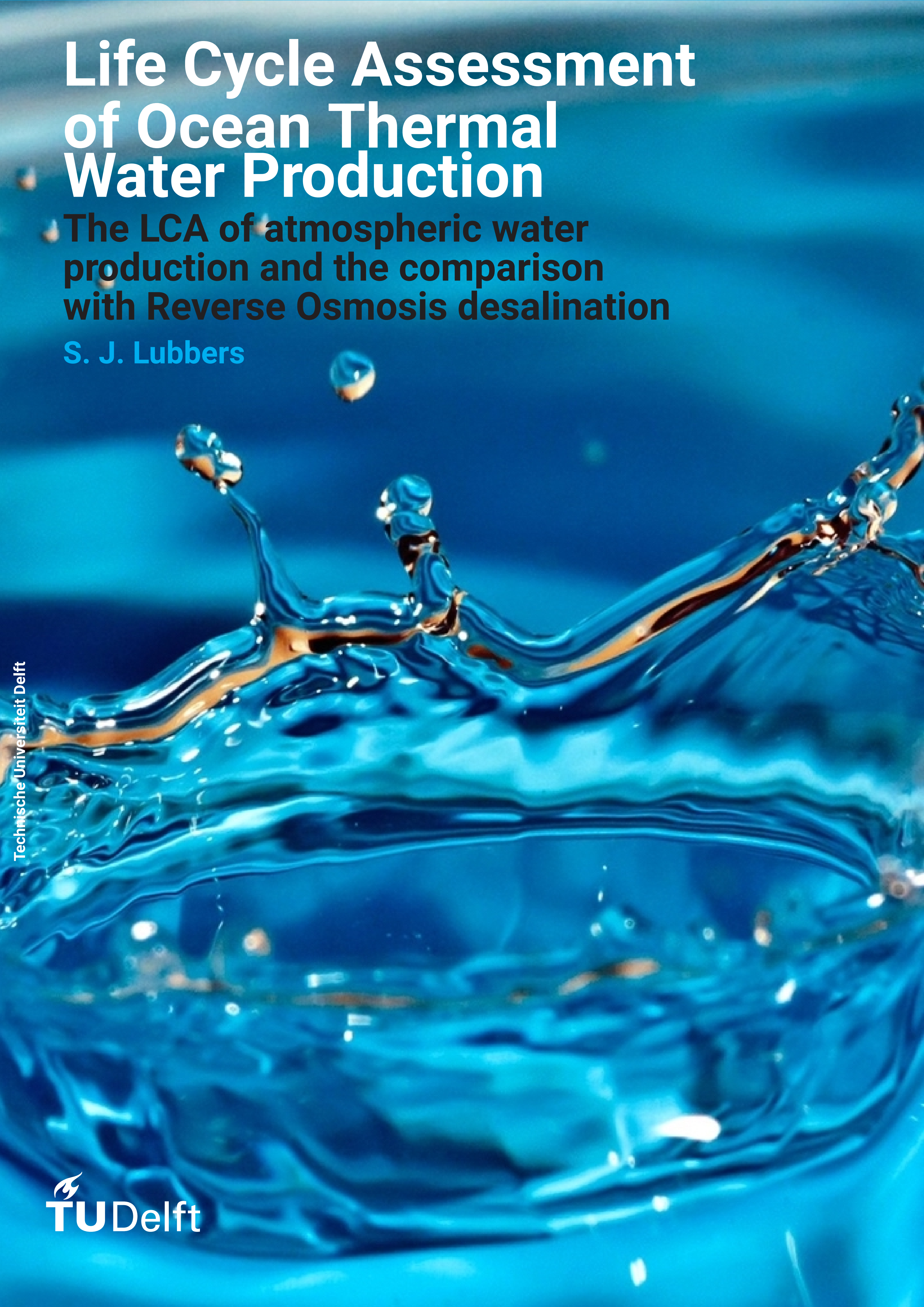

Life Cycle Assessment of Ocean Thermal Water Production

The LCA of atmospheric water production and the comparison with Reverse Osmosis desalination

S. J. Lubbers

Technische Universiteit Delft

TU Delft

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by

S. J. Lubbers

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Thesis committee:	Prof. ir. A. Q. C. van der Horst,	TU Delft
	Dr. ir. G. Korevaar,	TU Delft
	Ir. B. Kleute,	Bluerise B.V.

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TU Delft

Preface

This report is the final master thesis of the Life Cycle Assessment (LCA) of the Ocean Thermal Water Production system, which also includes a comparison with a Reverse Osmosis plant. Readers who are particularly interested in the processed results of this LCA can find them in chapter 6.

I would like to begin by thanking the Bluerise B.V. team for giving me the opportunity to work on such a fascinating project, in particular Berend Jan Kleute for the guidance and support. I would like to express my gratitude to Prof. ir. A. Q. C. van der Horst from the Civil Engineering faculty of the Delft University of Technology to be the professor of this thesis and the valuable advice which I received. I would like to extend my appreciation to Dr. ir. G. Korevaar, assistant professor at the faculty of Technology, Policy and Management of the Delft University of Technology, who provided advice and structure during the thesis and which I personally see as the expert on LCAs.
Furthermore, I would like to thank M. Roorda from the company Kapp Nederland BV, S. Dyrdal of the company Iron Pump, M. de Beun of the company Hoyer BV, S. Koetzier of the company Spraybest Europe BV, J. Constancia of Aqualectra Distribution in Curacao, for their willingness and enthusiasm in responding to inquiries.
Also I would like to thank the company Thales Nederland for their financial support during my master study.
Last but certainly not least I would thank my parents, sister and two brothers for their unconditional love and support. I am very grateful!

I hope that this report will give more insights in the environmental impact on the water production system suitable for tropical regions and that this master thesis can contribute to the practical applications in the near future.

Stephanie J. Lubbers
Delft, July 2017

Summary

The fresh water sources on Earth are becoming more scares nowadays. One of the solutions is to obtain fresh water is by desalting seawater. Unfortunately, this process is very energy intensive and often the energy source is driven by fossil fuel instead of renewable energies. Hence, desalting seawater is not a very environmental friendly way for obtaining fresh water. To achieve fresh water in combination with low environmental impact, innovative technology is needed. The company Bluerise B.V. designed an Ocean Thermal Water Production (OTWP) system that is in symbiosis with an Ocean Thermal Energy Conversion (OTEC) system for the Caribbean. In the Caribbean fresh water is achieved by desalting seawater with reversed osmosis (RO) technology. To determine which technology has the highest environmental sustainability, a life cycle assessment (LCA) of these systems is able to provide an reasoned answer. The problem is that such a LCA does not exists for the OTWP system that can be compared with the environmental impact of the RO system. This knowledge of implementing the most suitable technologies for the fresh water production will become more important in the near future, since the transition towards a fossil free world has already started. To check the sustainable performance of a system, one of the areas is to analyze the environmental impact. Therefore, the main research question is formulated as follows:

What is the Life Cycle Assessment of an Ocean Thermal Water Production system and which fresh water production method has the highest environmental sustainability for the Caribbean?

The research approach is divided into three phases: system engineering, the LCA and upscaling influences. The system engineering phase reviews the system requirements, setup the boundaries of the studied system and specify the components of the system that match these requirements. The LCA is divided into four different phases: the goal and scope definition, the inventory analysis, the impact assessment and the interpretation. The goal and scope definition defines the purpose and initial choices made for the outline of the LCA. The inventory analysis represents the quantification of the system by the energy, water and material used, which results in an inventory table. The impact assessment processes the inventory table into potential environmental impacts. Here the evaluation methods CML-IA baseline, Eco-indicator 99 and Ecopoints 97 with the relevant corresponding impact categories are selected. The interpretation evaluates the results of these environmental impact with the corresponding uncertainties and assumptions and generates the conclusion of these results. For the upscaling influences the LCA of an upscaled OTWP system is created. This gives the opportunity to investigate the influences that an upscaled system has on the environmental impact.

The first sub-question is stated as followed: *How do the most important components of the pilot OTWP system look like and what is its operating energy consumption?*

Figure 1 shows the schematic components of the OTWP system, which is in symbiosis with OTEC system. The condenser consists out of hollow plastic column filled with metallic packings. The heat exchanger is made out of titanium plates, carbon steel frame material and rubber gasket material. The gasket is assumed to be replaced every 10 years. The seawater and fresh water pump consists out of bronze and cast iron material, respectively. The ventilator is build up from galvanized and carbon steel. Also a water tank is added, this is made out of plastic and assumed to be replaced every 10 years. The energy consumption is 0.134 kWh/m^3 for the system, which is required by the water pumps and ventilator. From these components a model in SimaPro is built to create the LCA of the OTWP system.

The second sub-question is formulated by: *What are the relevant environmental impacts of the pilot OTWP system calculated with different evaluation methods and how do the airborne emissions compare to reverse osmosis system?*

The relevant environmental impacts are expressed in the corresponding impact categories for the different evaluation methods, see chapter 5 for the details on this. The LCA of the OTWP is also analyzed for the

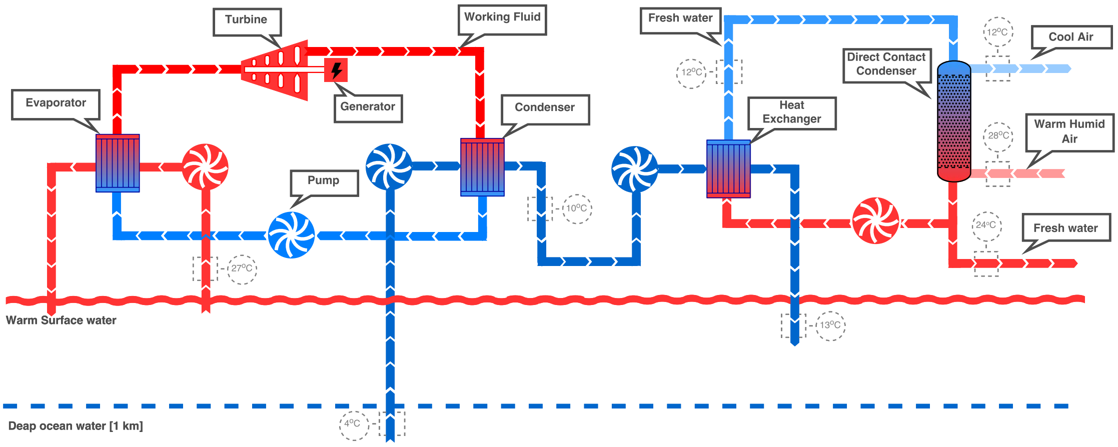

Figure 1: Schematic representation of OTEC and OTWP system [40].

installation, operation and dismantling phases. On average the installation is responsible for 82.1% of the environmental impact. The operation phase has the lowest impact with 7.8%, due to low energy consumption required by the system. The dismantling phase counts for 10.1% on average for the environmental impact. Here a 100% landfill is assumed, if recycling is considered this value will be reduced. The comparison of the pilot OTWP and RO system for the relevant airborne emissions results in a reduction in emissions with 78.8% on average, when replacing RO by OTWP.

The third and final sub-question is described by: *What are the environmental impact relation between the pilot and the upscaled system and how do the airborne emissions compare to reverse osmosis system?*

The upscaled OTWP system is created by doubling the diameter of the condenser, which multiplies the volume by a factor of 4. To compare the LCA results of the upscaled with the pilot OTWP system, a modular system is created by using 4 pilot systems as one modular system. It follows that the upscaled system has lower environmental impact than the modular system, between 4.6% and 7.1% depending on the evaluation method.

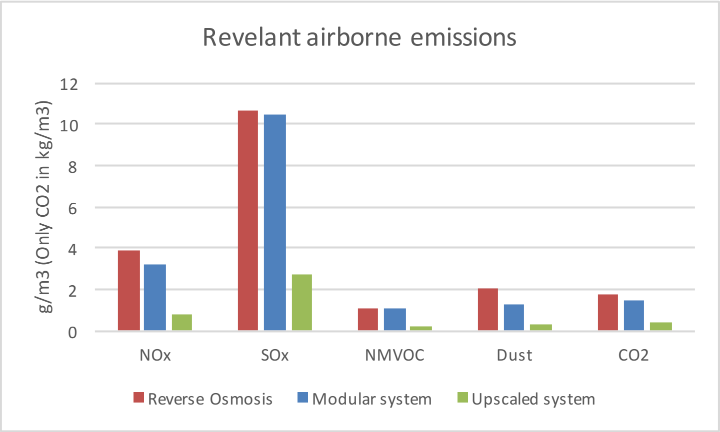

Figure 2: The relevant airborne emissions of the RO (4kWh/m3), modular and upscaled systems.

The final comparison is done with the relevant airborne emissions of the RO plant (4 kWh/m3), the modular and the upscaled OTWP system. From figure 2 it is concluded that the highest environmental impact is caused by the RO plant and the lowest by the upscaled OTWP system. Therefore, it is concluded that the OTWP system is the system with the lowest environmental impact, with all the assumptions made to develop the LCA of the OTWP. Hence, compared with the RO plant the OTWP system is the system with the highest environmental sustainability for the use in the Caribbean.

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Nomenclature

Acronyms

CML	CML-IA baseline
Eco 97	Ecopoints 97
EI 99	Eco-indicator 99
HRAD	High radioactive dose
ISO	International Organization for Standards
LCA	Life cycle assessment
LCI	Life cycle inventory
LMRAD	Low medium radioactive dose
MED	Multi-effect distillation
MMA	Methyl methacrylate
MSF	Multi-stage flash
NMVOC	Non methane volatile organic compounds
OTEC	Ocean Thermal Energy Conversion
OTWP	Ocean Thermal Water Production
PC	Polycarbonate
PM10	Particulate matter 10 micrometers or less in diameter
PMMA	Polymethyl methacrylate
RO	Reverse osmosis
UCPTE	Union for the Coordination of Production and Transmission of Electricity

1

Introduction

Fresh water sources are becoming more scare, nowadays it is less than 3% of all the water on Earth. This represents groundwater for around 30% and almost 70% is captured in glaciers and ice caps [46]. Fortunately, there is plenty of salty seawater available, which only needs to be desalinated. The downside of this process is that it costs huge amounts of energy, where the main energy source still comes from fossil fuels. This is in conflict with the transition towards a fossil free world and asks for innovative technologies to solve this with suitable sustainable solutions. The company Bluerise B.V. is designing an Ocean Thermal Water Production (OTWP) system that is in symbiosis with Ocean Thermal Energy Conversion (OTEC) system for the Caribbean. By condensing atmospheric water vapor fresh water is produced. The current state of fresh water supply in the Caribbean is met by desalination of seawater, mostly by reverse osmosis (RO). This is again a very energy intensive process and produces brine that has a negative environmental effect. Therefore, a life cycle assessment comparison between these two fresh water production processes will be made to determine the best option for the Caribbean.

1.1. Fresh water technologies

Desalination process can be described as converting saline water into fresh water. This is done either by thermal or membrane separation methods. The thermal desalination technologies are based on the boiling or evaporation followed by condensation of the formed water vapor. The thermal energy is obtained from power generation units, which can be conventional fossil fuel based sources, nuclear energy or non-conventional like renewable energy sources or using waste heat. The two most commonly used thermal desalination technologies are multi-stage flash (MSF) and multi-effect distillation (MED). For the membrane desalination technology it is the process reverse osmosis (RO). In this process the water passes through semi-permeable and ion specific membranes under high pressure, leaving the highly concentrated brine solution behind. The primary energy source of this process is electricity [22].

The current trends in desalination industry represents 63% RO, 23% of MSF and 8% of MED processes, and the reminder including electrodialysis and other hybrid processes [28]. In general, the RO technology has a much lower environmental impact than the thermal desalination processes MSF and MED [52]. Also more RO plants are currently running in the Caribbean for the fresh water production [19, 51]. These are the reasons to limit this research to a comparison of only RO plants with the OTWP of Bluerise B.V.

1.1.1. Reverse osmosis

Osmosis is a natural phenomena that occurs when a water solution flows through a semi-permeable membrane leaving certain salts behind, while the water is diffusing through the membrane towards the side with a higher concentration. This process stops when both sides are in equilibrium concentrations, when osmotic pressure is reached. Reverse osmosis occurs when a pressure is applied that is bigger than the osmotic pressure. Now the water is forced to pass through the membrane. No heat or phase changes occur during this process. The most important factors that control the value of the required pressure are the temperature and salinity of the feed water and the required production. The pressure required for seawater desalination if between 54 and 68 atm [38], powered by high pressure pumps that run on electricity.

Before receiving the fresh water several processes are included for RO desalination, see figure 1.1. During the pretreatment process the feed water is cleaned by removing suspended solids. Also the pH is adjusted and chemicals are added to make the feed water compatible with the membranes. After the pretreatment, the feed water passes through the membranes. Most of the concentrated brine is left behind, but a very small percentage is able to pass through the membranes due to imperfections. Therefore, the stabilization of the water is done in the post-treatment process. The pH of the fresh water is adjusted and disinfection takes place before the water will be ready for distribution [51].

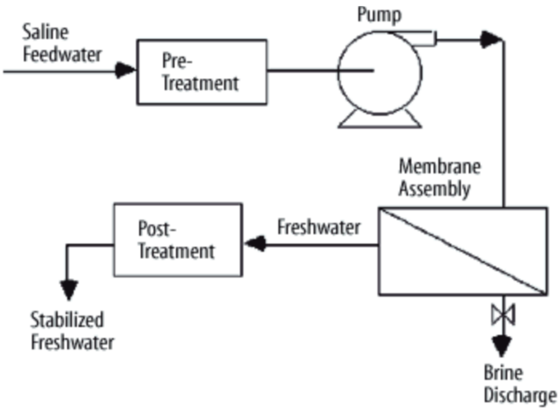


Figure 1.1: Schematic overview of RO desalination process [61].

1.1.2. Atmospheric water extraction

Ocean Thermal Energy Conversion (OTEC) technology is based on the temperature difference between the warm ocean surface layer and the cold deep ocean of approximately 1 km. A cooling fluid is first heated by the warm seawater and then cooled by the deep ocean water. This establishes a thermodynamic cycle, a cooling fluid evaporates when it is heated and the vapor is used in a turbine to produce electricity. The vapor is condensed when it is cooled by the cold seawater such that it can be reused in the cycle. The left cycle in figure 1.2 shows the schematic overview of the OTEC cycle.

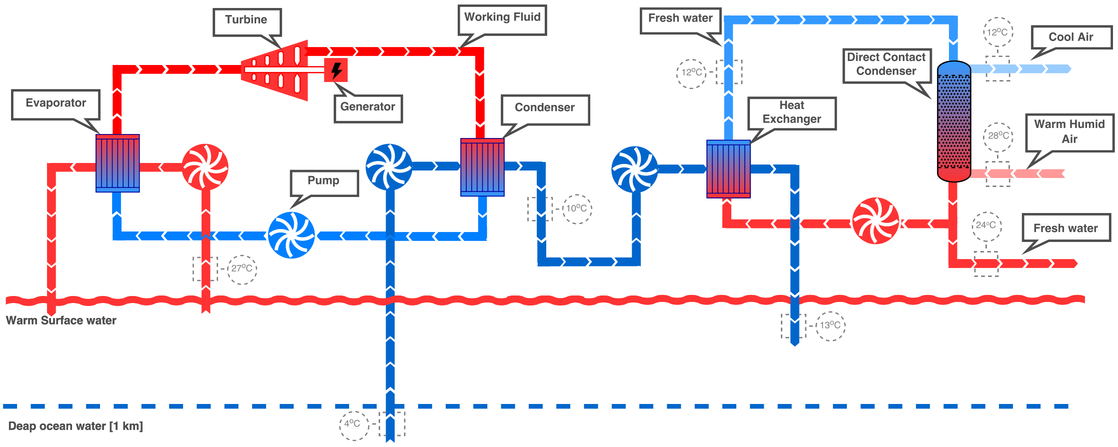


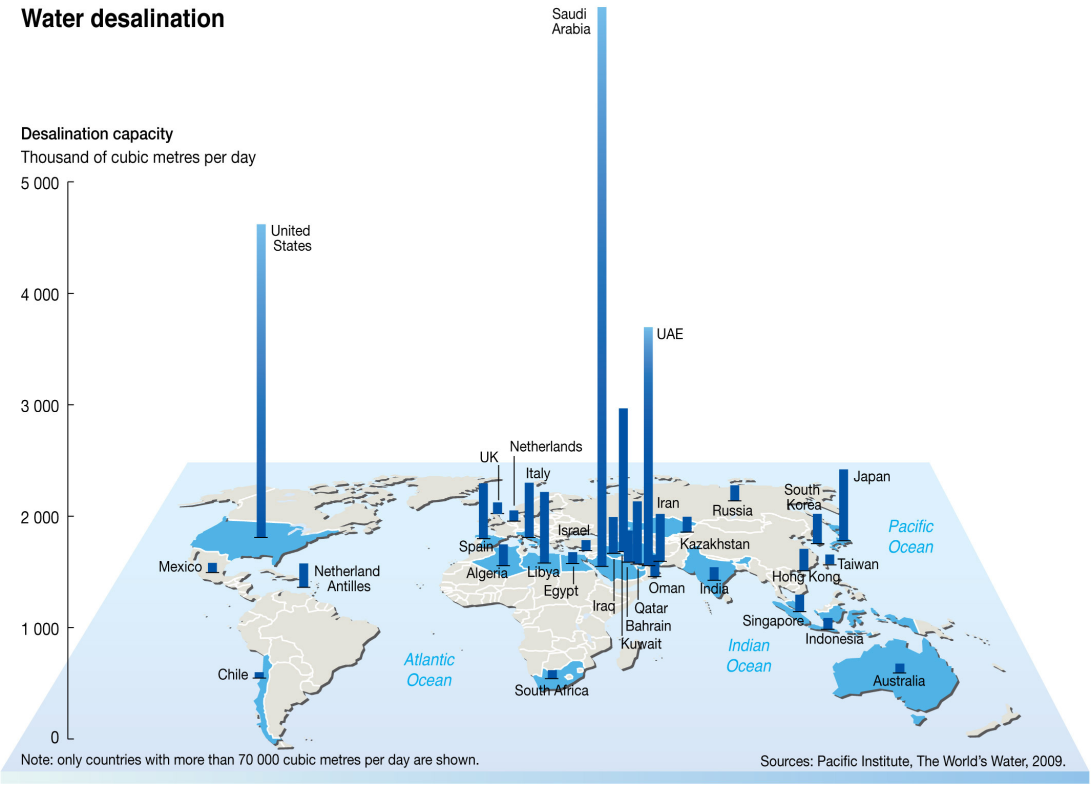
Figure 1.2: Schematic representation of OTEC and OTWP system [40].

The Ocean Thermal Water Production (OTWP) system of Bluerise is designed to work in symbiosis with OTEC on Curacao. By condensing atmospheric water vapor fresh water is produced. The cold deep seawater of approximately 4 °C is first used as a heat sink at the condenser of the OTEC system. Next, the cold water serves at a heat sink for the heat exchanger. Here the heat is exchanged from a fresh water flow to the seawater.

The fresh water flow goes to the direct contact condenser where warm humid air, of approximately 28 °C with absolute humidity of 19 g/kg dry air, is used as an input. Here the water is sprayed over a packed bed to form a liquid film with a high specific heat transfer area. When the air is cooled the air is capable of absorbing less water particles. The moisture extracted from the incoming air is then collected at the bottom of the condenser and fresh water with a temperature of around 25 °C flows out [40]. See figure 1.2 for the schematic overview of the combined systems of OTEC and OTWP.

1.2. Problem definition

In figure 1.3 a global overview is given of the desalination capacity of several countries [1]. In 1996 The Netherlands Antilles distillate 210 905 m^3 per day [27]. The most common desalination technology in the Caribbean is RO, although some islands like Antigua, the Bahamas and the British Virgin Islands have MSF plants as well. Most plants are private owned and with long term contract they sell the fresh water to the government or contracting industry [19].



Note: only countries with more than 70 000 cubic metres per day are shown.

Sources: Pacific Institute, The World's Water, 2009.

Figure 1.3: The world water desalination capacity [7]

In 1928 the first land-based desalination plant was installed on the island of Curacao [10]. The technologies were initially based on evaporation and moving forward to co-generation [2] powered drinking water. The first seawater RO plant was installed in 2005 [36] and by 2015 the total demand is achieved by two RO plants, owned by the water and electricity provider Aqualectra. In table 1.1 an overview of the current production capacity in Curacao is presented [13]. The average daily use is 37 000 m^3 on the island [16].

The scarcity of fresh water will only grow in the future as well as the global warming effects, if no actions are undertaken to produce water with innovative technologies and reduce the use of fossil fuels. The investment of the deep seawater pipelines is significant and can make up to 70 % of the total project costs of the OTEC system [62]. Therefore, combining OTEC systems with other ocean thermal technologies can be financially attractive, since the investments for the seep seawater pipelines and the total overhead costs

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[1] This figure is created with data from 1996. Currently the only public data available.

[2] "Is the use of a heat engine or power station to generate electricity and useful heat at the same time" [65].

Table 1.1: The RO production capacity on Curacao

Location	**Production capacity** [m^3/day]
Mundo Nobo	25 120
Santa Barbara	25 100
Total	50 220

can be spread over different technologies. Bluerise B.V. is a company that is specialized in Ocean Thermal Energy solutions, such as OTEC, Seawater Air Conditioning technologies (SWAC) and related deep seawater applications. One of the developments of Bluerise is the combination of OTEC with an Ocean Thermal Water Production (OTWP) system. Research on experimental scale is done on the fresh water production using atmospheric water extraction. Therefore, knowing the environmental impact of this process will give new insights on design improvements can be made to reduce this impact even further. This system is designed for a low energy consumption, where the required energy will be provided by the OTEC system. A very sustainable way of producing electricity and fresh water is created on paper, which will contribute to the transition towards a fossil free world.

This study is relevant since the knowledge of implementing the most suitable technologies for fresh water production will become more important in the near future. To check the sustainable performance of a system, the environmental impacts should be analyzed. One should have a clear overview what those impacts are for extraction of raw materials, during construction, operation and final disposal. A good method for this is life cycle assessment (LCA), which is a tool useful for quantifying the impact of different stages of a system and for comparing environmental impact of different systems. Therefore, the following problem statement is made: *There exists no life cycle assessment of the OTWP system, which can determine the most sustainable method for producing fresh water in the Caribbean by comparing the environmental impact with RO plants.*

1.3. Research questions

The main research question is formulated as follows:

What is the Life Cycle Assessment of an Ocean Thermal Water Production system and which fresh water production method has the highest environmental sustainability for the Caribbean?

The following sub-questions are considered to provide an answer for the main question:

1. How do the most important components of the pilot OTWP system look like and what is its operating energy consumption?
2. What are the relevant environmental impacts of the pilot OTWP system calculated with different evaluation methods and how do the airborne emissions compare to reverse osmosis system?
3. What are the environmental impact relation between the pilot and the upscaled system and how do the airborne emissions compare to reverse osmosis system?

The research approach to answer these questions is presented in chapter 2.

1.4. Thesis structure

This thesis will present the LCA of the OTWP system and the comparison with RO desalination plant. The structure of this research is as follows. In chapter 2 the research approach is discussed. In chapter 3 a first attempt is done on the system engineering of the pilot scale OTWP for Curacao. Chapter 4 follows with the inventory analysis, which will be used in SimaPro to calculate the environmental impacts. These impacts are presented in chapter 5, providing numbers to the environmental impact. Next are the interpretations of the impact assessments presented in chapter 6, including the contribution analysis of the system, a sensitivity analysis of the energy consumption and the comparison with RO. The analysis of the up scaled system is presented in chapter 7. Finally, the conclusions and recommendations are given in chapter 8.

2

Research Approach

The aim of this research is to develop the life cycle assessment (LCA) of an Ocean Thermal Water Production (OTWP) system, compare the environmental impacts with reverse osmosis system and determine which system has the highest environmental sustainability for the Caribbean. The research is divided into several phases to describe the research approach which will achieve this aim. The three phases are: system engineering, life cycle assessment and upscaling influences.

Three sub-questions are formulated and will be answered with the three phases:

1. How do the most important components of the pilot OTWP system look like and what is its operating energy consumption?
2. What are the relevant environmental impacts of the pilot OTWP system calculated with different evaluation methods and how do the airborne emissions compare to reverse osmosis system?
3. What are the environmental impact relation between the pilot and the upscaled system and how do the airborne emissions compare to reverse osmosis system?

With an answer to these sub-questions a well formulated and argumentative answer is provided on the main research question. This question is as follows:

What is the Life Cycle Assessment of an Ocean Thermal Water Production system and which fresh water production method has the highest environmental sustainability for the Caribbean?.

In this chapter the research approach is presented, starting in section 2.1 with the description of the system engineering process. Followed by an introduction to LCA in section 2.2, with a general description of the four phases. Next, these LCA phases are described in more detail. The goal and scope approach is shown in section 2.3. The inventory analysis is given in section 2.4. The several steps that are done in the impact assessment are given in section 2.5, with a motivation for the selected evaluation methods and their impact categories. Next, the section 2.6 presents the interpretation phase. Finishing off with section 2.7 describing the upscaling influences.

2.1. Introduction to system engineering

The first step of this research is system engineering, represented in chapter 3. The definition of system engineering is defined in the NASA Systems Engineering Handbook is used as a reference:

"System engineering is a robust approach to the design, creation and operation of systems. In simple terms, the approach consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets the goals." [3]

This definition describes all the different aspects that are necessary for system engineering. Due to the time and the focus of this research, the creation of alternative system design concepts, verification of the design and post-implementation assessment are left out of the scope of this thesis. The main focus of the system engineering is to review the requirements, setup the boundaries of the system and specify the components of the system that match these requirements. The output of this process is to generate a list of components that are selected to represent a part of the system fulfilling the system requirements. This knowledge is needed to create the LCA and in this way an answer will be provided on the first sub-question: *How do the most important components of the pilot OTWP system look like and what is its operating energy consumption?*

2.2. Introduction to LCA

Two decades ago the first LCAs were published, the research of Ahbe et al. [6] about the Ecopoints methodology in 1990 and the study of Heijungs et al. [32] about the CML 1992 methodology. Followed by the International Organization for Standardization (ISO) which provided a framework for LCAs in 1993. The life cycle assessment is a scientific tool to analyze the entire scope of the environmental impacts of a product, activity or process, from the recources extraction, manufacturing processes and operational phase to the final disposal [30]. This LCA approach is standardiszed by the ISO and defines the LCA as *"compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle"* [1]. The LCA is divided into four different phases [18], see figure 2.1 for the schematic overview of these phases:

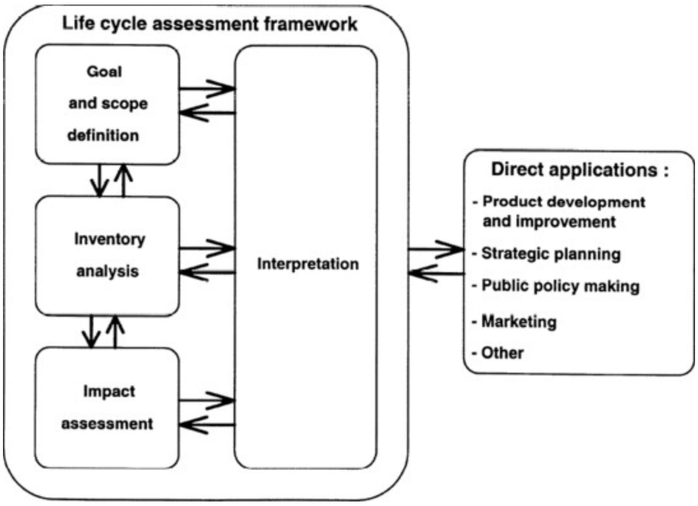

Figure 2.1: Phases of a LCA [1].

1. The goal and scope definition: defines the purpose and initial choices made for the outline of the LCA.
2. The inventory analysis: represents the quantification of the system by the energy, water and material used, which results in an inventory table.
3. The impact assessment: processes the inventory table into potential environmental impacts.
4. The interpretation: evaluates the results of these environmental impacts with the corresponding uncertainties and assumptions and generates the conclusion of these results.

The economy is often only focused on the final consumption of the final product, excluding the system that produces this product and all the environmental impact that comes along with the creation of the final product. The LCA can influences the indirect environmental management along the product process. It avoids problem shifting in the different stages of the final product. Since comparing the environmental impacts for different materials and there manufacturing processes becomes easier this way and good argumentation can be formed about which process is most environmental friendly [30].

Going over these four LCA phases will provide an answer to the second sub-question: *What are the relevant environmental impacts of the pilot OTWP system calculated with different evaluation methods and how do the airborne emissions compare to reverse osmosis system?.*

2.3. Goal and scope definition

The goal and scope definition is the first phase of the LCA and forms the organizational stage of the study. In the goal definition the aim of the study is stated, the intended use of the results and for whom this study is mend are explained. The scope definition describes temporal, geographical and technology coverage of this study as well as the boundaries of the system. The system boundaries are defined by the several process stages (e.g. manufacturing, transportation and waste treatment) and the operational stages (e.g. inputs and outputs). Finally, the function, functional unit and reference flows are defined. The function is the service that is provided by the system, the functional unit quantifies the performance of the system and the reference flow measures the outputs from provided by the system [30].

2.4. Inventory analysis

The second phase in the LCA is the inventory analysis. In this phase the results of the system engineering phase will be used to create the inventory list. This is done by collecting the data needed to create the system in the softeware SimaPro, this data will be in the form of materials, manufacturing processes, transport and energy consumption. In this way all the inputs and outputs to the environment of the different system processes, also referred to elementary flows, are processed into one large dataset in the inventory table [30].

This data can come from specific companies, countries, literature or in a more general form from databases, like Ecoinvent. The inventory list is modeled by selecting the corresponding unit processes from the databases in SimaPro. The description of the diverent databases used for this research are presented in appendix A. Average data can be used to simplify the LCA to get a first impression of the potential environmental impacts of the system. The downside of this is that the data can be outdated, representing experimental or pilot plant data and can give a false representation of latest technology developments on commercial scale [64]. Therefore, the system boundaries must be stated and all assumptions made should be reported accordingly.

2.5. Impact assessment

The life cycle impact assessment (LCIA) converts the inventory results into numbers of potential contributions to the environmental impacts. This process is carried out is five steps: selection, classification, characterization, normalization and weighting [30, 31]. The selection step includes a selection of the impact categories, category indicators and characterization models, this process is described in subsection 2.5.1. Classification is described as the quantitative process where the elementary flows of the inventory are assigned to the relevant impact categories. The LCA program SimaPro does this step by itself, therefore no further elaboration is done on classification. During characterization the inventory data is modeled within impact categories, using characterization factors (also known as equivalency factors). This is further described in subsection 2.5.2. The final optional step for the impact assessment is the normalization and/or weighting, which processes the results further. This is described in subsection 2.5.3. Each process manipulates the data of the inventory in such a way that the final results are simplified for interpretation. The down side of this is that with each manipulative step a certain subjectivity is added.

2.5.1. Evaluation methods and impact categories

The information of the inventory list is translated to environmental impacts, with the use of the software SimaPro, version 8.1. The emphasis of the different impacts depends on the selected evaluation methods and the corresponding impact categories. These evaluation methods are developed by several research groups world wide and there is no clear answer on which method is the best or most suitable, yet [29, 53]. According to the study of Renou et al. [54] for LCA of waste water treatment, the choice between these methods is not a critical issue for impacts such as greenhouse gas emission, acidification, eutrophication and resource depletion, since they provide similar results. The results will also be compared with the LCA results of RO, hence it is decided to use the same evauation methods as used for the RO LCA from the research of Raluy et al. [52], which are CML-IA baseline (CML), Eco-indicator 99 (EI 99) and Ecopoints 97 (Eco 97). In this way, uncertainties and interpretations in the use of methods can be limited. The evaluation methods with the selected impact categories are presented in table 2.1.

Table 2.1: Impact catergories included the evaluation methods.

CML-IA baseline	**Eco-indicator 99**	**Ecopoints 97**
Abiotic depletion	Carcinogens	NO_x
Global warming	Respiratory inorganic	SO_x
Human toxicity	Climate change	NMVOC
Fresh water aquatic ecotoxicity	Ecotoxicity	Dust PM10
Marine aquatic ecotoxicity	Acidification/eutrophication	CO_2
Acidification	Minerals	Cd (air)
	Fossil fuels	Waste
		LMRAD
		HRAD
		Energy
		Heavy metals (water): Zn, Cu, Cd, Hg

The selected evaluation methods are briefly described bellow, a detailed description can be found in appendix B.

- The CML-IA baseline is a LCA methodology developed by the Center of Environmental Science (CML) of Leiden University in The Netherlands. This method is an update of the CML 2 baseline 2000 and defined for the midpoint approach, which is a problem-oriented approach (definition for category indicators close to environmental interventions).
- The Eco-indicator 99 is a LCA methodology developed by scientists in collaboration with a panel, consisting out of Swiss LCA interest group of people. This method uses a damage-oriented approach, also known as an endpoint approach, which translates environmental impacts into issues of concern. The results have a higher level of uncertainty compared to midpoint results.
- The Ecopoints 97 methodology is developed by the Swiss Ministery of the Envrionment (BUWAL). This method is based on real pollution and critical targets from Swiss policy. It is based on the distance-to-target method, which assess the impact on an individual basis. No classification and a different normalization principle are used, since target values are used.

The inputs and outputs of the inventory are quantified to the impact categories, this step is called classification and is done by the software SimaPro. It is possible that an output is counted twice as it is assigned to two different impact categories, but is only done if the effects are independent. Taking the ISO standard into account for "the selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration" [1]. During the impact assessment first all the impact categories were considered, but to simplify and keep the analysis clear only the impact categories with a low percentage in the environmental impact are neglected. For the CML and EI 99 methods this percentage is set at 0.2%, for the Eco 97 method it is 1.0% since this method considers more impact categories. The descriptions of the items that are covered by the impact categories are listed bellow [30]:

- Abiotic depletion: the depletion of abiotic resources is described as the extraction of natural resources (including energy resources) that are characterized as non-living. The abiotic depletion of elements and ultimate reserves is related to extraction of minerals due to inputs in the system. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals (kg antimony equivalents/kg extraction) based on concentration reserves and rate of deaccumulation. Abiotic depletion of fossil fuels is related to the lower heating value (LVH) expressed in MJ per kg of m^3 fossil fuel. The reason for taking the LHV is that fossil fuels are considered to be fully substitution.
- Global warming/climate change: the impact of human emissions on the radiative forcing of the atmosphere, measures the emissions of greenhouse gases into the air. Resulting from an increase of diseases

and death caused by climate change. On a global scale carbon dioxide (CO_2) is for approximatley 65% of all the greenhouse gases emitted by human activities [5].

- Fresh water aquatic ecotoxicity: the impacts of toxic substances on fresh water aquatic ecosystems, measures the emissions of toxic substances into the air, water and soil. Freshwater is a vital component in the global ecosystem. Freshwater is a unique environmental habitat and also essential for human life. Freshwater pollution not only poses a risk to the environment, but it can also impact human health as well. Therefore, it is important to maintain anthropogenic pollution below a threshold that would characterise a risk [25]. A practical example of this impact category is that ”models suggest that it is better to empty a jerrycan of benzene into a fountain that to throw a nickel coin into it... 5 kg benzene has a fresh water aquatic ecotoxicity potential of 0.45 kg 1,4-DB equivalent while 10 g of nickel scores a 32 1,4-DB equivalent” Heijungs et al. [33].

- Acidification: the impact of acidifying pollutants on soil, groundwater, surface waters, biological organisms, ecosystems and materials (buildings). The major acidifying pollutants are SO_2, NO_x and NH_x, measured in emissions of acidifying substances into the air.

- Eutrophication: refers to the emissions of nutrients in the air, water and soil. Due to the enrichment by macro nutrients (mostly nitrogen and phosphorus), an undesirable shift in species composition and biomass growth may occur in aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to a depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition. Degradable organic matter emissions have similar impact and are treated under the same impact category.

- Human toxicity: the impact on human health due to toxic substances in the form of emissions to air, water and soil are included [30].

- Marine aquatic ecotoxicity: refers to the impacts of toxic substances on the sediment of seawater ecosystems. The LCI results in emissions of toxic substances to air, water and soil in kg, with the marine aquatic ecotoxicity potential for each emission [30].

- Waste heat: the emissions of heat in MJ that are release into water are taken into account, like cooling water emissions from power stations. These emissions contribute only to local temperature increments, resulting impact on local aquatic ecosystems. The emissions to the air are negligible since waste heat does not contribute on global warming scale with greenhouse gases.

- Carcinogens: reverse to the toxicological risk and potential impacts of carcinogenic chemicals released in the air, water and soil [60]. The non methane volatile organic compounds (NMVOC) contain carbon in the moleculair structure and in general include the following chemical groups: alcohols, aldehydes, alkanes, aromatics, ketones and halogenated derivatives of these substances. Depending on their composition and toxicity, they can be extremely dangerous for human health.

- Respiratory inorganic: reverse to the respiratory health risks of inorganic particles in the air [60]. The respiratory effects resulting from winter smog caused by emissions of dust[1], sulphur and nitrogen oxides to air.

- Ecotoxicity: damage to ecosystem quality, as a result of emission of ecotoxic substances to air, water and soil.

- Heavy metals: these particles bring emissions to surface water and damage the aquatic ecosystem by accumulating in organisms, where they can cause growth impairments and metabolic disturbances. They are able to propagate through the food chain [26].

- Waste: the indicator for the reaction potential of waste is its carbon content, which can cause longterm problems when stored in landfills [26].

- LMRAD and HRAD: low-level, medium-level and high radioactive dose. The generation of electicity in nuclear power plants produces radioactive wastes that must eventually be consigned to final storage [26].

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[1] Dust PM10 is particulate matter 10 micrometers or less in diameter [35].

If some data from the inventory results cannot be assigned to impact categories due to lack of environmental relevance or a dataset does not represent elementary flows, this information is missing in the impact assessment. The problematic consequence is that this is causing a reduction in the number of data entries and this knowledge is disappearing. The strategy for solving this by reporting, stating when environmental (ir)relevance is assumed [30, 31].

2.5.2. Characterization

In the characterization step the classified values for each impact category are translated to a common indicator score. This is done by multiplying the classified values with a characterization factor [30, 31]. As an example, the indicator score of the impact category global warming is expressed in CO_2 equivalent. The characterization factor of CO_2 can be 1 and the factor of methane 21. If 1 kg of methane is used in the process this cause the same results as using 21 kg of CO_2 [53]. Depending on the evaluation method used, different characterization factors will be used and the program SimaPro will characterizes this for each impact category. These factors must be scientifically justifiable and internationally accepted. For the selected evaluation methods this is the case and therefore no further investigation in these characterization factors is done in this study.

2.5.3. Normalization and weighting

Normalization is the calculation step that provides better insights in the environmental impact results. By comparing the impact results to average reference data over a given period of time, such as a person or country. Normalized values are expressed on a common scale (dimensionless) and therefore provide a good way to make comparisons between the different impact categories and between whole systems. In most LCA studies external normailzation is used. Meaning that the environmental profile of the reference system is independent of the studied system [31]. For the studied system most products have a global system boundary and are therefore not regionally bounded. Therefore, a global normalization reference is selected for the CML evaluation method [34].

The last optional step for the impact assessment is weighting, done to assess the indicator results across impact categories. The results are multiplied with weighting factors. These factors are based on the relative importance between the different impact categories and are based on value choices. The weighting is done for the EI 99 and Eco 97 evaluation methods.

2.6. Interpretation

The final phase of the LCA is the interpretation phase, which represents the evaluation of the the environmental impacts. Here the analysis of the assumptions and uncertainties are made. This will lead to the overall conclusions of the results of the inventory analysis and impact assessment. Now a comparison analysis can be made between other systems and final recommendations can be stated about the systems environmental impacts [30].

2.7. Upscaling influences

From the interpretation phase of the LCA a good impression of the environmental impacts is given and the outstanding aspects are discussed. This gives the opportunity to investigate the influences that an upscaled system has on the environmental impacts. With the information available it is interesting what happens if the diameter of the condenser will be doubled, hence representing the upscaled system. In this way the third sub-question will be answered, which is: *What are the environmental impact relation between the pilot and the upscaled system and how do the airborne emissions compare to reverse osmosis system?*

3

System Engineering

In this chapter system engineering of the OTWP is done to provide input for the inventory analysis. From already available data and requirements of the OTWP system, the system boundary for this study and suitable components are selected. In this way a good first estimation can be made for the inventory analysis and the flow diagrams for the components are created. In section 3.1 these system requirements and boundary conditions are presented. The condenser components are described in section 3.2. The heat exchanger is given in section 3.3. The components that consume energy are the water pumps and air ventilator, which are shown in section 3.4 and 3.5, respectively. To conclude, the water storage characteristics are given in section 3.6.

3.1. System requirements and boundaries

For the design of the OTWP system in Curacao a Python model is made by Bluerise [40]. All relevant condenser and heat exchanger input and output data for this model are presented in table 3.1, copied from the thesis report of Lopez [40]. It follows that the fresh water production mass flow rate is 0.25 kg/s, this leads to a daily production capacity of 21.6 m^3.

Table 3.1: Condenser and heat exchanger data from the model, modified from Lopez [40]

Parameter	Unit		
Condenser		**Inlet**	**Outlet**
Temperature water	°C	12.75	17.60
Temperature air	°C	28.20	15.51
Mass flow air	kg/s	32.726	32.476
Absolute humidity	kg/kg	0.0186	0.0110
Pressure drop	Pa	0	412
Efficiency	%		78
Heat exchanger		**Fresh water**	**OTEC water**
Temperature inlet	°C	17.40	10.00
Temperature outlet	°C	12.75	13.86
Mass flow rate	kg/s	54.182	65.201

In figure 3.1 the system boundaries are presented for the LCA. This diagram shows the different processes, from the raw material used for the construction of the system, the operational phase, till the dismantling and the final transfer to land at the end-of-life. The main inputs of materials for all systems occur in the construction phase, and the energy inputs are concentrated in the operating phase. Included in the analysis of the system are the following aspects:

- The system lifetime is assumed to be 30 years.
- The annual operation hours are assumed to be 8395, which corresponds to a daily operating time of 23 hours and a system availability of 95.8 %.

- The raw materials and their transformation to components for installations, including the transportation.
- The installation of the components of the system.
- The systems that delivers the energy supply for the water treatment.
- The operation and maintenance of the system.
- The dismantling and final disposal (excluding recycling) of the entire system.

What is excluded are the emissions, since these environmental impact will be determined by the LCA. The water input and out flows are defined as the fresh water flows that run through the system. Also the water input, output and distribution are not taken into account as inputs for the LCA.

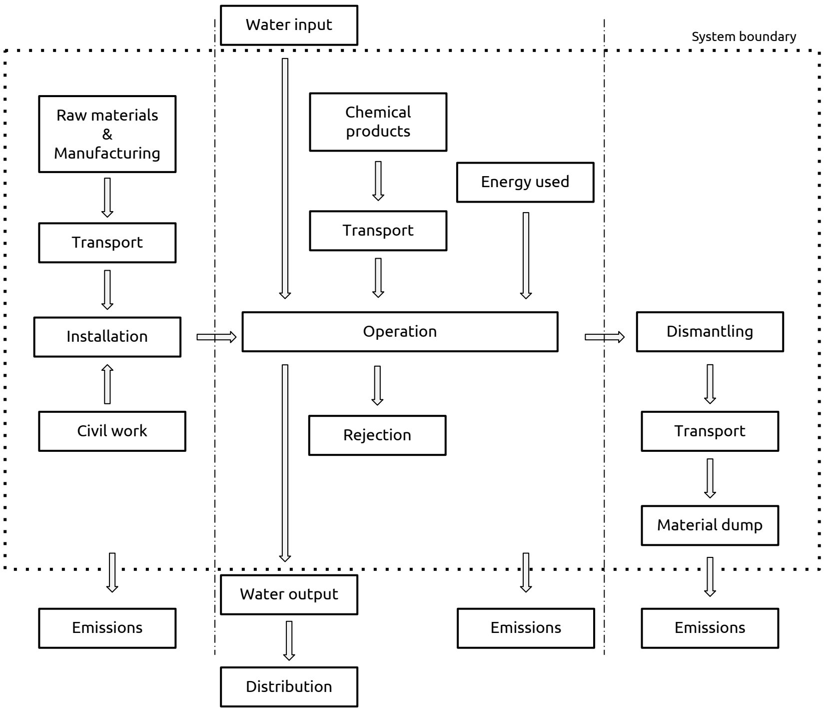

Figure 3.1: The system boundary, modified from Raluy [53]

To develop the LCA of the OTWP several assumptions and limitations are made. The system boundaries are the assembly, operation and decommissioning of the OTWP. This includes the system components, construction material and installation, the operation and maintenance phase, and the dismantling at the 30 years lifetime. What not is included in the design are the following:

- The system integration of the individual components. The pilot model represents a collection of single components.
- The pipe design of the OTWP, due to complexity of the pipe design for now it is neglected.
- The quality of the produced fresh water. For now it is assumed that the quality of the water can be compared to the water quality of water produced by a RO plant.

3.2. Condenser

The condenser can be divided into three parts: the column, the packing and the nozzle. The frame of the condenser is represented by the column, which is filled with the packing. The nozzle will spray the fresh water over the packing from the top of the condenser. At the bottom, the humid air will enter and mass and heat transfer will take place to let the fresh water in the air condensate, creating more fresh water.

3.2.1. Condenser column

The condenser column has a cylindrical shape, which is very common in industrial chemical processes. In the research of Lopez [40] the effect of the column diameter against the energy consumption has been studied. The range of the diameter varied from 1 to 10 meters. The outcome is that the lowest energy consumption occur with a diameter of 3 m, see appendix C for this graph. From the previous research done by Bauer et al. [11] the optimum height of the column is proposed to be 1 m. After the height of 1 m the air becomes to dry for further water extraction. Therefore, the constrains for the sizes of the column are predetermined by previous research.

An other requirement coming from Bluerise is that the column needs to be transparent. The minimum wall thicness for a metal vessal with a diameter between 3 and 3.5 meters is 12 mm [58]. To limit the heat exchange between the inside of the column and the outside atmosphere, metal is not a good material option. Instead, plastic is a much better fit. The thermal conductivity of plastics is much lower than that of steel. Unfortunately, the ratio of the diameter and the minimum wall thickness for plastic materials is not publicly available. Therefore, a factor of 5 of the minimum steel thickness is assumed for the thickness of the wall, which results in a thickness of 60 mm. This creates a certain uncertainty, since this is a random assumed factor and further research into the thickness is needed. At least is it known that the thickness should not exceed 750 mm. The world's largest aquarium is made out of PMMA (Polymethyl methacrylate) and holds 10 million liters of water, which is about 4 olympic sized swimming pools [59].

The results of the column are shown in table 3.2. For the calculations of the mass, see appendix D.

Table 3.2: Data table of the column of the condenser

Specification	**Value**
Diameter [m]	3
Height [m]	1
Thickness [mm]	60
Material [-]	Polymethyl methacrylate (PMMA)
Mass of column [kg]	337

3.2.2. Condenser packing

The experimental setup uses a random packing of metallic pall rings currently. Research is still in full progress on the most suitable packing material, but for now it is assumed that this will be the packing material that will be used for the pilot OTWP system. These pall rings have cylindrical dimensions with two rows of punched out holes with fingers or webs turned into the center of the cylinder. This design significantly increases the performance of the packing, in terms of throughput, efficiency and pressure drop. In table 3.3 the specifications of the chosen pall rings are presented [15]. The mass of the packing is calculated by the volume of the column multiplied with the specific weight of the packing.

Table 3.3: Data table of the metallic pall rings

Specification	**Value**
Packing size [mm]	16
Free space [%]	93
Specific surface area [m^2/m^3]	316
Number per unit volume [no./m^3]	210 000
Specific weight [kg/m^3]	535
Material type	Stainless steel 304

3.2.3. Condenser nozzle

For the experimental setup the nozzle MP125 of the company BETE [12] is used. This nozzle is made of stainless steel 316 and has a full cone spray pattern of 60°, which is good for a maximum water mass flow of 0.03 kg/s through the condenser at a pressure of 0.2 bar. To select the appropriate nozzle of the system at a full scale the required volume flow needs to be fulfilled. The volume flow rates of the different nozzles is obtained from the table in appendix E, as well as the calculations on the number of nozzles and the selection. See table 3.4 for the specifications of the nozzles.

Table 3.4: Selected nozzle specifications

Specification	**Value**
Number required nozzles	7
Nozzle number	MP1500
Mass [kg]	19.88
Pressure [bar]	0.5
Volume flow rate [L/min]	3913
Mass flow rate [kg/s]	65.24
Material	Stainless steel 316

3.2.4. Flow diagram condenser

From the selected components for the condenser, the following flow diagram is created in SimaPro, see figure 3.2. Here the flows are given for the normalized impact category abiotic depletion as percentages and the width of these arrows represents the impact of the specific process on the condenser. Only the top processes are shown here. For the detailed flow diagram see appendix K. Keep in mind that the numbers presented in this flow diagram change per impact category and evaluation method, see chapter 5 for more detail on the environmental impact.

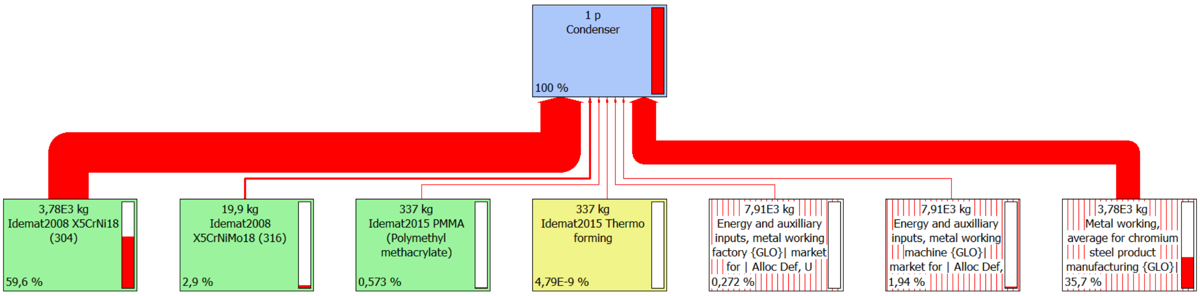

Figure 3.2: Flow diagram of condenser.

3.3. Heat exchanger

The cold deep seawater serves as the heat sink for both OTEC and OTWP. This cold water is pumped up at approximately 1 km depth, where it has a temperature of 4 °C. After this cold water flow leaves the condenser of the OTEC system, it will flow into the heat exchanger of the OTWP system with a temperature of 10 °C. Here it will cool down the fresh water loop to a temperature of 12.75 °C. The company Kapp Nederland BV [55], specialized in producing heat exchangers, calculated the specifications for the heat exchanger that will be used in the OTWP pilot, see appendix F for the details of this design, including technical drawings.

Due to the small temperature differences of the fluids, plate heat exchanger is the most suitable design. The plates cause for a large surface area, with an optimized design in corrugation leads to the highest heat transfer rates. On one side of the plate the cold flow passes through and on the other side the warm flow. The gasket between the plates prevents mixing of these two flows. Table 3.5 shows the details of the heat exchanger design. The heat exchanger is a static equipment, therefore it is realistic to assume that no wearing occurs. The plate material titanium is resistance to the highly corrosive environment of seawater. Hence, there is no need to replace these plates. The gasket material is recommended to be replaced every 10 years, assuming a lifetime of 30 years this will be replaced twice.

Table 3.5: Heat exchanger design data

Design data	**Value**
Heat exchanger type	Gasketed plate NT150S
Heat transfer area [m^2]	73.53
Number of plates	131
Plate length [mm]	1323
Plate width [mm]	545
Plate thickness [mm]	0.5
Plate material	Titanium
Plate mass [kg]	217.25
Gasket material	NBR (25kg)
Gasket type	Glueless
Internal flow (passes x channels)	1 x 65
No. of frames	1
Frame height [mm]	1507
Frame width [mm]	640
Frame material	S355J2+N with RAL5002 paint
Total mass[kg]	1009 (with AISI316L plates)
Operating mass [kg]	1238

3.3.1. Flow diagram of heat exchanger

In figure 3.3 the flow diagram of the heat exchanger is given. The same conditions as for the condenser flow diagram hold, see section 3.2.4.

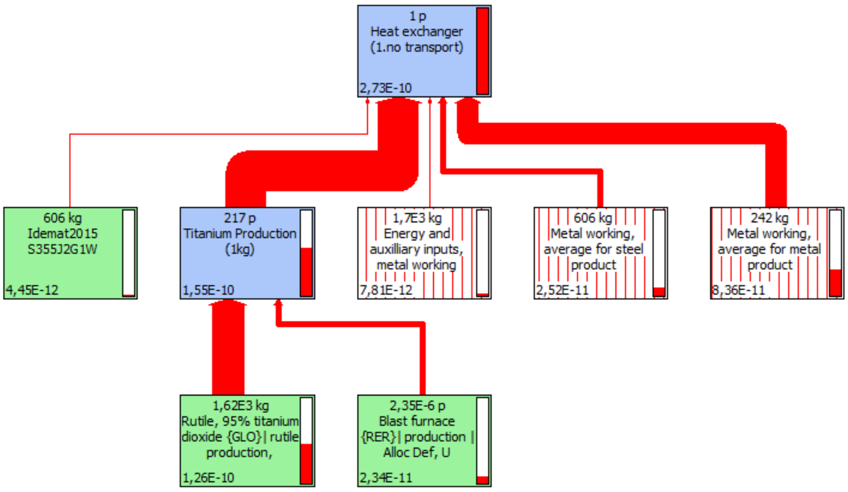

Figure 3.3: Flow diagram of heat exchanger.

In figure 3.4 the details of the titanium process are presented in the flow diagram. This is the flow diagram for the production of 1 kg titanium. This flow diagram is built in SimaPro, but modified from the study of Aalbers [2] for 1 kg production, in his research more detail on the numbers is provided.

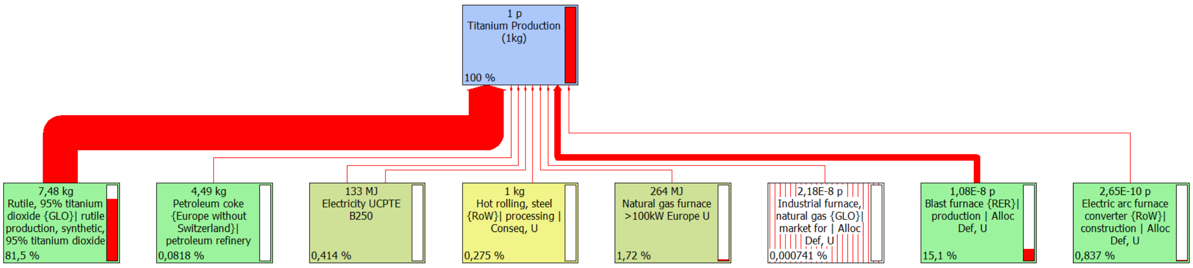

Figure 3.4: Flow diagram of titanium production.

3.4. Water pumps

The energy consumption of the OTWP system depends on the energy use of the water pumps and the air ventilator. Centrifugal pumps are the most energy efficient pumps and widely used in utility installations with moderate to high flow and low head. These pumps have a wide range of capacities and an uniform flow at constant speed and head [42]. This system uses two water pumps, one for the seawater flow from the OTEC system to the heat exchanger and the fresh water flow from the condenser to back to the heat exchanger. For the first selection of suitable pumps, a volume flow of 230 m^3/h is used. From the several pump performance charts available, the power and efficiency at this volume flow rate are compared. To determine the most efficient pump, the energy consumption per m^3 produced fresh water is calculated by equation 3.1.

$$E_{pump} = \frac{1.1 \cdot P \cdot \rho_L}{3.6 \cdot m_{fw}} \tag{3.1}$$

Where P is the power of the pump in kW, ρ_L the density of water in the liquid phase in kg/m^3 and m_{fw} the mass flow rate of the fresh water production in kg/s. A 10 % margin of the power has been selected to add to the energy consumption as a contingency contribution. This should take losses in the operating processes into account, like transmission losses. It follows that the energy consumption of the pump is 0.0394 kWh per m^3 of fresh water production.

Table 3.6: Selected water pump specifications

Specification	**Value**
Seawater pump material	bronze
Fresh water pump material	cast iron
Mass of the pump [kg]	185
Volume flow [m^3/h]	230
Efficiency [%]	77
Power [kW]	24.7
Mass motor	246
Motor material	cast iron
Energy consumption [kWh/m^3]	0.0394

Although the pump head is required to determine the specific amount of power needed, this will provide a first estimation for the LCA of the pilot system. The pump head consists of the pressure on the suction side, plus the pump differential pressure. Therefore, to know the exact performance of the pump these data should be available. For the required volume flow most pump manufacturers have medium to large head corresponding, hence a head of 30 m is chosen to continue with the selection. This broad estimation will lead to a higher energy consumption of the pump, since a lower head requires less pump power.

The pump type CNLe of the company Iron Pump is selected. This EU EcoDesign compliant vertical, in-line centrifugal pump offers a lightweight design with a minimum of components. This pump can be used for both fresh and seawater. The pump casing is available in GJL-250 cast iron and RG10 seaworthy bronze, good for the fresh water and seawater flow, respectively. The details of this pump are presented in appendix G. In table 3.6 the pump specification are given.

For the most energy efficient motor, the energy class IE4 for electric motors is recommended. Pump manufactures normally choose a motor with a nominal power overhead of 10-20% bearing in mind that the actual consumed effect will not be more than what the pump will require for a given duty [20]. Hoyer Motors is a motor manufacture and produce IE3 cast iron motors. Depending on the number of poles the mass of the motor increases. The lightest 30 kW motor is the model HMC3 200L1-2, which has a mass of 246 kg and an efficiency between 92-93.7% [43].

3.4.1. Flow diagrams of the water pumps

In figure 3.5 the flow diagram of the fresh water pump is presented, only the top processes. The same conditions as for the condenser flow diagram hold, see section 3.2.4.

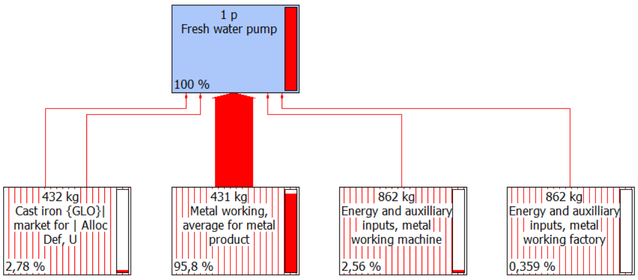

Figure 3.5: Flow diagram of fresh water pump.

In figure 3.6 the flow diagram of the seawater pump is shown. The same conditions as for the condenser flow diagram hold, see section 3.2.4. Here the two main processes are shown, for the detailed version see appendix K.

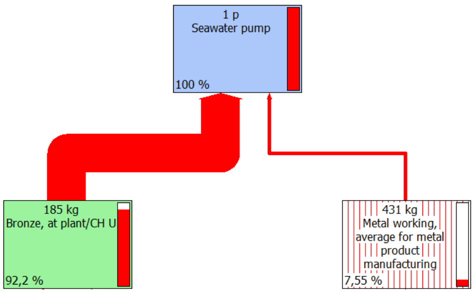

Figure 3.6: Flow diagram of seawater pump.

3.5. Air ventilator

The ventilator has the function to blow the humid air into the condenser. A centrifugal ventilator is the mechanical device that provides the increase in the volume and speed of the humid air stream by the rotating impellers. This stream of humid air will pass through the ventilator into the condenser. The ventilator consists of the fan frame, impellers, the motor, the flanges and mounting. Made out of high grade hot galvanizing steel, except the motor that is made out of carbon steel. In appendix H a description in more detail of the material and manufacturing process, as well as the selection are given.

To meet the standards of the mass flow rate of the humid air pumped into the condenser by a ventilator, a certain ventilator needs to be selected. First the volume flow rate in m^3/s is calculated by expression 3.2:

$$\dot{V} = \frac{\dot{m}_{air}}{\rho_{air}} \tag{3.2}$$

where $\dot{m}_{air}$ is the mass flow in kg/s and ρ_{air} is the density of the humid air in kg/m^3. Since ventilators data is often presented in m^3/h, it is worth mentioning that the conversion from m^3/s to m^3/h is done by multiplying with the factor 3600. From the performance charts of several industrial ventilators a selection between these ventilators is made based on the volume flow rate of 100 000 m^3/h, corresponding with a dynamic pressure of 180 Pa and an outlet velocity of 17.5 m/s. All the ventilator performances are measured in standard conditions, with an air inlet pressure of P_a = 101.325 kPa, temperature of T = 20 ° C and density of ρ = 1.2 kg/m^3. To see the complete performance charts of these ventilators go to appendix H.

To calculate the total energy consumed by the ventilator per m^3 produced fresh water in kWh, equation 3.3 is used:

$$E_{ventilator} = \frac{1.1 \cdot P \cdot \rho_L}{3.6 \cdot m_{fw}} \tag{3.3}$$

where P is the power of the ventilator in kW, ρ_L the density of water in the liquid phase in kg/m^3 and m_{fw} the mass flow rate of the fresh water production in kg/m^3. A 10 % margin of the power has been selected to add to the energy consumption due to several losses in the operating process, e.g. transmission losses and different operating inlet values, the ductwork and air filters.

From this comparison between several ventilators (see appendix H) this one is selected based on low mass and energy consumption, the specifications are presented in table 3.7.

Table 3.7: Selected ventilator specifications

Specification	**Value**
Type	SYD1000-K
Ventilator material	galvanizing steel
Motor material	carbon steel
Mass of the ventilator [kg]	480
Volume flow [m^3/h]	100 000
Efficiency [%]	49
Power [kW]	22
Energy consumption [kWh/m^3]	0.055

In figure 3.7 the flow diagram of the ventilator is given for its top processes only. The same conditions as for the condenser flow diagram hold, see section 3.2.4. The green line indicates a positive environmental impact for the normalized CML abiotic depletion, meaning that this particular material (carbon steel/manganese) is abundant on Earth. The detailed flow diagram is shown in appendix K.

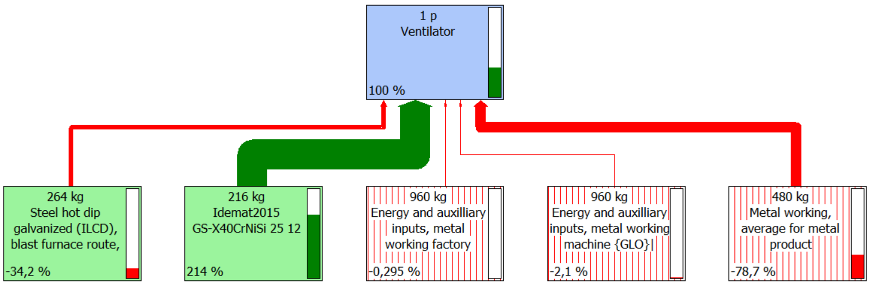

Figure 3.7: Flow diagram of ventilator.

3.6. Water storage

The water that will be produced will be temporarily be stored in a water tank. Plastic tanks are often used for small volumes up to 50 m^3 and are relatively cheap [39], high density polyethylene (HDPE) is a common material used for water distribution purposes [23]. In contrast to large capacities, steel tanks are used to withstand the pressures. Curacao has two locations where fresh water is produced with RO, with two or more steel reservoirs. Also several steel distribution reservoirs are located on the island, see appendix I for more details on the water storage reservoirs on Curacao. The daily production capacity of the RO plants are approximate 25 000 m^3 each. Since the reservoir volume vary a lot, from almost double the amount compared to production capacity to a factor less than 1/3, the water storage volume of the OTWP system will be estimated at approximately half the daily production capacity. The other assumption that is made is that further transport from the reservoir to applications that make use of this water are not taken into account. For future large scale water production, the current water distribution network on Curacao will be available for further transport. For the pilot OTWP the storage capacity will be estimated at 10 m^3, which is half of the daily production volume, the details of this tank is presented in table 3.8. These types of water tanks are easily ordered from the manufactures. The warranty for such a tank is approximately 3 years, assuming that replacement of this tank will occur every 10 years.

Table 3.8: Water storage for pilot OTWP

Dimension	Value
Diameter [m]	2.41
Height [m]	2.31
Weight [kg]	178.26
Material	HDPE

In figure 3.8 the flow diagram of the water tank is presented. The same conditions as for the condenser flow diagram hold, see section 3.2.4. Here the top processes are shown, the detailed version is in appendix K.

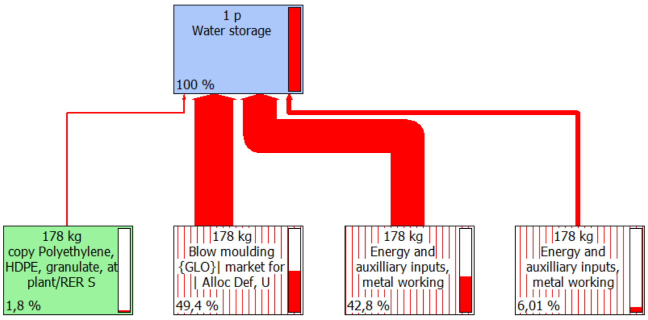

Figure 3.8: Flow diagram of water tank.

4

Inventory Analysis of OTWP

In this chapter the goal and scope definition are given in section 4.1. The inventory list is presented in section 4.2, including the descriptions of the general data of manufacturing, transport and electricity used in SimaPro.

4.1. Goal and scope definition

The main objective of this LCA is to obtain a first estimation of the environmental development of the entire process of the fresh water production of the OTWP of Bluerise and to make a comparison between the already existing LCA of reverse osmosis desalination of Raluy et al. [52]. In this way the main environmental impacts associated with this new technology to produce fresh water become clear and the comparison with RO desalination will conclude which technology is the least harmful to the environment. The emissions related to the entire life cycle will be mapped out, from raw materials till the end-of-life.

The temporal coverage of this study is 8 months (general required time for a master thesis in sustainable energy technology at the TU Delft). This includes the start of the thesis with a literature study, the data collection, verification process and the report and the final presentation. The specific location of the OTWP is on Curacao, in the Caribbean.

4.1.1. Function, functional unit and reference flows

One of the goals of this LCA is to compare the results of the OTWP with that of RO. Since the working principles of these two technologies are completely different but the systems provide the same purpose, which is producing fresh water, the function, functional unit and reference flow are introduced. The function is the service that is provided by the system, the functional unit quantifies the performance of the system and the reference flow measures the outputs from provided by the system [30]. These characteristics are summarized in table 4.1 for the LCA study. A water production of 1 m^3/day of drinking water is taken as the functional unit. Fresh water can be produced by using different desalination methods, as described in section 1.1. The reference flow that will be used to compare the results of this LCA study will be the production of 1 m^3/day fresh water by RO plant and an up scaled OTWP.

Table 4.1: Function, functional unit and reference flows

Function	Production of fresh water in Curacao
Functional unit	1 m^3/day of fresh water
Reference flows	Production of 1 m^3/day of fresh water by up scaled OTWP, with a daily capacity of 82.8 m^3
	Production of 1 m^3/day of fresh water by RO, with a daily capacity of 45 500 m^3

4.2. Inventory list

The inventory list contains all the data necessary to construct the different subsystems of the OTWP. From the data obtained in chapter 3, the summary of the inventory data is presented in table 8.1 of the system. The detailed inventory analysis can be found in the external appendix[1]. This table shows all inputs and output substances, which are the raw materials, air emissions, water, soil and waste. The process, product or activity is divided into one of the three phases: assembly, operation and decommissioning. The assembly phase contains the different components or equipment that create the subsystems, which includes the material, processes and transport required. For the operation phase the energy consumption is taken into account. The decommissioning phase takes the dismantling of the system, the transport of the waste material and final disposal to the landfill (excluding the consideration of recycling the material). The flow diagrams of all the individual components are shown in detail in appendix K.

Table 4.2: Summary bill of materials

Component	Part	Material	Mass [kg]
Condenser	Column	Polymethyl methacrylate (PMMA)	337
	Packing	Stainless steel 304	3782
	Nozzles	Stainless steel 316	20
Heat exchanger	Plate material	Titanium	217
	Frame material	Carbon steel S355J2+N	606
	Gasket material	NBR	25
Water pump	Seawater pump	RG10 bronze	185
	Fresh water pump	GJL-250 cast iron	185
	Motor (2x)	Cast iron	246
Ventilator	Casing	Steel hot dip galvanized	168
	Impellers	Steel hot dip galvanized	48
	Motor	Carbon steel 40 Cr	216
	Flanges and mounting	Steel hot dip galvanized	48
Water storage	Water tank	High density polyethylene (HDPE)	178

4.2.1. General manufacturing

It is often very difficult to collect specific data from manufacturers about the manufacturing process. Ecoinvent, one of the leading life cycle inventory databases, has created general manufacturing data based on real metal manufacturing data. Therefore, for most components these type of data are used. For the general manufacturing of metal products three different input data are considered: metal working factory operation, metal working machine operation and metal product manufacturing [17].

Energy and auxiliary inputs, metal working factory operation

This dataset includes ancillary processes to operate a metal working factory. Electricity for lighting and general water consumption are included processes. The heat energy is from average sources. The data is an estimation based on the average consumption of factories separated into process specific and ancillary processes. Obtained from several local to global sized companies with the main focus on Germany and Europe, expecting to cover the whole range of metal working.

Energy and auxiliary inputs, metal working machine operation

This dataset includes the materials, energies and emissions related to the machines used for machining metal products. This is mainly electricity, compressed air and solvents, where the process heat is from average sources. The data is an estimation based on the average consumption of factories into process specific, where the ancillary processes are included in the metal working factory operation data. Again the data are from several local to global sized companies, with the main focus on Germany and Europe, expected to cover the whole range of metal working.

Metal working, average for metal/steel/chromium product manufacturing

The included processes for this dataset are the manufacturing processes to make a semi-manufactured prod-

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[1] The detailed inventory list is available on request. Due to the many extra pages this will add to the thesis, it is not included in this report.

uct into a final product. The average values for the processing by machines as well as the factory infrastructure and operation are included. Furthermore, an additional metal/steel/chromium input is considered for the loss during processing. Degreasing is not included and has to be added if necessary. The data is an estimation based on the average consumption of factories separated into process specific, where the ancillary processes are included in the metal working factory operation data. The data is an average of mostly European companies from several local to global size and their production technologies.

4.2.2. Transport

For the transport of all the components it is assumed that they will be transported from the harbor Rotterdam, in The Netherlands, to the harbor Willemstad, in Curacao. This distance is approximately 8000 km (8 tkm) and is covered by a sea transoceanic freight ship. The dataset represents the entire transport life cycle including the production, operation and maintenance of the ship and the construction of the port. The data of the port represents the conditions at the port of Rotterdam. This ship is able to transport goods with a tank size of 50 000 dwt (deadweight tonnage) on an average of slow speed between steam turbine (5%) and diesel engine (95%) propulsion, with heavy fuel oil usage. The exhaust emissions from marine diesel engines comprise CO_2, CO, SO_x, NO_x and partially reacted and non-combusted hydrocrabons and particles. Metals and organic micro-pollutants are emitted in very small quantities [17].

The transport on the island is assumed to be in a freight lorry of 16-32 metric ton, which can transport a container. The distance from the harbor to the airport is approximately 15 km. For the transport on land a freight lorry of 16-32 metric ton is assumed to be used. The transport of all the components from their manufactures in Europe and the rest of the world to the harbor in The Netherlands is set to 85 km in total. The transport on the island from the harbor to the airport is approximately 15 km. In total an average transport of 100 km (0.1 tkm) is done with this freight lorry.

4.2.3. General electricity data

For the energy consumption, which the system uses during the operation phase, the UPCTE B250 energy data is used. This is chosen since the LCA of RO also uses this type as the energy source. Therefore the comparison will become much more reliable and easier. The UCPTE (Union for the Coordination of Production and Transmission of Electricity) data represents the primary sources of European electricity production system and transport, excluding the infrastructure of the energy systems. The medium voltage energy has an average efficiency of 31% (including 1.8% grid losses) built up from: 43% thermal orgin, 40% nuclear orgin and 17% hydropower origin [17, 52]. The flow diagram is given in figure 4.1.

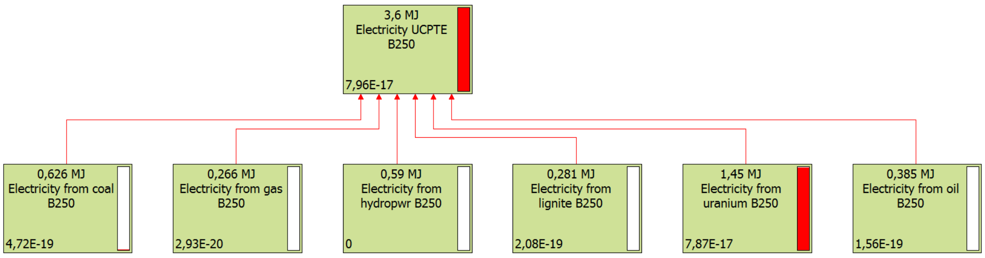


Figure 4.1: The flow diagram of the selected general energy process UCPTE, obtained with normalized impact category abiotic depletion of CML.

5

Impact Assessment

The impact assessment with the relevant impact category results of the different evaluation methods are presented in this chapter. As already discussed in the previous chapters these results are obtained from the model built in SimaPro 8.1, for more details about the model see chapters 3 and 4. In section 5.1 the characterized and normalized results are given of the evaluation method CML-IA baseline (CML). All the impact categories with a relevance of less 0.2% are not considered, as well for Eco-indicator 99 (EI 99), for more details see chapter 2. For the evaluation methods EI 99 and Ecopoints 97 (Eco 97) the characterized and weighted results are presented in section 5.2 and 5.3, respectively. For EP 97 all impact categories with less that 1.0% of the total impact are neglected.

5.1. CML-IA baseline

The characterized values of the different impact categories are presented in table 5.1. By analyzing the model with the environmental data in SimaPro, the result is that for each impact category a certain amount of a substance is given. This is divided into the three phases of the OTWP system: installation, operation and dismantling. Observe that for all the impact categories the values of the installation phase are the highest, followed by the operation phase. The lowest values are found in the dismantling phase. Since these values are not comparable between the different impact categories, normalization is done.

Table 5.1: Environmental impact results of the general model from CML-IA baseline method

Impact category	**Unit**	**Installation**	**Operation**	**Dismantling**	**Total**
Abiotic depletion	kg Sb eq	$8.54\cdot10^{-1}$	$1.48\cdot10^{-3}$	$2.13\cdot10^{-4}$	$8.56\cdot10^{-1}$
Abiotic depletion (fossil fuels)	MJ	$8.07\cdot10^{5}$	$1.95\ \cdot10^{5}$	$2.87\cdot10^{3}$	$1.01\cdot10^{6}$
Global warming (GWP100a)	kg CO_2	$6.48\cdot10^{4}$	$1.58\cdot10^{4}$	$4.17\cdot10^{3}$	$8.47\cdot10^{4}$
Human toxicity	kg 1,4-DB[1]	$1.20\cdot10^{5}$	$2.21\cdot10^{3}$	$2.33\cdot10^{3}$	$1.24\cdot10^{5}$
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	$5.93\cdot10^{4}$	$9.34\cdot10^{2}$	$1.78\cdot10^{4}$	$7.81\cdot10^{4}$
Marine aquatic ecotoxicity	kg 1,4-DB	$1.39\cdot10^{8}$	$1.22\cdot10^{7}$	$9.63\cdot10^{6}$	$1.61\cdot10^{8}$
Acidification	kg SO_2	$6.93\cdot10^{2}$	$1.07\cdot10^{2}$	1.05	$8.01\cdot10^{2}$

In figure 5.1 the normalized values of the impact categories are presented. In appendix J the specific data is given as a reference, since it can be difficult to read the exact numbers from this figure. The installation phase represents for 86.6% the environmental impact. It can be observed that the operation and dismantling phases are much smaller compared to the installation phase with 7.1% and 6.3%, respectively. The largest impact category is the marine aquatic ecotoxicity with 89.6%. Followed by the impact categories human toxicity and fresh water aquatic ecotoxicity with 5.2% and 3.6%, respectively. The lowest impact on the environment is caused by the impact category global warming with 0.2%.

Notice that the percentages within the different phases of the system are not all descending. For the impact category global warming the installation and dismantling phase both are 0.2% in their phases, whereas for the operation phase this is increased to 0.6%. The impact category abiotic depletion has a total impact

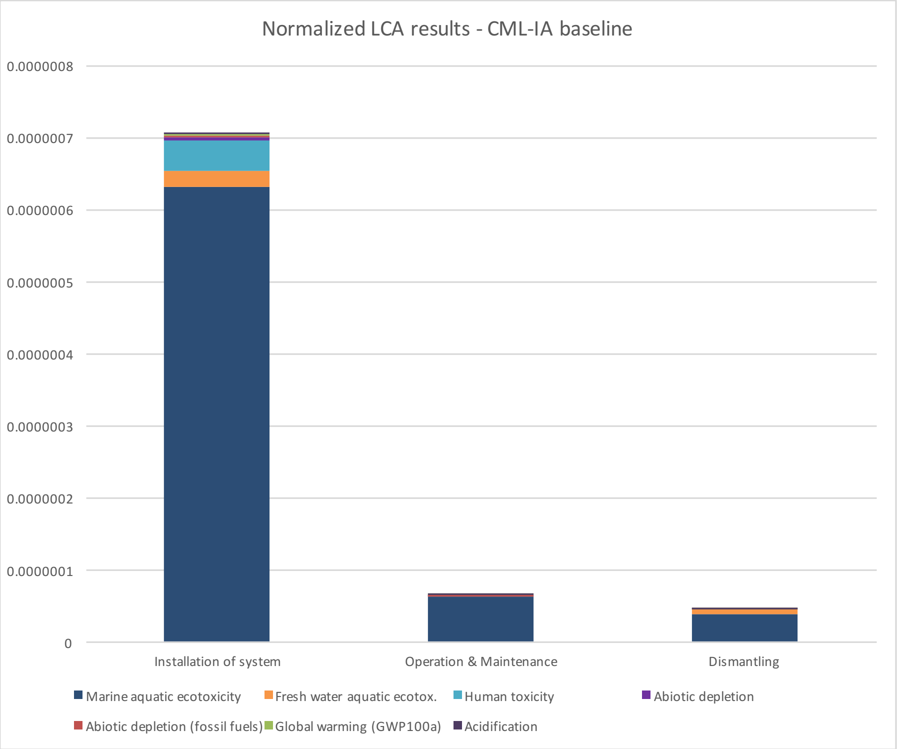


Figure 5.1: Normalized results of LCA with CML-IA baseline normalization World 2000.

of 0.5%, which is all in the installation phase. The impact category abiotic depletion (fossil fuels) represents for 0.2% of the impact in the installation, 0.8% during operation, a negligible percentage for the dismantling phase and in total the impact is responsible for 0.3%. For 0.4% of the total impact acidification is representing, which is for 0.4% in the installation phase and 0.7% during the operational phase, again with a negligible percentage for dismantling. The dominant three impact categories during the installation phase are marine aquatic ecotoxicity (89.5%), human toxicity (5.8%) and fresh water aquatic ecotoxicity (3.1%). The impact category fresh water aquatic ecotoxicity has a relatively low impact during the operational phase (0.6%) but high during the dismantling phase (12.6%). For the impact category marine aquatic ecotoxicity this increase during operation to 95.8% and decreases for the dismantling phase to 85.0%. The impact category human toxicity stays more constant, with 1.3% during operation and 1.5% for dismantling.

5.2. Eco-Indicator 99

The impact category results for the Eco-indicator 99 (EI 99) are calculated with the hierarchist perspective, for the agrumentation see appendix B. The characterized results are presented in table 5.2. Also for this evaluation method for most impact categories the results are the highest for the installation phase of the system, followed by the operational and the dismantling phase. Notice that for the impact categories carcinogens and ecotoxicity this is not the case, here the operational phase has the lowest results. Another remarkable observation is that the values for the operation and dismantling phases are relatively low compared to the installation phase for the impact category minerals.

After the characterized results normalization and weighting is done. The results of the weighted impact categories are given in appendix J. In figure 5.2 these results are presented in graphs for the different phases of the system. It can be observed that the largest impact is during the installation phase (84.8%), followed by the operational phase (9.2%) and the lowest phase (6.0%) is during the dismantling. In total the largest contribution is with 35.5% the impact category respiratory inorganic, followed by the carcinogens with 23.8%. The lowest environmental impact with 1.0% is the impact category acidification/eutrophication.

Within the different phases the largest contributor to the environmental impact varies for the impact

Table 5.2: Impact category results obtained from Eco-Indicator 99.

Impact category	**Unit**	**Installation**	Operation	**Dismantling**	**Total**
Carcinogens	DALY	$4.80 \cdot 10^{-2}$	$1.59 \cdot 10^{-3}$	$1.13 \cdot 10^{-2}$	$6.08 \cdot 10^{-2}$
Resp. inorganics	DALY	$8.13 \cdot 10^{-2}$	$9.29 \cdot 10^{-3}$	$1.93 \cdot 10^{-4}$	$9.07 \cdot 10^{-2}$
Climate change	DALY	$1.35 \cdot 10^{-2}$	$3.28 \cdot 10^{-3}$	$7.21 \cdot 10^{-4}$	$1.75 \cdot 10^{-2}$
Ecotoxicity	PAF·m^2·yr	$9.21 \cdot 10^{4}$	$3.84 \cdot 10^{3}$	$1.86 \cdot 10^{4}$	$1.15 \cdot 10^{5}$
Acidification	PDF·m^2·yr	$1.45 \cdot 10^{3}$	$2.64 \cdot 10^{2}$	6.70	$1.72 \cdot 10^{3}$
Minerals	MJ Surplus	$3.40 \cdot 10^{4}$	$1.72 \cdot 10^{1}$	5.39	$3.40 \cdot 10^{4}$
Fossil fuels	MJ Surplus	$6.58 \cdot 10^{4}$	$1.46 \cdot 10^{4}$	$3.66 \cdot 10^{2}$	$8.08 \cdot 10^{4}$

categories. For the installation and operation this is the impact category respiratory inorganics, with 37.4% and 39.3%, respectively. Whereas for the dismantling phase is shifts to the impact category carcinogens with 73.9%. The impact category carcinogens contributes for 22.1% to the environmental impact in the installation phase and for 6.8% to the operation phase. The impact category respiratory inorganics only contributes for 1.3% to the dismantling phase.

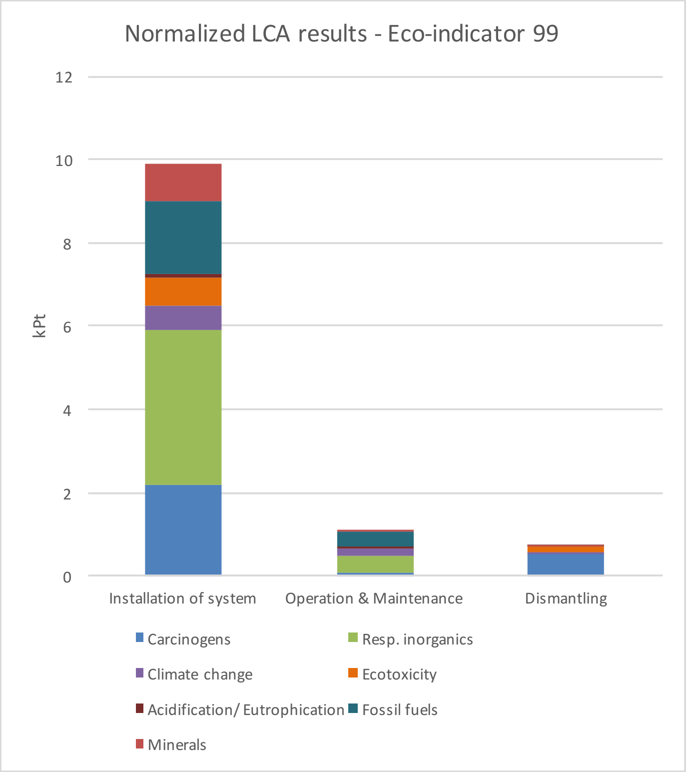


Figure 5.2: Weighted results of impact categories obtained through Eco-indicator 99.

The impact category climate change represents for a total percentage of 6.8% the environmental impact, which scores as the second lowest impact category. Notice that the largest percentage is found in the operational phase with 13.9%, while the other two phases installation and dismantling have lower percentages 6.2% and 4.7%, respectively. The overall environmental impact percentage of the impact category ecotoxicity is 6.9%. In the installation phase this has a contribution of 6.5%, in the operation phase of 2.5% and for the distmantling phase 18.6%. Ecotoxicity plays the second largest role in the dismantling phase. The total impact percentage of the impact category mineral is 7.7%, all of which is in the installation phase for 9.1% and the other phases have negligible impact. The last impact category is fossil fuels and is responsible for 18.3% of the environmental impact. For which is 17.6% present in the installation phase, 35.8% in the operation phase (second largest) and only 1.4% in the dismantling phase.

5.3. Ecopoints 97

The Ecopoints 97 (Eco 97) method makes it possible to weight environmental impacts within the context of a LCA. Hence, the representation of the environmental impacts are in the amount of certain particles, see table 5.3. The impact categories that contribute less than 1.0% are not included. Most impact categories have the highest numbers in the installation phase, followed by the operational phase and the lowest values in the dismantling phase. This hold not for the particles that emit their emissions to water and the impact category waste. Here the values in the operational phase are lower than that of the dismantling phase.

Table 5.3: Impact categories emissions obtained from Ecopoints 97.

Impact category	Unit	Installation	Operation	Dismantling	Total
NO_x	g	$1.49 \cdot 10^5$	$3.21 \cdot 10^4$	$1.06 \cdot 10^3$	$1.82 \cdot 10^5$
SO_x	g SO_2 eq.	$5.17 \cdot 10^5$	$7.79 \cdot 10^4$	$6.28 \cdot 10^2$	$5.95 \cdot 10^5$
NMVOC	g	$4.95 \cdot 10^4$	$1.12 \cdot 10^4$	$2.33 \cdot 10^2$	$6.09 \cdot 10^4$
Dust PM10	g	$7.06 \cdot 10^4$	$1.01 \cdot 10^3$	$1.17 \cdot 10^2$	$7.17 \cdot 10^4$
CO_2	g CO_2 eq.	$6.48 \cdot 10^7$	$1.56 \cdot 10^7$	$3.42 \cdot 10^6$	$8.39 \cdot 10^7$
Cd (air)	g	$1.80 \cdot 10^1$	$3.14 \cdot 10^{-1}$	$1.42 \cdot 10^{-2}$	$1.83 \cdot 10^1$
Zn (water)	g	$1.40 \cdot 10^4$	$1.79 \cdot 10^2$	$9.11 \cdot 10^3$	$2.33 \cdot 10^4$
Cu (water)	g	$7.11 \cdot 10^3$	$1.98 \cdot 10^2$	$1.00 \cdot 10^4$	$1.73 \cdot 10^4$
Cd (water)	g	$2.36 \cdot 10^2$	1.79	$1.52 \cdot 10^2$	$3.90 \cdot 10^2$
Hg (water)	g	6.38	$2.10 \cdot 10^{-1}$	$1.22 \cdot 10^1$	$1.88 \cdot 10^1$
Waste	g	$1.83 \cdot 10^7$	$1.27 \cdot 10^5$	$9.26 \cdot 10^6$	$2.77 \cdot 10^7$
LMRAD	g	$8.39 \cdot 10^2$	$1.86 \cdot 10^1$	2.68	$8.61 \cdot 10^2$
HRAD	cm^3	$1.27 \cdot 10^2$	1.86	$5.85 \cdot 10^{-1}$	$1.29 \cdot 10^2$
Energy	MJ LHV	$1.06 \cdot 10^6$	$3.87 \cdot 10^5$	$3.74 \cdot 10^3$	$1.45 \cdot 10^6$

After the characterized results normalization and weighting is done. The specific values of the weighted impact categories results are given in appendix J. The results of this are given in figure 5.3. Again the highest impact is found in the installation phase with 73.4%. The second highest impact is in the dismantling phase with 18.3%. The lowest impact is in the operational phase with 8.3%. The impact category with the overall highest percentage is SO_x with 22.7%, followed by Cu (water) with 15.0% and CO_2 with 12.1%. The lowest impact categories is energy with 1.0%.

Observe from figure 5.3 that for the installation phase the largest contribution to the environmental impact is emitted by the impact category SO_x, with 28.5%. The second largest impact category is CO_2 with 13.5%. The smallest impact category is energy with 1.1%. All the other impact categories contribute between the 10.4% and 1.6% to the environmental impact in the installation phase.

The largest blocks visible in figure 5.3 within the operation phase are the impact categories SO_x, CO_2 and NO_x with 38.0%, 28.8% and 19.8%, respectively. Smaller contributions to the environmental impact are coming from the impact categories energy, NMVOC, Cu (water) with 3.6%, 3.3% and 2.2%, respectively. All the other impact categories add for 1.0% or less emission to the environment in the operation phase.

Notice that for the dismantling phase consists of half (50.0%) of the environmental impact of the impact category Cu (water). The second largest emissions come from the impact category waste with 19.3%. The impact categories Hg (water), Zn (water) and Cd (water) are the other visible blocks in the figure with 12.2%, 8.0% and 7.0%, respectively. A very small block still visible is from the impact category CO_2 with 2.8%. All the other impact categories contribute less than 1.0% or a negligible amount to the dismantling environmental impact.

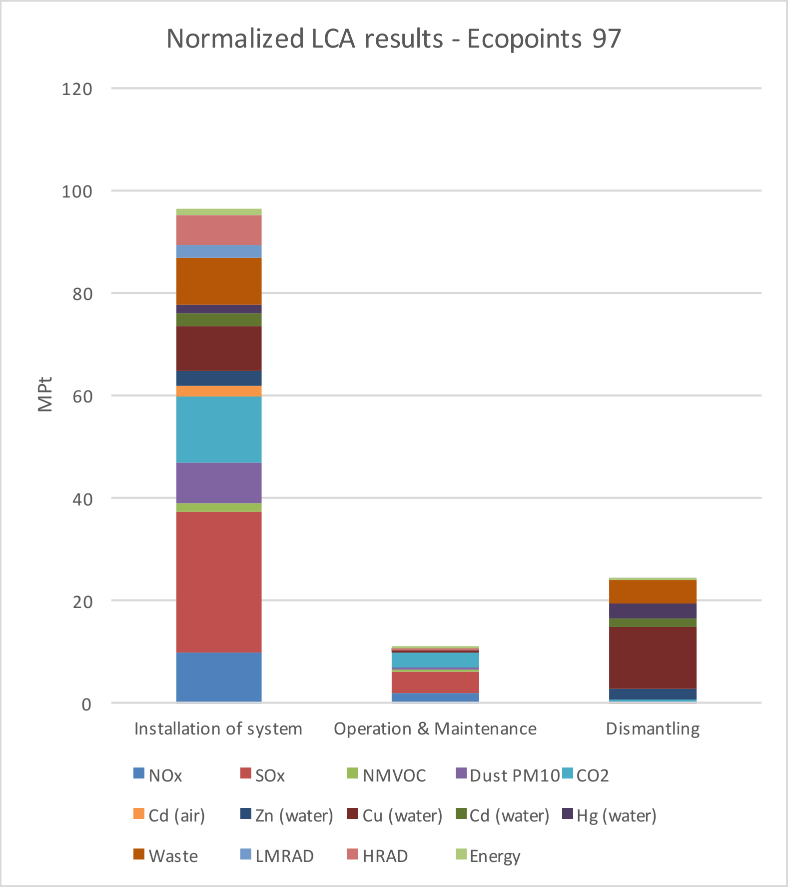


Figure 5.3: Weighted results of impact category emissions with Ecopoints 97.

5.4. Conclusions of the impact assessment

This impact assessment is done for the three evaluation methods: CML-IA baseline, Eco-indicator 99 and Ecopoints 97. Several relevant impact categories are assessed and presented in the sections above. This is done for the characterized results in tables and in figures for the normalized and weighted results. The details on these normalization and/or weighting values can be found in appendix J. This impact assessment is divided into three phases of the system: installation, operation and dismantling. For all the evaluation methods the highest environmental impact is found in the installation phase. For the evaluation methods CML and EI 99 the second highest impact is in the operational phase and the lowest in the dismantling phase. For Eco 97 these two phases are reversed. In table 5.4 these observation are expressed in the corresponding percentages. For more detail, see the corresponding sections of this chapter.

Table 5.4: The system phases expressed in their percentages obtained from the evaluation methods.

	CML	EI 99	Eco 97
Installation [%]	86.6	86.4	73.4
Operation [%]	7.1	8.0	8.3
Dismantling [%]	6.3	5.6	18.3

6

Interpretation of LCA

In this chapter the interpretation of the LCA is presented, which is the last phase of the LCA. After the focus of the research is set in the goal and scope definition, the data are collected in the inventory analysis and the calculations are made in the impact assessment, evaluation, analysis of these results and the conclusions and recommendations are made. In section 6.1 the contribution analysis of the life cycle phases as well as the different components are presented. The sensitivity analysis of the energy consumption is given in section 6.2. The comparison of the OTWP system with the RO plant is given in section 6.3. The last section of this chapter 6.4 shows the comparison between the energy sources of OTEC and general electricity.

6.1. Contribution analysis

The contribution analysis divides the results of the LCA into contributing processes. In this way it becomes clear how much a certain component or phase contributes to the life cycle. From this perspective specific possible improvements can be applied. The contribution analysis is divided into two different analysis: the life cycle phases in subsection 6.1.1 and the component analysis in subsection 6.1.2.

6.1.1. Life cycle phases contribution analysis

From the impact assessment results in chapter 5 it is concluded that the installation phase for all the three evaluation methods the largest impact on the environment causes, with an average of 82.1%. The installation phase is built up from the extraction of the raw material, the manufacturing of the subsystems and the transport of the entire system overseas. The raw materials including the manufacturing processes are the most important factor.

The environmental impact of the operation phase is much lower than that of the installation phase, with an average of 7.8% of the three evaluation methods. Therefore, this phase is considered as the phase with the lowest environmental impact. This is caused by the low energy consumption of the system ad well as the low maintenance it requires. The maintenance takes into account the repair of the gasket for the heat exchanger and the replacement of the water tank. Both are happening twice in the lifetime of the system. These replacement do contain the extraction of raw materials, manufacturing and transport.

Table 6.1: The system phases expressed in their percentages obtained from the evaluation methods.

	CML	**EI 99**	**Eco 97**	**Average**
Installation [%]	86.6	86.4	73.4	82.1
Operation [%]	7.1	8.0	8.3	7.8
Dismantling [%]	6.3	5.6	18.3	10.1

The dismantling phase has on average a higher environmental impact than the operation phase but lower than the installation phase, with 8.9%. For the dismantling phase only landfill is considered, without any form of recycling. Therefore, it can be concluded that if recycling of certain components will be considered in the future, the impact will become even lower. In table 6.1 the different phases of the OTWP are expressed in their percentage by the different evaluation methods.

From the observations in chapter 5 of the evaluation method Ecopoints 97 it is interesting to make a distinction between two sorts of emissions: relevant airborne emissions and heavy metal emissions in water. These two categories of emissions are together responsible for 85.4% of the environmental impact.

The relevant airborne emissions are NO_x, SO_x, NMVOC, Dust and CO_2. During the installation and operation phase these emissions contribute for 62% and 91% to the environmental impact, respectively. With a 3.4% for the dismantling phase it hardly plays a role in the impact. Therefore, it is interesting to demonstrate what the emissions are per produced m^3 water by the OTWP system. The water production of the OTWP is set to 20.7 m^3 on a daily basis, including an availability of 95.8% over a lifetime of 30 years. There will be 226665 m^3 water produced in its lifetime. The relevant airborne emissions are in table 6.2 presented in mass per m^3 fresh water produced.

Table 6.2: Relevant airborne emissions produced by the OTWP

Impact category	**Unit**	**Installation**	**Operation**	**Dismantling**	**Total**
NO_x	g/m^3	$6.57 \cdot 10^{-1}$	$1.42 \cdot 10^{-1}$	$4.67 \cdot 10^{-3}$	$8.04 \cdot 10^{-1}$
SO_x	g/m^3	2.28	$3.44 \cdot 10^{-1}$	$2.77 \cdot 10^{-3}$	2.63
NMVOC	g/m^3	$2.18 \cdot 10^{-1}$	$4.93 \cdot 10^{-2}$	$1.03 \cdot 10^{-3}$	$2.68 \cdot 10^{-1}$
Dust PM10	g/m^3	$3.11 \cdot 10^{-1}$	$4.46 \cdot 10^{-3}$	$5.16 \cdot 10^{-4}$	$3.16 \cdot 10^{-1}$
CO_2	kg/m^3	$2.86 \cdot 10^{-1}$	$6.90 \cdot 10^{-2}$	$1.51 \cdot 10^{-2}$	$3.70 \cdot 10^{-1}$

The heavy metal emission group consist out of Cu (Copper), Cd (Cadmium), Hg (Mercury), Zn (Zinc) and for this analysis also the impact category waste is included, due to the relevant impact this category has. Environmental impact of these particles is due to the emissions into surface water through erosion of soil particles and leaching to ground water [44]. This group is contribution for 96.5% to the dismantling phase. A smaller contribution with 25.7% is in the installation phase and with 3.8% hardly any impact in the operation phase. Since the largest contribution is present in the dismantling phase and for this phase a 100% landfill is assumed, this phase needs more investigation into the influences of recycling of components and no further elaboration is done on this group.

6.1.2. Components contribution analysis

For the contribution analysis of the components only one impact category is used. This is done to simplify this analysis, since there is a lot of data available from the impact assessment, as is observed in chapter 5. This will give a clear overview of what the influences are of the different components, but keep in mind that this will vary slightly per impact category. The global warming (GWP100a) impact category is selected, since internationally the most focus is always laid on this subject. The different greenhouse gas emissions are converted to CO_2 equivalents, which represents the impact of human emissions on the radiative forcing of the atmosphere.

By analyzing each component separately the identification of hot-spots for the component will be revealed. In this way potential improvements within the component can be suggested. Figure 6.1 shows the cumulative contribution of each component in percentages for the different phases and all combined with and without the input of OTEC energy. For the installation phase the condenser is considered as the component with the highest influence on the environmental impact, over more than 40%. During operation the ventilator and two pumps are consuming energy. The heat exchanger and water tank require maintenance, which is included in the operation phase. If the electricity is generated by the OTEC system the energy consuming components have a smaller impact on the environment, due to the fact that the global warming impact category of 1 kWh of OTEC system is smaller that that of general electricity (UPTCE). The LCA values from the 10 MW OTEC system are obtained from the LCA study of Aalbers [2]. For the dismantling phase holds that the condenser plays again the larges role in the environmental, because of the relatively large mass it requires compared to the other components. The three phases are added together and form the entire life cycle of the system. This is done for the system that operates with general electricity and with OTEC energy.

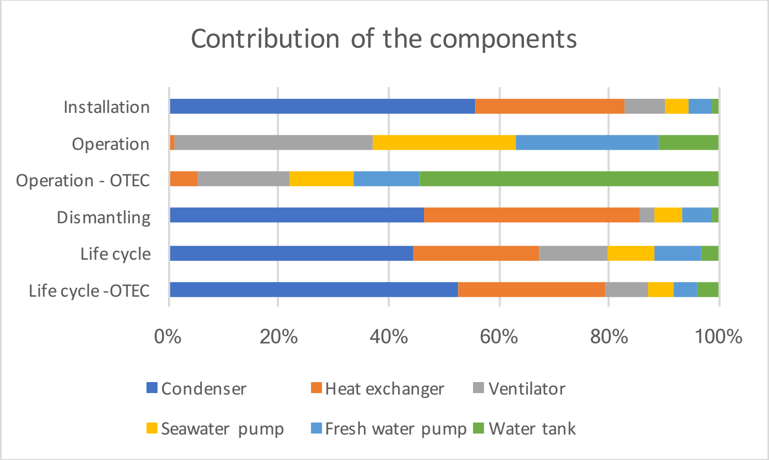


Figure 6.1: Cumulative contribution of the different components of the OTWP system representing the global warming impact category.

Condenser

Figure 6.2 shows the contribution in percentage of the different processes that represent the condenser. The largest two contributions are from the packing of the condenser with 42% and the metal working product manufacturing for chromium with 28%. The mass of the packing is relatively large compared to the mass of the other components, e.g. a factor 11 more than the mass of the column, hence this is way its contribution is large. This also explains why the metal working product manufacturing process contribution is higher. This process takes into account the mass of the packing (and nozzles). Hardly any impact is given by the nozzles, thermoforming and transport. These processes are contributing 0%, since there individual values are relatively low (but not zero) to the other processes.

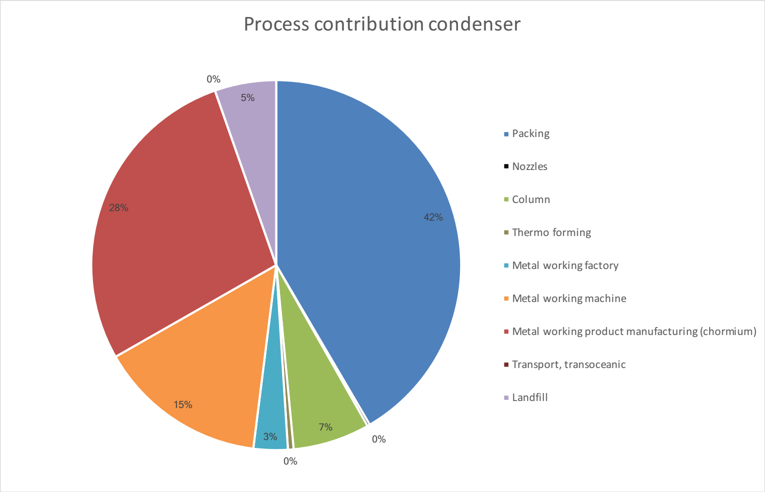


Figure 6.2: Contribution of condenser processes representing the global warming impact category.

Improvements on the packing of the column will minimize the environmental impacts. Now random packing design is assumed during the system engineering phase, but looking at another form of using packing regarding a light weighted design is beneficial to reduce the impact. Once this is achieved automatic improvements on the metal working product manufacturing, machine and factory will follow, since the largest input of these processes is the mass of the packing. A recommendation on the metal working processes should also be mentioned, for this model the average processes are selected due to lack of more specific data. It might be that the average data results in higher or lower impact because new technologies on packing manufacturing is not included in average data. When this specific data on manufacturing of the packing will be used in the model, this will improve the accuracy.

Heat exchanger

In figure 6.3 the heat exchanger process contribution is presented. The largest process contribution is the plate material of the heat exchanger, with 67%. These plates are made out pf titanium, which is an energy intensive production process and therefore has a high environmental impact. Due to the 100% landfill assumption, the landfill process also has a relatively high environmental impact, with 9%. The frame material contributes for 6% to the environmental impact of the heat exchanger in the global warming impact category. To manufacture the heat exchanger the metal working factory, machine and product manufacturing are assumed to be necessary. Together there processes contribute for 17%. The maintenance only contributes for 1%, which contains gasket material, the manufacturing process and transport twice for the replacement during the lifetime. Transport and gasket material have the smallest contributions both with 0%.

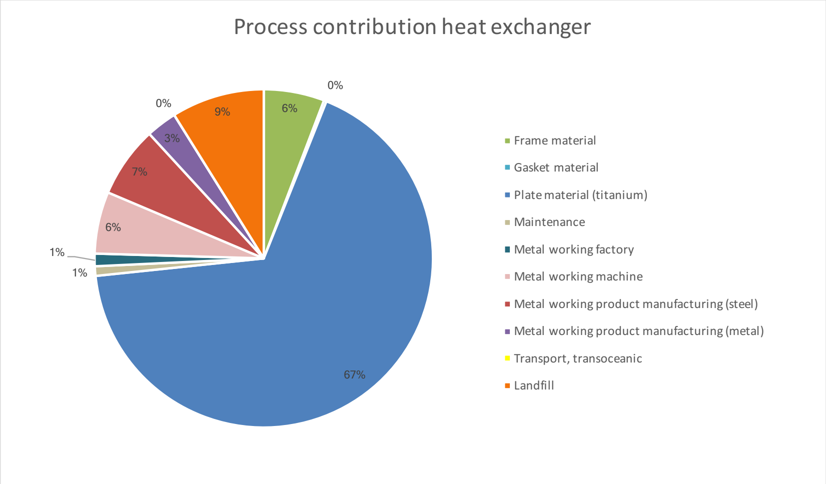


Figure 6.3: Contribution of heat exchanger processes representing the global warming impact category.

Water tank

Figure 6.4 presents the process contribution of the water tank. The material usage of high density polyethylene has the highest environmental impact with 37% compared to the other process contribution of the water tank. The lowest with 0% is the transport. The other large contribution is the manufacturing process blow moulding and the assumed metal working machine.

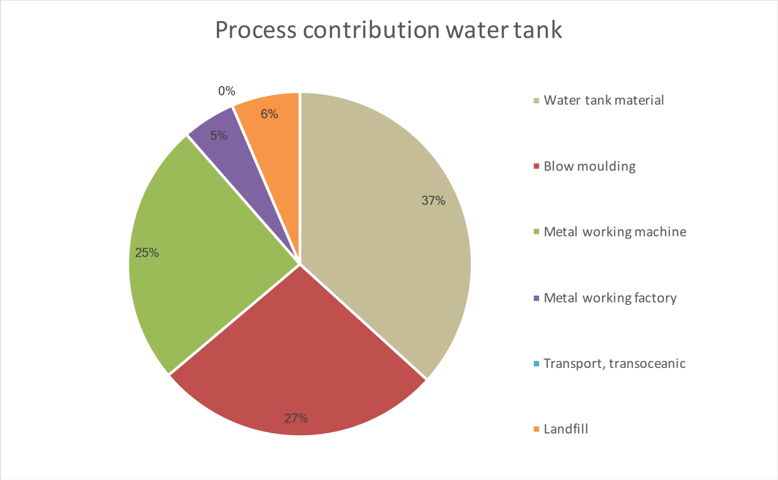
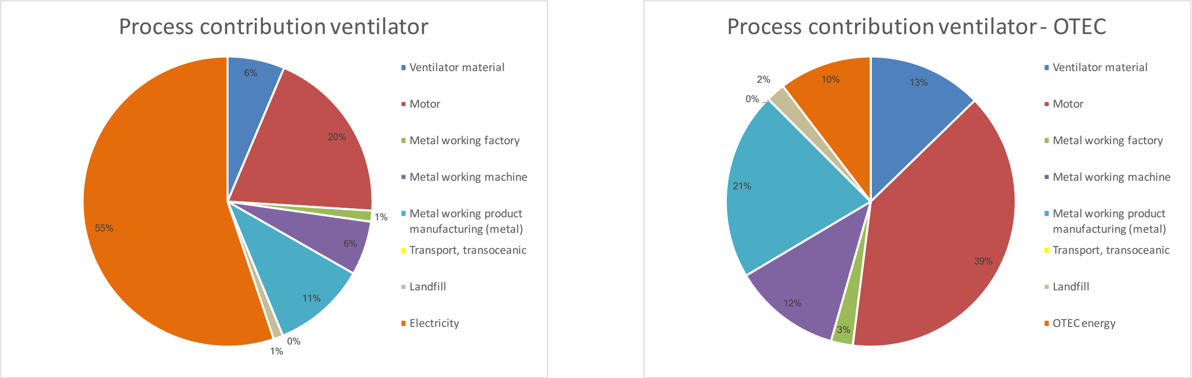


Figure 6.4: Contribution of water tank processes representing the global warming impact category.

Ventilator

The process contribution of the ventilator is shown in figure 6.5a. The energy consumption has the largest contribution with 56%. Followed by the carbon steel motor with 20%. The smallest processes are transport with 0% and metal working factory and landfill with both 1%.



(a) Contribution of ventilator processes representing the global warming impact category.

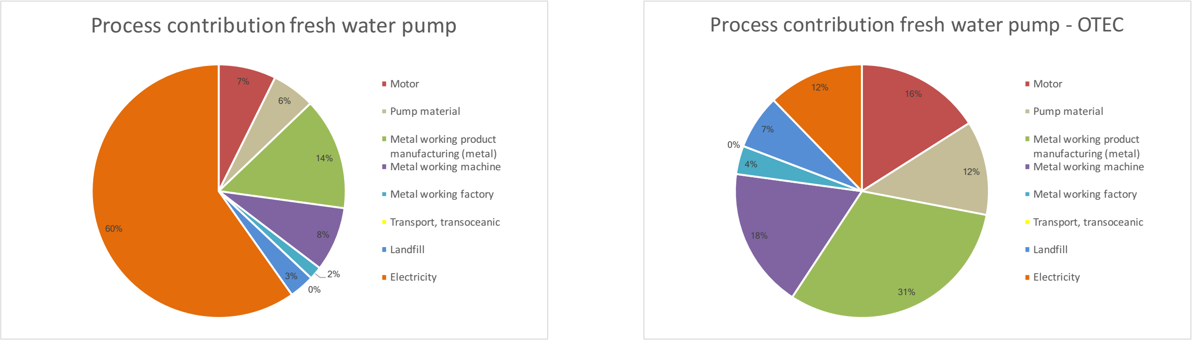
(b) Contribution of ventilator processes representing the global warming impact category OTEC

Figure 6.5: Process contribution of ventilator with different energy sources

In figure 6.5b the contribution processes are shown when the energy consumption is delivered by the OTEC system. Now a large decrease for the contribution of the electricity is present. This process only contributes now for 10% to the environmental impact of the ventilator. The largest process contribution is the motor with 39%. Followed by the manufacturing with 21% and the ventilator material with 13%. From this it can be concluded that the material carbon steel causes for a much higher environmental impact that that of the ventilator material galvanized steel. The mass difference between those two only differ with a factor 1.22 and the environmental impact difference is 18%.

Water pumps

In figures 6.6a and 6.7a the process contribution of the fresh water pump and seawater pump are given, respectively. The only difference in these two pumps is the pump material, the fresh water pump is made out of cast iron and the seawater pump out of bronze. The energy consumption contains the largest part of the environmental impact for the impact category global warming, for both pumps this is around 60%. Followed by the manufacturing of the pumps with 14%. The smallest and negligible contribution is caused by the transport overseas.

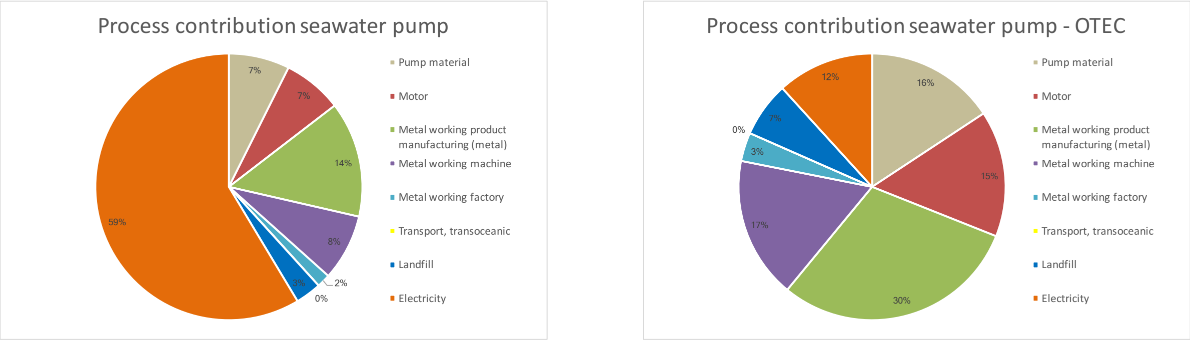


(a) Contribution of fresh water pump processes with general electricity as input.

(b) Contribution of fresh water pump processes with energy input of the OTEC system.

Figure 6.6: Process contribution of fresh water pump representing the global warming impact category with different energy sources.

Interesting to see is that if the energy is coming from the OTEC system, instead of the general energy process, the contribution for the pumps undergoes great change. This is shown in figures 6.6b and 6.7b for the fresh water and seawater pump, respectively. Now the electricity is only contributing for 12% to the environmental impact. The largest contribution is then caused by the manufacturing process of the pumps. The pump material for the fresh water pump contributes for 12%, against the 16% of that of the seawater pump. Meaning that the use of bronze material has a higher environmental impact then the use of cast iron.



(a) Contribution of seawater pump processes with general electricity as input.

(b) Contribution of seawater pump processes with energy input of the OTEC system.

Figure 6.7: Process contribution of seawater pump representing the global warming impact category with different energy sources.

6.2. Sensitivity analysis

This sensitivity analysis addresses parameter variations for uncertainties in data, assumptions and choices. It this way the influence of changes in data can be studied in more detail. The input energy consumption of the system has a high uncertainty and the sensitivity of this output to the change is analyzed and how this contributes to the LCA in subsection 6.2.1.

6.2.1. Energy consumption of pumps

During the operational phase of the OTWP system, the pumps and ventilator consume energy. The daily energy consumption is estimated to 2.77 kWh for the production of 20.7 m^3 water for the lifetime of 30 years. This results in 0.134 kWh/m^3 but is very low compared to the technology of current RO plants in operations, which is around 4 kWh/m^3. Therefore, there is an uncertainty in the assumed energy consumption used for the operational phase of the OTWP system, since the system is excluding the integration of the system (see chapter 3 for the made assumptions). In order to investigate the sensitivity the energy consumption of 1, 2 and 4 kWh/m^3 are used. The operation phase for the different energy consumption is analyzed and description below per evaluation method. Since the installation and dismantling phase are constant it is not relevant to include these values here, see chapter 5 for the total scores.

In figure 6.8 the overview of the operation phase scores for the different energy consumptions is presented by the evaluation methods CML. The higher the energy consumption the higher the environmental impact will be. Increasing the energy consumption from 1 to 2 kWh/m^3, will increase the total impact with a factor of 1.969, which is almost double the amount in the environmental impact. When doubling the energy consumption from 2 to 4 kWh/m^3 the environmental impact is also almost doubled, with a slightly higher factor of 1.984. From this it can be concluded that the higher the energy consumption of the system, the higher the influence will be on the environmental impact in a negative way.

Table 6.3: Output change on the entire LCA of the different energy consumptions for the evaluation methods.

	Original to 1 kWh/m^3	**From 1 to 2 kWh/m^3**	**From 2 to 4 kWh/m^3**
CML [%]	41.7	34.0	50.7
EI 99 [%]	52.3	39.7	56.8
Eco 97 [%]	50.8	38.9	56.0

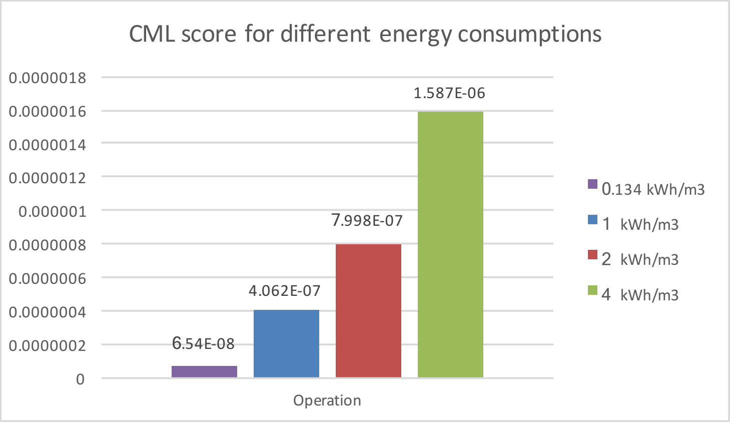
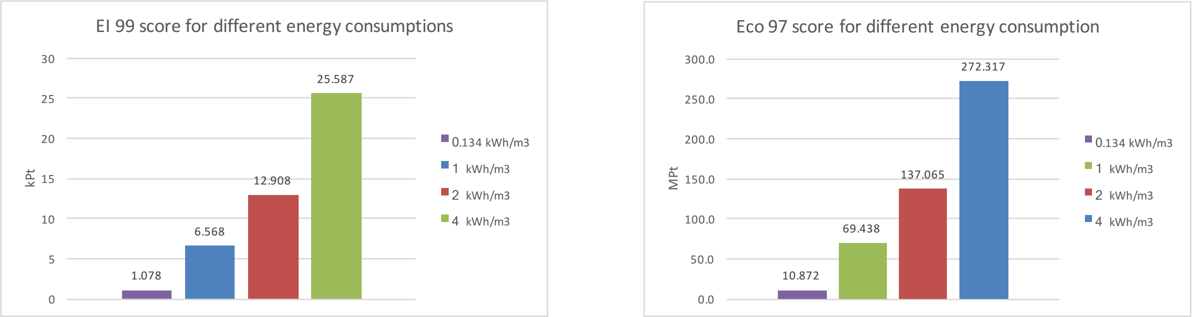


Figure 6.8: The operation phase normalized LCA scores for the different energy consumptions obtained from the evaluation method CML.

The same conclusions hold for the operation phase when analyzing this with the other evaluation methods, see figures 6.9a and 6.9b for the graphs of the EI 99 and Eco 97 methods, respectively. In table 6.3 the influences expressed in percentages are given for the entire LCA (including installation and dismantling) for the evaluation methods.



(a) Evaluation method EI 99.

(b) Evaluation method Eco 97.

Figure 6.9: The operation phase normalized LCA scores for the different energy consumptions obtained from the evaluation method EI 99 and Eco 97.

Table 6.4 shows the relevant airborne emissions of the OTWP for different assumed energy consumptions per m^3 water production. Doubling the energy consumption from 1 kWh/m^3 to 2 kWh/m^3 results in an increase of approximately 58% of the relevant airborne emissions. From 2 kWh/m^3 to 4 kWh/m^3 the development in these emissions is even higher with average of around 74%. Hence, the higher the total energy consumption the higher the environmental impact of the relevant airborne emissions is on the production of water. Notice that the impact category dust PM10 is not influenced by the different energy consumption inputs. This is due to the fact that this is an impact category that is not contributed by electricity [57]. It is clear that the sensitivity of the energy consumption plays a critical role. The lower the energy consumption, the lower the results of the impact categories and therefore better for the environment.

Table 6.4: Relevant airborne emissions produced by the OTWP for different energy consumption during the entire lifetime.

Impact category	**Unit**	**4 kWh/m^3**	**2 kWh/m^3**	**1 kWh/m^3**	**0.134 kWh/m^3**
NO_x	g/m^3	4.361	2.521	1.600	0.804
SO_x	g/m^3	11.642	6.978	4.646	2.627
NMVOC	g/m^3	1.316	0.774	0.503	0.268
Dust PM10	g/m^3	0.316	0.316	0.316	0.316
CO_2	kg/m^3	2.117	1.213	0.761	0.370

6.3. Comparison with Reverse Osmosis desalination

The relevant airborne emissions of the two water production systems, reverse osmosis and OTWP, are compared with each other in figure 6.10. The values of the RO plant are obtained from the study of Raluy et al. [52]. The RO plant operates on 4 kWh/m^3 desalted water, with a daily production of 45 000 m^3 and a lifetime of 25 years. For the current design of the OTWP, with an energy consumption of 0.134 kWh/m^3, a large different in reduction of the emissions can be concluded from the blue and orange graphs, with an average of 78.8%.

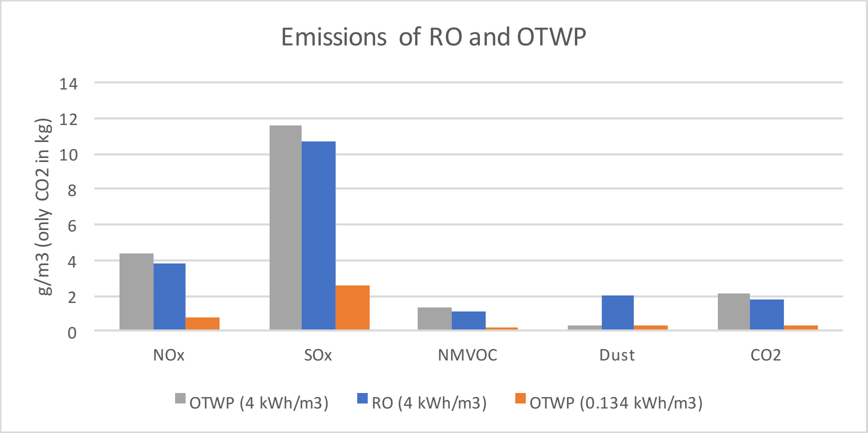


Figure 6.10: Relevant airborne emissions of RO plant and OTWP.

Since the energy consumption of these two systems vary, it is interesting to see the influences if the energy consumption would be equal. If the OTWP system operates with 4 kWh/m^3 produced water, all the emissions will have a higher environment impact then that of a RO plant, with the exception of dust. This holds for the gray and blue graphs in figure 6.10. The contribution from building materials to the impact category dust PM10 for electricity is zero [56]. Therefore, the changes in this category for the RO values should come from the use of energy recovery systems for RO to reduce the energy consumption. For the analysis of the OTWP system for different energy consumption values only the input of the energy consumption is changed. No other changes are made to the model in SimaPro. Therefore, it can be concluded that it is necessary to keep the energy consumption lower than the a RO plant. For within the current assumptions taken to create this LCA of the OTWP. One assumption taken is that the OTWP system produces the same quality of water as that of the RO plant. The RO plant uses chemicals to transform the desalted water into drinkable fresh water. Such chemicals are not included in the LCA for the OTWP system.

In figure 6.11 the emissions for a RO plant that consumes 2 kWh/m^3 (values again from the research of Raluy et al. [52]) and that of the OTWP system running on 2 and 1 kWh/m^3. Again the RO emissions are lower than that of the OTWP system for equal energy consumption. Hence, it can be concluded that for the same energy consumption the RO system has a lower impact on the environment for the relevant airborne emissions then that of OTWP. Therefore, the main goal of the OTWP system is to design the system in such a way that the energy consumption will always be lower than that of RO. Or design the system in such a way that less material is required that have large impact on the environment. The last can be a very difficult challenge since certain material needs to be used to avoid corrosion.

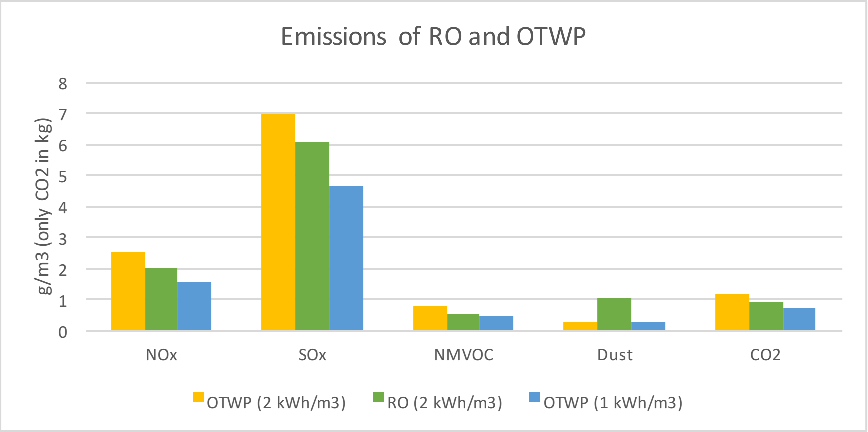


Figure 6.11: Relevant airborne emissions of RO plant and OTWP.

6.4. Comparison between OTEC and general electricity

The OTWP system is initially designed as one of the applications of the OTEC plant. This will operates in symbioses with and receives the required energy from the OTEC plant. From the contribution analysis in section 6.1 it is seen that there is a difference in the type of energy. This analysis is only made for one impact category global warming. To give a complete overview the influences of the different impact categories, the comparison between the impact assessment results of the general and OTEC energy is made. The general energy (UCPTE) contains the data that are used for the LCA of the pilot OTWP system and the OTEC energy data obtained from the LCA research of Aalbers [2]. Figure 6.12 shows the six relevant impact category results, which are all obtained with the evaluation method CML. Notice that the data of general electricity is excluding the construction of infrastructure the medium voltage electricity distribution (including cables, poles, buildings and transformers). The OTEC data does take into account the infrastructure of the OTEC system in order to be able to generate electricity.

Abiotic depletion

From graph 6.12a the impact category abiotic depletion is shown. Here there is an obvious difference in the amount of emissions. The OTEC energy is with approximately a factor 4 larger then the general energy. This is because this impact category abiotic resource depletion is divided into a category for elements and one for fossil fuels. The elements impact category ”is a hetrogeneous group, consisting of elements and compounds with a variety of functions (all functions being considered of equal importance)” van Oers et al. [63] and uranium. The other impact category fossil fuels includes energy carriers, like oil, natural gas and coal, which are assumed to be mutually substitutable and interchangeable for other applications [63]. The general electricity data is indeed split into these two impact categories, where the result of the elements are shown in figure 6.12a and for the abiotic depletion fossil fuels this value results in 5.02 MJ for 1 kWh electricity. For the OTEC results these two additional impact categories within the abiotic resources depletion is not considered. All the data is converted to kg Sb equivalent.

Global warming

The OTEC system does contributes in a positive way to the global warming aspect, see figure 6.12b. With a decrease of 95.8%, less CO_2 equivalent will be entering the atmosphere.

Human toxicity

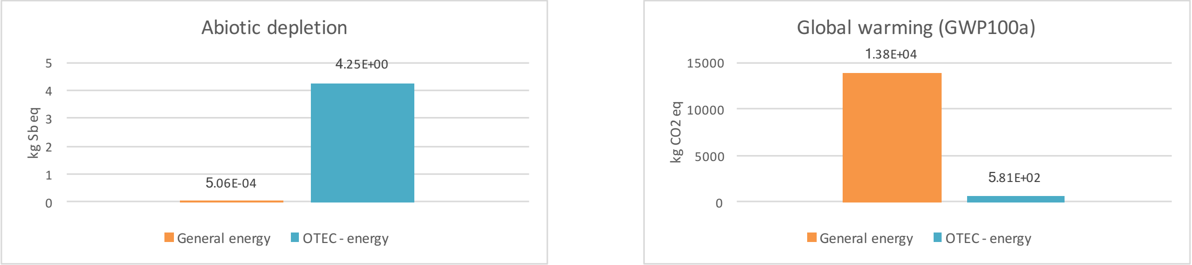
For the human toxicity impact category the general energy has a higher emission value than that of the OTEC energy, presented in figure 6.12c. This means that using OTEC energy will cause a 28.7% reduction on the environmental impact concerning human toxicity.

Ecotoxicity

The first relevant impact category that is grouped in the ecotoxicity is fresh water aquatic ecotoxicity. From figure 6.12d it is observed that the OTEC energy has a higher value that than of the general energy. Therefore, it can be concluded that for this specific impact category using OTEC energy is a larger burden to the environment, with 24.9%. The second ecotoxicity impact category is the marine aquatic ecotoxicity. Here there is a large difference between the use of OTEC and general energy, as shown in figure 6.12e. Using OTEC energy will cause a 93.3% reduction to this impact category. When normalizing the impact category results as seen in chapter 5, this specific impact category has a large influence on the environmental impact. Therefore, it can be concluded that for the ecotoxicity impact categories using OTEC is again an improvement on the environmental burdens.

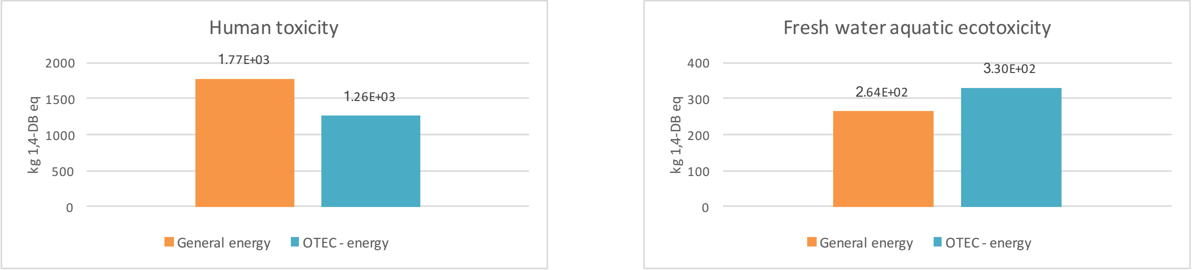
Acidification

In figure 6.12f the comparison within the acidification impact category is given. The OTEC system adds a positive contribution to the environmental emissions, with a decrease of 95.4% compared to the general energy.



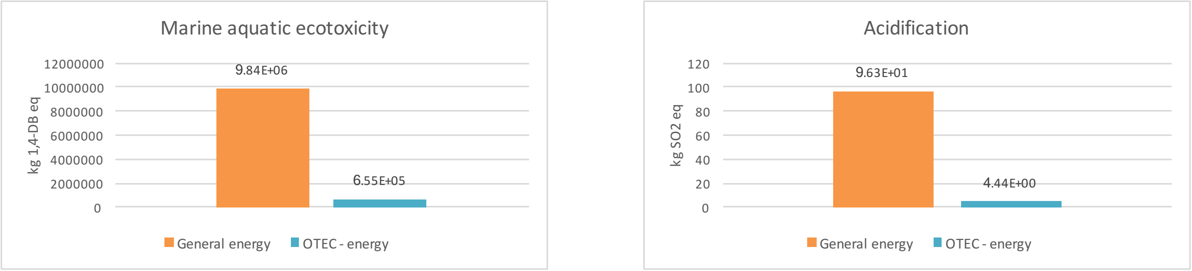
(a) Abiotic impact category

(b) Global warming impact category



(c) Human toxicity impact category

(d) Fresh water aquatic ecotoxicity impact category



(e) Marine aquatic ecotoxicity impact category

(f) Acidification impact category

Figure 6.12: Comparison between general and OTEC energy for the relevant impact categories of the OTWP system lifetime, for the evaluation method CML.

7

Upscaling the System

In this chapter the upscaled LCA of the system is presented. For this upscaled system the diameter of the condenser is doubled. From here other adjustments are made to make the design realistic, this is described in section 7.1. In section 7.2 the results of the impact assessment are shown, here the same methods and models are used as for the pilot OTWP system as described in detail in the previous chapters. Followed by the comparison between the upscaled system and a modular system of the pilot model as well as a comparison between the RO plant, in section 7.3.

7.1. System engineering

The upscaled OTWP system is build up by first focusing on the diameter of the condenser, this is doubled, from 3 m to 6 m. The height of the condenser stays the same as that of the pilot OWTP system, due to the fact that after 1 m the air becomes to dry for further water extraction. From these dimensions it follows that the volume will increase with a factor 4. Hence, the water production increases from 20.7 m^3 to 82.8 m^3 on a daily basis. The motivation behind the chosen upscaled system is to investigate the influences of the environmental footprint of the OTWP system. This is done with the assumption that such dimensions will be technical feasible. In reality, such an upscaling requires more that simply multiplying values. One should investigate the optimal integrated system performance, e.g. analyze the number and types of ventilators needed for optimal and efficient flow of the humid air entering into the condenser. Also it needs to be technical feasible, currently there is a doubt about the amount of air in combination with the pressure drop.

Heat exchanger

The specifications of the upscaled heat exchanger can be found in appendix L. This design is provided by the company Kapp Nederland [55]. The mass of the heat exchanger is approximately tripled.

Water tank

The water tank is assumed to have a volume of around 40 m^3 and made out of the same material as the original pilot OTWP system. For volumes of this size or larger it can become more beneficial to select different types and/or materials, but this is left out of the scope of this upscaling investigation. The mass of this upscaled water tank is more than 4 times the mass of the water tank of the pilot OTWP system [47].

Ventilator

The same principles as in chapter 3 are applied for the selection of a suitable ventilator. The type is SYH1600, which as the capacity of 400 000 m^3/h. The mass is 1820 kg, power 300 kW and an efficiency of 42%. This results in an energy consumption of 0.219 kWh/m^3. The fan exists of the casing, impeller, flanges and mounting. For the performance sheet of this ventialtor see appendix L.

Water pumps

The same principles as in chapter 3 hold for the water pumps. The water pumps have a capacity of 800 m^3/h, with a power of 84.1 kW and an efficiency of 80%. This results in an energy consumption of 0.0323 kWh/m^3. The pumps each have a mass of 480 kg. The 4-pole motor has a power of 90 kW with a mass of 638 kg. For the specifications of the pump see appendix L.

7.1.1. Inventory list

Table 7.1 summarizes the used materials and masses of the different components for the upscaled OTWP system.

Table 7.1: Summary of the materials used for the upscaled OTWP system.

Component	**Part**	**Material**	**Mass [kg]**
Condenser	Column	Polymethyl methacrylate (PMMA)	1347.89
	Packing	Stainless steel 304	15 126.77
	Nozzles	Stainless steel 316	36.92
Heat exchanger	Plate material	Titanium	595.36
	Frame material	Carbon steel S355J2+N	2167.59
	Gasket material	NBR	25
Water pump	Seawater pump	RG10 bronze	480
	Fresh water pump	GJL-250 cast iron	480
	Motor (2x)	Cast iron	638
Ventilator	Fan	Steel hot dip galvanized	1001
	Motor	Carbon steel 40 Cr	819
Water storage	Water tank	High density polyethylene (HDPE)	1097.69

7.2. Results of the LCA

The same evaluation methods and corresponding impact categories are used as for the pilot OTWP system, were the results of the LCA are presented in chapter 5. For the upscaled OTWP the normalized results are shown in figures 7.1, 7.2a and 7.2b for the CML, EI 99 and Eco 97 methods, respectively. More or less the same observations can be made as described in detail in chapter 5.

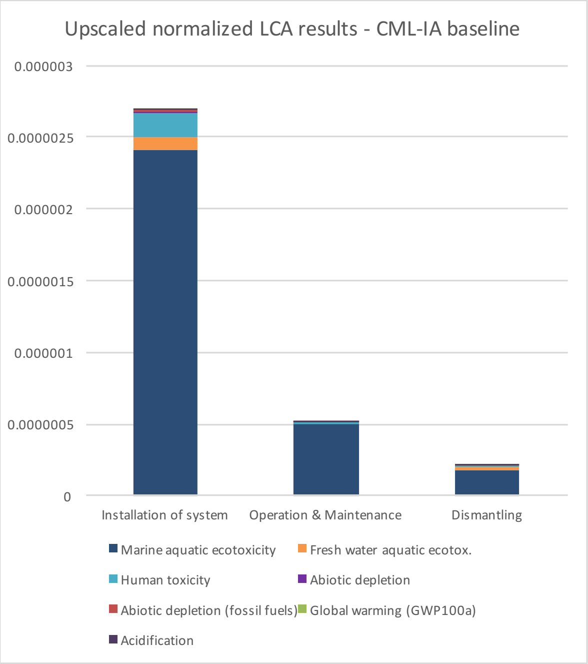
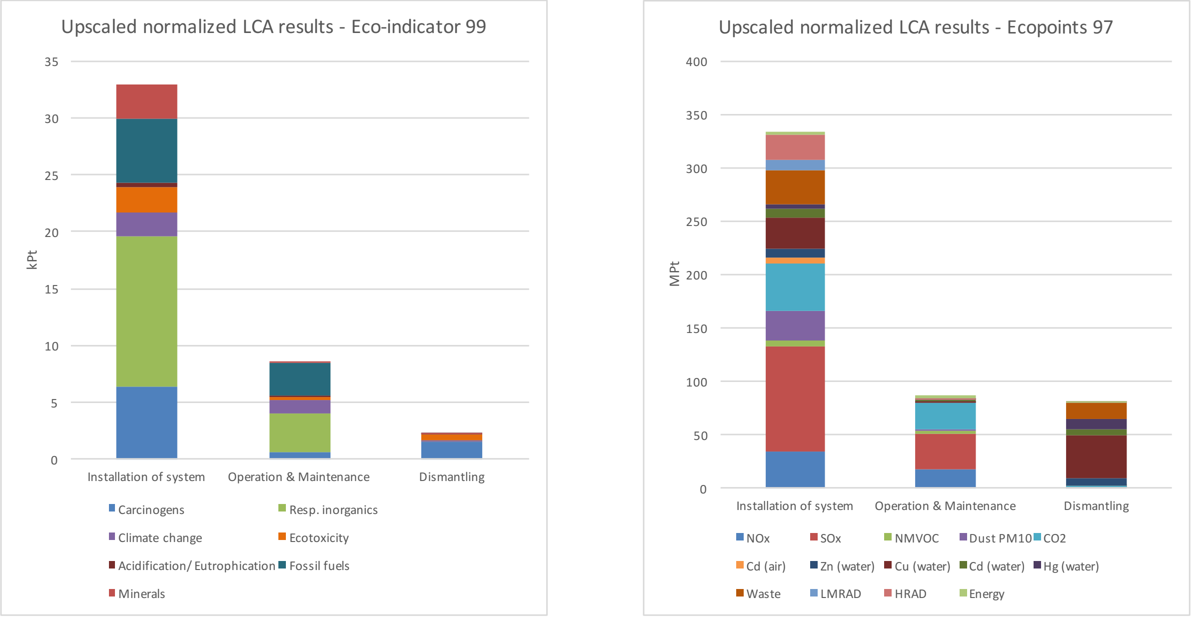


Figure 7.1: Normalized LCA results of the upscaled OTWP by CML.



(a) LCA results from Eco-indicator 99.

(b) LCA results from Ecopoints 97.

Figure 7.2: Weighted results of the LCA of the upscaled OTWP system.

7.3. Comparison of the OTWP systems

To compare the upscaled OTWP system with the pilot OTWP system, it is assumed that the pilot system can be operate as a modular system. With 4 pilot OTWP systems operating modular the same daily water production is created as for one upscaled system. For the modular system the LCA results in chapter 5 of the pilot system are multiplied with a factor 4. The comparison between the two systems is presented in 7.3, 7.4a and 7.4b for the CML, EI 99 and Eco 97 evaluation methods, respectively.

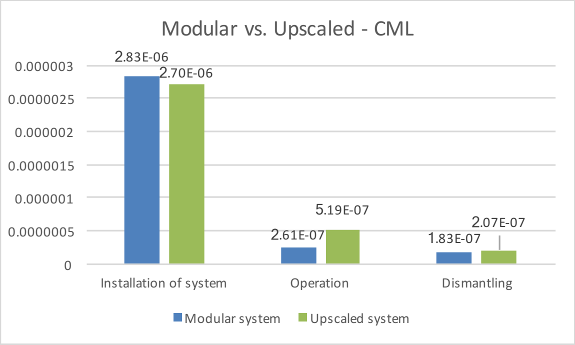
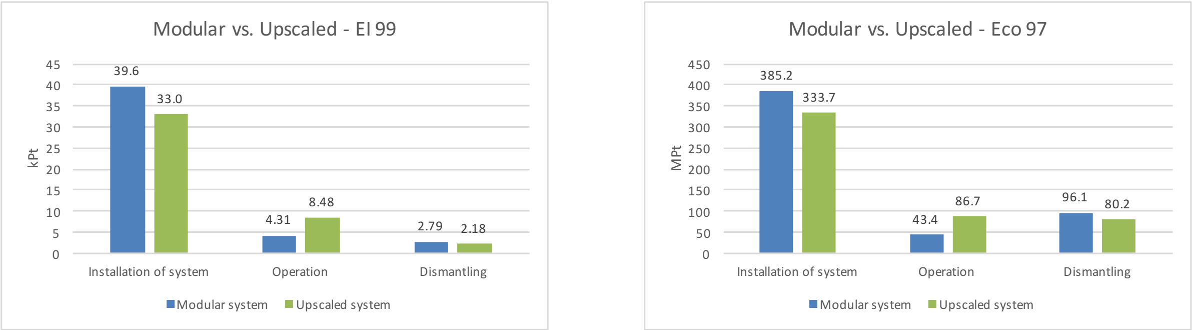


Figure 7.3: Comparison between the modular and upscaled system with the evaluation method CML.

Divided again into the three system phases, it can be concluded that for the installation and dismantling phases the modular system has a higher environmental impact then the upscaled system. This is due to the fact that the modular system uses more materials, since it requires 4 times of all the components. For all the analyzed evaluation methods the upscaled system has a higher environmental impact during the operation phase. This is caused by water tank, since the total mass for the upscaled system is higher that that of 4 times the water tank of the pilot OTWP system. This concludes that for the storage of water in plastic tanks the optimal use for environmental impact can be found in the lower volumes, around 40 m^3 is already to much of an environmental burden. To optimize this design more investigation in the most environmental sustainable water tank should be made. In total the environmental impact of the upscaled system is between 4.6% and 7.1% lower than that of the modular system.



(a) Evaluation method Eco-indicator 99.

(b) Evaluation method Ecopoints 97.

Figure 7.4: The normalized system phases of the modular and upscaled system for the evaluation methods.

Figure 7.5 shows the amounts of the relevant airborne emissions for the RO plant with an energy consumption of 4 kWh/m^3, the modular system and the upscaled system. From these graphs it follows that these emissions are the highest for the RO plant, followed by the modular system and relatively very low for the upscaled system. Again this concludes that for the relevant airborne emissions the lowest environmental impact is caused by the OTWP systems, in particular now for the upscaled system.

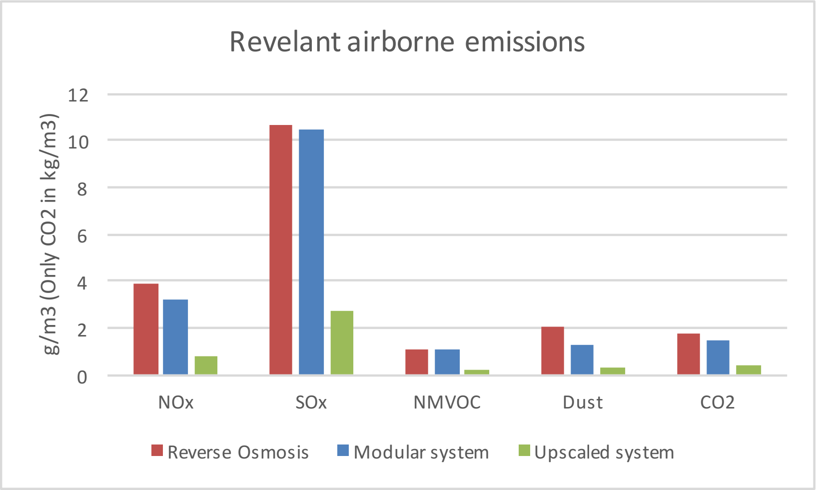


Figure 7.5: The relevant airborne emissions of the RO (4kWh/m3), modular and upscaled systems.

8

Conclusions and Recommendations

The next two sections will describe the conclusion and recommendations. In the conclusions the answers to the research questions will be answered. The recommendations provide suggestions for further improvements on the current presented research.

8.1. Conclusions

The main research question of this study is formulated as follows: ***What is the Life Cycle Assessment of an Ocean Thermal Water Production system and which fresh water production method has the highest environmental sustainability for the Caribbean?*** This question will be answered by answering the three following sub-questions.

8.1.1. Sub-question 1 - System engineering

The first sub-question is stated as followed: *How do the most important components of the pilot OTWP system look like and what is its operating energy consumption?*

This is the first step towards the LCA of the OTWP system, knowing which components are required for the assembly of the system. From the requirements given for the design of the pilot OTWP by Bluerise, different components are found that meet these requirements. The OTWP system consists of a condenser, one heat exchanger, two water pumps, a ventilator and a water tank. In figure 8.1 the schematic overview of the OTWP system is given, which is in symbiosis with the OTEC system. The summary of the inventory of these important components is given in table 8.1. The total energy consumption is 0.134 kWh/m^3 produced fresh water.

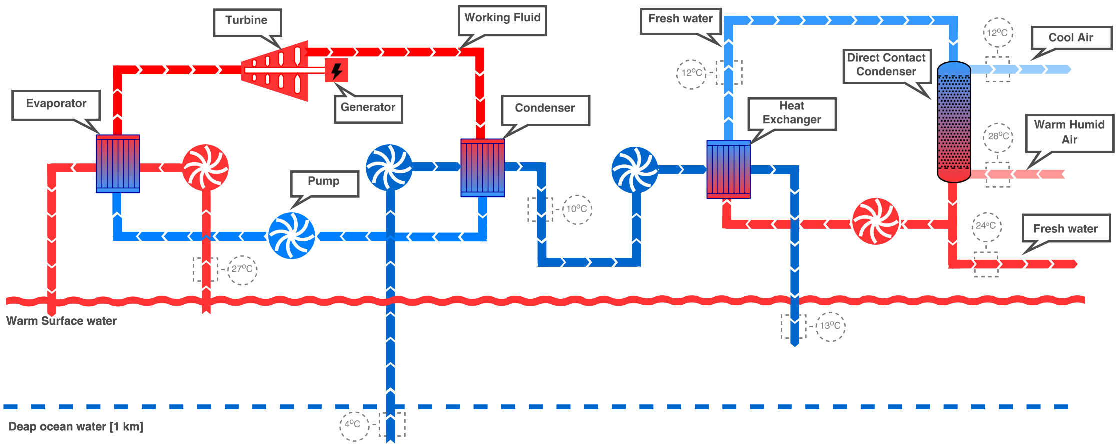


Figure 8.1: Schematic representation of OTEC and OTWP system [40].

Table 8.1: Summary bill of materials

Component	Part	Material	Mass [kg]
Condenser	Column	Polymethyl methacrylate (PMMA)	337
	Packing	Stainless steel 304	3782
	Nozzles	Stainless steel 316	20
Heat exchanger	Plate material	Titanium	217
	Frame material	Carbon steel S355J2+N	606
	Gasket material	NBR	25
Water pump	Seawater pump	RG10 bronze	185
	Fresh water pump	GJL-250 cast iron	185
	Motor (2x)	Cast iron	246
Ventilator	Casing	Steel hot dip galvanized	168
	Impellers	Steel hot dip galvanized	48
	Motor	Carbon steel 40 Cr	216
	Flanges and mounting	Steel hot dip galvanized	48
Water storage	Water tank	High density polyethylene (HDPE)	178

The condenser consists out of hollow plastic column filled with metallic packings. Here the humid are flows through and is cooled by the cold water that is sprayed down by the nozzles. In this way fresh water is produced. In the heat exchanger the cold output water of the OTEC system is used to cool down the warm fresh water flow, which is used in the condenser. The heat exchanger is made out of titanium plates, carbon steel frame material and rubber gasket material. The gasket is assumed to be replaced every 10 years. The two water pumps are used to pump the water through the OTWP system. One pumps seawater from the OTEC system to the heat exchanger. The other pumps fresh water through the OTWP system. Both pumps are assumed to have each a energy consumption of 0.0394 kWh/m^3 of fresh water produced. The ventilator blows the humid air into the condenser. This component is build up from galvanized steel for the casing, impellers, flanges and mounting of the ventilator. The motor is made of carbon steel. The energy consumption is assumed to be 0.055 kWh/m^3 produced fresh water. To store the fresh water production a small water tank is used. This is made out of plastic and assumed to be replaced every 10 years.

8.1.2. Sub-question 2 - LCA

The second sub-question is formulated by: *What are the relevant environmental impacts of the pilot OTWP system calculated with different evaluation methods and how do the airborne emissions compare to reverse osmosis system?*

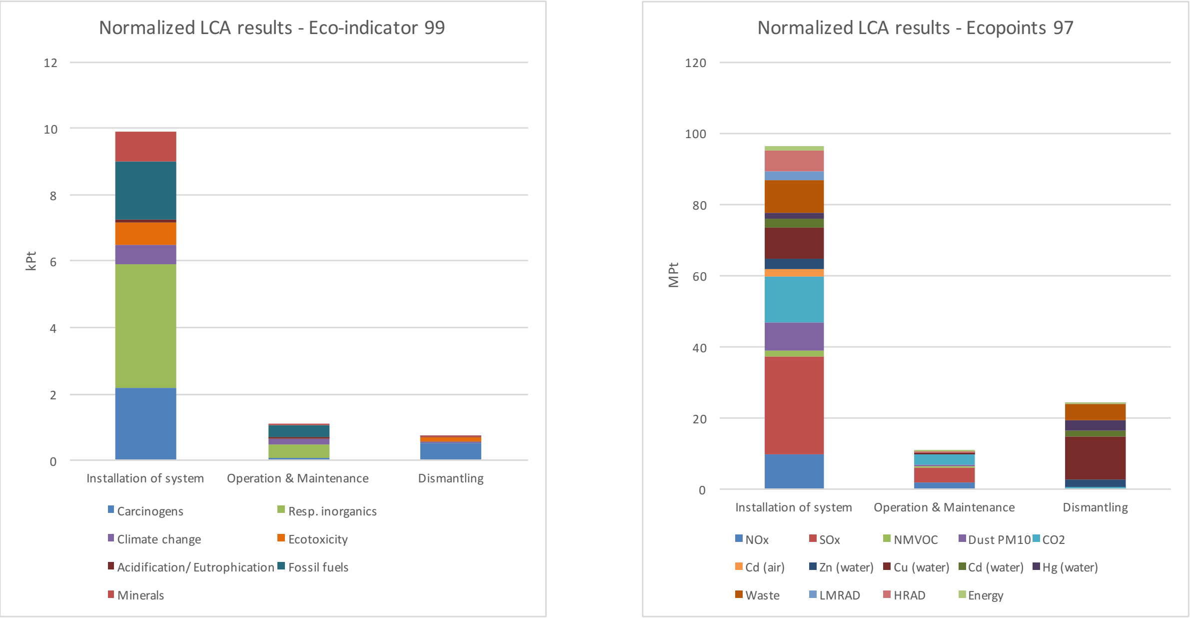
The environmental impacts are calculated by a SimaPro model. The evaluation methods CML-IA baseline, Eco-indicator 99 and Ecopoints 97 are used with several impact categories that are found to be relevant for this model. For the details on the selected impact categories see chapter 2. The system is divided into three phases: installation, operation and dismantling. From the inventory table the characterized results are calculated, see table 8.2 for the characterized results obtained by CML, with the corresponding impact categories as relevant environmental impacts.

Table 8.2: Environmental impact results of the general model from CML-IA baseline method

Impact category	**Unit**	**Installation**	**Operation**	**Dismantling**	**Total**
Abiotic depletion	kg Sb eq	$8.54{\cdot}10^{-1}$	$1.48{\cdot}10^{-3}$	$2.13{\cdot}10^{-4}$	$8.56{\cdot}10^{-1}$
Abiotic depletion (fossil fuels)	MJ	$8.07{\cdot}10^{5}$	$1.95\ {\cdot}10^{5}$	$2.87{\cdot}10^{3}$	$1.01{\cdot}10^{6}$
Global warming (GWP100a)	kg CO_2	$6.48{\cdot}10^{4}$	$1.58{\cdot}10^{4}$	$4.17{\cdot}10^{3}$	$8.47{\cdot}10^{4}$
Human toxicity	kg 1,4-DB[1]	$1.20{\cdot}10^{5}$	$2.21{\cdot}10^{3}$	$2.33{\cdot}10^{3}$	$1.24{\cdot}10^{5}$
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	$5.93{\cdot}10^{4}$	$9.34{\cdot}10^{2}$	$1.78{\cdot}10^{4}$	$7.81{\cdot}10^{4}$
Marine aquatic ecotoxicity	kg 1,4-DB	$1.39{\cdot}10^{8}$	$1.22{\cdot}10^{7}$	$9.63{\cdot}10^{6}$	$1.61{\cdot}10^{8}$
Acidification	kg SO_2	$6.93{\cdot}10^{2}$	$1.07{\cdot}10^{2}$	1.05	$8.01{\cdot}10^{2}$

Now the normalized (or weighted) results are determined. With these results the different impact categories can be compared within a certain evaluation method. The installation phase has the highest impact on the environment with 82.1% on average of the three evaluation methods. Followed by the dismantling phase with 10.1% and with 7.8% the operation phase has the lowest contributions to the environmental impact. The dismantling phase is calculated with the assumption that a 100% is considered as landfill. This is of course not a ideal solution and therefore it can be expected that when recycling is considered the environmental impact of the dismantling phase will become lower.

For the CML evaluation method the most important impact category is the marine aquatic ecotoxicity, which is for 86% responsible of the environmental impact. For the EI 99 this impact category is respiratory inorganic with 36.8%. SO_x is the largest impact category for the evaluation method Eco 97 with 24.3%. In figures 8.2a and 8.2b the graphs of the weighted impact categories are given, with the relevant environmental impacts for the corresponding evaluation method.



(a) LCA results from Eco-indicator 99.

(b) LCA results from Ecopoints 97.

Figure 8.2: Weighted results of the LCA of the pilot OTWP system.

The relevant airborne emissions of the OTWP system and the RO plant are compared. Here it follows that the pilot OTWP system with a very low energy consumption score better on the release of these emissions. But if the energy consumptions would be the same the RO plant has a lower impact on the environment. In figure 8.3 this is made visible in graphs. Therefore, it is important for the design of the OTWP system that the energy consumption should be lower that than of the RO plant in order to benefit from the lower environmental emissions into the air.

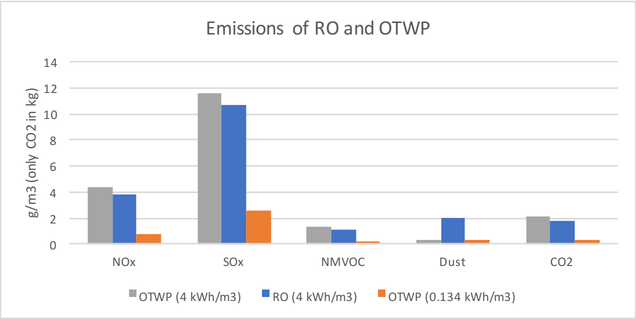


Figure 8.3: Relevant airborne emissions of RO plant and OTWP.

The OTWP system is designed to work in symbiosis with the OTEC system. The environmental impact of the OTEC system is for most impact categories lower than that of the general electricity model UCPTE, which is used for the LCA of the OTWP system.

8.1.3. Sub-question 3 - Upscaling

The third and final sub-question is described by: *What are the environmental impact relation between the pilot and the upscaled system and how do the airborne emissions compare to reverse osmosis system?*

An upscaled version of the pilot OTWP system is created by doubling the diameter of the condenser while keeping the height equal. Also the other components are changed accordingly to match the new volumes and flows, for details see chapter 7. To compare the pilot OTWP system with the upscaled system, a modular pilot system is used. This modular system consists of 4 pilot systems.

The modular and upscaled OTWP systems are compared with each other. For the installation and dismantling phases the upscaled system has a lower impact on the environment than that of the modular system. This is due to the fact that the upscaled system requires less material in most cases, whereas the modular system needs 4 times all the material. For the operational phase this is to other way around, due to the fact that the mass of water tank of the upscaled system is more than 4 times the mass of the water tank of the pilot OTWP. Despite the higher environmental impact during the operation phase, the total environmental impacts of the upscaled system are between the 4.6% and 7.1% lower than the modular system, depending on the evaluation method.

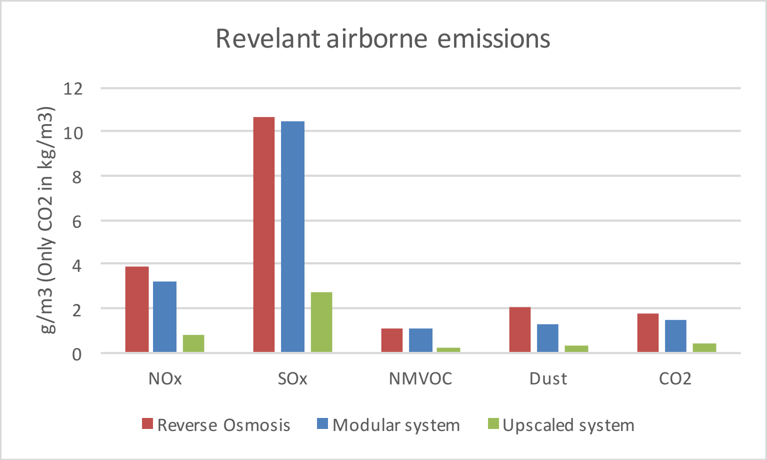


Figure 8.4: The relevant airborne emissions of the RO (4kWh/m3), modular and upscaled systems.

The final comparison is done with the relevant airborne emissions of the RO plant (4 kWh/m3), the modular and the upscaled OTWP system. From figure 8.4 it can be concluded that the highest environmental impact is caused by the RO plant and the lowest by the upscaled OTWP system. Therefore, it is concluded that the OTWP system is the system with the lowest environmental impact, with all the assumptions made to develop the LCA of the OTWP. Hence, compared with the RO plant the OTWP system is the system with the highest environmental sustainability for the use in the Caribbean.

On this I would like to add that for the already operating water production technologies, like RO, improvements on the efficiency of the energy consumption can also lead to lower emission reductions. This may or might not lead to the best environmental sustainable solution, but taking small steps towards the transition in a fossil fuel is world is better then taking none.

8.2. Recommendations

There are some recommendations for future research on the LCA of the OTWP system, which will improve the current LCA are listed below:

- The dismantling phase is in the current design assumed to be a 100% landfill. This is not a very sustainable way of dealing with the remainders of the system. Instead recycling should be considered. Hence, a more complex LCA model should be developed in order the calculate which amount can be recycled and what the environmental impact will be. To achieve this more data of the environmental impact should become available on recycling in the databases of LCA programs like SimaPro.
- The current LCA does not take into account the energy it requires to actually built the system on site. Most LCA assume that this energy is small and therefore it can be neglected. But it seems to be difficult to find such information and data on the environmental impact. Therefore, it would be interesting to investigate this in more detail and see what the effect on the LCA is.
- Since the OTWP is originally designed to work in symbiosis with the OTEC system, it is interesting to investigate what the effect of this symbioses is on all the different impact categories for the evaluation methods. Therefore, a LCA of the OTEC system should be built into SimaPro. To extend the library in SimaPro, this is a good example what is still missing in the program. Since data is available for wind and solar energy.
- The current system engineering should be looked at in more detail and create an integrated system. The smaller components will also play a role in the LCA, and in this way nothing is left out in the analysis.
- The current upscaled system produces 82.8 m^3 water on a daily basis. It is interesting to know what the environmental impacts are of a much larger system, e.g. with the production volume of 25000 m^3/day. Curacao uses currently two RO plants for the fresh water production, each approximately producing 25000 m^3/day. In 2015 the latest investments into the RO plant Santa Barbara is done. Also interesting to investigate are the influences of the energy driven by 100% renewable technologies, for both RO and the OTWP.
- The water quality is assumed to be equal as that of RO. More research is required to know if this is a realistic assumption, since the water quality obtained from the RO plant is treated with chemicals and in the LCA of the OTWP these chemicals are not included.
- Another improvement on the current research can be done by creating a sustainability assessment of the system. Using a sustainability approach the quality of the selected system can be evaluated. In a sustainability assessment the economic, environmental and social indicators are addressed. Afgan and Carvalho describe the sustainability as a reinvented key word for: *"a political discourse concerning quality of life issues, limitation of natural resources and the sense of the commitment to the future generations"* [4].

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A

SimaPro library databases

A.1. Ecoinvent

Ecoinvent is a life cycle inventory (LCI) database created by the Swiss center for life cycle inventories with the goal of providing a set of unified and generic LCI data of high quality. Ecoinvent version 3.1 is complied in 2014 and has approximately 10 000 interlinked datasets of various sectors like energy products, transport, building materials, chemical and metal production. The data is available as unit or system processes. Unit processes contain links to other unit processes, from which the inventory flows can be calculated. System processes contain the already calculated inventory flows and do not contain links to other processes. System processes are often selected when they are used for background processes to increase the calculation speed, whereas the unit processes are used for detailed interpretation. Another option in this database is for market and transformation processes. The market processes include inputs from production in several countries as well as inputs of transport processes. When the specific supplier is not known, it is recommended to use the market processes. Transformation processes contain all the inputs for making a product or service, except for transport, and all the associated emissions and resources extraction [17, 21].

Ecoinvent has three different system models available, for more detail about these model visit the website of Ecoinvent [21]. The system model that is selected for this research is the allocation default model because this will provide the closest match to compare other potential LCA studies. This model is uses the average supply of products, meaning that the product is always available even if it is scare. It also allocates waste (and by-products) at the point of substitution. Here, the benefit from recycling materials is attributed to the market processes that provide the secondary materials or by-products (such as heat or electricity from the incineration of waste).

A.2. BUWAL 250

This inventory database contains packing materials for the Swiss Packing Institute, made by EMPA. Based on the Swiss consumption the inventory includes emissions from production of raw material, energy, semi-manufactures and auxiliary materials, transport and production process of materials. The energy systems are based on ETH data, excluding capital goods. Data of plastics are based on PWI data [17, 21].

A.3. ELCD

The European Life Cycle Database (ELCD, version 3.1 of 2015) includes data from front-running EU-level business associations and other sources for key materials, energy carriers, transport, and waste management. Data quality, consistency and applicability are the elements of focus for this library database, were the data is officially provided and approved by the named industry association per process [17, 21].

A.4. ETH

”Inventory data for Swiss and the Western European energy supply situation concerning production and imports of fossil and fissile fuels and production and trade of electricity, including emissions from primary energy extraction, refining and delivery, mineral resource extraction, raw material production, production of semi-manufactures, auxiliary and working materials, supply of transport and waste treatment services, the construction of infrastructures and energy conversion and transmission. The data cover the Swiss and Western European situation. Hereby the Swiss situation and life cycle inventory data is sometimes used to approximate an average European situation" [17, 21].

A.5. Idemat

The Idemat database is based on the Ecoinvent databse with additional LCIs for alloys, wood, electronic and electric components, textile, platics and End-of-Life data. "Furthermore it made a selection on LCIs for energy and transport. This is to provide students of the Delft University of Technology with a practical database for design, engineering and architecture (Ecoinvent as such appeared to be unsatisfactory and unsufficient for practical design issues). Idemat names with *estimate* in it have been derived from CO_2 data, adding the other emissions by the same ratio as the average emissions in European of energy (UTCE). A further function of Idemat is to eliminate the double counting (of CO_2 and depletion of fossil fuels) of electricity in eco-costs" [17, 21]. The available versions are from 2008, 2010, 2012, 2014 and 2015. Where possible the latest version is used.

B

Evaluation methods

In this appendix the evaluation methods are further elaborated. First the CML-IA baseline method is explained in section B.1, followed by the Eco-indicator 99 in section B.2 and in the final section B.3 the Eco-points 97 method is presented.

B.1. CML-IA baseline

The CML-IA baseline method is a midpoint approach and developed by the Center for Environmental Science of Leiden University. The impact categories for this method are often used in LCA studies. The selected impact categories for this thesis are described bellow [30, 50]:

- Depletion of abiotic resources: defined as natural resources regarded as non-living, focused on extraction and depletion. The characterization factors of this impact category are based on the characterization model concentration-based reserves and rate of de-accumulation approach. The factors are expressed as abiotic depletion potential (ADP) for each extraction of minerals and fossil fuels in kg antimony equvalents/kg extraction.

- Climate change: defined as the impact of human emissions on the radiative forcing of the atmosphere. The characterization factors of this impact category are based on the characterization model developed by the Intergovermental Panel on Climate Change (IPCC). The factors are expressed as the global warmin potential for a 100-year time horizon (GWP100) for each greenhouse gas emission to the air in kg CO_2 equivalent/kg emission.

- Fresh-water aquatic eco-toxicity: defined as the impacts of toxic substances on freshwater aquatic ecosystems. The characterization factors of this impact category are based on USES 2.0 model developed at RIVM, describing fate, exposure and effects of toxic substances, adapted to LCA. The factors are expressed as freshwater aquatic ecotoxicity potential (FAETP) for each emission of a toxic substance to air, water and/or soil in kg 1,4-dichlorobenzene equivalents/kg emission.

- Acidification: acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials. The characterization factors of this impact category are based on RAINS10 model, developed at IIASA, describing the fate and deposition of acidifying substances, adapted to LCA. The factors are expressed as acidification potential (AP) for each acidifying emission to the air in kg SO_2 equivalents/kg emission.

Normalization is the calculation step that provides better insights in the environmental impact results. By comparing the impact results to average reference data over a given period of time, such as a person or country. This normalization is done by dividing the impact results by the reference information, see equation B.1.

$$NS_i^{sys} = \frac{CS_i^{sys}}{CS_i^{ref}} \tag{B.1}$$

Where, NS_i^{sys} is the normalized impact result for impact category i of the system (sys) under study, CS_i^{sys} is the characterized impact result for impact category i of the system under study and CS_i^{ref} the characterized impact result for impact category i of the reference system (ref), also called the normalization reference for the impact category i [31].

Normalized values are expressed on a common scale (dimensionless) and therefore provide a good way to make comparisons between the different impact categories and between whole systems. In most LCA studies external normailzation is used. Meaning that the environmental profile of the reference system is independent of the studied system. The available external normalization reference sets for the CML-IA method are [48]: World 1990, 1995, 2000; EU28, 2000; EU25, 2000; West Europe, 1995 and Netherlands, 1997. For the studied system most products have a global system boundary and are therefore not regionally bounded. When this occurs it is adviced to select global normalization references [34]. The detailed content of these normalization references can be be found at the department of industrial ecology at Leiden University [45] and will be out of the scope of this research.

The step weighting is not part of this evaluation method.

B.2. Eco-indicator 99

The Eco-indicator 99 is a damage-oriented approach. Together with a panel, consisting of 365 persons from a Swiss LCA interest group, the weight of the damage caused by the impact categories were assessed. Three damage categories are developed and calculated with complex damage models [50]:

1. Human Health, the damage is expressed as the number of year life lost and the number of years lived disabled. These are combined as Disability Adjusted Life Years (DALY).
2. Ecosystem Quality, the damage of the loss of species over an certain area, in a time frame. Expressed in Potentially Disappeared Fraction (PDF·m^2·yr)
3. Resources, the damage of the surplus energy needed for future extractions of minerals and fossil fuels (MJ surplus energy).

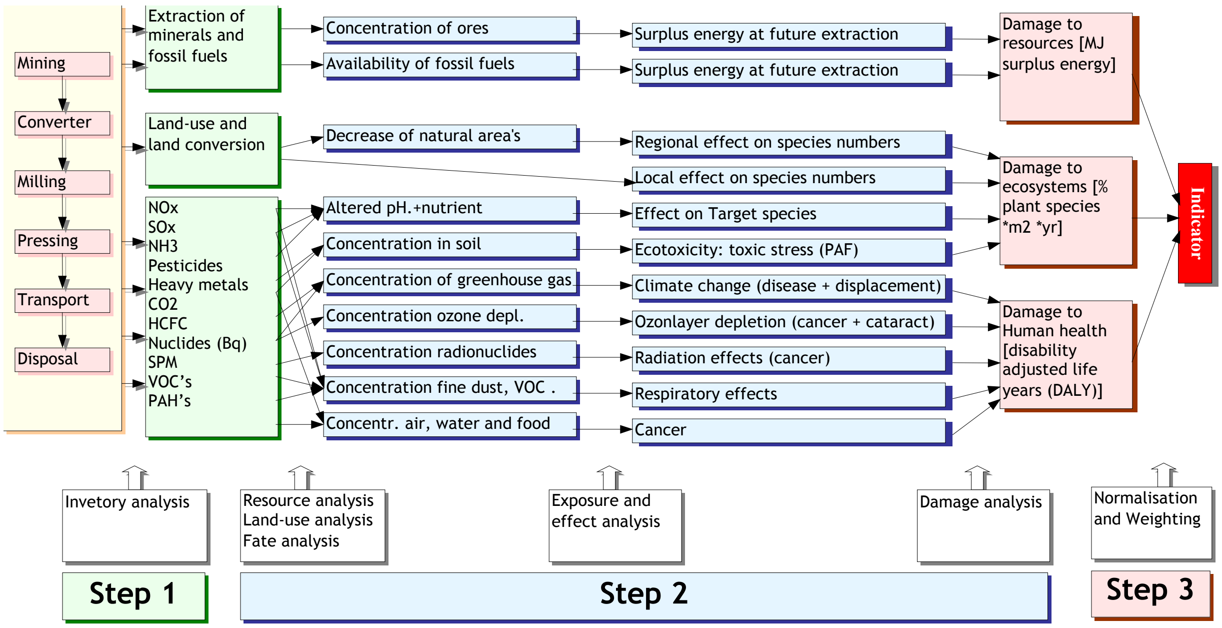


Figure B.1: Overview of the damage model of Eco-indicator 99 [50]

A schematic overview of the damage model that represents the Eco-indicator 99 method is given in figure B.1. The damage model for emissions includes fate analysis, exposure, effects analysis and damage analysis. The selected impact categories that the damage model calculates are [50]:

- Carcinogens: carcinogenic affects due to emissions of carcinogenic substances to air, water and soil. Damage is expressed in Disability Adjusted Life Year (DALY) / kg emission.
- Respiratory inorganics: respiratory effects resulting from winter smog caused by emissions of dust, sulfur and nitrogen oxides to air. Damage is expressed in Disability Adjusted Life Year (DALY) / kg emission.
- Climate change: climate change effects caused an increase of diseases and death. Damage is expressed in Disability Adjusted Life Year (DALY) / kg emission.
- Ecotoxicity: ecotoxic substances to air, water and soil cause a damage to the ecosystem quality. Damage is expressed in Potentially Affected Fraction (PAF)·m^2·year/kg emission.
- Acidification/Eutrophication: acidifying substances to air causing damage to the ecosystem quality. Damage is expressed in Potentially Disappeared Fraction (PDF)·m^2·year/kg emission.
- Resource depletion: damage of future fossil fuel extraction, expressed in surplus energy per extracted MJ, as a result of lower quality resources.

To deal with the uncertainties of the subjective options in the model, such as the time frame or including a certain consequence, Eco-indicator has chosen three different perspectives [50]:

- Hierarchist perspective: the time frame for this option is average, a balance between a long and short temporal perspective. Substances are included if it there is a match with its effect. By good management it is assumed that damages are avoidable and fossil fuels are not easily replaced.
- Egalitarian perspective: the time frame for this option is set as long and substances are included if there is a minimum indication to its effect. The damage are assumed to be unavoidable and cn lead to catastrophic events. For fossil fuel it is assumed that they cannot be replaced.
- Individualist perspective: there is a short time frame and substances are only included if there is proof regarding their effect. Damages are assumed to be recoverable with technological and economical innovations. Fossil fuels are assumed that they cannot completely be depleted.

The selected perspective for this thesis is the hierarchist option because of its moderated vision, while the other options have a more extreme perception of reality. The damage categories are normalized based on European level normalization data from 1993. This option uses average weighting as default and in general the value choices are scientifically and politically acceptable [50].

B.3. Ecopoints 97

The evaluation method Ecopoints 97 is developed by the Swiss Ministry of Environment (BUWAL) and calculates the single scores of the environmental impacts. This method is based on the following three aspects [50]:

1. Classification is not applicable, all impacts are individual assessed. The advantage is the very detailed assessment of the impact but the disadvantage is that only a few impacts are assessed.
2. A target normalization principle is used.
3. The Swiss policy levels are used instead of sustainability levels, meaning a mixture of political and environmental considerations.

The normalization is determined by equation B.2 [50]:

$$Ecofactor = \frac{1}{F_k} \cdot \frac{F}{F_k} \tag{B.2}$$

Where $\frac{1}{F_k}$ describe the normalization factor and $\frac{F}{F_k}$ the evaluation factor. With the dimensionless normalized values the different impact categories can be compared with each other and provide if necessary which impact category requires more attention.

For the weighting the formula B.3 is used [50]:

$$f = \frac{F}{F_k^2} \cdot C \tag{B.3}$$

Here, F_k is the target norm for total load, F the actual total current load and C a constant of the value 10^{12}. Now the normalization step is multiplied with weighting factors, giving a final result expressed in points. This method makes it possible to weight environmental impacts within the context of a LCA.

C

Column diameter versus energy Consumption

Lopez [40] calculated the energy consumption as function of the column diameter for the pilot OTWP, presented in figure C.1. Here the energy consumption per m^3 water produced is looked at. This is done to compare two different types of packings.

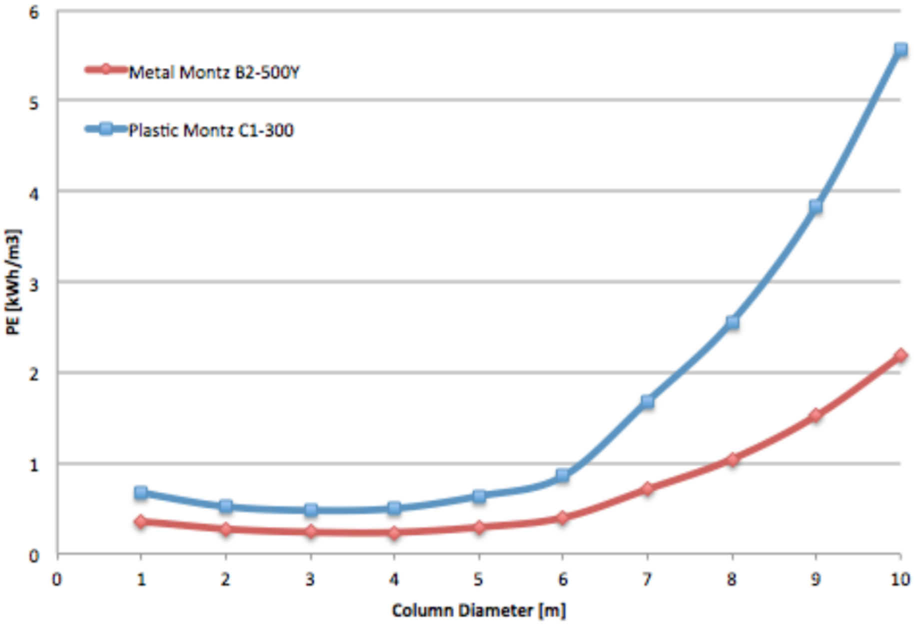


Figure C.1: Energy consumption as function of column diameter results of Montz Pak C1-300 and Montz Pak B2-500Y are compared at each column diameter between 1 and 10 m [40]

D

Condenser column calculations

In this appendix the calculations are given of the column of the condenser. To calculate the mass of the column casing, first the volume in m^3 of the casing of the column needs to be determined. This is done by equation D.1:

$$V = \pi \cdot h(R_{out}^2 - R_{in}^2) \tag{D.1}$$

where h is the height of the column, R_{out} is the outer radius of the column , this includes the wall thickness and R_{in} represents the inner radius of the column, which is assumed to be 3 m.

The chosen material for the column casing is the plastic Polymethyl methacrylate (PMMA). This is a transparent plastic that is impact resistant, when it is modified. The alternative plastic Polycarbonate (PC) is often used when extreme strength is needed. Unfortunately, the toxic substance bisphenol-A is released when PC is in contact with water. Therefore, PC is not an option for this application. The mass of the column casing is determined by equation D.2:

$$m = \rho \cdot V \tag{D.2}$$

where ρ is the density of the material, for PMMA this is 1180 kg/m^3.

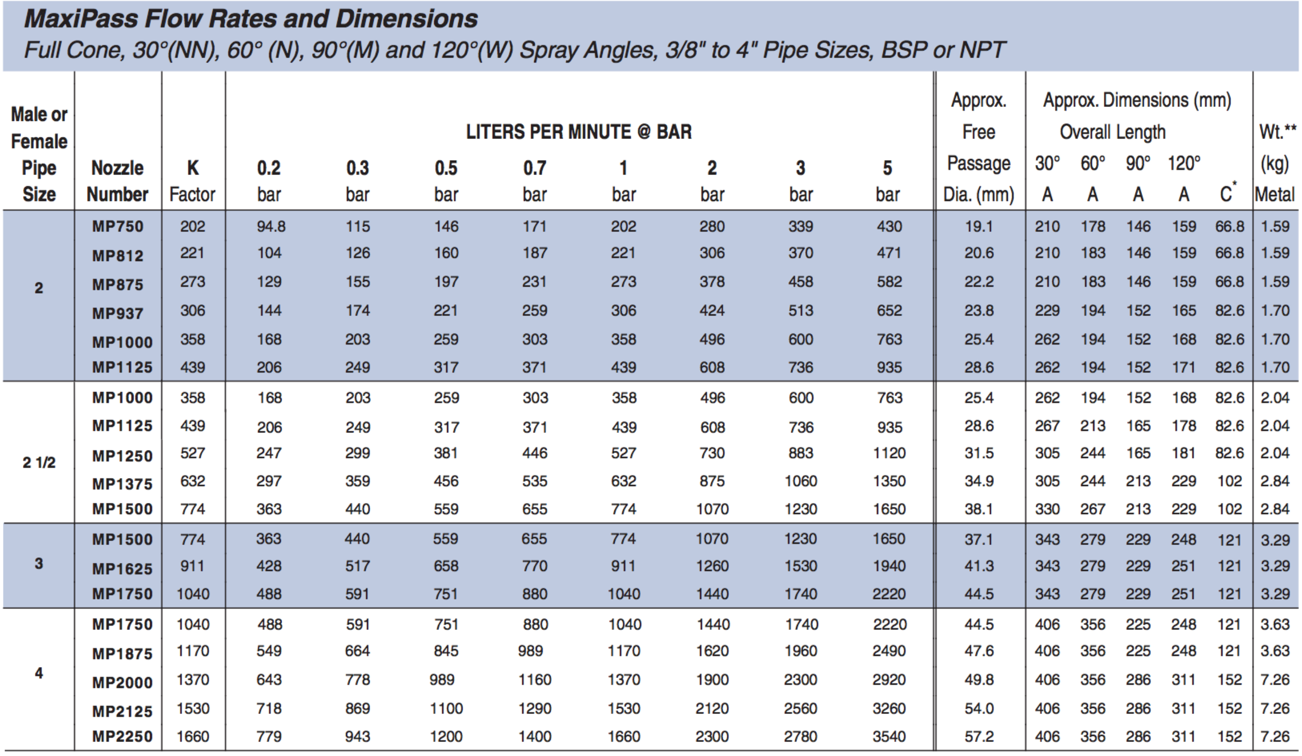
E

Condenser nozzles calculations

The nozzle data sheets are presented in figure E.1 and E.2. Formula E.1 is used to convert the volume flow rate in l/min to the mass flow rate in kg/s.

$$\dot{m} = \frac{\dot{V} \cdot \rho_L}{60000} \tag{E.1}$$

where $\dot{V}$ is the volume flow rate in L/min and ρ_L is the density of liquid water in kg/m^3. From this process the following nozzles are selected as the most appropriate nozzles, while keeping in mind a lightweight engineering approach.



MaxiPass Flow Rates and Dimensions

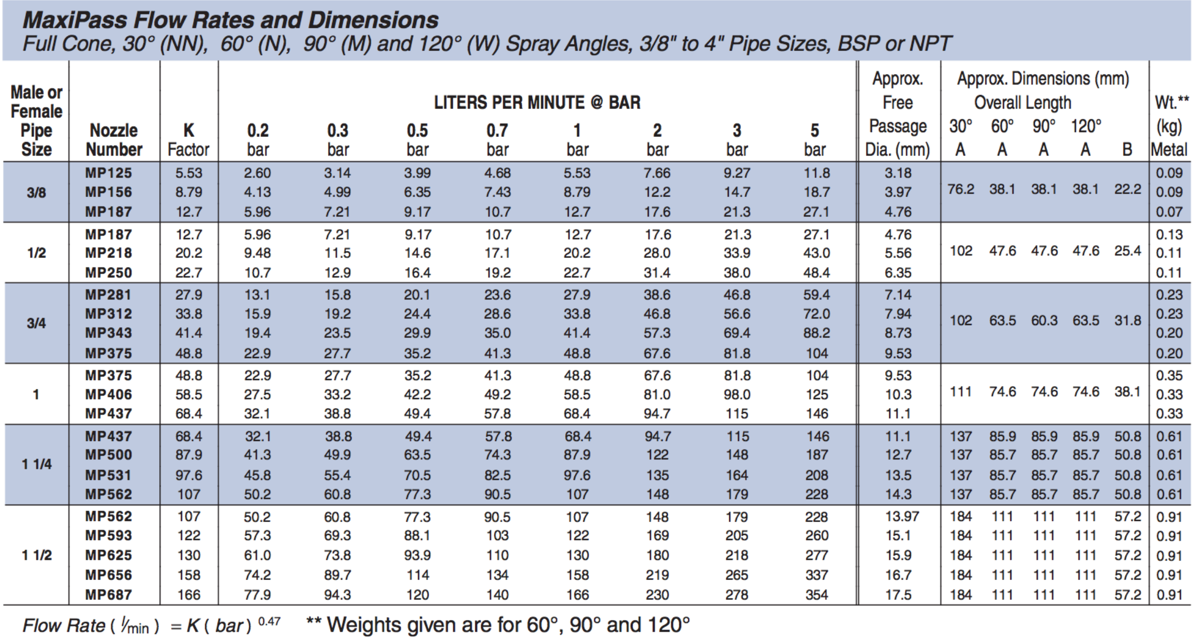
Full Cone, 30°(NN), 60° (N), 90°(M) and 120°(W) Spray Angles, 3/8" to 4" Pipe Sizes, BSP or NPT

Male or Female Pipe Size	Nozzle Number	K Factor	LITERS PER MINUTE @ BAR								Approx. Free Passage Dia. (mm)	Approx. Dimensions (mm) Overall Length					Wt.** (kg) Metal
			0.2 bar	0.3 bar	0.5 bar	0.7 bar	1 bar	2 bar	3 bar	5 bar		30° A	60° A	90° A	120° A	C*	
2	MP750	202	94.8	115	146	171	202	280	339	430	19.1	210	178	146	159	66.8	1.59
	MP812	221	104	126	160	187	221	306	370	471	20.6	210	183	146	159	66.8	1.59
	MP875	273	129	155	197	231	273	378	458	582	22.2	210	183	146	159	66.8	1.59
	MP937	306	144	174	221	259	306	424	513	652	23.8	229	194	152	165	82.6	1.70
	MP1000	358	168	203	259	303	358	496	600	763	25.4	262	194	152	168	82.6	1.70
	MP1125	439	206	249	317	371	439	608	736	935	28.6	262	194	152	171	82.6	1.70
2 1/2	MP1000	358	168	203	259	303	358	496	600	763	25.4	262	194	152	168	82.6	2.04
	MP1125	439	206	249	317	371	439	608	736	935	28.6	267	213	165	178	82.6	2.04
	MP1250	527	247	299	381	446	527	730	883	1120	31.5	305	244	165	181	82.6	2.04
	MP1375	632	297	359	456	535	632	875	1060	1350	34.9	305	244	213	229	102	2.84
	MP1500	774	363	440	559	655	774	1070	1230	1650	38.1	330	267	213	229	102	2.84
3	MP1500	774	363	440	559	655	774	1070	1230	1650	37.1	343	279	229	248	121	3.29
	MP1625	911	428	517	658	770	911	1260	1530	1940	41.3	343	279	229	251	121	3.29
	MP1750	1040	488	591	751	880	1040	1440	1740	2220	44.5	343	279	229	251	121	3.29
4	MP1750	1040	488	591	751	880	1040	1440	1740	2220	44.5	406	356	225	248	121	3.63
	MP1875	1170	549	664	845	989	1170	1620	1960	2490	47.6	406	356	225	248	121	3.63
	MP2000	1370	643	778	989	1160	1370	1900	2300	2920	49.8	406	356	286	311	152	7.26
	MP2125	1530	718	869	1100	1290	1530	2120	2560	3260	54.0	406	356	286	311	152	7.26
	MP2250	1660	779	943	1200	1400	1660	2300	2780	3540	57.2	406	356	286	311	152	7.26

Figure E.1: The nozzle flow rates and dimensions [12]

To determine the spraying width of the different spraying angles of the nozzle, the following formulas are applied [37]:

$$W_{60^\circ} = 1.15 \cdot H \tag{E.2}$$



MaxiPass Flow Rates and Dimensions

Full Cone, 30° (NN), 60° (N), 90° (M) and 120° (W) Spray Angles, 3/8" to 4" Pipe Sizes, BSP or NPT

Male or Female Pipe Size	Nozzle Number	K Factor	LITERS PER MINUTE @ BAR 0.2 bar	0.3 bar	0.5 bar	0.7 bar	1 bar	2 bar	3 bar	5 bar	Approx. Free Passage Dia. (mm)	Approx. Dimensions (mm) Overall Length 30° A	60° A	90° A	120° A	B	Wt.** (kg) Metal
3/8	MP125	5.53	2.60	3.14	3.99	4.68	5.53	7.66	9.27	11.8	3.18	76.2	38.1	38.1	38.1	22.2	0.09
	MP156	8.79	4.13	4.99	6.35	7.43	8.79	12.2	14.7	18.7	3.97						0.09
	MP187	12.7	5.96	7.21	9.17	10.7	12.7	17.6	21.3	27.1	4.76						0.07
1/2	MP187	12.7	5.96	7.21	9.17	10.7	12.7	17.6	21.3	27.1	4.76	102	47.6	47.6	47.6	25.4	0.13
	MP218	20.2	9.48	11.5	14.6	17.1	20.2	28.0	33.9	43.0	5.56						0.11
	MP250	22.7	10.7	12.9	16.4	19.2	22.7	31.4	38.0	48.4	6.35						0.11
3/4	MP281	27.9	13.1	15.8	20.1	23.6	27.9	38.6	46.8	59.4	7.14	102	63.5	60.3	63.5	31.8	0.23
	MP312	33.8	15.9	19.2	24.4	28.6	33.8	46.8	56.6	72.0	7.94						0.23
	MP343	41.4	19.4	23.5	29.9	35.0	41.4	57.3	69.4	88.2	8.73						0.20
	MP375	48.8	22.9	27.7	35.2	41.3	48.8	67.6	81.8	104	9.53						0.20
1	MP375	48.8	22.9	27.7	35.2	41.3	48.8	67.6	81.8	104	9.53	111	74.6	74.6	74.6	38.1	0.35
	MP406	58.5	27.5	33.2	42.2	49.2	58.5	81.0	98.0	125	10.3						0.33
	MP437	68.4	32.1	38.8	49.4	57.8	68.4	94.7	115	146	11.1						0.33
1 1/4	MP437	68.4	32.1	38.8	49.4	57.8	68.4	94.7	115	146	11.1	137	85.9	85.9	85.9	50.8	0.61
	MP500	87.9	41.3	49.9	63.5	74.3	87.9	122	148	187	12.7	137	85.7	85.7	85.7	50.8	0.61
	MP531	97.6	45.8	55.4	70.5	82.5	97.6	135	164	208	13.5	137	85.7	85.7	85.7	50.8	0.61
	MP562	107	50.2	60.8	77.3	90.5	107	148	179	228	14.3	137	85.7	85.7	85.7	50.8	0.61
1 1/2	MP562	107	50.2	60.8	77.3	90.5	107	148	179	228	13.97	184	111	111	111	57.2	0.91
	MP593	122	57.3	69.3	88.1	103	122	169	205	260	15.1	184	111	111	111	57.2	0.91
	MP625	130	61.0	73.8	93.9	110	130	180	218	277	15.9	184	111	111	111	57.2	0.91
	MP656	158	74.2	89.7	114	134	158	219	265	337	16.7	184	111	111	111	57.2	0.91
	MP687	166	77.9	94.3	120	140	166	230	278	354	17.5	184	111	111	111	57.2	0.91

Flow Rate ($^{l}/_{min}$) $= K\,(\mathit{bar})^{0.47}$ ** Weights given are for 60°, 90° and 120°

Figure E.2: The nozzle flow rates and dimensions [12]

$$W_{90^\circ} = 2.00 \cdot H \tag{E.3}$$

$$W_{120^\circ} = 3.46 \cdot H \tag{E.4}$$

Here, the spraying angles are 60°, 90° or 120° and H represents the height in meters of the sprayed area.

In figure E.3 a top view is shown of the spray width of the 7 nozzles in the condenser, provided by the company Spraybest Europe. Notice that with this configuration some water will be sprayed against the inner wall, this will have a negative influence on the heat exchange. Therefore, recommended is to invest more time to optimize the nozzle configuration.

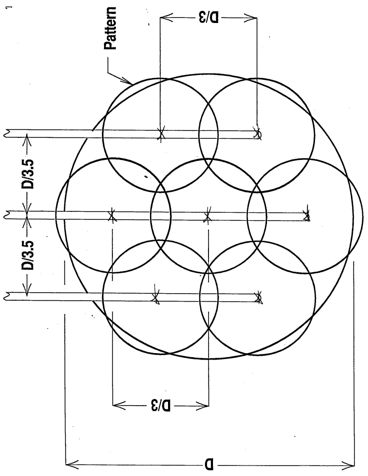


Figure E.3: Nozzles array [37]

F

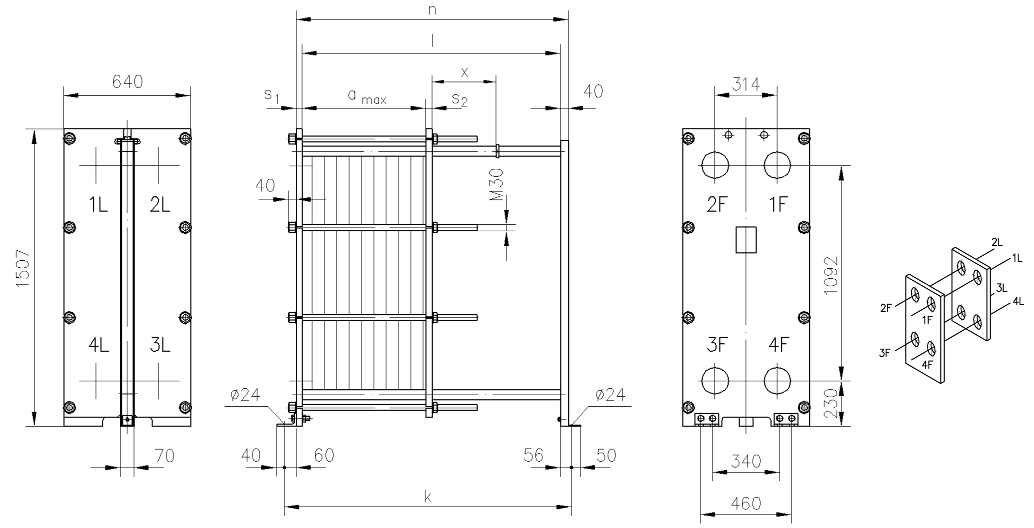
Heat exchanger drawings and parameters

In this appendix the heat exchanger selected for the pilot OTWP system details are presented. In table F.1 the specifications of the plate heat exchanger are given and in figure the heat exchanger drawings are presented in figure F.1, all provided by the company Kapp Nederland BV [55].

Table F.1: Plate heat exchanger specifications

Parameter	**Unit**	**Hot side**	**Cold side**
Mass flow	kg/h	195120	234720
Volume flow	m^3/h	195.31	234.85
Temperature inlet	°C	17.40	10.00
Temperature outlet	°C	12.75	13.86
Pressure drop	kPa	33.395	47.400
Working pressure inlet	barg	5.00	5.00
Velocity gap	m/s	0.54	0.65
Velocity connection	m/s	3.07	3.69
Volume	L	116.22	116.22
OHTC needed / clean	W/m^2K	4591	5057
Heat exchanged	kW	1055.68	
Surface margin	%	10.15	
Log. mean Δ T	K	3.13	
Fouling factor	m^2K/W E-6	20	
Product properties			
Density	kg/m^3	999.0480	999.4576
Heat capacity	J/kgK	4188.73	4192.60
Thermal conductivity	W/mK	0.58888	0.58269
Dyn. viscosity inlet	cP	1.069	1.306
Dyn. viscosity oulet	cP	1.209	1.173

Kelvion PHE Type : NT150S CD-10



n:	1295 mm	s_1:	40.00 mm	a-max frame:	566 mm	Weight:	1009 kg
k:	1371 mm	s_2:	40.00 mm	a-max actual:	478 mm	Weight oper:	1238 kg
l:	1215 mm					Bolt length:	900 mm

Pos	Size	Type	Media	In	Out	Add.	m
1F	DN150	Rubber insert EN1092-1-PN16	Water I	x	-	-	4 mm
2F	DN150	Rubber insert EN1092-1-PN16	Water II	-	x	-	4 mm
3F	DN150	Rubber insert EN1092-1-PN16	Water II	x	-	-	4 mm
4F	DN150	Rubber insert EN1092-1-PN16	Water I	-	x	-	4 mm

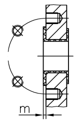
			
Rubber insert			
EN1092-1-PN16			
NBR			
1F;2F;3F;4F			

Figure F.1: Plate heat exchanger drawings for pilot OTWP

G

Water pump

The performance chart of this pump is given in figure G.1, provided by the company Iron pump [20]. The test fluid data to obtain this performance curve are seawater with a density of 1020 kg/m^3, viscosity of 0.8889 cP, temperature of 32 °C, vapor pressure of 0.04171 bar and 1.014 bar for the atmospheric pressure. The details on the specifications of this pump are presented in table G.1 [20].

Table G.1: Pump data of CNLe 150-125/315

Parameter	Unit	Value
Flow	[m^3/h]	230
Head	[m]	30
Efficiency	[%]	77
Power	[kW]	24.7
NPSHr	[m]	3.37
BEP	[%, m^3/h]	80 @ 194
Speed	[rpm]	1775
Diameter	[mm]	288
Suction	[mm]	150
Discharge	[mm]	125
Pressure max	[bar g]	10
Mass without	motor [kg]	185
Motor size	[kW]	30
Motor frame	[L]	200

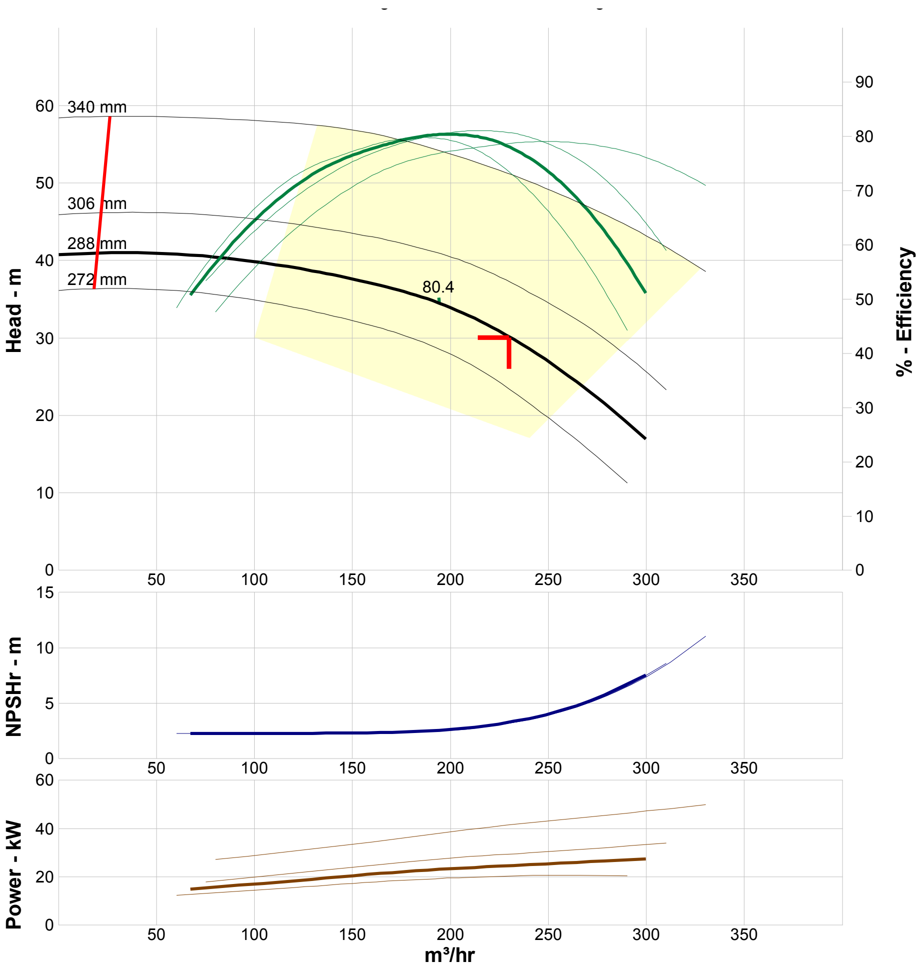


Figure G.1: The performance chart of the selected water pump [20]

H

Ventilator details

In this appendix more details about the ventilator are presented. In section H.1 the material and manufacturing process of these type of ventilators are described. In section H.2 the trade off process between the suitable ventilators is presented and in section H.3 the ventilator performance sheets are given as references for all the values.

H.1. Material and manufacturing process

A centrifugal ventilator is made out of a frame, impellers, motor, flanges and mounting. Depending on the type of ventilator the impellers are forward or backward radial curved. The forward radial curved impellers are made of high grade hot galvanizing steel sheets and are connected to the ventilator by riveting grippers on the middle disk plate and the end ring. The backward radial curved impellers are made of high grade cold-rolled and flat steel. For the connection to the ventilator the impellers are welded between the middle tray and the rear before leaving the factory.

The frame of the ventilator is welded with angle and flat steel. A polyester coating is used to finish off the frame, this assures the sufficient rigidity and intensity. The inlet flange is made of hot galvanizing steel sheet. The flange plates are connected to the side plates with electrical spot welding. The outlet flange is made of galvanized steel and the connection points are made by a TOX non-welding process.

The motor is made of 40 Cr or C45 carbon steel bars. The shaft is first roughly machined followed by stress relieving process before the final machining. The diameter is machined to very accurate tolerance levels and fully checked to assure the perfect fit. After assembly a coating is applied to provide a corrosion resistance. In the ventilator bearing balls are used to minimize the noise level. These bearings are pre-lubricated, sealed and self-centered. [41]

To estimate the mass of the different components, the percentage in table H.1 are considered [24].

Table H.1: Ventilator components mass distribution

Part	Percentage of total mass
Frame	35
Impellers	10
Motor	45
Flanges & mounting	10

H.2. Ventilator performance and selection

In table H.2 the parameters of the different ventilators that all fulfill the performance requirements are given [1]. Since all of the above ventilators are suitable for the required performance, the two most important factors for the trade-off are the mass and the energy consumption of the ventilator. The lower the mass, the less material is needed and therefore the a lower environmental impact during the production process. Also, for an offshore construction the platform needs to be able to carry less weight if a light weight system is build on top. The lower the energy consumption, the more efficient the system is. In this way, the water production will have a lower price. Therefore, the selected ventilator is the model SDY1000-K with the minimal operating configurations. This ventilator has forward impeller blades. Note, that the performance of the ventilator will be slightly different when placed in Curacao. This is due to difference in operating and testing weather conditions. For the current required mass flow through the system this model has a good range to optimize the perfect operating conditions on site. For an up scaled version, one could look into one of the other models, which offer higher volume flow rates.

Table H.2: Different ventilator performance parameters

Type	Power [kW]	Total efficiency [%]	Total pressure [Pa]	Mass [kg]	Energy consumption [kWh/m^3]
SYD1000-K_{min}	22	49	400	480	0.055
SYD1000-K_{max}	60	66	1400	480	0.112
SYQ1000-K_{min}	32	36	450	530	0.109
SYQ1000-K_{max}	50	62	1080	530	0.099
SYQ1000-Z_{max}	82	75	2250	535	0.134
SHY1000-K_{min}	22	22	195	530	0.123
SHY1000-K_{max}	58	63	1200	530	0.113
SHY1000-Z_{max}	85	70	2225	535	0.149

---

[1] The min and max subscripts stands for the minimal and maximal operation conditions, derived from the performance sheets.

H.3. Performance sheets

The ventilator performance data sheets are presented in figure H.1, H.2 and H.3, all obtained from Yilida [41].

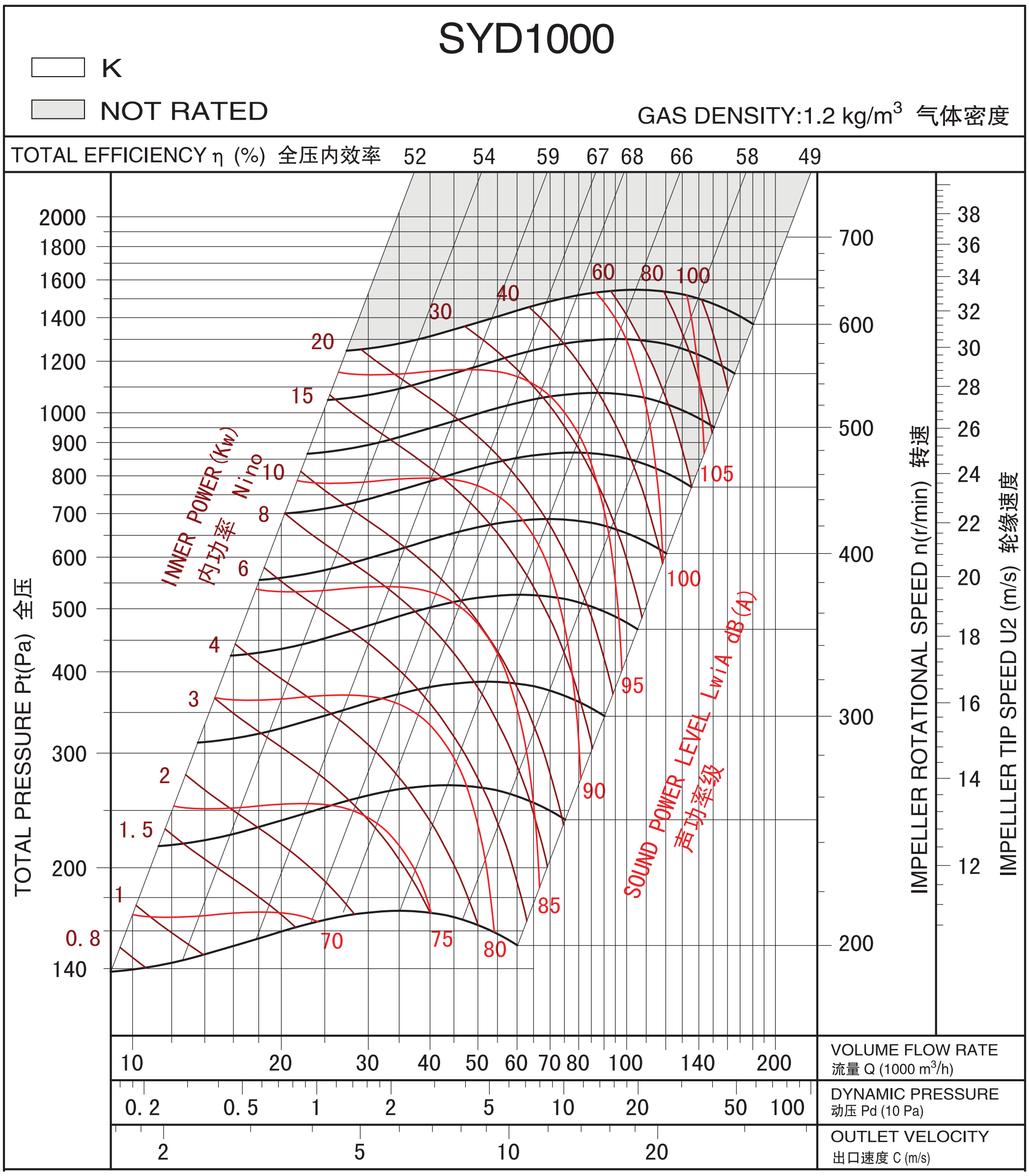


Figure H.1: Performance sheet of ventilator model SYD1000.

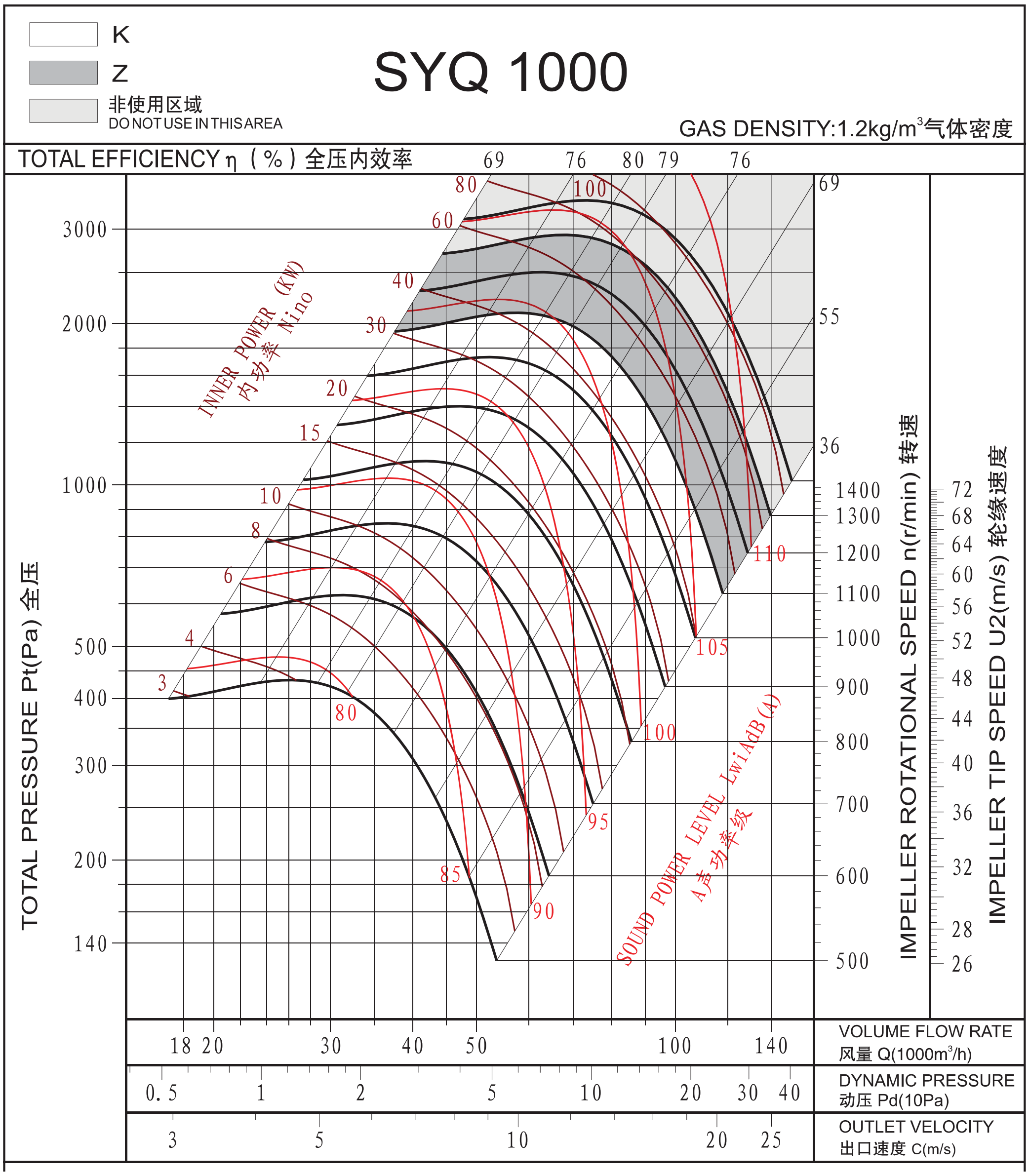


Figure H.2: Performance sheet of ventilator model SYQ1000.

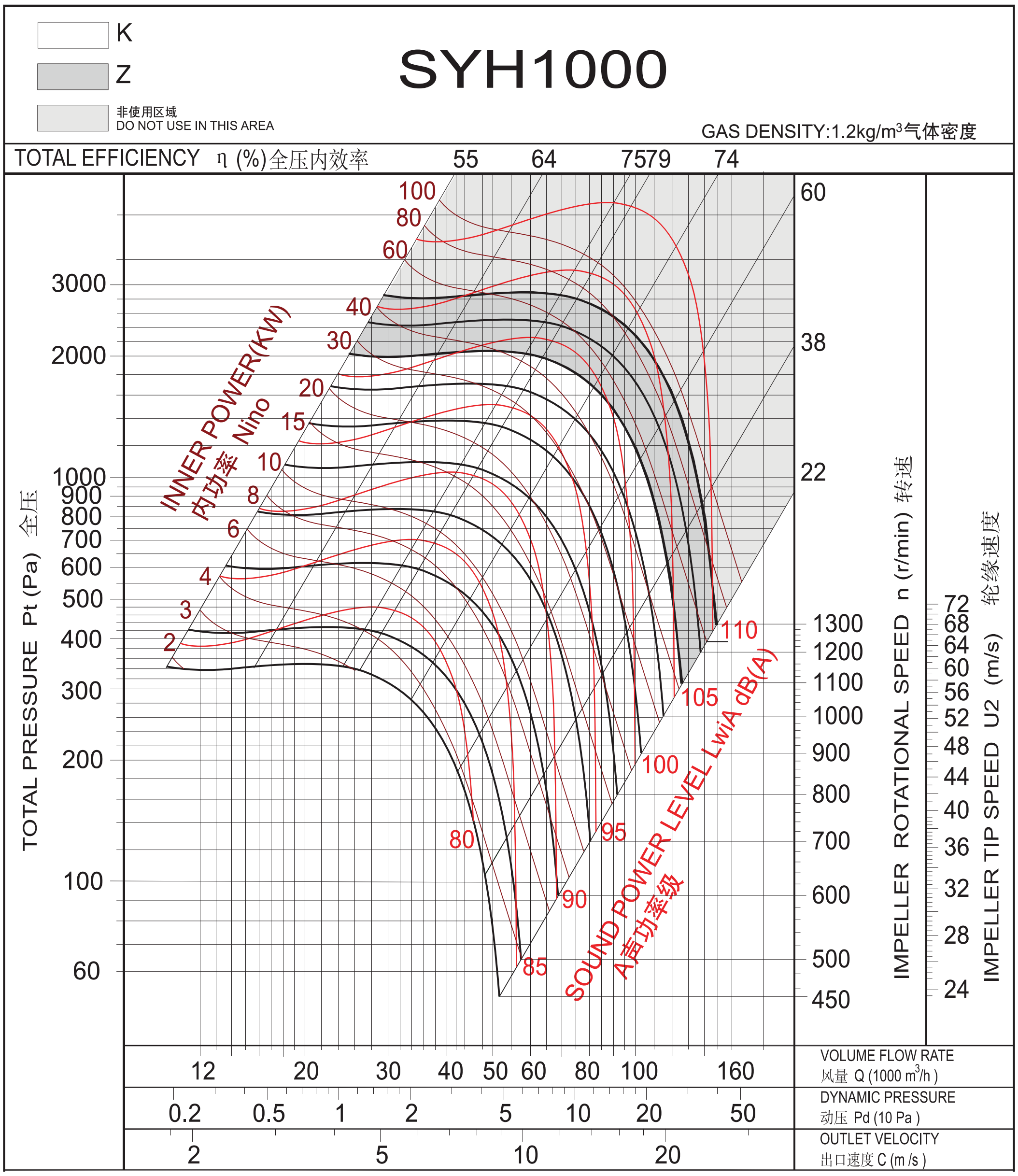


Figure H.3: Performance sheet of ventilator model SYH1000.

I

Reservoirs on Curacao

Curacao makes uses of a number of reservoirs to storage the produced fresh water. In table I.1 information on these reservoirs is presented.

Table I.1: Reservoir information of Curacao

Location	Number of reservoirs	Volume [m^3]
Production		
Mundo Nobo	4	48 400
Santa Barbara	2	7000
Distribution		
Tafelberg	2	19 944
Seru Pretu	3	31 566
Manuel Kuiper	2	16 670
Kintjan	2	9418
Scharloo	2	3700
Seinpost	2	10 663
Cocorie	1	4958
Domi	2	4248
Stenen Koraal	2	10 464
Trai Seru	1	5681
Lelienberg	1	5266
Fontein	1	5232
Flip (hydrofoor)	1	20
Total	28	183 230

Reservoirs, standpipes and elevated water storage tanks are the three different types of steel tanks. A reservoir is a ground supported, flat bottom cylindrical tank with a sheel height less than or equal to its diameter. Standpipes are ground-supported flat-bottom cylindrical storage tanks that are taller than their diameter. They are usually built where there is little elevated terrain and extra height is needed to create pressure for water distribution. A reservoir is the most frequently used tank for large volumes, due to the low weight of the structure is becomes economical to fabricate, assemble and maintain [8]. For the up scaled OTWP the production capacity is 25 000 m^3/day, and half of that volume will be used for the storage tank. The American Water Works Association [8] developed typical reservoir sizes, presented in table I.2. The corresponding reservoir capacity volume is 11 360 m^3, with a diameter of 34.7 m and height 12.2 m. In order to deliver during peak demands, the other distribution reservoirs in Curacao will take their responsibility in this. To take care of the water quality issues in the reservoir, the tank should be washed out every 3 years. This is done with low volume, moderate pressure (16.5 MPa) pumps.

Table I.2: Typical welded steel water-storage reservoir sizes

Capacity volume [m^3]	Diameter [m]	Height to TCL [m]
189	5.9	7.3
227	6.4	7.3
284	7.2	7.3
379	7.2	9.8
	8.2	7.3
473	7.9	9.8
	9.2	7.3
568	8.7	9.8
	10.0	7.3
757	10.0	9.8
	11.7	7.3
946	11.3	9.8
	13.0	7.3
1135	12.3	9.8
	14.3	7.3
1515	14.2	9.8
	16.5	7.3
1890	14.2	12.2
	15.9	9.8
	18.4	7.3
2270	15.6	12.2
	17.4	9.8
	17.4	12.2
2840	17.4	12.2
	19.5	9.8
3785	20.1	12.2
	22.6	9.8
5680	24.5	12.2
	27.6	9.8
7570	28.4	12.2
	31.9	9.8
11 360	34.7	12.2
	38.9	9.8
15 140	40.1	12.2
	44.9	9.8
18 930	44.8	12.2
	50.3	9.8
28 390	54.9	12.2
	61.4	9.8
37 850	71.0	9.8
	63.5	12.2

J

Impact assessment data

In this appendix the normalized and weighted values, which are used to created the figures for the impact assessment in chapter 5, are presented. This is done as a reference for the interested reader, since reading the exact values from the figures can be difficult.

J.1. CML-IA baseline

To present the overall scores of the different phases, the normalized values are given in table J.1, these values are dimensionless. All the impact categories with a 0.2% have been considered.

Table J.1: Normalized results obtained by CML-IA baseline method.

Impact category	**Installation**	**Operation**	**Dismantling**
Abiotic depletion	$4.08{\cdot}10^{-9}$	$7.07{\cdot}10^{-12}$	$1.02{\cdot}10^{-12}$
Abiotic depletion (fossil fuels)	$2.12{\cdot}10^{-9}$	$5.14{\cdot}10^{-10}$	$7.54{\cdot}10^{-12}$
Global warming (GWP100a)	$1.55{\cdot}10^{-9}$	$3.77{\cdot}10^{-10}$	$9.95{\cdot}10^{-11}$
Ozone layer depletion	$2.43{\cdot}10^{-11}$	$1.24{\cdot}10^{-11}$	$1.35{\cdot}10^{-13}$
Human toxicity	$4.65{\cdot}10^{-8}$	$8.58{\cdot}10^{-10}$	$9.02{\cdot}10^{-10}$
Fresh water aquatic ecotoxicity	$2.51{\cdot}10^{-8}$	$3.95{\cdot}10^{-10}$	$7.53{\cdot}10^{-9}$
Marine aquatic ecotoxicity	$7.17{\cdot}10^{-7}$	$6.28{\cdot}10^{-8}$	$4.97{\cdot}10^{-8}$
Terrestrial ecotoxicity	$3.27{\cdot}10^{-10}$	$1.46{\cdot}10^{-11}$	$1.15{\cdot}10^{-11}$
Photochemical oxidation	$8.81{\cdot}10^{-10}$	$1.12{\cdot}10^{-10}$	$3.00{\cdot}10^{-11}$
Acidification	$2.90{\cdot}10^{-9}$	$4.48{\cdot}10^{-10}$	$4.42{\cdot}10^{-12}$
Eutrophication	$9.43{\cdot}10^{-10}$	$4.60{\cdot}10^{-11}$	$1.57{\cdot}10^{-10}$
Total [%]	86.6	7.1	6.3

J.2. Eco-indicator 99

After the characterized results normalization and weighting is done. The results of the weighted impact categories are given in table J.2, all the values have the unit kPt. All the impact categories with a 0.2% have been considered. These values can be considered as dimensionless figures, where the developers of EI 99 named it Eco-indicator points (Pt). The main purpose is to compare the the relative differences between products. 1 Pt represents one thousandth of the yearly environmental load of one average European inhabitant, calculated by dividing the total environmental load in Europe by the number of inhabitants and multiplying with a scale factor of 1000 [9].

Table J.2: Weighted impact category results obtained from Eco-Indicator 99.

Impact category	**Installation**	**Operation**	**Dismantling**
Carcinogens	9.94	$7.28{\cdot}10^{-2}$	$6.99{\cdot}10^{-1}$
Resp. inorganics	3.71	$4.24{\cdot}10^{-1}$	$8.81{\cdot}10^{-3}$
Climate change	$6.16{\cdot}10^{-1}$	$1.50{\cdot}10^{-1}$	$3.29{\cdot}10^{-2}$
Ecotoxicity	$6.44{\cdot}10^{-1}$	$2.68{\cdot}10^{-2}$	$1.30{\cdot}10^{-1}$
Acidification	$1.01{\cdot}10^{-1}$	$1.85{\cdot}10^{-2}$	$4.69{\cdot}10^{-4}$
Minerals	$9.00{\cdot}10^{-1}$	$4.57{\cdot}10^{-3}$	$1.43{\cdot}10^{-4}$
Fossil fuels	1.74	$3.86{\cdot}10^{-1}$	$9.69{\cdot}10^{-3}$
Total [%[]	86.4	8.0	5.6

J.3. Ecopoints 97

The weighted results are modeled with the Ecopoints version, the normalization factors are equal to 1 [49]. These results are presented in table J.3, all the values have the unit MPt. All the impact categories with a 1.0% have been considered.

Table J.3: Weighted results of relevant airborne emissions obtained from Ecopoints 97.

Impact category	Installation	Operation	Dismantling
NO_x	9.98	2.15	$7.10\cdot10^{-2}$
SO_x	$2.74\cdot10^{1}$	4.13	$3.33\cdot10^{-2}$
NMVOC	1.58	$3.57\cdot10^{-1}$	$7.45{\cdot}10^{-3}$
Dust PM10	7.77	$1.11\cdot10^{-1}$	$1.29\cdot10^{-2}$
CO_2	$1.30\cdot10^{1}$	3.13	$6.83{\cdot}10^{-1}$
Cd (air)	2.16	$3.76\cdot10^{-2}$	$1.70\cdot10^{-3}$
Zn (water)	2.95	$3.77\cdot10^{-2}$	1.91
Cu (water)	8.53	$2.38\cdot10^{-1}$	$1.20\cdot10^{1}$
Cd (water)	2.60	$1.97\cdot10^{-2}$	1.68
Hg (water)	1.53	$5.03\cdot10^{-2}$	2.94
Waste	9.17	$6.35\cdot10^{-2}$	4.63
LMRAD	2.77	$6.13\cdot10^{-2}$	$8.86\cdot10^{-3}$
HRAD	5.84	$8.58\cdot10^{-2}$	$2.69\cdot10^{-2}$
Energy	1.06	$3.87\cdot10^{-1}$	$3.74\cdot10^{-3}$
Total [%[]	73.4	8.3	18.3

K

Flow Diagrams of the LCA subsystems

In this appendix the detailed flow diagrams of the components of the pilot OTWP system are given. All flow diagrams are produced with the normalized impact category values of abiotic depletion of the evaluation method CML.

K.1. Ventilator

In figure K.1 the detailed flow diagram of the ventilator is presented. Here a node cut-off of 1% is applied.

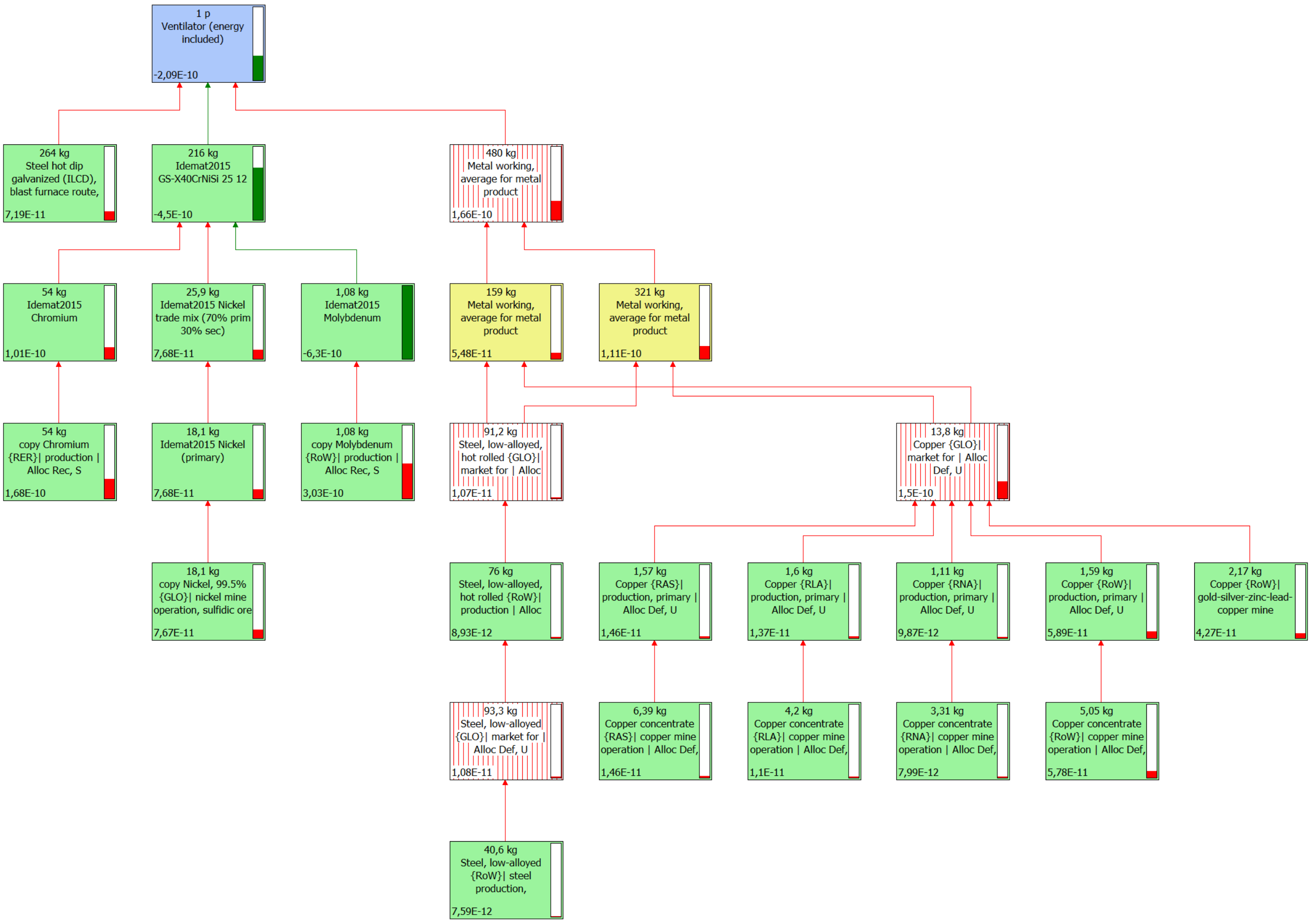


Figure K.1: The flow diagram of the ventilator in SimaPro.

K.2. Condenser and heat exchanger

In figure K.2 the flow diagram of the heat exchanger is presented, with a 5.9% node cut-off. In figure K.3 the detailed flow diagram of the condenser is given.

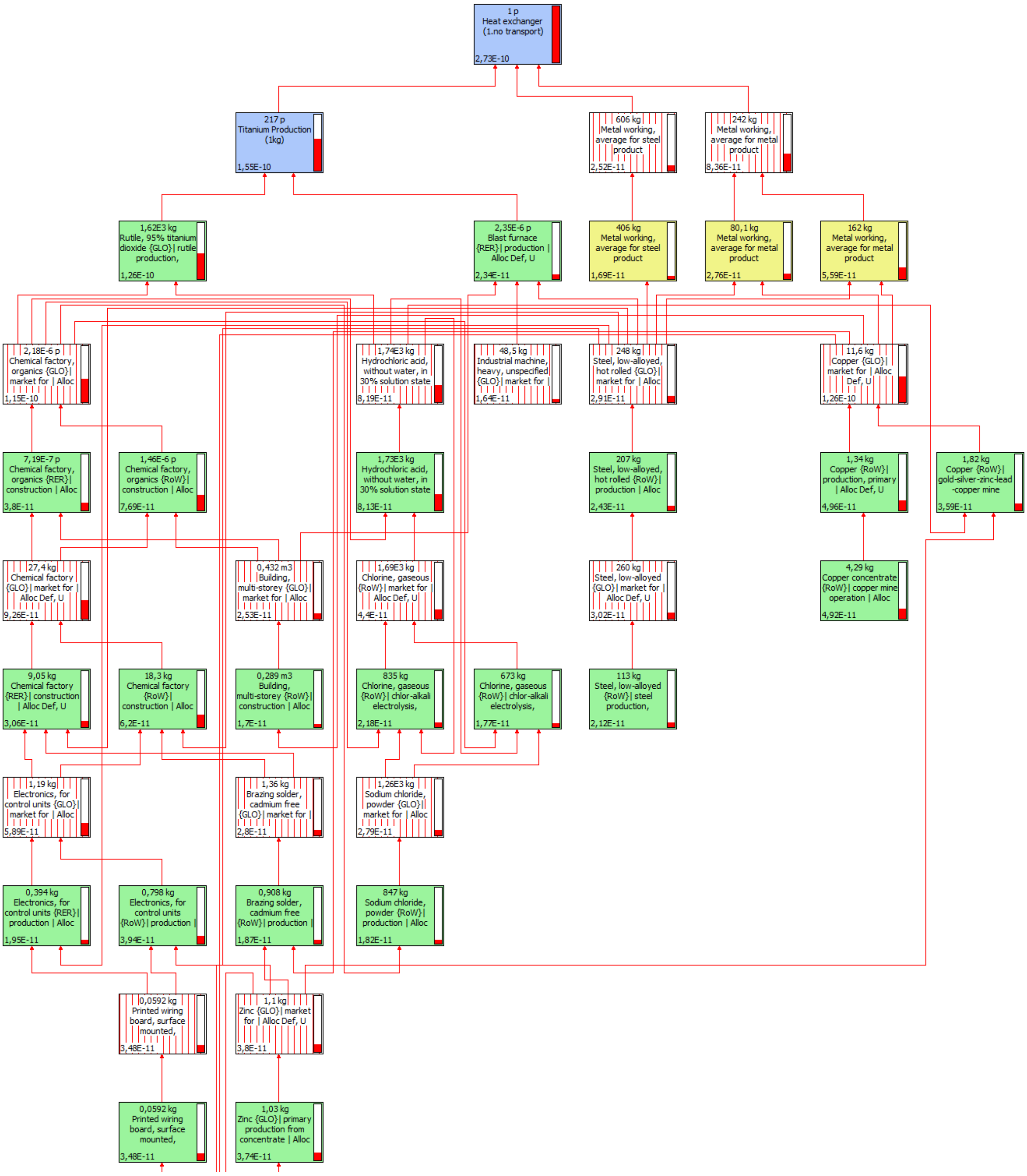


Figure K.2: Flow diagram of heat exchanger.

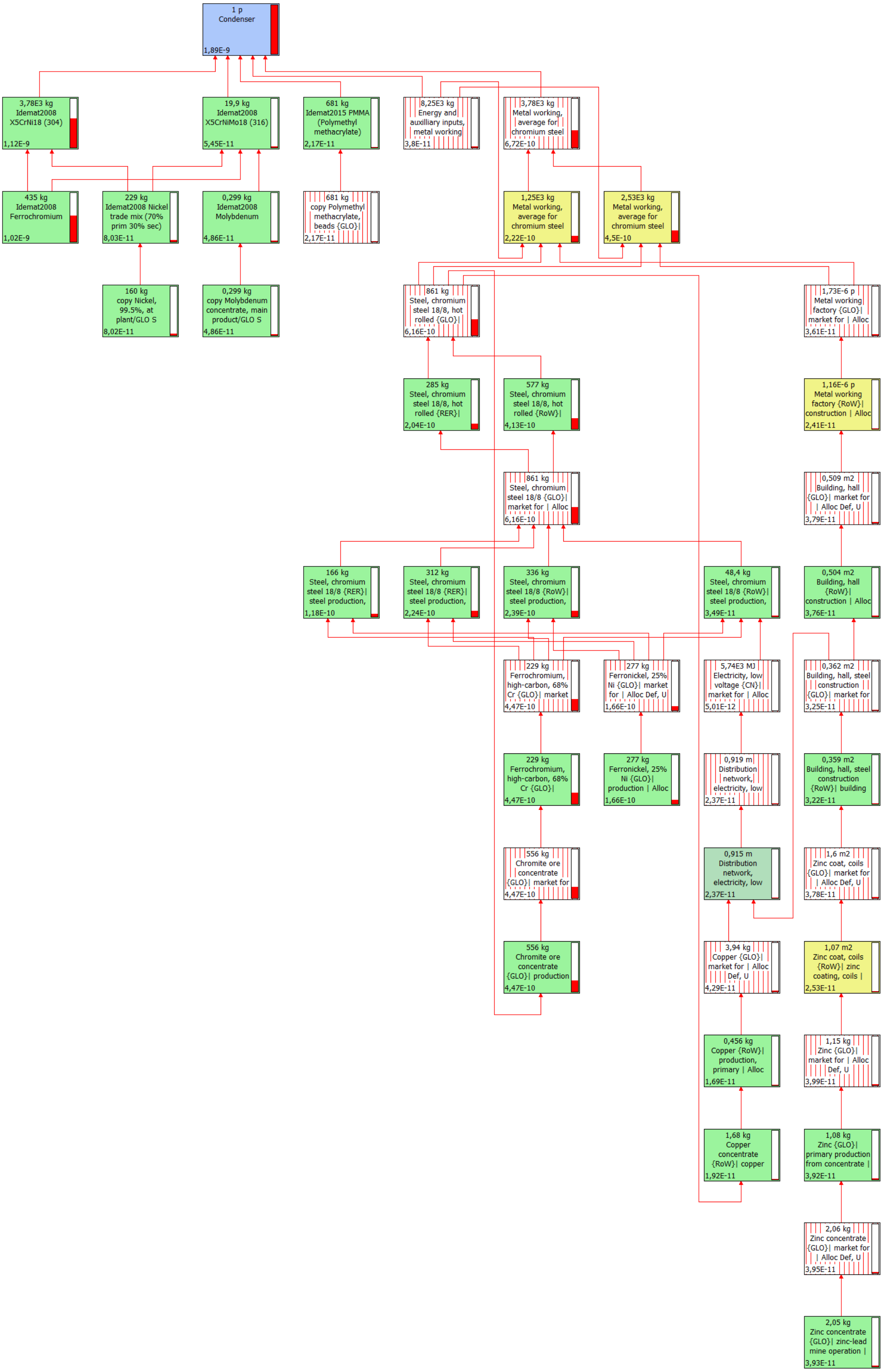


Figure K.3: Flow diagram of condenser.

K.3. Pumps

In figure K.4 the flow diagram of the seawater pump is given, with a 2% node cut-off.

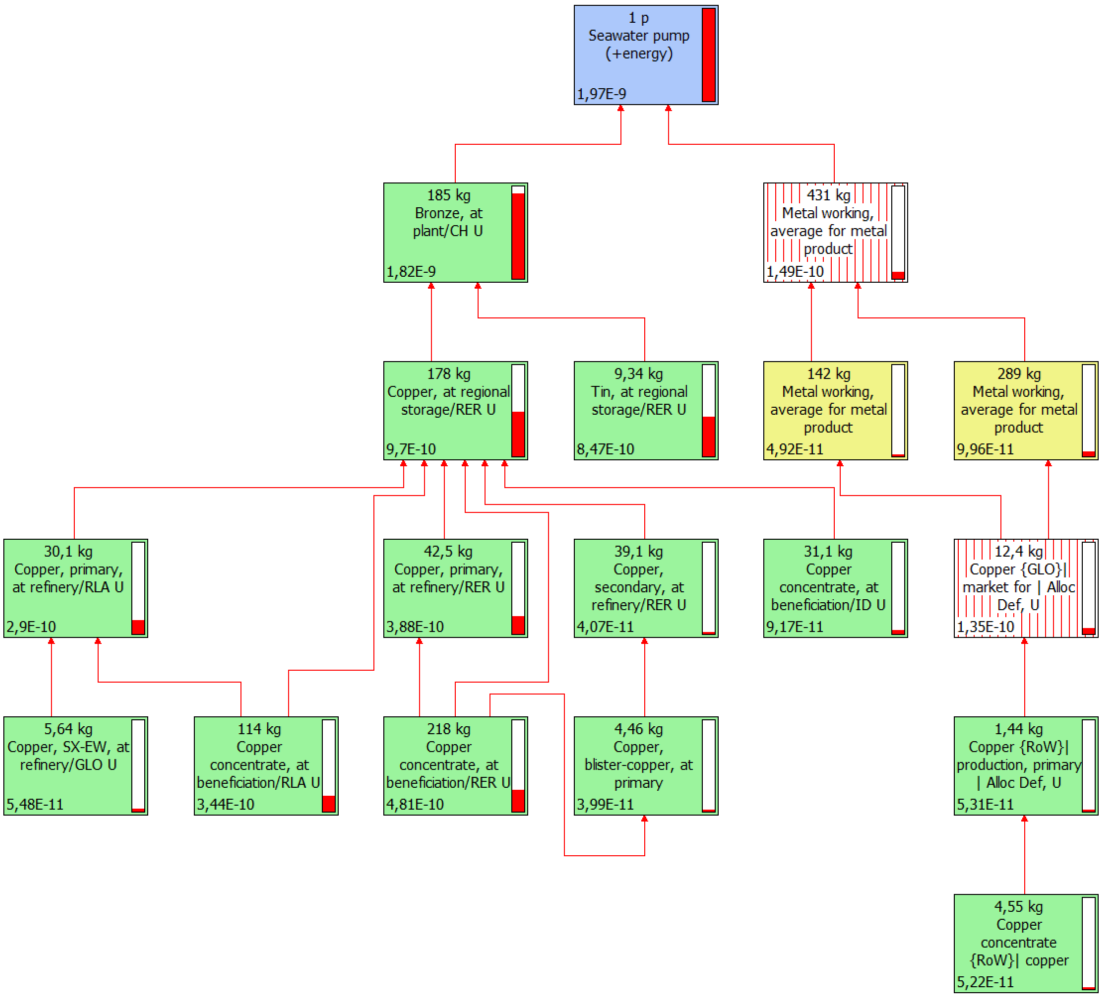


Figure K.4: The flow diagram of seawater pump.

In figure K.5 the flow diagram of the fresh water pump is presented, with a 4% node cut-off.

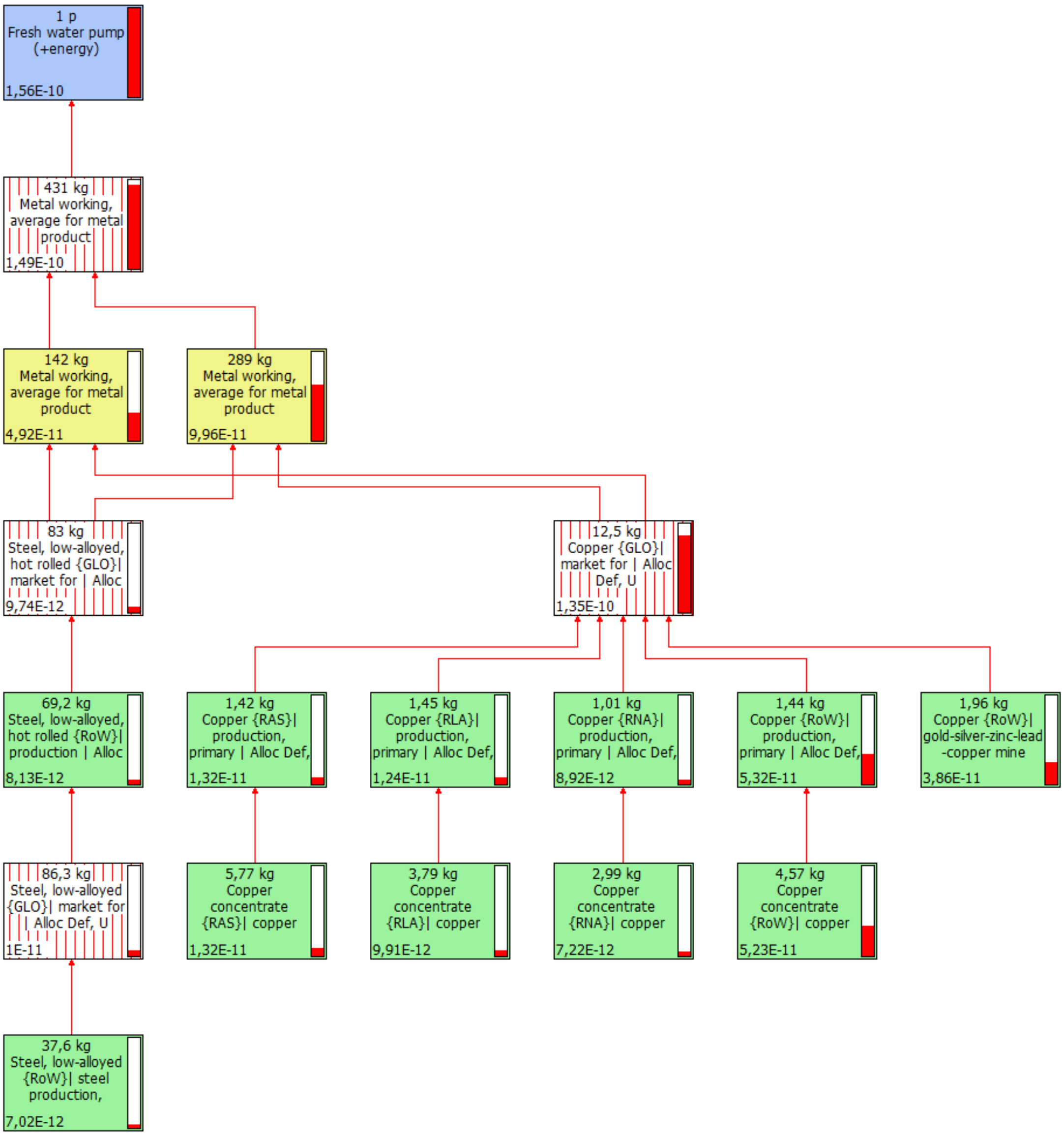


Figure K.5: Flow diagram of fresh water pump.

K.4. Water tank

In figure K.6 the flow diagram of the water tank is given. Here a node cut-off of 8% is applied.

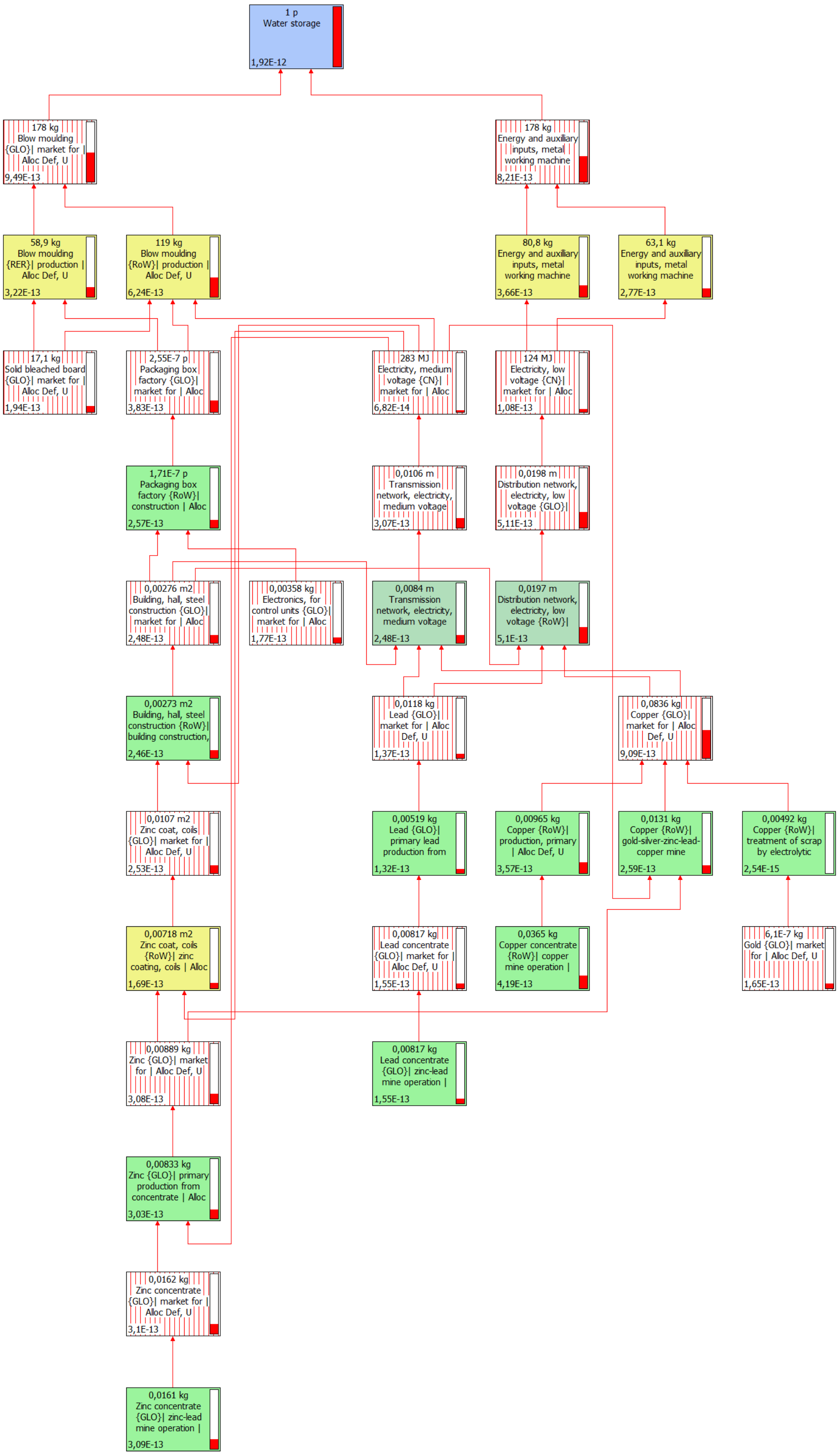


Figure K.6: Flow diagram of water tank.

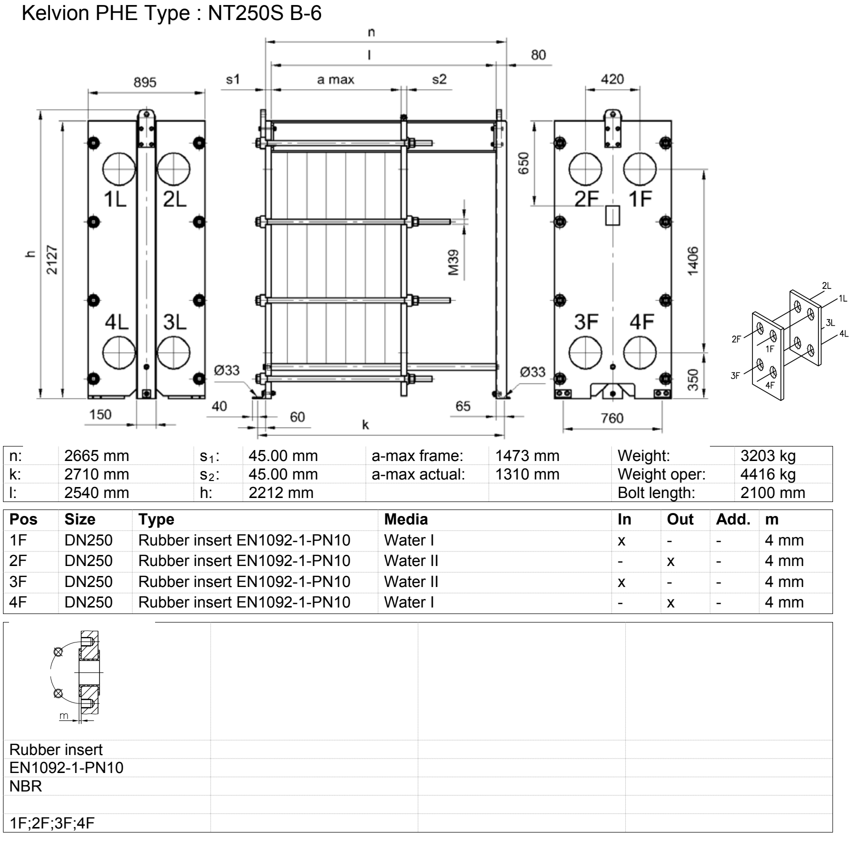
L

Upscaled component specifications

In this appendix the upscaled component specifications are given bellow for the heat exchanger, ventilator and water pump, respectively.

L.1. Heat exchanger

In figure L.1 the upscaled heat exchanger drawings are shown and in figure L.2 the table of the specifications is presented. All information is provided by the company Kapp Nederland BV [55].


Kelvion PHE Type : NT250S B-6

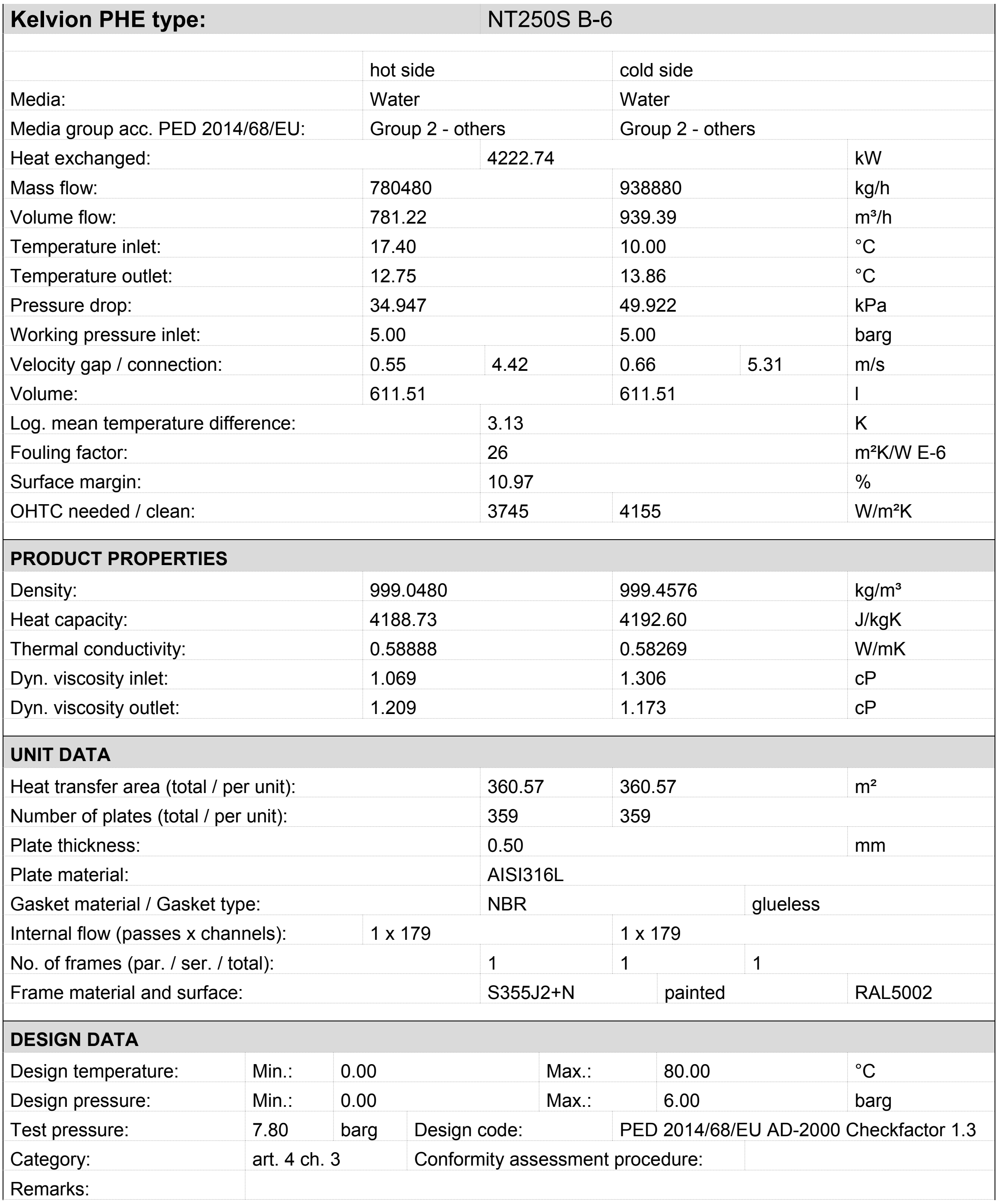
n:	2665 mm	s_1:	45.00 mm	a-max frame:	1473 mm	Weight:	3203 kg
k:	2710 mm	s_2:	45.00 mm	a-max actual:	1310 mm	Weight oper:	4416 kg
l:	2540 mm	h:	2212 mm			Bolt length:	2100 mm

Pos	Size	Type	Media	In	Out	Add.	m
1F	DN250	Rubber insert EN1092-1-PN10	Water I	x	-	-	4 mm
2F	DN250	Rubber insert EN1092-1-PN10	Water II	-	x	-	4 mm
3F	DN250	Rubber insert EN1092-1-PN10	Water II	x	-	-	4 mm
4F	DN250	Rubber insert EN1092-1-PN10	Water I	-	x	-	4 mm

Rubber insert
EN1092-1-PN10
NBR

1F;2F;3F;4F

Figure L.1: The upscaled plate heat exchanger drawings [55].



Kelvion PHE type:		NT250S B-6			
	hot side		cold side		
Media:	Water		Water		
Media group acc. PED 2014/68/EU:	Group 2 - others		Group 2 - others		
Heat exchanged:		4222.74			kW
Mass flow:	780480		938880		kg/h
Volume flow:	781.22		939.39		m³/h
Temperature inlet:	17.40		10.00		°C
Temperature outlet:	12.75		13.86		°C
Pressure drop:	34.947		49.922		kPa
Working pressure inlet:	5.00		5.00		barg
Velocity gap / connection:	0.55	4.42	0.66	5.31	m/s
Volume:	611.51		611.51		l
Log. mean temperature difference:		3.13			K
Fouling factor:		26			m²K/W E-6
Surface margin:		10.97			%
OHTC needed / clean:		3745	4155		W/m²K
PRODUCT PROPERTIES					
Density:	999.0480		999.4576		kg/m³
Heat capacity:	4188.73		4192.60		J/kgK
Thermal conductivity:	0.58888		0.58269		W/mK
Dyn. viscosity inlet:	1.069		1.306		cP
Dyn. viscosity outlet:	1.209		1.173		cP
UNIT DATA					
Heat transfer area (total / per unit):		360.57	360.57		m²
Number of plates (total / per unit):		359	359		
Plate thickness:		0.50			mm
Plate material:		AISI316L			
Gasket material / Gasket type:		NBR		glueless	
Internal flow (passes x channels):	1 x 179		1 x 179		
No. of frames (par. / ser. / total):		1	1	1	
Frame material and surface:		S355J2+N	painted		RAL5002

DESIGN DATA					
Design temperature:	Min.:	0.00	Max.:	80.00	°C
Design pressure:	Min.:	0.00	Max.:	6.00	barg
Test pressure:	7.80	barg	Design code:	PED 2014/68/EU AD-2000 Checkfactor 1.3	
Category:	art. 4 ch. 3		Conformity assessment procedure:		
Remarks:					

Figure L.2: The upscaled plate heat exchanger specifications [55].

L.2. Ventilator

In figure L.3 the upscaled ventialtor performance sheet is presented. This is copied from the company Yilida [41].

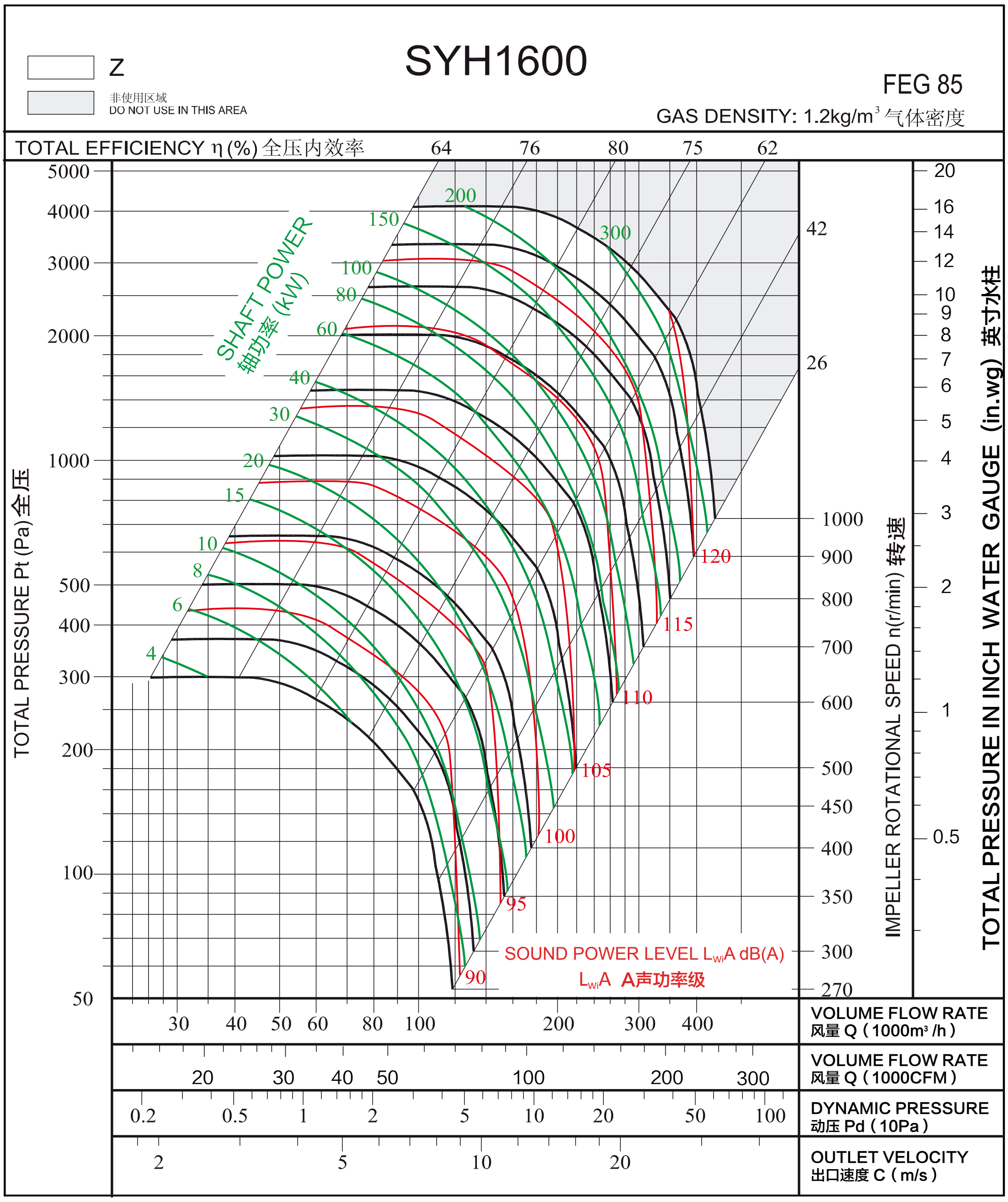
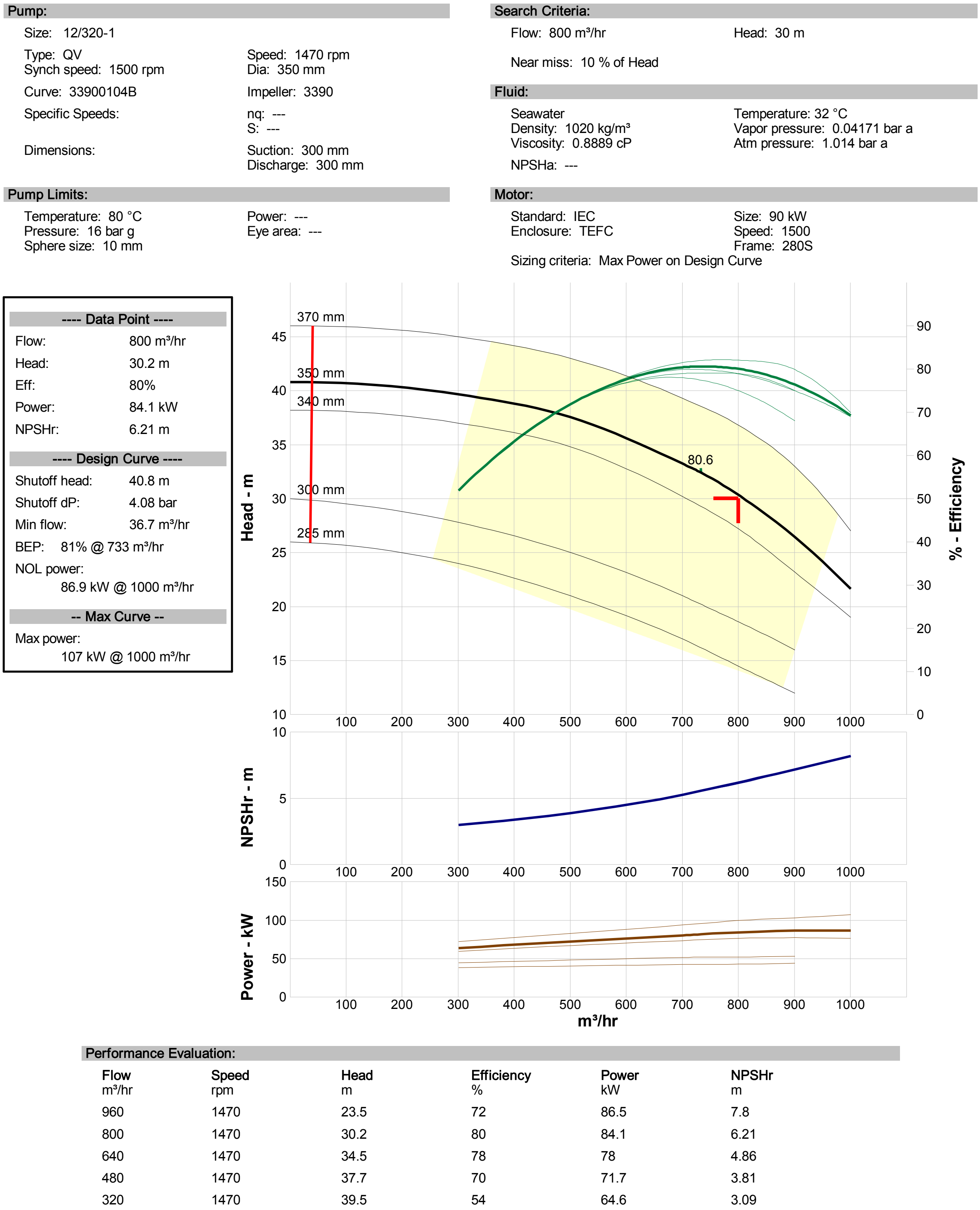


Figure L.3: The upscaled ventilator performance sheet [41].

L.3. Water pump

In figure L.4 the upscaled water pump data is available. Provided by the company Iron Pump [20].



Pump:

Size: 12/320-1

Type: QV
Synch speed: 1500 rpm

Speed: 1470 rpm
Dia: 350 mm

Curve: 33900104B

Impeller: 3390

Specific Speeds:

nq: ---
S: ---

Dimensions:

Suction: 300 mm
Discharge: 300 mm

Search Criteria:

Flow: 800 m³/hr

Head: 30 m

Near miss: 10 % of Head

Fluid:

Seawater
Density: 1020 kg/m³
Viscosity: 0.8889 cP

Temperature: 32 °C
Vapor pressure: 0.04171 bar a
Atm pressure: 1.014 bar a

NPSHa: ---

Pump Limits:

Temperature: 80 °C
Pressure: 16 bar g
Sphere size: 10 mm

Power: ---
Eye area: ---

Motor:

Standard: IEC
Enclosure: TEFC

Size: 90 kW
Speed: 1500
Frame: 280S

Sizing criteria: Max Power on Design Curve

---- Data Point ----	
Flow:	800 m³/hr
Head:	30.2 m
Eff:	80%
Power:	84.1 kW
NPSHr:	6.21 m

---- Design Curve ----	
Shutoff head:	40.8 m
Shutoff dP:	4.08 bar
Min flow:	36.7 m³/hr
BEP:	81% @ 733 m³/hr
NOL power:	86.9 kW @ 1000 m³/hr

-- Max Curve --	
Max power:	107 kW @ 1000 m³/hr

Performance Evaluation:

Flow m³/hr	Speed rpm	Head m	Efficiency %	Power kW	NPSHr m
960	1470	23.5	72	86.5	7.8
800	1470	30.2	80	84.1	6.21
640	1470	34.5	78	78	4.86
480	1470	37.7	70	71.7	3.81
320	1470	39.5	54	64.6	3.09

Figure L.4: The upscaled water pump data sheet [20].