Environmental Impact of Wastewater Treatment

- A Study of Membrane Bioreactor and Iso-Disc Technologies from a Life Cycle Perspective

Isabelle Zilling and Krister Lestander

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Department of Technology and Society
Faculty of Engineering at Lund University

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‘What gets measured gets managed, and that what is not measured or measurable runs the risk of being neglected.’

- Hauschild, Rosenbaum and Olsen (Life Cycle Assessment Theory and Practice, 2018, p. v).

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LUND UNIVERSITY
Department of Technology and Society
Environmental and Energy Systems Studies
Box 118
SE - 221 00 Lund, Sweden
Telephone: int+46 46-222 00 00
Telefax: int+46 46-222 86 44

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Isabelle Zilling
Krister Lestander

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Abstract

This study evaluates and compares two different wastewater treatment technologies from a life cycle perspective. The evaluating technologies are Membrane Bioreactor (MBR) technology with a microfiltration membrane and Iso-Disc technology. Both technologies are gaining market share and are an important step in a wastewater treatment plant to guarantee good effluent quality of water. In this study we use the ReCiPe Midpoint (H) methodology and eleven impact categories are evaluated.

Our result shows that the Iso-Disc technology has the lowest environmental impact of all eleven impact categories when production, operation and transport are compared to the MBR technology. The operation phase has the greatest impact on the environment of all categories for both technologies. The study highlights the differences in environmental impact depending on the location of the wastewater treatment plant, where the electricity mixes of Australia, Denmark and Sweden are evaluated. When the purification level of each technology is considered, the results are changed. When indirect emissions of phosphorus and nitrogen in the suspended solids of the effluent are included, the MBR technology will be the best alternative from the impact category marine eutrophication potential. This goes for all three locations, whether it is in Sweden, Australia or Denmark. The MBR technology will also be the best alternative from the impact category freshwater eutrophication potential if the plant is located in Denmark or Sweden. When the plant is located in Australia, the Iso-Disc will still be the better alternative from the impact category freshwater eutrophication potential. The result implies, that since the electricity mix have a big impact on the result, it is important to consider the location of the plant while choosing technology from an eutrophication aspect. A better purification level will not always reduce the total emissions according to eutrophication, especially if the electricity mix consists of a large share of fossil electricity and the technology is energy intensive. It is also important to include parameters such as the purification level while doing a life cycle assessment, where different wastewater treatment technologies are being compared. The reason for this is because indirect emissions linked to the purification level, were shown to have a big impact on the environment according to eutrophication.

Keywords

MBR technology, Iso-Disc technology, Life cycle assessment, Wastewater treatment, Conventional activated sludge process, Activated sludge process, Electricity mix

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Lund, 2019-05-27

Isabelle Zilling & Krister Lestander

Terminology

Biochemical Oxygen Demand (BOD) is a measurement of organic matter levels while removing organics (Judd & Judd, 2011). Microorganisms consume oxygen in polluted water. This demand of oxygen can be measured in order to measure the extent of the pollution (Henze et al., 2002). BOD_7 stands for the amount of oxygen that the microorganisms need in order to decompose organic matter in the water, during a time period of seven days (Naturvårdsverket, 2019). The lower the BOD concentration is, the cleaner the water is. Clean water has BOD 0 and sewage has BOD of several hundreds mg/l (Naturvårdsverket, 2019).

Blue water is groundwater and surface water that is evaporated as a result of human use (Boyd & McNevin, 2015).

Disinfection is selective destruction of bacteria and virus. This shall not be confused with sterilisation, which destroys all organisms (Singh, 2015).

Emerging pollutants are naturally and synthetic chemicals or microorganisms that can cause unfavourable ecological and/or human health effects, but are not commonly observed in the environment (UNESCO, 2017).

Flux is the quantity of substance passing through a unit area of membrane per unit of time (Judd & Judd, 2011).

Microorganisms are defined as organisms on a micro level such as bacteria or virus (Lindskog & Zetterberg, 1975).

MLSS stands for Mixed Liquor Suspended Solids (Judd & Judd, 2011).

Population equivalent (PE) stands for 0.2 m^3/person/day (Henze et al., 2008).

TSS stands for Total Suspended Solids (Tchobanoglous, Burton & Stensel, 2003).

Wastewater is used water that contains dissolved or suspended waste materials (US EPA, 2016).

Contents

1 Introduction

Wastewater treatment is a matter of highest importance and should be a top priority not only now, but also for future generations. Clean fresh water is a prerequisite for humans, animals and plants (McNabb, 2017). Hence, wastewater treatment is necessary to prevent pollution of the world's finite water resources. In 2015, the United Nations presented Agenda 2030, consisting of 17 sustainable development goals, where target 6.3 states how untreated wastewater is reduced by 50 % by 2030 (Regeringskansliet, 2015). It is not only a crucial goal but also a necessity, since an alarming report from UNESCO (2017) declares that presumably 80 % of worldwide wastewater is released into the environment without adequate treatment. In some developing countries, more than 95 % of wastewater is released into the environment without any treatment at all (UNESCO, 2017).

Untreated wastewater can have devastating consequences on ecosystems, animals and humans. This is demonstrated by eutrophication among other things, which for example can lead to lack of oxygen and the death of fish and other aquatic organisms (Axe & Johansson, 2014). Today, when wastewater treatment plants are installed, these plants must counteract the consequences of untreated wastewater. Wastewater treatment consists of different treatment steps, with the aim to treat wastewater before it is returned to nature (André et al., n.d). Wastewater from industry, agriculture and municipalities, ends up in a wastewater treatment plant and may consist of a lot of different substances, which need to be removed from the wastewater before it is released (UNESCO, 2017). In Sweden, there are different limit values of what may be discharged from a wastewater treatment plant (Naturvårdsverket, 2018b). For example, the urban wastewater directive regulates a limitation value of phosphorus of 1-2 mg/litre. The maximum permissible emission value for nitrogen is 10-15 mg/litre and BOD_7 15 mg/litre in Sweden (Naturvårdsverket, 2018b). With stricter regulations of the effluent and an increased usage of pharmaceuticals that end up in the wastewater, advanced treatment plays an important role (Krezeminski et al., 2017; Sundin et al., 2017).

Two technologies that are increasingly gaining market share are the Membrane Bioreactor (MBR) technology and the Iso-Disc Cloth Media Filter technology. The MBR system is a combination of membrane filtration with an activated sludge process, where the membrane pore size determines the purification level[1]. The Iso-Disc system is a filtration disc combined with a conventional activated sludge (CAS) process[1]. Just like the function of the membranes, particles smaller than the cloth screen will pass through the filter (Tchobanoglous, Burton & Stensel, 2003). Both technologies are important in order to ensure a higher purification level on the effluent water. The reason why MBRs are gaining market share is primarily because of a higher level of purification. However, it competes with the CAS system, since the MBR is more expensive due to its energy requirements, the need of chemicals for cleaning and the fact that they must be regularly replaced (Krezeminski et al., 2017). The aim of this study is to evaluate these two technologies from an environmental point of view, applied to a municipal wastewater treatment plant.

Although wastewater treatment is indispensable, it is important to make sure that the technology that is used is optimal from an environmental point of view. If not, there is a concern that the pollution is not removed but only moved from one place to another (Rodriguez-Garcia et al.,

[1] Bengtsson, Jessica; Global Sales Manager – Membrane Water and Food Components, Alfa Laval. 2019. Personal Communication

2011). In order to evaluate the environmental impact of different wastewater technologies, Life Cycle Assessment (LCA) can be used. LCA becomes an important tool for mapping the environmental impact and for comparing different wastewater treatment technologies to each other (Larsen, 2018).

When studying MBR and wastewater treatment, the same conclusion can be drawn; the great energy demand is one of the major challenges for MBR technology (Ioannou-Ttofa et al., 2016; Krezeminski et al., 2017; Pretel et al., 2013). Due to the obstacles with MBR energy issues, many researchers as well as MBR suppliers have now focused their attention to studies in efficiency and energy consumption regarding MBR technology (Krezeminski et al., 2017). To minimize the energy demand, Alfa Laval has launched a new technology for their MBR products. In this technology, an airlift system is used, instead of energy demanding pumps (Alfa Laval, 2018).

The technologies that are investigated in this study play a key role when it comes to sustainability since wastewater management is crucial in order not to pollute oceans and seas. Still, it is of high importance that wastewater management provides efficient systems with minimal environmental impact. To the best of our knowledge, no previous study has investigated MBR modules with the technology Alfa Laval provides. This study contributes to the existing literature by evaluating the impact of the MBR technology, where the sludge recycle pumps are replaced by an airlift system. Taking limited resources into account, this can be an interesting alternative for future wastewater management. Further, the study compares the new MBR technology with the Iso-Disc Cloth Media Filter technology, both supplied by Alfa Laval, in order to evaluate the environmental differences between these technologies.

1.1 Goal and Purpose

The goal of this study is to present an LCA on two wastewater treatment processes, both designed for a 9 500 population equivalent (PE) sized plant (i.e. 1 900 m^3 water/day). The purpose is to show and compare the environmental impact of the MBR technology with a microfiltration membrane combined with an activated sludge process, and Iso-Disc filter technology combined with a conventional activated sludge process. Both the activated sludge process and the conventional activated sludge process are designed for a biological nitrogen removal process. Further, the purpose is to evaluate which parts have the most environmental impact and to identify which improvements can be done in order to decrease the environmental impact of each technology.

1.2 Research Questions

In order to achieve the purpose of the study, the following research questions are formulated;

- How do the two technologies differ from each other by environmental impact and primary energy consumption?

- Which parts contribute the most to the impact of the result?

- What improvement opportunities are identified based on environmental impact and energy consumption of each technology?

1.3 Outline of Report

The study is divided into a literature review and a life cycle assessment followed by an interpretation and discussion. The purpose of the literature review is to give an underlying understanding and create knowledge on the importance of wastewater treatment and create an overview of the research situation. The purpose of this part is to create an understanding of wastewater treatment technologies that is necessary in order to determine the quality of the life cycle assessment. The literature review is presented in the next section. Thereafter the methodology is outlined, where the life cycle assessment is fully described and the delimitations that have been made are presented under 'System Boundaries'. The methodology is followed up by the life cycle assessment part.

2 Literature Review

2.1 Short History of Wastewater

The timeline illustrated in figure 2.1, shows important steps in the development of human wastewater management from the Minoan Era and forward. During the Minoan Era (about 3200-1100 BC), advanced hydraulic water and wastewater techniques were established in the Ancient Greece (Vannevel, 2017). The inventions created opportunities to collect, store and distribute rainwater and groundwater. It also enabled drainage of runoff and sewage water. From tunnelling networks the Greeks produced a public supply network system for providing running water and flushing toilets (Vannevel, 2017). Between 50 AD and 455 AD, the Romans constructed a water supply and a discharge system in Cologne. The construction of the underground sewers was made of bricks. The sewers consisted of downpipes and inlet pipes made of wood or clay and had headroom up to 2.5 metre. In 1310 AD, a sewer was constructed in Prague even though the streets in the city consisted of open channels for centuries (Vannevel, 2017). However, the innovations were forgotten over time and many innovations during the sanitary revolution (19^{th} century) were in fact more or less re-innovations (Vannevel, 2017).

London can be seen as the first city that experienced environmental effects due to the industrial revolution (Vannevel, 2017). Fossil fuels were widely used, and the environmental issues continued to grow (Gröndahl & Svanström, 2010). In the beginning of the 20^{th} century the water closet (WC) was introduced. The sanitary problem in the cities, with diseases as a result, was considered to have a solution with the introduction of the WC (Gröndahl & Svanström, 2010). Gröndahl and Svanström (2010) explain how the sewers led directly to rivers, lakes and seas nearby the cities and the actions were explained with the dilution philosophy (Gröndahl & Svanström, 2010) with the mistaken belief 'the solution to pollution is dilution' (UNESCO, 2017). The nature itself would be able to handle the emissions, since the impact of the dilution in the watercourses was small in the beginning (Gröndahl & Svanström, 2010). In 1880, twelve cities in Sweden were equipped with underground sewer systems, which led directly to lakes or coastal waters nearby the cities (André et al., n.d). The dilution philosophy was adapted for many years, and it was not until the middle of the 1950s that a change would take place (Gröndahl & Svanström, 2010). In 1920, the Swedish government rejected a legal proposal from a state inquiry committee with restrictions for polluted emissions (Gröndahl & Svanström, 2010). The first wastewater treatment plant in Sweden was installed in Stockholm in 1934 (Stockholm vatten och avfall, 2017). A vague regulation on treatment of wastewater was included in the Swedish legislation in 1940 but the Swedish society was still very characterized by the dilution philosophy and environment protections were not financed. In 1956, the Swedish government introduced a regulation against discharge of unclean wastewater, which also can be seen as the start of the filter philosophy where end-of-pipe treatment occurred (Gröndahl & Svanström, 2010). During the 1970s the Swedish government put extensive investments in municipal wastewater capacity, which resulted in cleaner lakes and rivers, fish returning and bathing areas to reopen (André et al., n.d).

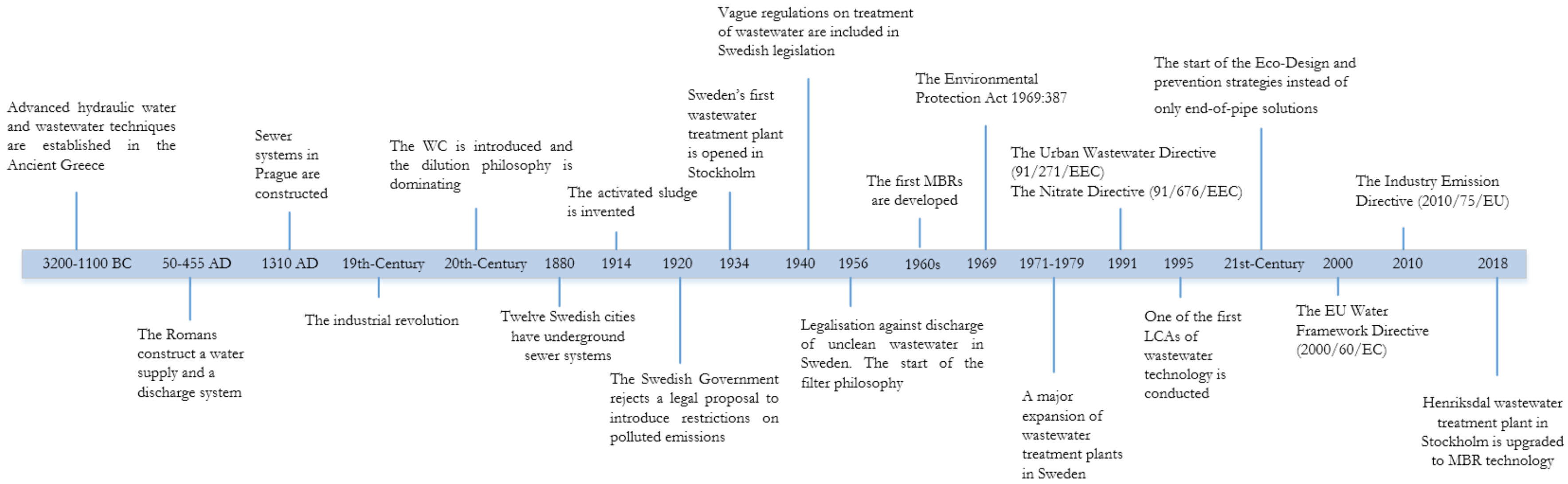

Figure 2.1: Timeline of important steps in the development of human wastewater management in both Sweden and in a global context.

As described above, wastewater techniques are not a modern invention, even though more advanced and efficient techniques occur in modern times like the Membrane Bioreactor (MBR) technology, invented in the late 1960s (Judd & Judd, 2011). The MBR technology was combined with an activated sludge process, a treatment technology invented in the United Kingdom in 1914 (Daigger, 2014). In 2018, the Henriksdal wastewater treatment plant in Stockholm was upgraded to MBR technology, making it one of the largest MBR plants in the world (Krezeminski et al., 2017).

Regulations

After the legalisation against discharge of unclean wastewater in Sweden in 1956 (Gröndahl & Svanström, 2010), the Swedish governement established the Environmental Protection Act (1969:387) in 1969 (André et al., n.d). Other important directives that have been establised in Europe are the Urban Wastewater Directive (91/271/EEC), which was regulated in order to protect the environment from wastewater discharges (European Commission, 2019a). In the same year, the Nitrate Directive was established (European Commission, 2018). In 2000, the EU Water Framework Directive (2000/60/EC) was regulated to save groundwater and surface water in Europe. The goal of the updated directive is to ensure that clean water is kept clean at the same time as polluted water will be clean again (European Commission, 2016). In 2010, the Industry Emission Directive was established in order to regulate emissions such as discharges of wastewater from industrial installations (European Commission, 2019b). In 2017, twelve wastewater treatment plants in Sweden did not reach the requirements of the EU Urban Wastewater Directive, a crime that can lead to high fines (Vinthagen, 2017).

The Eco Design Era

In the 21st century the eco design era is taking place, where actions are made to prevent emissions instead of doing nothing at all or only mitigate the damage with different filter systems (UNESCO, 2017). LCA has become an important tool and in the middle of the 1990s the first LCA of wastewater treatment was conducted (Larsen, 2018; Corominas et al., 2013).

Circular economy (CE) plays an important role in the political agenda in order to achieve sustainable environmental and economic development (Korhonen et al. 2018; Kalmykova, Sadagopan & Rosado, 2018). The idea of a circular economy opposes the traditional linear 'extract-produce-use-dump' material and energy flow (Korhonen et al., 2018). Instead the circular economy keeps the material flow circulating (Kalmykova, Sadagopan & Rosado, 2018). Focus is now on renewable energy and how to eliminate toxic chemicals. Through careful design, waste will be eradicated since the amount of needed material and energy in the manufacturing process will be minimized and reused (Kalmykova, Sadagopan & Rosado, 2018). In the circular economy, wastewater management plays an important role and can support the green economy and generate new business opportunities (UNESCO, 2017).

Over time, wastewater has usually been seen as a burden (UNESCO, 2017). However, the report of UNESCO (2017) describes how wastewater can be a sustainable source of water, energy, nutrients, organic matter and other by-products. Energy can be transformed from the sludge of the wastewater treatment plant to biogas (UNESCO, 2017). The extractable mineral phosphorus is predicted to become scarce over the next decades (UNESCO, 2017). However, the report of UNESCO (2017) predicts wastewater to become an important component in order to extract nitrogen and phosphorus, which can be collected through urine. Case studies in Asia have shown that by-products from wastewater such as fertilizer can generate revenues higher than the operational costs of the wastewater system (UNESCO, 2017). Wastewater treatment that harvests by-products can be a profit-producing business model, which opposes the general picture of being expensive (UNESCO, 2017).

2.2 Human Water Consumption

Of the total water in the world, approximately 97.5 % is salt water. Of the remaining 2.5 % of freshwater, only 1% is available for withdrawal and human use (Corcoran et al., 2010). This corresponds to an amount of 200 000 km^3 water (Moström, 2012). Steffen et al. (2015) present an updated version of the planetary boundaries. The planetary boundaries refer to the environmental boundaries that govern the earth's stability, which shall not be exceeded. The report by Steffen et al. (2015) shows that four out of nine planetary boundaries are today exceeded; climate change, biogeochemical flows of phosphorus and nitrogen, genetic diversity and land-system change. However, the report shows that the use of freshwater is in the zone 'below boundary' and is thereby classified as safe. The global planetary boundary of freshwater is set to 4 000 km^3/year and measures the consumptive use of blue water (Steffen et al., 2015). However, the report of Jaramillo and Destouni (2015) shows that human consumption today exceeds the proposed limit of 4 000 km^3/year (Jaramillo & Destouni, 2015). It also shows that the total global human annual blue water consumption is 4 370 $^+$/- 979 km^3. Due to the evapotranspiration effect, the global water footprint is estimated to 10 688 $^+$/- 979 km^3/year (Jaramillo & Destouni, 2015).

The human water footprint describes the actual volume of freshwater that a person consumes per year but also the water consumption used for producing goods and services that the person consumes (Moström, 2012). Figure 2.2 illustrates a rough overview of the water footprint per person in different places around the world. The human water footprint per person is measured in cubic metre. The figure clearly illustrates the big differences of water consumption per person depending on country (Moström, 2012). The average water footprint in the world is 1 385 m^3 per person and year. This can be compared to Congo-Kinshasa where 552 m^3 freshwater per person and year is used. Sweden has a water footprint of 1 428 m^3 per person and year (Moström, 2012).

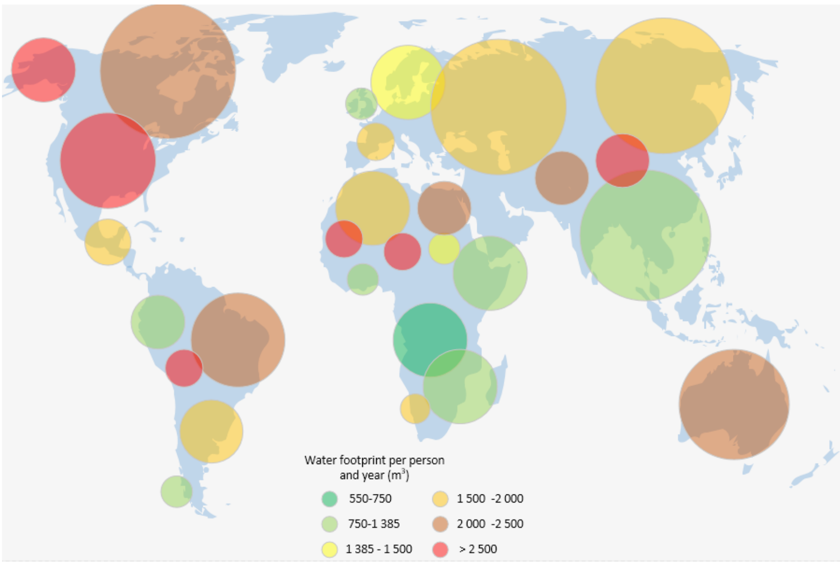

Figure 2.2: Water footprint per person and year (illustration modified from Moström, 2012).

From a global perspective, 70 % of the freshwater that is used is traced to irrigation in agriculture. 22 % is used in the industry and the remaining 8 % is used in the household

(Moström, 2012). However, in Europe the majority of the freshwater use is traced to the industry (52.4 %) while the percentage share of the agriculture falls down to just above 30 % (Moström, 2012).

2.3 Consequences of Untreated Wastewater

UNESCO (2017) estimates that over 80 % of all wastewater globally is discharged without any kind of treatment. High-income countries treat about 70 % of the municipal and industrial wastewater that they generate. This percentage drops to 38 % when it comes to middle-income countries, and to 28 % in the lower middle-income countries. Only 8 % of low-income countries have some kind of treatment (UNESCO, 2017). The report from UNESCO (2017) explains that the common practice to release untreated wastewater in nature is due to financial costs, lack of infrastructure-, technical- and institutional capacity.

Different sources of wastewater contain different types of components (UNESCO, 2017). The content of the wastewater affects the damage that may occur, where large volumes of water can be contaminated by very small amounts of compounds. High bacterial loads are likely to be found in municipal and domestic wastewater (UNESCO, 2017). Emerging pollutants are found in both untreated and treated municipal wastewater, industrial effluents and agricultural runoffs that end up in lakes, rivers and coastal waters. The emerging pollutants can also be found in drinking water. Emerging pollutants in wastewater are for example pharmaceuticals and hormones or personal care products such as sunscreen agents, fragrances and insect repellents (UNESCO, 2017). Human health risks occur from emerging pollutants via polluted drinking water or via agricultural products that have been irrigated through polluted water (UNESCO, 2017).

Many of the substances found in wastewater are naturally found in the environment (Cronholm, 2017). However, problems arise when these substances occur in large quantities or in the wrong places. Organic material can cause a lack of oxygen in the water. Phosphorus and nitrogen stimulates algae growth and can thus cause eutrophication if released in the water, which can also lead to a lack of oxygen (Cronholm, 2017).

Approximately 20 million hectares (corresponding 10 % of the total irrigated land surface worldwide) is irrigated with diluted wastewater, mostly in Asia, Latin America and sub-Saharan Africa (Keraita, Jimenez & Drechsel, 2008). This irrigation can lead to human health risks (Dickin et al., 2016; Keraita, Jimenez & Drechsel, 2008; Melloul, Hassani & Rafouk, 2001). Exhibited health effects of farmers and consumers are for example worm infections (Dickin et al., 2016), diarrheal diseases (Dickin et al., 2016; Keraita, Jimenez & Drechsel, 2008), salmonellas (Keraita, Jimenez & Drechsel, 2008; Melloul, Hassani & Rafouk, 2001), cholera, hepatitis A, giardiasis and chronic health effects (Keraita, Jimenez & Drechsel, 2008). Further, farmers can exhibit skin diseases due to frequent contact with untreated wastewater such as dermatitis (eczema) (Dickin et al., 2016; Keraita, Jimenez & Drechsel, 2008) and rashes (Keraita, Jimenez & Drechsel, 2008). When wastewater is used for irrigation, salinization of agricultural land can happen, which destroys the irrigated land (Keraita, Jimenez & Drechsel, 2008). According to Keraita, Jimenez and Drechsel (2008) accumulation of heavy metals, pharmaceutically active compounds, endocrine disrupting chemicals and pesticides on soils can happen due to constant agricultural use of wastewater.

Mining extraction and melting activities, textile industries and nuclear power are examples of human sources of heavy metals that end up in wastewater (Akpor, Ohiobor & Olaolu, 2014).

Akpor, Ohiobor and Olaolu (2014) explain how heavy metals in wastewater can cause damage both for human, animals and ecosystems. For example, they describe how toxic metals in corn products and vegetables can be accumulated in the kidney, which in turn can lead to physical dysfunction. Further they explain how damage of the nerve system and learning disabilities can occur. The death of aquatic life, algal blooms, reduction of chlorophyll production and plant growth can occur due to the presence of heavy metals in wastewater (Akpor, Ohiobor & Olaolu, 2014).

When taking pharmaceuticals, many of them are excreted intact with the urine, which ends up in the wastewater. In Sweden, various endocrine disrupters and antidepressants are currently close to effect levels for aquatic organisms and it is therefore of great importance to remove pharmaceuticals residues from wastewater (Ek et al., 2013). In the early 1990s, anglers caught almost exclusively female fish, and much fish was also found to be hermaphrodite in the English Channels (Sundin et al., 2017). Studies were conducted where male fish was kept in cages in connection to English wastewater treatment plants. The males started producing the protein vitellogenin, a protein that should only be found in fertile females. The effect could be traced back to the treated wastewater content of synthetic and natural estrogen from contraceptive pills and humans. The synthetic estrogen in contraceptive pills, called ethinylestradiol, has also shown effects on the development of ovaries on amphibians. In Umeå and Stockholm (Sweden), rainbow trout that have been exposed to outgoing wastewater, have shown levels of levonorgestrel (progesterone-like substances found in some contraceptive pills) that exceeded the human therapeutic dose (Sundin et al., 2017). Studies have shown that exposure to antidepressants can affect the tendency of the perch to hide from predators, making them an easier target. High levels of pharmaceutical substances have been found in blue mussels. A large amount of pharmaceuticals have been found in seabirds, which proves that pharmaceuticals accumulate in the food chain (Sundin et al., 2017).

2.4 The Need for Clean Technology

It is important to ensure that pollution is removed with wastewater treatment and not only displaced (Rodriguez-Garcia et al., 2011). Larsen (2018) describes how avoiding an obvious problem may induce a bigger problem somewhere else. An example of this is how the sanitary problems in the cities were avoided by leading the sewers directly to rivers (Gröndahl & Svanström, 2010). This solution was soon proved to be an even bigger environmental problem. In order to treat wastewater, it is thereby important to apply an environmentally adapted technology to not just remove the pollution from one place to another. A challenge when it comes to wastewater treatment is the achievement of higher effluent water quality without the side effect of higher energy consumption (Larsen, 2018). Environmental costs for wastewater treatment usually arise due to energy use and the use of chemicals. When energy is required, emissions will appear during the conversion of energy. It is therefore important that the used technology is designed in the most energy efficient way as possible, in order to minimize the amount of energy required. In addition to resource-efficient processes, energy sources should also be taken into account (Sundin et al., 2017).

2.5 Available Technologies

Wastewater treatment consists of a combination of different technologies in order to achieve the demands of the outgoing water (André et al., n.d). Wastewater treatment usually varies between mechanical, biological and chemical treatment. Advanced treatment can be added in order to meet higher demands on the effluent (André et al., n.d). Common water treatment techniques are presented below. Since there are many different ways to treat wastewater, all possible treatment techniques are not addressed during this literature review due to the scope of the thesis. However, the most common and most relevant techniques are being described. In figure 2.3 an overview of wastewater treatment steps are described. The figure illustrates in which order different treatment steps may occur.

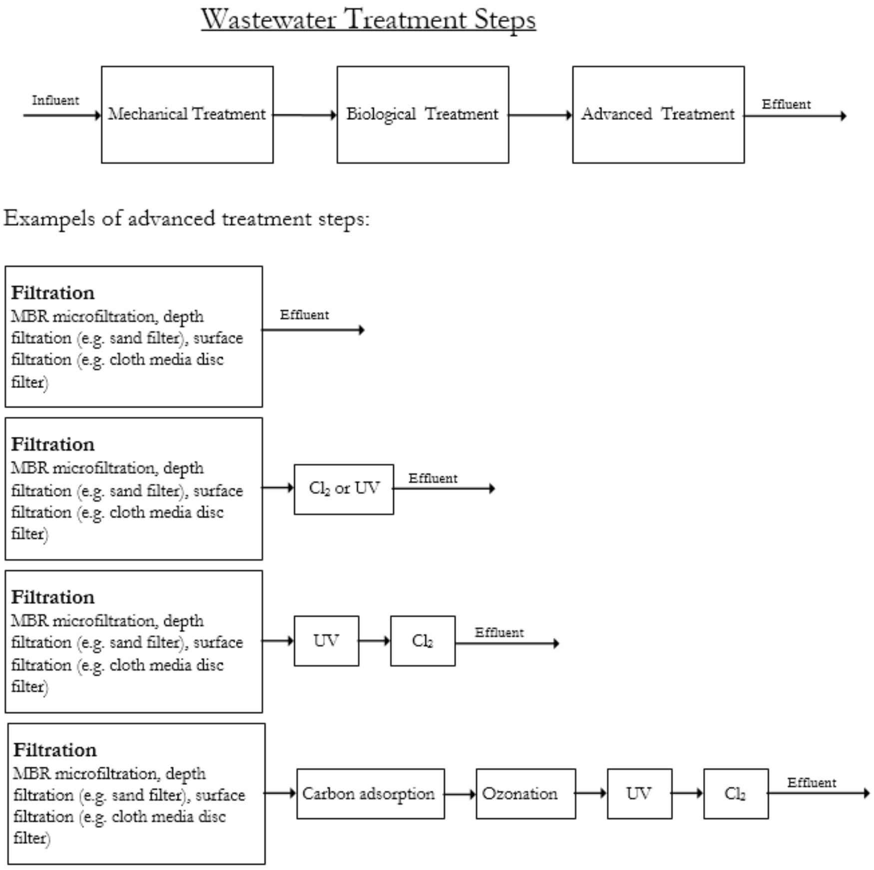

Figure 2.3: An overview of wastewater treatment steps (Illustration modified from Tchobanoglous, Burton & Stensel, 2003).

2.5.1 Mechanical Treatment

Mechanical treatment includes screens, grinders, fat-, oil-, grease- (FOG) and grit removal and primary treatment, which consist of a clarifier. Below is a description of each part in more detail.

Screens

Mechanical cleaning in the form of screening is typically the first step of the treatment process (Tchobanoglous, Burton & Stensel, 2003). The screening is done in order to remove coarse materials, which in turn reduces the risk of damaging the process equipment. This also minimizes the risks of having a process that is ineffective and unreliable with contaminated waterways as a result (Tchobanoglous, Burton & Stensel, 2003). Examples of materials removed in this step are plastics, textiles, stones, hair, sand and pieces of wood (André et al., n.d). The screens are usually classified into coarse screens (6 to 150 mm) and fine screens (0.2 to 6 mm). The size of the screens needs to consider the effects on downstream processes. The coarse screens are used in order to protect equipment such as pumps, valves and pipelines (Tchobanoglous, Burton & Stensel, 2003). If membrane bioreactors are used later on in the treatment process, fine screens need to be included in order not to damage the MBR modules and to prevent excessive fouling of the membranes, which leads to poor performance[2]. At small wastewater treatment plants (up to a capacity of 0.13 m^3/s), fine screens can replace the traditional primary treatment. Micro screens can be used to remove fine solids from already treated effluents (Tchobanoglous, Burton & Stensel, 2003).

Grinders

The material that is not directly discharged in a container for disposal during screening ends up in the grinders. Here the material is crushed by a rotating assembly, which cuts the passing material into small pieces (Tchobanoglous, Burton & Stensel, 2003).

FOG and Grit Removal

After the wastewater has passed the different screens, a fat-, oil- and grease (FOG) and grit trap takes place in the form of a tank that is slightly aerated with a low velocity to enhance settling and flotation[2]. The aeration encourages the grit to settle at the bottom and the FOG to float to the top of the tank, hence removing it from the water[2]. Grit consists of sand, gravel, cinders and other heavy materials (Tchobanoglous, Burton & Stensel, 2003).

Primary Treatment

Primary treatment, also referred to as primary sedimentation, removes particles that were not removed in earlier treatment steps (André et al., n.d). In order to remove these particles, gravity separation is used (Tchobanoglous, Burton & Stensel, 2003). Heavy particles sink to the bottom of the tank, where scrapers collect the particles that are moved to the sludge treatment (André et al., n.d). Primary treatment tanks (clarifiers) should be able to remove 50 to 70 % of the suspended solids and 25 to 40 % of the BOD (Tchobanoglous, Burton & Stensel, 2003). Primary treatment is in modern wastewater treatment plants left out to a great extent, as the following biological treatment requires the BOD that the primary treatment removes[2]. On the other hand it is an important part of energy neutral wastewater treatment plants where primary treatment is used to enhance the recovery of easily digested solids from the wastewater to enhance biogas production[2].

2.5.2 Biological Treatment

The purpose of biological treatment is to remove organic matter from the wastewater. Activated sludge and biofilters are two main types of biological treatment (Henze et al., 2002).

Activated Sludge/Conventional Activated Sludge

The activated sludge process is a biological process where the sludge is kept by aeration or by stirring in suspension. It is important to keep the sludge suspended, in order to keep contact with influent wastewater. In the suspended solids (containing inorganic as well as organic particles), some of the organic particles can be degraded by hydrolysis (Henze et al., 2002).

[2] Gurieff, Nicholas; Global Sales Business Development – Membranes & Wastewater, Alfa Laval. 2019. Personal Communication

In figure 2.4, the elements defining a conventional activated sludge process are outlined, which is illustrated by an activated sludge process with a following settling (clarifier) tank. Organic particles that enter the conventional activated sludge process will either end up in carbon dioxide, excess sludge or in the effluent (Henze et al., 2002). During the biological treatment, microorganisms (mainly bacteria) are used, which are fed by the organic matter present in the wastewater (André et al., n.d). Different species of organisms are used in the treatment depending on external conditions (Henze et al., 2002).

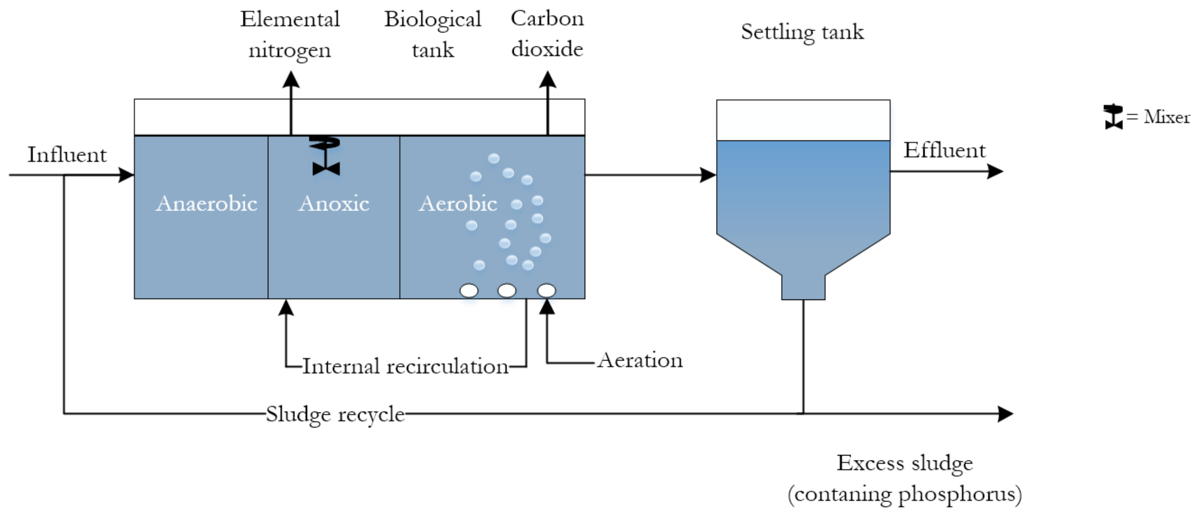

Figure 2.4: Conventional activated sludge process.

The following expression describes the carbon dioxide production that occur in the aerobic tank[2]:

$$3 \cdot C_6H_{12}O_6 + 8 \cdot O_2 + 2 \cdot NH_3 \rightarrow 2 \cdot C_5H_7NO_2 + 8 \cdot CO_2 + 14 \cdot H_2O$$

The expression describes an ideal system, where glucose is used as the carbon source[2]. When the carbon source is consumed, biomass, carbon dioxide and water will be produced. Estimating the exact amount of carbon dioxide is not possible, as it is not known what amount of cell materials that is being consumed. This is due to the uncertainties of the composition of BOD in the wastewater and the amount of cell materials being consumed as a carbon source. Therefore, the amount of carbon dioxide that is being produced depends on the carbon source available, the growth rates of the bacteria and the transfer of oxygen to the microbes[2].

The anoxic, aerobic and settling (clarifier) tanks illustrate a biological nitrogen removal process. In the anoxic tank the microorganisms convert nitrate (NO^-_3) into elemental nitrogen (N_2) (Henze et al., 2002), see figure 2.4. Intermediate products such as nitrite (NO^-_2), nitric oxide (NO) and dinitrogen oxide (N_2O) emerge due to the denitrification process (Henze et al., 2002). When the system is stressed, for example when the system is short of organic matter (Henze et al., 2002) or when non optimal aeration is applied, the toxic intermediate products are emitted to a larger extent[2]. Difficulties arise when measuring the emitted amounts of these products because of the tiny amounts of the emissions coming from the huge tank areas[2]. Denitrification is a complicated process where tanks both with and without oxygen are needed (André et al., n.d). The anoxic tank consists of zero oxygen, with the electron donor being nitrate[2]. The nitrate will be removed from the system by denitrifying bacteria that will convert nitrate to elemental nitrogen. To drive this reaction, the denitrifying bacteria will consume BOD, which means that nitrogen is removed, and at the same time, BOD is reduced from the wastewater[2]. After the anoxic tank, the wastewater flows into the aerobic nitrification tank. In this tank, the ammonia in the wastewater is converted into nitrate. At the same time, the bacteria are consuming dissolved oxygen[2]. There is a large recycle from the aerobic nitrification tank back to the anoxic denitrification tank. The recycle allows the nitrate produced in the aerobic nitrification tank to be converted to elemental nitrogen, thanks to BOD, which comes from new raw wastewater[2]. About 50 to 75 % of the nitrogen is removed during the nitrogen removal (André et al., n.d).

In order to accomplish phosphorus removal, an anaerobic zone is placed before an anoxic zone (Tchobanoglous, Burton & Stensel, 2003). The anaerobic process is defined as a process where no oxygen or nitrate is present (Henze et al., 2002). In the anaerobic zone, the bacteria accumulate polyhydroxyalkanoate (PHA) and release phosphorus. The accumulated PHA can be used as an energy source for the bacteria during the aerobic process. In the aerobic zone, the bacteria consume the stored PHA and take up and store phosphorus as poly-phosphate[2]. When the bacteria are removed from the wastewater by the sludge, so is the internally stored poly-phosphate (phosphorus), which has been accumulated in the cells of the bacteria (Seviour, Mino & Onuki, 2003). In total, the bacteria accumulate more phosphorus as poly-phosphate in the aerobic tank than was released in the anaerobic tank, leading to a net removal of phosphorus from the system[2].

Biofilters

Biofilters contain bacteria that are attached to a solid surface (Henze et al., 2002). One negative aspect of using biofilters is the low efficiency. This is due to the fact that the substances must pass through the biofilm in order to get removed by the bacteria. This transportation of the substances is achieved by molecular diffusion. In practice, the molecular diffusion is limiting the removal of substances (Henze et al., 2002).

2.5.3 Chemical Treatment

Chemicals in wastewater treatment plants can be used in different stages of the treatment process. Coagulation of particulate matter, wastewater disinfection and the precipitation of phosphorus are the most important steps. When adding chemicals to the wastewater, it is important to be aware of the increased dissolved constituents in the water (Tchobanoglous, Burton & Stensel, 2003). Flocculation is created when coagulant chemicals are added to the wastewater. When the chemicals are added the particles expand. Particles in the range of 0.01 to 1.0 μm need coagulant and flocculation chemicals in order to be removed from the water by non-membrane filtration and gravity sedimentation. Chemicals that can be used for the process are metal salt such as poly iron chloride and ferric sulphate or synthetic and natural organic polymers (Tchobanoglous, Burton & Stensel, 2003). In order to improve the performance of the wastewater treatment plants, chemical precipitation can be used. While adding chemicals to the wastewater, dissolved and suspended solids will change their physical state. Earlier, the chemical precipitation was mainly used to remove BOD and total suspended solids (TSS). Today the main reason for using chemical precipitation is for removal of phosphorus and heavy metals. In order to remove phosphorus, chemicals as metal salts, polymers and lime can be added during different phases of the wastewater treatment process (Tchobanoglous, Burton & Stensel, 2003).

2.5.4 Advanced Treatment

In order to meet strict discharge and reuse requirements on wastewater effluent, advanced treatment is necessary (Tchobanoglous, Burton & Stensel, 2003). Advanced treatment is defined as the steps after the biological treatment or the secondary clarifier, where the remaining dissolved and suspended materials in the water are removed (Tchobanoglous et al., 2014).

Activated Carbon

Carbon adsorption is an efficient treatment against pharmaceutical residuals in wastewater (Ek et al., 2013; Ternes et al., 2002). Besides from pharmaceutical compounds, the activated carbon also removes personal care products, dyes, heavy metals and organic pollutants from the wastewater (Wong et al., 2018). The activated carbon adsorbs molecules since carbon molecules are held together by weak Van Der Waals forces of attraction. The attractive forces have the ability to capture fluid molecules as they contact the surface (Perrich, 2018). Activated carbon can consist of different materials, such as bituminous coal, lignite, wood, peat, lignin and petroleum residues (Perrich, 2018). It can also consist of almond, coconut and walnut hulls (Tchobanoglous, Burton & Stensel, 2003). Specifically in wastewater treatment, the activated carbon is produced from coconut shells, coals, woods and lignite (Wong et al., 2018). The carbon needs to be regenerated and reactivated after the adsorptive capacity has been reached, which limits the treatment (Tchobanoglous, Burton & Stensel, 2003).

Ek et al. (2013) conducted a study to find out the separation efficiency for activated carbon treatment. The study was conducted in 2011 and 2012 as a final step in Henriksdal's wastewater treatment plant in Stockholm. The study concluded that activated carbon removed the studied pharmaceutical substances to a very high extent. Out of 37 studied pharmaceutical substances, less than 20 were found in the effluent from Henriksdal. When the system had a capacity of 50 m^3 water/kg coal, only 5 to 10 % of these compounds passed the first column reactor. As the capacity increased to 70 m^3 water/kg coal in the first column reactor, the study still did not detect any quantifiable amounts of pharmaceutical from column reactor number two. The result shows that with more than one column reactor, the capacity can increase and still treat the water in an efficient way.

Depth Filtration

Depth filtration is a principal treatment of potable water, but it can also be used for filtration of effluent from wastewater (Tchobanoglous, Burton & Stensel, 2003). It is used for wastewater treatment in order to achieve supplemental removals of suspended solids. Further, it can also be used as a pre treatment step to the membrane filtration. The technology removes particles from the wastewater by passing the water through different layers of a filter bed. The filtering medium can consist of sand or anthracite or a combination of these two, see figure 2.5. Even layers of gravel can be used directly after the sand layers. Further, the filtering medium can consist of synthetic fiber (Tchobanoglous, Burton & Stensel, 2003). Studies of slow sand filtration have shown a removal efficiency of 70 to 84 % of the total suspended solids (Langenbach et al., 2009).

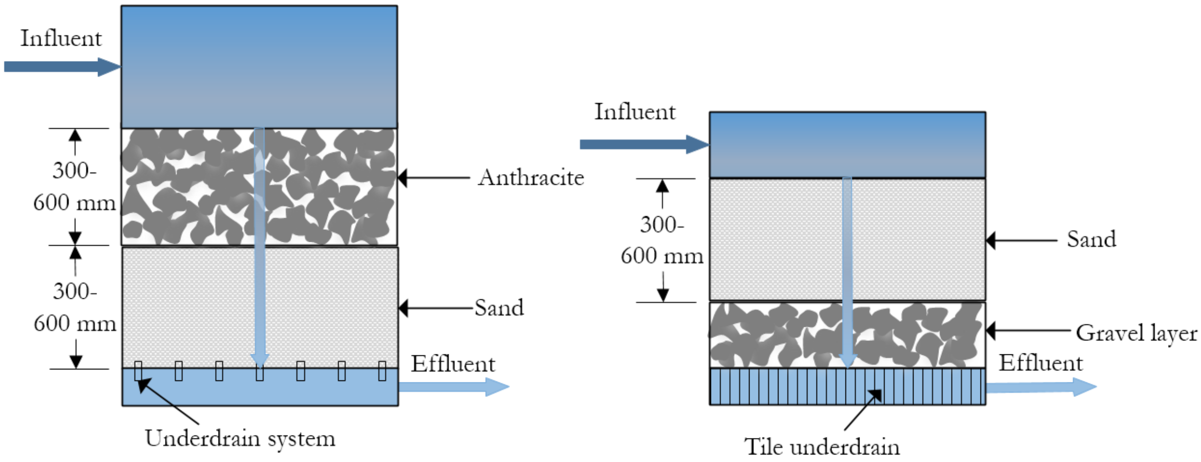

Figure 2.5: Different sand filters (Illustration modified from Tchobanoglous, Burton & Stensel, 2003).

Surface Filtration

Surface filtration is used in order to remove residual suspended solids with filtration devices such as a Cloth-Media Disc Filter (Tchobanoglous, Burton & Stensel, 2003). In figure 2.6 a wastewater treatment system is outlined with mechanical, biological and finally advanced treatment in the form of a Cloth-Media Disc Filter, supplied by Alfa Laval under the name AS-H Iso-Disc Cloth Media Filter. The reason for adding a filter after the clarifier is to enhance the performance of disinfection (Munch, n.d). Many companies today are moving towards UV disinfection. In order for the UV disinfection to work properly, it is important to have clear waters (high UV transmittance). Placing a filter before the UV disinfection, ensures a high UV transmittance. A filter is therefore a very important step prior to UV disinfection treatment (Munch, n.d).

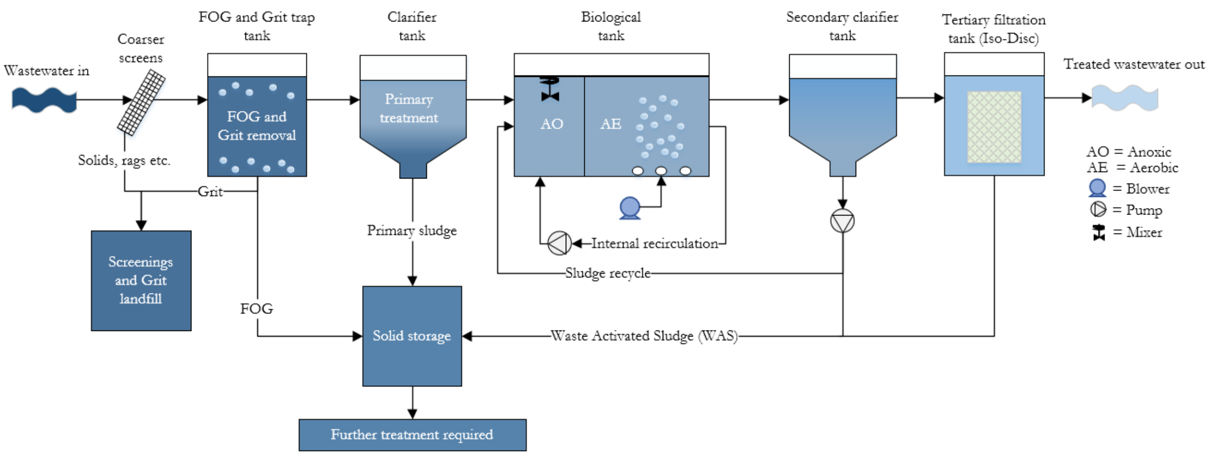

Figure 2.6: The figure illustrates a wastewater treatment system, consisting of mechanical treatment, a conventional activated sludge (CAS) process and Iso-Disc technology.

The water passes through the thin filter materials, usually consisting of woven metal fabrics, cloth fabrics of different weaves or different synthetic materials. Particles smaller than the openings in the cloth screen (usually in the range of 10 to 30 µm) pass through the filter with the effluent water while particles larger than the screen are retained (Tchobanoglous, Burton & Stensel, 2003). In order to clean the disc, a method called backwashing is used. This method involves flushing particles out of the disc using pressurized water (Tchobanoglous, Burton & Stensel, 2003). Filters such as the Iso-Disc have advantages over a traditional sand filter (Munch, n.d). The filter media cloth is placed in a vertical position as opposed to the sand filter, where the media is positioned horizontally. This provides a higher hydraulic throughput, smaller space requirements and a smaller environmental footprint, which drives this technology forward compared to sand filters. Additionally, the technology is more cost effective compared to a sand filter (Munch, n.d). Further, if the Iso-Disc is placed before an eventual chlorine disinfection, the dose of chlorine may be reduced (Munch, n.d). The aim of this study is to evaluate an AS-H Iso-Disc Cloth Media Filter, where the filter cloth is made of polyester. The Iso-Disc is evaluated together with a CAS system where the biology process is designed for a biological nitrogen removal process, as shown in figure 2.6.

Membrane Bioreactor Filtration

In figure 2.7 a wastewater treatment system is outlined with mechanical, biological and finally advanced treatment in the form of membrane filtration technology.

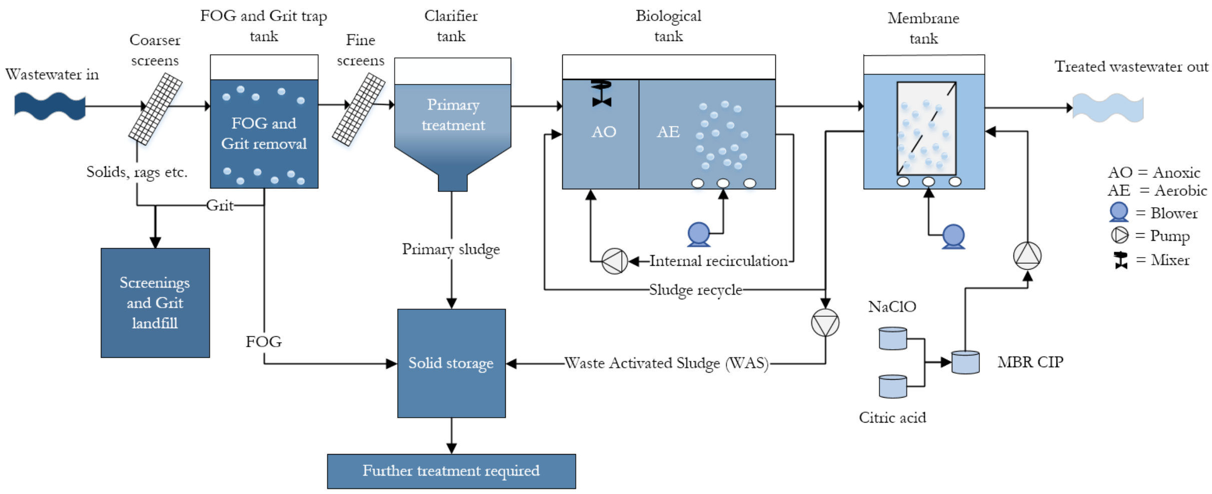

Figure 2.7: The figure illustrates a wastewater treatment system, consisting of mechanical treatment, an activated sludge process and MBR technology.

The purpose of the membranes is that some physical and chemical components can pass through the membranes more easily compared to others (Judd & Judd, 2011). Hydraulic pressure is used in order to get the desired separation (Tchobanoglous, Burton & Stensel, 2003). Different types of membranes are available; reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF) and microfiltration (MF), where the membrane pore size depends on the degree of selectivity (Judd & Judd, 2011). The coarsest membrane is able to reject particulate matter (Judd & Judd, 2011). This type of membrane is associated with MF. The most selective membrane is able to reject charged ions, for example chloride (Cl^-) and sodium (Na^+). This type of membrane is associated with RO. The pores of an RO membrane are only visible with very powerful microscopes (Judd & Judd, 2011).

The membranes usually consist of polymeric or ceramic materials (Judd & Judd, 2011). The operation of the membranes is usually done as follows; a pump is used in order to pressurize the solution and to press it through the module. Further, a valve is used to maintain the pressure of the concentrate. Permeate is withdrawn, and the remaining components from the wastewater are accumulated on the membranes (referred to as membrane fouling) (Tchobanoglous, Burton & Stensel, 2003). The pores are blocked by particles and when the membrane fouling occurs, the membrane fluxes decrease (Tchobanoglous, Burton & Stensel, 2003). When the performance of the membranes has decreased to a given level, the modules are backwashed and/or chemically cleaned in order to recover the performance of the membranes (Tchobanoglous, Burton & Stensel, 2003).

The MBR technology offers a high effluent quality (Pretel et al., 2016). One of the benefits of the MBRs is the low space requirement, since many countries today have space limits. If a CAS system is upgraded to an MBR system, the treatment capacity can increase up to three times without additional space requirements (Krezeminski et al., 2017). The MBR market is driven by strict treated effluent discharge or reuse limits (Krezeminski et al., 2017). According to the report of BCC Research (2019), the market of MBRs is expected to more than double in the coming five years. In 2023, the market is estimated to reach $ 3.8 billion (BCC Research, 2019). However, even though there are many benefits with the MBR technology, the competitiveness of the MBR technology is threatened by the CAS systems due to their low operating cost (Pretel et al., 2016). Even though the MBR is not as expensive as before, thanks to design and process optimization, it is still an expensive technology compared to the CAS process (Krezeminski et al., 2017). A negative aspect of the MBR technology is the high energy demand (Krezeminski et al., 2017; Ioannou-Ttofa et al., 2016; Pretel et al., 2013). The great energy demand results in higher operational costs, compared to other technologies. Also, regular membrane replacements increase the operational costs of the MBR technology (Krezeminski et al., 2017; Tchobanoglous, Burton & Stensel, 2003). The aim of this study is to evaluate the MF membrane together with an activated sludge system designed for a biological nitrogen removal process, as shown in figure 2.7.

Ultraviolet Treatment

Ultraviolet (UV) treatment is an effective way to both be bactericidal and destroy or inactivate viruses, with no known toxic by-products as a result of the treatment (Tchobanoglous, Burton & Stensel, 2003). Even though UV treatment has been installed in water treatment plants since the beginning of the 20th century, it was not until the end of the 1990s that the treatment broke through (Eriksson, 2009). The reason for the breakthrough was partly a result of the by-products that occurred due to chlorine treatment and the health effects of these. Further, UV treatment is effective against the microorganism cryptosporidium and giardia, which to a high extent is resistant to chlorine (Eriksson, 2009).

UV-light is a part of the electromagnetic spectrum and is in the range of 10-340 nm. The UV-light is divided into four areas; UV A, UV B, UV C and Vacuum UV, see figure 2.8. UV A, which adjoins the visible light spectrum, has the longest wavelength (315-340 nm), while vacuum UV adjoins the X-areas (10-150 nm). According to UV disinfection, the UV C is mainly used but also UV B is used to some extent (Eriksson, 2009).

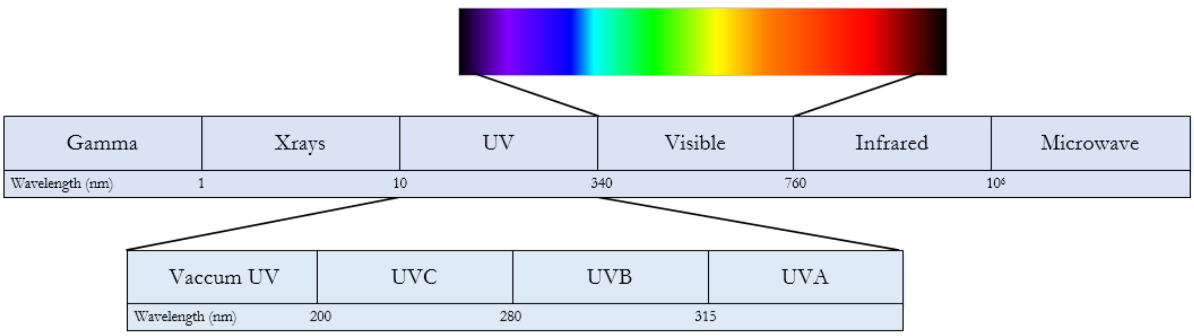

Figure 2.8: The electromagnetic spectrum (illustration modified from Eriksson, 2009).

The bacteria and the virus can be inactivated when they are exposed to UV light (Gehr et al., 2003). The UV light penetrates the cell of the microorganism. The UV light reacts with the proteins of the DNA-molecule, which in turn prevents the reproduction of the DNA helix from working. Because of this reaction, the microorganisms are no longer able to reproduce (Eriksson, 2009). Even though UV light is an effective treatment to inactivate microorganisms to prevent infection, particles larger than 10 μm are difficult to disinfect with the treatment (Gehr et al., 2003; Tchobanoglous, Burton & Stensel, 2003). Different microorganisms are sensitive to UV light in various degrees, for example escherichia coli, giardia and cryptosporidium are specifically sensitive to the UV treatment (Eriksson, 2009). The UV dose refers to the amount of UV light a certain point is exposed to, and is usually measured in J/m^2 or mJ/cm^2 (Eriksson, 2009).

In order to measure the inactivation of a microorganism 'log-reduction' is used, with the following formula (Eriksson, 2009);

$$\text{Log-reduction} = \log (N_0/N)$$

N_0 is the content of microorganisms before disinfection and N is the content of microorganisms after the disinfection (Eriksson, 2009). Log reduction of 1 imply an inactivation of 90 % of the microorganisms. In the same way, log reduction 2 means an inactivation of 99 % and log reduction 3 is an inactivation of 99.9 % of the microorganisms (Eriksson, 2009). Gehr et al. (2003) describe how bacteria with low resistance to UV treatment such as faecal coliforms require approximately 2.5-3 mJ/cm^2 in order to get a 1-log inactivation. Many viruses and bacteriophages are more resistant and require over 10 mJ/cm^2 per log inactivation (Gehr et al., 2003).

Ozone Disinfection

Ozone (O_3) can be used in order to disinfect wastewater. Ozone is usually used for control of taste odour and colour producing agents for drinking water. However, it can also be used for removal of soluble refractory organics in wastewater treatment (Tchobanoglous, Burton & Stensel, 2003). Even though ozone treatment is a popular disinfection method for drinking water, it has not been widely used for wastewater treatment (Gehr et al., 2003). Gehr et al. (2003) explain this is due to the high ozone demand of many effluents. They claim that many operation and maintenance problems occurred due to ozone disinfection. However, ozone is an effective disinfection method against microorganisms found in wastewater (Snyder et al., 2006; Tchobanoglous, Burton & Stensel, 2003; Gehr et al., 2003). Organisms such as giardia, cryptosporidium and poliovirus Type 3, which are resistant to chlorine disinfection, can be inactivated by ozone (Gehr et al., 2003). Ozone reacts with the organic contaminants in the water. This happens either by a reaction with molecular ozone or by formation of free radicals, including the hydroxyl radical (·OH) (Snyder et al., 2006). Due to the cell wall disintegration, the bacteria are killed directly (Tchobanoglous, Burton & Stensel, 2003). Studies with escherichia coli and giardia have shown that the treatment with ozone has a greater inactivation when ozone decomposition is slow and the ozone residuals persist, compared to rapidly decomposed ozone (which for example may happen when the organic concentration is high) (Gehr et al., 2003). Ozone disinfection with strong oxidation and activated carbon is the most effective treatments when it comes to removal of pharmaceutical residues in wastewater (Ek et al., 2013).

Chlorine Disinfection

Chlorine can be used for wastewater treatment in order to destroy harmful pathogens (Wang, Hu & Wang, 2007), and is a commonly used disinfectant worldwide (Tchobanoglous, Burton & Stensel, 2003). Chlorine has a strong oxidizing action in the cell structure of the organism, which destroys the enzymatic processes and kills the cell (Singh, 2015). However, harmful by-products may occur because of the use of chlorine disinfection that can cause negative ecological and health effects (Wang, Hu & Wang, 2007). During the 1970s, it was discovered that chlorinated drinking water contained toxic disinfection by-products due to reactions between chlorine and natural organic substances. The disinfection by-products led to an increase in miscarriages and bladder cancer (Sedlak & von Gunten, 2011). After these discoveries, more strict regulations were made as a result of disinfected by-products (Sedlak & von Gunten, 2011). Further, there is a concern of long-term effects, which are still unknown, because of the discharge of chloro-organic compounds (Tchobanoglous, Burton & Stensel, 2003). Today many wastewater treatment plants remove nitrogen from the wastewater. In those plants where nitrogen is fully removed from the effluent, the added chlorine will be present as free chlorine. The presence of free chlorine will reduce the required dosage of chlorine. There may be uncertainties to what degree the plant is nitrifying at any given time to thereby be able to add the right dose of chlorine to the wastewater. Free chlorine can also lead to the undesirable by-product N-nitrosodimethylamine (NDMA) (Tchobanoglous, Burton & Stensel, 2003). A study by Liu et al. (2018) has found support for disseminate antibiotic resistance in the nature as a result of the use of chlorine disinfection. Some antibiotic resistance genes have been higher in the effluent compared to the influent. This observed increase in antibiotic resistance genes via the treatment process is worrying (Liu et al., 2018). The study of Liu et al. (2018) observed an increase in the intracellular antibiotic resistance up to 7.8 times and the extracellular antibiotic resistance genes up to 3.8 times after chlorine disinfection with chlorine dioxide (ClO_2).

2.6 LCA of Wastewater Treatment

Life Cycle Assessment (LCA) is a scientific methodology to map the environmental impact of a product, service or process (Hauschild, Rosenbaum & Olsen, 2018). In order to get results, system boundaries are set up, which can include 'cradle to grave', where all steps are included from raw material production to waste management (Klöpffer & Grahl, 2014). Figure 2.9 shows an illustrative image of the life cycle of wastewater treatment, from cradle (extraction of raw material) to grave (disposal). Between these steps, manufacturing of the wastewater treatment plant (WWTP), transport and operation can be found. An LCA breaks down the product, service or process into distinct processes (Stokes & Horvath, 2010). Thereafter data is collected from available and reliable sources in order to evaluate the input and output of each process (Stokes & Horvath, 2010).

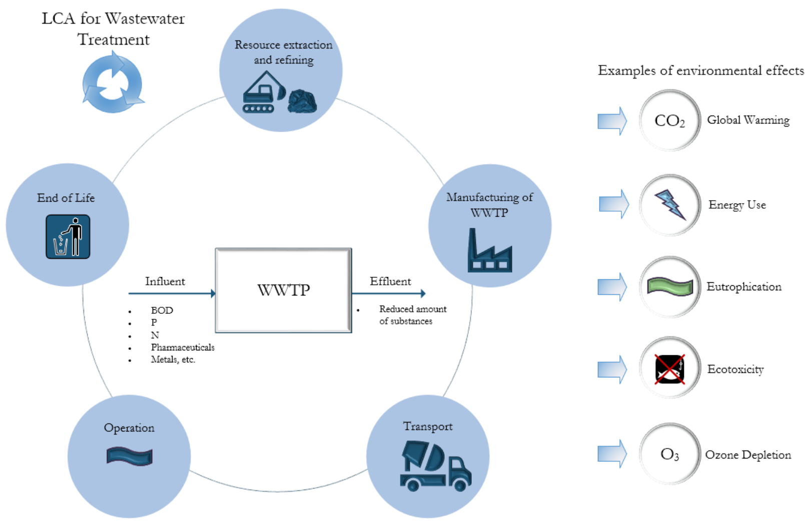

Figure 2.9: Life cycle assessment of wastewater treatment (Illustration modified from Ecoinvent, 2019).

Several LCA studies on wastewater treatment have been conducted since the mid 1990s (Larsen, 2018). When it comes to LCA of wastewater treatment, the plant operation stage has a dominating role due to the use of electricity. Further, the emissions from pollutants of the wastewater to air have a big impact, as well as the emissions from the pollutants, which are in the sludge and effluent. Transport is not typically dominating according to earlier LCA studies of wastewater treatment technologies (Larsen, 2018).

One of the first LCA studies of wastewater treatment was conducted by Emmerson et al. (1995) (Larsen, 2018). Emmersson et al. (2015) identified the energy to be an area of improvements and also that pumping requirements is a major contribution to the operational energy use. Even today, when studying the MBR technology in wastewater treatment, many researchers come to the same conclusion; the great energy demand of the MBR technology is the biggest challenge in order to minimize the environmental impact of the technology (Ioannou-Ttofa et al., 2016; Krezeminski et al., 2017; Pretel et al., 2013).

In recent times, eutrophication and global warming potential (including direct emissions from the plant, such as dinitrogen oxide) are in focus. Another change in focus when it comes to wastewater and LCAs, is the toxicity-related impact categories, which are included in a higher extent in the LCAs nowadays. LCA is also used in order to compare alternative treatment systems (Larsen, 2018). One of the strengths of the LCA method is the comprehensiveness of different products and processes (Hauschild, Rosenbaum & Olsen, 2018).

The aim of the study is to evaluate the MBR technology with a reduced energy demand provided by Alfa Laval, and how it emerges from a life cycle perspective. This is important since the great energy demand is listed as the main obstacles in previous research. This study contributes further by studying the new MBR technology of Alfa Laval, where an airlift system can be used instead of energy demanding pumps, which are compared to the Iso-Disc Cloth Media Filter technology. The study also has a broad environmental perspective by including eleven impact categories. This is further described in the next chapter, where the methodology of the life cycle assessment is outlined.

3 Methodology

In order to achieve the purpose of the study, a life cycle assessment (LCA) is conducted. Figure 3.1 shows the methodological framework for an LCA with the four parts; Goal and Scope Definition, Inventory Analysis, Impact Assessment and Interpretation. Further, figure 3.1 specifies what is included for each part of this study.

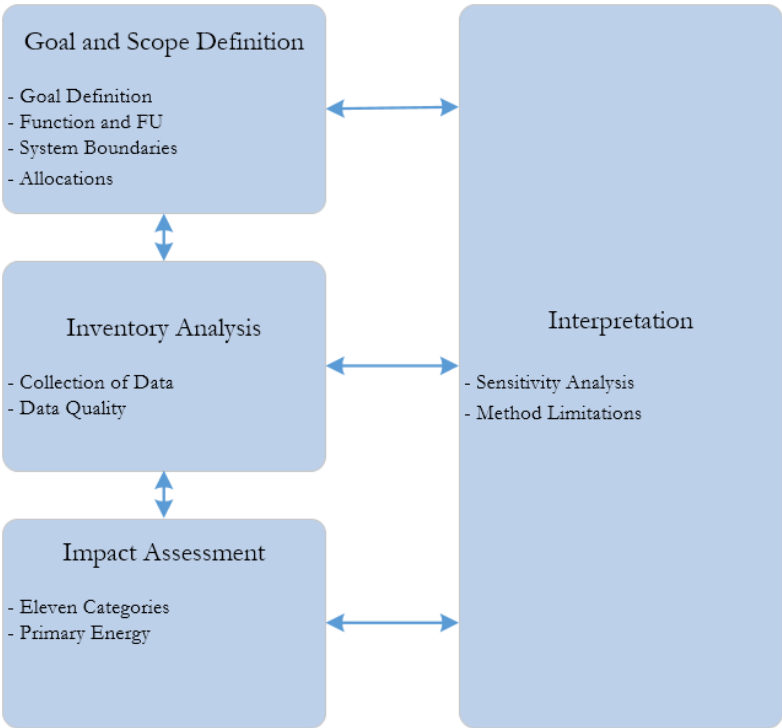

Figure 3.1: Overall sketch of the methodological framework for the LCA.

3.1 Goal and Scope

The goal of the life cycle assessment is to compare two different wastewater treatment processes and evaluate the environmental impact of each technology. The processes that will be evaluated include an activated sludge process with MBR technology and a conventional activated sludge process with an AS-H Iso-Disc Cloth Media Filter. The study uses a standardized LCA framework, ISO 14044, developed by the International Organization for Standardization (Swedish Standards Institute, 2006).

3.1.1 Function and Functional Unit (FU)

The function of the two processes is to treat sewage in a municipal wastewater treatment plant. The functional unit (FU) is set to 1 m^3 treated wastewater of a 9 500 PE sized plant (i.e. 1 900 m^3 water/day) over a 20 year period. The two technologies will treat the same type of wastewater in a municipal wastewater treatment plant and must achieve an effluent concentration of 5 mg TSS/litre or less.

Volume, expressed in m^3 or ML, was the most commonly used FU when Corominas et al. (2013) reviewed 45 LCA studies of treated wastewater. Corominas et al. (2013) give some caveats regarding only considering volume as a FU. They describe how the result can be misleading if two systems are compared with different removal efficiencies and different influent loads. To prevent a misleading result the FU includes the size of the plant, which has been set to 9 500 PE. We know that the result can be misleading since the removal efficiencies will be different for the two compared systems. The MBR technology has an effluent concentration of 1 mg TSS/litre and the Iso-Disc has an effluent concentration of 5 mg TSS/litre, which means that the MBR technology emits fewer substances in the effluent water. However, it is still of high relevance to compare the two technologies since they have the same position in the wastewater treatment process and can replace each other. In order to prevent a misleading result due to different removal efficiencies, the interpretation part will include a sensitivity analysis where the different purification levels will be evaluated according to eutrophication. The lifetime of the plant is included in the FU, since replacement of some components has to be done during the period, and the choice of lifetime will have an impact on the result.

3.1.2 System Boundaries

The technical system boundaries are illustrated in each flowchart regarding the two systems. The flowchart of the MBR system can be seen in figure 3.2, and the flowchart of the Iso-Disc system is illustrated in figure 3.3. The stretched lines in each of the flowcharts are not included in the study. The assembling and disassembling of the plant is not included in the study, which can be seen in figure 3.2 and figure 3.3. Since information of recycling was limited, all material was assumed to end up in landfill at the end of life.

The construction of sewer systems, power plants, infrastructure maintenance and manufacturing of machines for production are not considered in this study. Unexpected downtime for the systems is not included either. The process is assumed to work properly and no dinitrogen oxide emitted to air from the biological tanks is considered in the study. Emitted carbon dioxide from the biological tanks is not included in the study either, since they are assumed to be small and the difference between the two systems is seen as irrelevant.

The amount of raw wastewater that flows into the plant is equal to 1 900 m^3/day. During the treatment process, some water loss will occur because of the wasted sludge[3]. The sludge will be dewatered and removed while the water will be brought back into the system[3]. Since there is only a small amount of water that is lost, the effluent water can still be considered close to 1 900 m^3 and the study does not consider any wastewater loss during the way through the wastewater plant.

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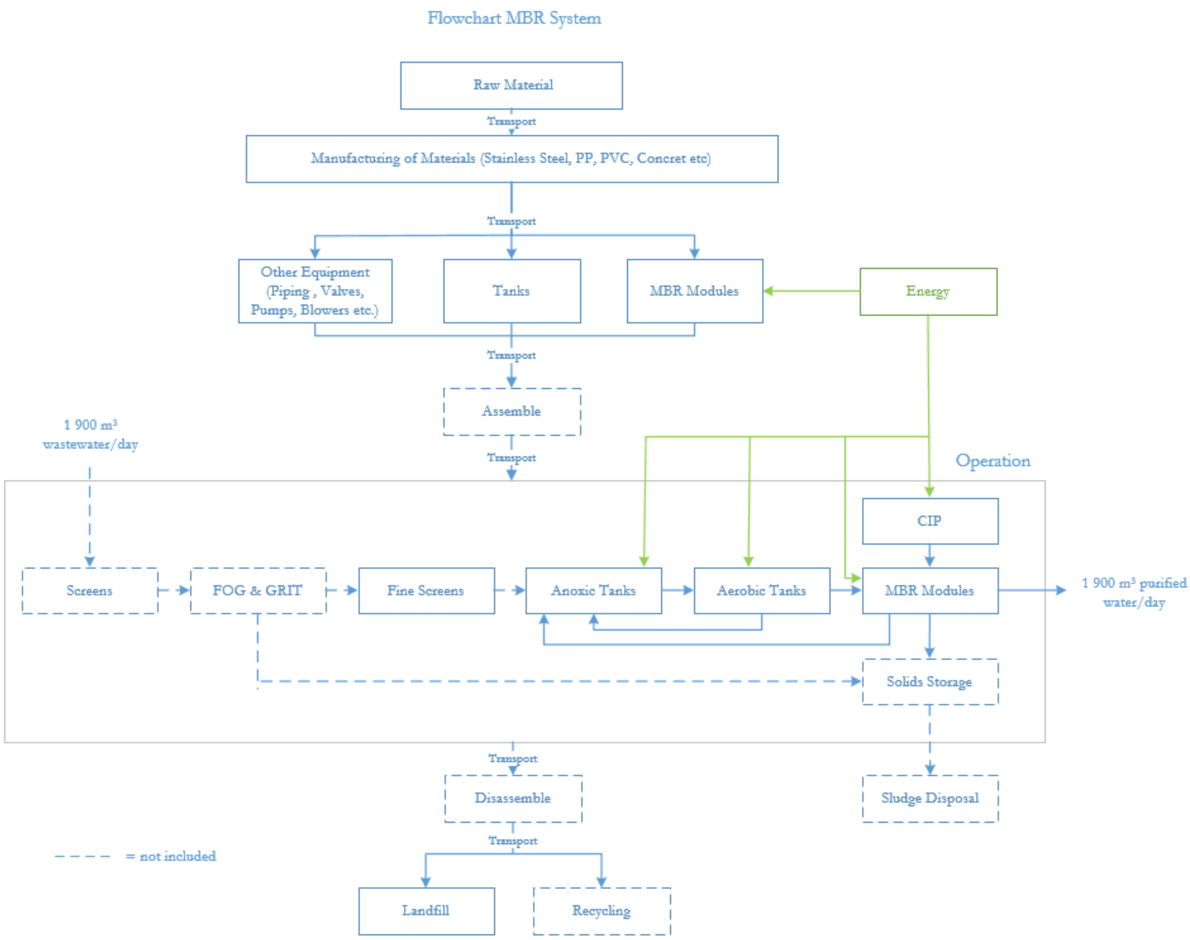


Figure 3.2: Flowchart of the MBR and activated sludge system.

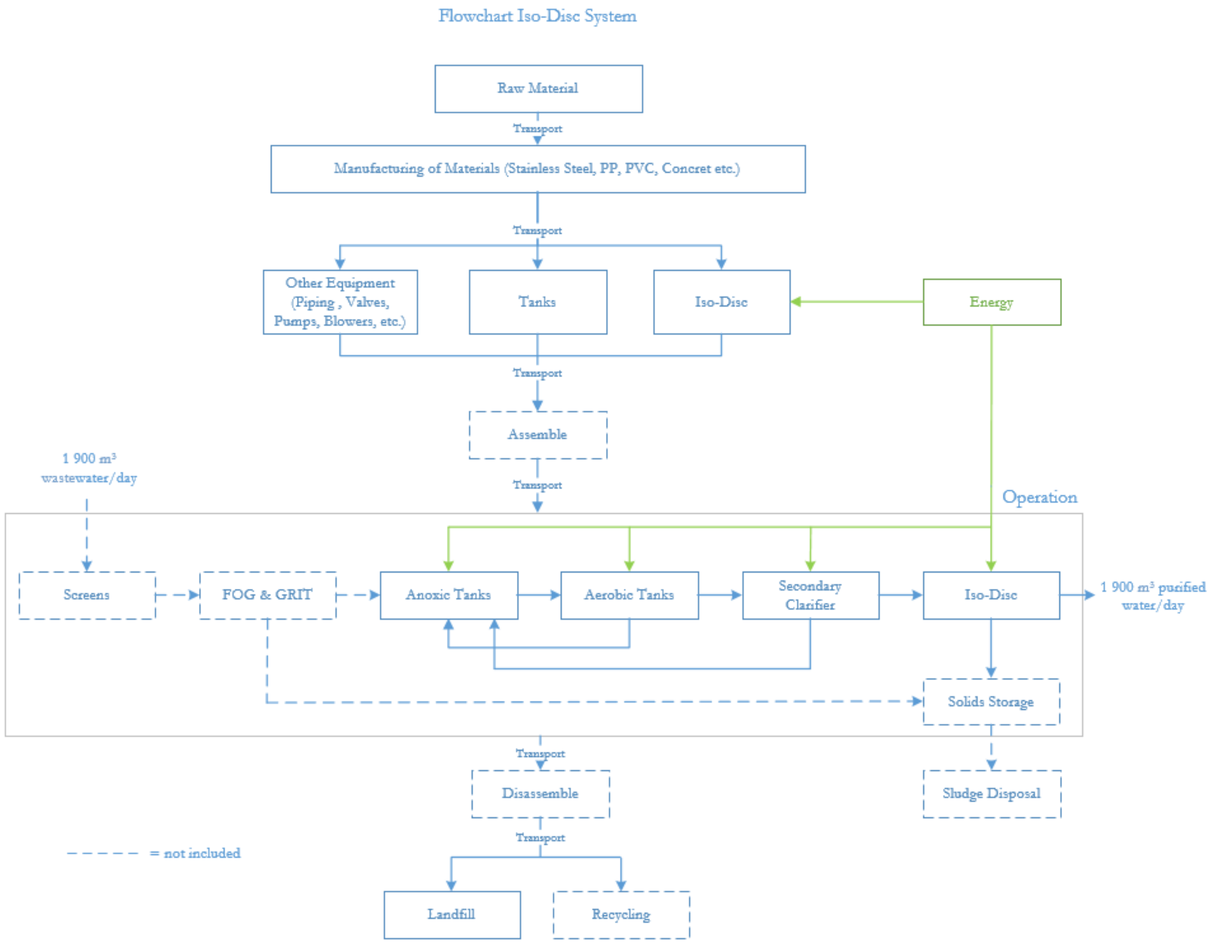


Figure 3.3: Flowchart of the Iso-Disc and CAS system.

Geographical System Boundaries

The study will be delimited into a basic case where the treatment plant is located in the Copenhagen region (Denmark). The manufacturing of the MBR modules will be done in Denmark and the manufacturing of the Iso-Disc will be done in United Kingdom. The electricity for the study will be based on domestic electricity mix production for the selected countries.

Transports from the suppliers to Alfa Laval's factory in Nakskov (Denmark) or Stoke (United Kingdom) are estimated to start in each capital of the manufacturing countries unless a specific city is appointed. Further, transport with truck less than 100 km is excluded from the study. Only transports from the suppliers to the factories of Alfa Laval and from Alfa Laval's factories to the treatment plant are included in the result part where transport is shown.

Time System Boundaries

The time system boundaries that are set up for the study have a lifespan of 20 years. With a lifespan of 20 years it means that some of the components need to be replaced during the chosen period, which will affect the result. A year is defined as a 365 day period.

Cut-offs

The following cut-offs have been made for the study, and each of the contributions have been excluded from the result:

- *Adhesive*: adhesive is needed for the packaging of the MBR modules, consisting of butyl. The butyl is considered to be insignificant for the study.
- *Oil for moving parts;* oil for moving parts such as engines is considered to be minimal and is therefore excluded from the study.
- *Operational time of the electric actuators;* the effect of the actuator is 10 W (Johnson & Sons LTD, 2018) and is only operating in short intervals, which in turn gives a low energy consumption.
- *Printed Circuit Board (PCB), sensors, cables and power supply;* PCBs are not considered in this study due to the complexity of the PCB unit structure. Sensors, cables and power supply are also excluded from the study.
- *pH-meter*; for the MBR system one pH-meter is required. The pH meter needs to be replaced at least once in a period of 20 years. The total weight of two pH-meters is 0.2 kg and the material mainly consists of polyetrafluoroethylene (PTFE), glass and silver chloride (Endress+Hauser AB, n.d.a).
- *Plastic plug (on air pipe inlet)*; the MBR module has one plastic plug with a total weight of 0.013 kg.
- *Wood pallet;* to transport the MBR modules and the Iso-Disc, wood pallets are used. Since the wood pallets are reused, they are excluded from the study.
- *Plastic for packaging:* when the MBR modules and the Iso-Disc are transported, they are wrapped in plastic. The total weight is likely to be very low, which makes this impact irrelevant for the study.

3.2 Allocations

In the database Ecoinvent, the system model that is used is allocation, cut-off by classification. This means that multi-product activities are divided by allocation based on physical, economic, mass or other properties (Wernet et al., 2016).

All the environmental impacts are allocated to the studied technologies. The sludge can be used as, for example biogas or fertilizer in agriculture. Hence, a system expansion could have been made with the result that the environmental impact is distributed between the various products.

3.3 Inventory Analysis

For this study, specific data will be used in order to get information about the products from the company Alfa Laval. Further, a field trip to Alfa Laval's factory in Nakskov (Denmark) brought knowledge about the manufacturing of the MBR module.

In order to find values for the impact assessment result, generic data was used from the database Ecoinvent 3.5, 2018. The database contains different methods that can be used in order to map the values, which are classified into different environmental impact categories.

3.3.1 Data Quality

Data for the study is collected from the company Alfa Laval, which provides information of the MBR modules and the Iso-Disc when it comes to weight, material, energy consumption and transport. In order to create comparability between the different technologies, both wastewater treatment processes have been dimensioned based on the same amount of water passing through the wastewater treatment plant per day. In order to create a larger comparability between the two technologies, adjacent processes that are crucial for the MBR modules and the Iso-Disc are also included in the study. The adjacent processes will differ in some respects, which will affect the processes in terms of size, required equipment and energy consumption. Alfa Laval does not distribute the required equipment outside the MBR module or Iso-Disc to the customer. For the study, Alfa Laval has provided recommendations of suppliers that hold the required equipment that Alfa Laval would recommend to the customer. Data has been obtained from available data sheets or through personal communication with the suppliers via mail or telephone. Since the material construction in the data sheets is not always described in detail, assumptions have been made. The characteristics of data vary, which creates an uncertainty factor in the data. Assumptions that have been made are described in the report. Furthermore, decisions have been made in accordance with general practice to overestimate the environmental impact rather than to underestimate it. The material that has the greatest environmental impact should account for a percentage that is rather too large than too small when decisions are made regarding dimensioning. All data has been modelled exclusively in the database of Ecoinvent, thereby creating comparability and consistency. Appendix 6 shows how the data has been modelled in Ecoinvent.

This thesis distinguishes between 'market activity' and 'activity' while modulating various steps in the manufacturing process of a product. Materials of the MBR module and Iso-Disc have been modelled as 'market activity' until manufacturing of the 'product', referred to as steel or plastic for example, see figure 3.4. For the steps listed as 'raw material' and 'semi-product' an average transport has already been included in Ecoinvent, which extends to the customer, in this case, the supplier of the 'product'. However, we wanted to add the transport from the supplier to Alfa Laval's factories in Nakskov and Stoke ourselves, since we knew the location of the suppliers, and did not want an average transport. The 'activity' was therefore chosen in order to modulate the last step of the material manufacturing. Transport was modelled according to transport distance and weight, where the transport distance was assumed to begin in the capital of each supplier's country, if the exact city was not announced. Transport was also added from the factory to the wastewater treatment plant, located in Copenhagen.

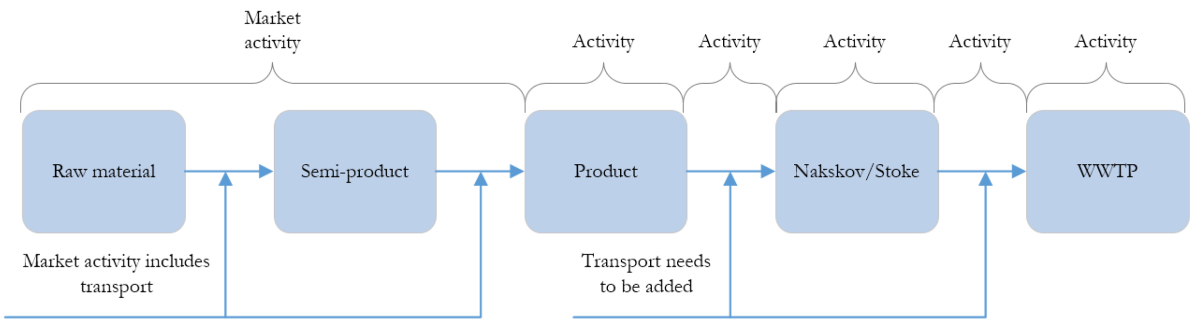


Figure 3.4: Differences between 'market activity' and 'activity' in Ecoinvent according to transport.

Electricity Mix

Energy supply was added to the manufacturing phase of the MBR module and the Iso-Disc, which was modulated based on each of the countries' specific electricity mix. Energy supply was added during operation, which was based on the electricity mix of the location of the wastewater treatment plant. The modulation of electricity mixes can be found in table A6.2 in Appendix 6. When the different electricity mixes are included, the data is in line with the geographical coverage. An uncertainty factor arises when the electricity mix is to be modelled, as the electricity mix may vary greatly from year to year. Parts of the changes are due to the fuel conversion from fossil to non-fossil electricity sources. For further description, see Appendix 7. It was not clear from Ecoinvent what year the electricity mixes were based on, only that they were updated regularly. Therefore, the percentages of each country's electricity mix are taken from the International Energy Agency (IEA, 2019) and are based on the year of 2016. Based on the percentages of IEA (2019), the electricity mixes were modelled in Ecoinvent. In figure A7.1 in Appendix 7, a comparison between the electricity mixes that this study is based on, has been compared to the same country's electricity mixes that are predefined in Ecoinvent. The percentages in Ecoinvent need to be updated on a regular basis in order for the electricity mixes to stay accurate. If not, these mixes might show inaccurate percentages of what currently constitutes a country's electricity mix. A good example of this is the large difference in the environmental impact of the electricity mix in UK, illustrated in figure A7.1 in Appendix 7. Since the lifetime of a wastewater treatment plant is very long, this will have consequences on the time related coverage, as the electricity mix might differ from one year to another. The emission values due to the electricity mix will thus both decrease and increase from year to year (Energiföretagen, 2018). The time-related data quality according to electricity mixes in the future is thus impossible to secure, since it is impossible to predict the future of a country's electricity mix. Difficulties arise in making a life cycle assessment that stretches into the future, especially since the LCA result is heavily dependent on the varying electricity mixes. For example, the average carbon dioxide emissions per generation of 1 kWh electricity in Denmark is expected to decline from 194 gram in 2017 to 61 gram per kWh in 2027 (Energinet, 2018).

3.4 Impact Assessment

The different impact assessment methods available for LCA are all based on scientific research (Althaus et al., 2010). Since the methods differ in some respects, an evaluation should be made before the choice of method is concluded. For example, TRACI[4] is a methodology that has been developed specifically for the US and is therefore best suited for US market activities (Althaus et al., 2010). However, Klöpffer and Grahl (2014) claim that it is up to each researcher to decide which method is best suited for the specific study.

In this study, ReCiPe Midpoint (H) v.1.13, consisting of 18 different impact categories (Werner et al., 2016) is used. The ReCiPe methodology is a development of the CML 2001 and Eco-indicator 99 methodologies (GaBi, n.d.). The methodology of ReCiPe has therefore both midpoint- and endpoint indicators (GaBi, n.d.). The inventory results group the substances that contribute to the same environmental effect into the different midpoint impact categories. The 18 midpoint impact categories can be divided into three endpoint impact categories; human health, ecosystem quality and resources (Rosenbaum et al., 2018).

[4] TRACI is a shortening for 'the Tool for the Reduction and Assessment of Chemical and other environmental Impacts' (Althaus et al., 2010).

ReCiPe Midpoint (H) v.1.13 is chosen for this study because of its common use in scientific research worldwide to map the environmental impact in LCA studies. The reason why Midpoint (H) was used, and not Midpoint (I) or Midpoint (E), is because H (Hierarchist) uses a 100-year timeframe (Gabi, n.d.). Midpoint E (Egalitarian) and I (Individualist) stands for a timeframe of a 1 000 and 20 years each (Gabi, n.d.). Environmental impacts require different time horizons in order to occur, which is dependent on the environmental mechanism and the speed of the processes. Therefore different timeframes can be used in order to include the effects from the emissions that will occur during a longer period (Rosenbaum et al., 2018).

The latest version of ReCiPe (v.1.13) in Ecoinvent was used. It is of high importance to use the same version of the methodology, since both categories and conversion factors differ between different versions. For example the conversion factor for methane (CH_4) to CO_2-equivalents has changed between ReCiPe 2008 and ReCiPe 2016 v. 1.1 from 25 to 34, which illustrates the importance of using one version (RIVM, 2018).

3.4.1 Environmental Impact Categories

Based on the 18 different impact categories available for ReCiPe Midpoint (H) v. 1.13, eleven impact categories are presented, which we have chosen as the most relevant for this study. Particulate matter formation, global warming and acidification are all important impact categories to include in an LCA for wastewater (Larsen, 2018). They are all typically related to energy production, which has shown to have a big impact on the LCA results of earlier wastewater treatment plants (Larsen, 2018). It is of high relevance to include eutrophication as an impact category, since the main reason for wastewater treatment plants are to remove organic matter and nutrients (nitrogen and phosphorus) (Larsen, 2018). The toxicity-related impact categories have a significant relevance if the chemical emissions from the effluent of the wastewater treatment plant are included when comparing different technologies. If the chemical emissions from the effluent are not included, the toxicity-related impact categories are still relevant according to air emissions from energy production (Larsen, 2018). Stratospheric ozone depletion is usually negligible regarding LCAs of wastewater treatment, but may play a minor role in some technologies (usually for advanced oxidation processes). Further, photochemical ozone formations have shown to play at least a minor role in several studies (Larsen, 2018). Below, the impact categories that were included in the study are presented in more detail.

Global Warming Potential: Greenhouse gases absorb infrared radiation, which no longer will be released into space. Instead it is kept in the atmosphere causing an increase in temperature as a result. Different greenhouse gases (e.g. carbon dioxide, methane and nitrous oxide) contribute to different global warming potential (GWP). The GWP_{100} stands for a timeframe of 100 years and the factor to calculate environmental impact of the gases is based on the atmospheric lifetime of the greenhouse gases. The global warming potential is measured in kg CO_2-equivalents (Rosenbaum et al., 2018).

Eutrophication Potential: Aquatic eutrophication is divided into two parts; freshwater-, and marine eutrophication. The aquatic eutrophication occurs due to waterborne emissions of nitrogen (N), phosphorus (P) and dissolved organic compounds. Environmental problems can be abnormal productivity such as algae growth in rivers and lakes. The growth of algae minimizes the ability of sunlight to reach the lower water layers. Aquatic eutrophication leads to depletion of oxygen in bottom layers, which in turn leads to suffocation of fish and bottom-dwelling species. Freshwater eutrophication potential is measured in kg P-equivalents and marine eutrophication potential is measured in kg N-equivalents (Rosenbaum et al., 2018).

Acidification Potential: Sulphur dioxides (SO_2) and nitrogen oxides (NO_2) are emissions that contribute to acidification the most. By acidification of aquatic ecosystems or soil, there is a reduction of the quantity of substances that are able to neutralise hydrogen ions (Rosenbaum et al., 2018). Acid rain will occur when water in the atmosphere reacts with acid gases. Environmental problems from acid rain are not always local at the emission source, instead they may travel long distances and cause damage continentally (Klöpffer & Grahl, 2014). Acidifying substances that reach Swedish lakes, watercourses and seas are derived mainly from winds after other countries' emissions and international shipping (Naturvårdsverket, 2018a). Acidification potential is measured in kg SO_2-equivalents (Rosenbaum et al., 2018).

Ecotoxicity Potential: Any substance may lead to toxic impacts. However, if a substance is harmful or not, depends on the emitted quantity, mobility, persistence, exposure patterns and level of toxicity. Different effects may occur, depending on the characteristics of the substance emitted and the environment condition for the specific place and time. Some substances can be toxic in small amounts while others are toxic first at large quantities. Ecotoxicity is divided into three groups; freshwater-, marine- and terrestrial ecotoxicity (Rosenbaum et al., 2018). The freshwater ecotoxicity potential and terrestrial ecotoxicity potential are both measured in kg 1.4 DCB-equivalents and marine ecotoxicity potential is measured in kg 1.4 DB-equivalents (Wernet et al., 2016).

Human Toxicity Potential: Human toxicity has many things in common with the impact category ecotoxicity. If a substance may be harmful or not, depends on the emitted quantity, mobility, persistence, exposure patterns and level of human toxicity. What differentiates human toxicity potential from ecotoxicity potential, is that the toxicity for humans are taken into account. Dietary habits for example, influences human exposure, which makes the human toxicity potential different according to the exposure pattern (Rosenbaum et al., 2018). Human toxicity potential is measured in kg 1.4 DCB- equivalents (Wernet et al., 2016).

Ozone Depletion: Stratospheric ozone concentration has been declining since the 1970s according to observations, and stratospheric ozone depletion is referring to this reduction. Gases like chlorinated chlorofluorocarbons (CFCs) are stable enough to reach up to the stratosphere, which destroys the ozone molecules. Due to this reaction, ultraviolet (UV) light will enter the atmosphere closer to earth in a higher extent, which can lead to harmful effects such as malignant melanoma. Stratospheric ozone depletion potential is measured in kg CFC-11-equivalents (Rosenbaum et al., 2018).

Photochemical Oxidant Formation: Photochemical oxidant formation is also referred to as photo smog, summer smog or photochemical ozone formation. Its environmental impact is referring to the forming of ozone and other reactive oxygen compounds in the stratosphere as secondary contaminants. Carbon monoxide (CO) and volatile organic compounds (VOCs) react with nitrogen oxides (NO_x) during sunlight and create tropospheric ozone (Rosenbaum et al., 2018). Photochemical oxidant formation potential is measured in kg NMVOC- equivalents (Wernet et al., 2016).

Particulate Matter Formation: Health impacts from exposure to particulate matter are referred to as particulate matter formation. Particulate matter is not included in the impact of human toxicity because of the differences between characterizations of the two impact categories. Road traffic and power plants are examples of sources, which produce particles like nitrogen oxides (NO_x) and sulphur oxides (SO_2). Health issues such as lung cancer and respiratory problems are caused by these particles. They are all small particles and the unit reference depends on the size, where the unit of PM_{10}-equivalents is referred to particles less than 10 μm in diameter size (Rosenbaum et al., 2018). Particulate matter formation potential is measured in kg PM_{10}- equivalents (Wernet et al., 2016).

In addition to the categories presented above, the primary energy consumption measured in MJ will be evaluated.

3.5 Interpretation

To validate the result, several sensitivity analyses are conducted. The first sensitivity analysis is conducted on the operation phase, due to its great environmental impact on the electricity use. Here, different electricity mixes are tested, in order to see how they change the environmental impact of the systems. The electricity mix in Sweden is chosen as the 'better' alternative. In the same way, the electricity mix in Australia is chosen as the 'worse' alternative, based on the share of fossil and non-fossil based electricity in the specific countries. A sensitivity analysis is conducted for the chemicals, where global citric acid production is replaced by local production from Europe. The impact on the lifespan of the plant is also evaluated.

Since the two technologies have different purification levels, a sensitivity analysis is conducted, where indirect emissions of phosphorus and nitrogen in the effluent water are included. The MBR technology has a purification level of 1 mg TSS/litre and the Iso-Disc has a purification level of 5 mg TSS/litre, which means that larger amounts of both nitrogen and phosphorus will be released with the effluent water of the Iso-Disc. For the composition of the TSS in the effluent, see table A5.1 in Appendix 5. A sensitivity analysis was therefore performed in order to see how this would effect the impact categories freshwater eutrophication potential and marine eutrophication potential.

3.5.1 Method Limitations

By using the database of Ecoinvent as a search tool, managing the large amount of data that is available will be a big challenge. In cases where the exact keywords are not used, there is a risk that important LCA results will be missed. Another problem with Ecoinvent is that some LCAs have less detailed descriptions and it becomes difficult to confirm the underlying data quality. However, Ecoinvent currently has a wide range of life cycle impact assessment (LCIA) results and is thus chosen for this study. Furthermore, data presented by Ecoinvent is clearly described regarding FU. For all LCAs, all the impact categories are presented, which creates consistency. The software SimaPro or OpenLCA could have been used to create a larger overview of existing LCAs in Ecoinvent. In order to achieve a result, all values from Ecoinvent were compiled in Microsoft Excel. Since large amounts of data were manually entered in Excel, it required a great deal of sorting. This obviously increases the risk of a potential error.

Using the ReCiPe Midpoint methodology instead of the ReCiPe Endpoint, where the 18 Midpoint categories are divided down into three Endpoint categories can be debated. The result of downscaling might be easier to understand for the general public (Gabi, n.d). It can be debated whether endpoint categories is easier for decision makers, since midpoint categories can be seen as more abstract (Bare et al., 2000). However, there are benefits of using the Midpoint methodology. Bare et al. (2000) argue that the Midpoint methodology has greater reliability, provides higher possibilities for scientific validation, creates higher certainty and confidence for the result compared to the Endpoint methodology. Choosing Midpoint as the methodology was thus made in order to maintain a high level of scientific work.

4 Inventory Analysis

The following chapter describes each wastewater treatment system based on selected technology and system boundaries, and lists the needed resources and the size of these. Common for the systems is the amount of raw wastewater to the plant (1 900 m^3/day) for a 20-year period, since the systems are dimensioned to the extent that the same amount of water will pass through the two systems. The two systems show both technological differences and differences in purification quality.

4.1 Membrane Bioreactor Technology

Figure 4.1 illustrates an overview of the MBR system, of which the study intends to map out the environmental impact. According to the flowchart and the scope of the study, the grey-marked steps will not be included. The system consists of two anoxic and two aerobic tanks designed for a biological nitrogen removal process. Further the system consists of four MBR tanks and one tank for the MBR CIP (cleaning in place). For material specifications of the tanks, see table A1.1 in Appendix 1. The anoxic and the aerobic tanks differ from the Iso-Disc system according to the size of the tanks, since the biological tanks of the MBR require less volume.

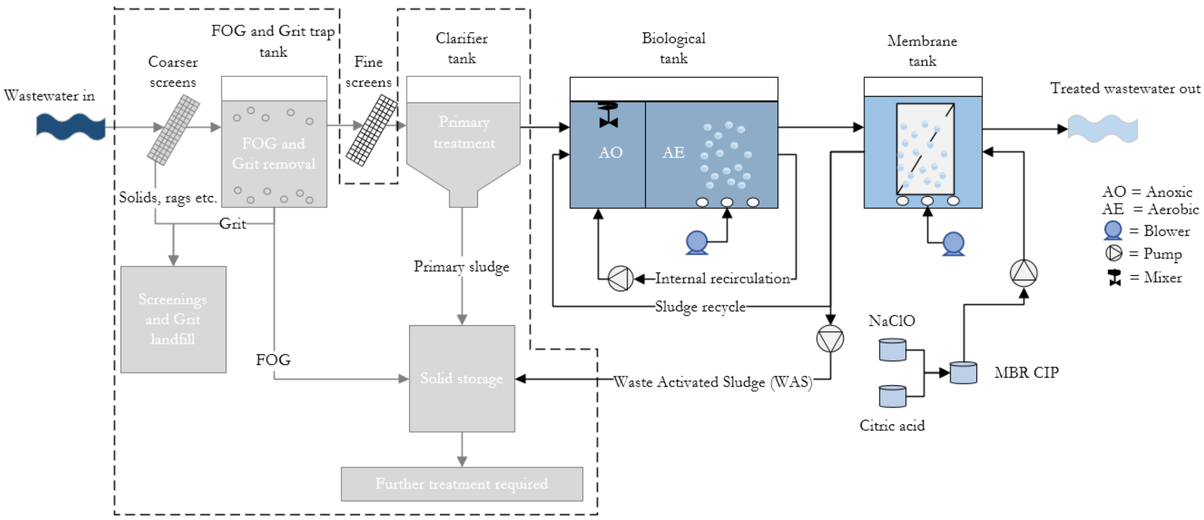


Figure 4.1: The MBR system where the grey-marked steps are excluded from this study.

4.1.1 Screens

The membranes require fine screens in order for them to work and are therefore included in the study. For the process, four fine screens are required[5], see table 4.1. For further specifications, see table A1.2 in Appendix 1.

Table 4.1: Material input of the screens

Component category	Pieces	Total weight (kg)
Fine screen (including engine)	4	1 080

4.1.2 Biological Wastewater Treatment

The biological wastewater treatment is divided into two different categories; anoxic denitrification and aerobic nitrification[5].

Anoxic Denitrification

The anoxic treatment occurs in two tanks, where the floor and the walls are made of reinforced concrete with a thickness of 0.4 metres[5]. The length, width and height of each of the tanks are 1.5, 4.4 and 5.1 meters. Each tank has a water depth of 4.5 meters[5]. For the anoxic denitrification two anoxic mixers are used (Grundfos AMD), one in each tank with an operational effect of 0.64 kW each. The total weight of each mixer is 10.8 kg and consists mostly of stainless steel (Grundfos Holding A/S, n.d.a).

Aerobic Nitrification

Just like the anoxic treatment, the aerobic treatment occurs in two tanks, where the floor and the walls are made up of reinforced concrete with a thickness of 0.4 meters[5]. The length, width and height of each of the tanks are 3.6, 4.4 and 5.1 meters and the tanks have a water depth of 4.5 meters[5]. The system needs two internal recycle pumps (Grundfos CRE 64-1) with an operational effect of 9.35 kW, one for each aerobic tank. The recycle pump mainly consists of stainless steel and cast iron and has a weight of 132 kg (Grundfos Holding A/S, n.d.b).

Air requirements of each tank are 503 mbar[5]. Two blowers are needed for the aerobic nitrification and 48 units of air diffusers are required[5]. The lifespan of the air diffusers is estimated between ten to fifteen years[6], which means that one replacement needs to be done during the lifespan of 20 years. Ten valves are required for air blower and diffuser isolation[5].

4.1.3 Summary of the Inventory of the Biological Wastewater Treatment

In addition to the components above, piping is needed, which is estimated to a total length of 114 meters, consisting of both stainless steel and PVC[5], see table A1.3 in Appendix 1. In table 4.2 the inventory findings are summarized.

[5] Gurieff, Nicholas; Global Sales Business Development – Membranes & Wastewater, Alfa Laval. 2019. Personal Communication
[6] Buhmann, Philip; Project Engineer, Jäger Umwelt-Technik GmbH. 2019. Communication via email 25th of March

Table 4.2: Material input of the biological treatment.

Component category	Unit	Total weight (kg)
Tank	4 pieces	301 745
Piping (including piping support)	114 meters	1 334
Mixer	2 pieces	22
Recycle pump	2 pieces	264
Air diffuser	96 pieces*	206
Valve (including electric actuator)	10 pieces	279
Blower (including engine)	2 pieces	1 158

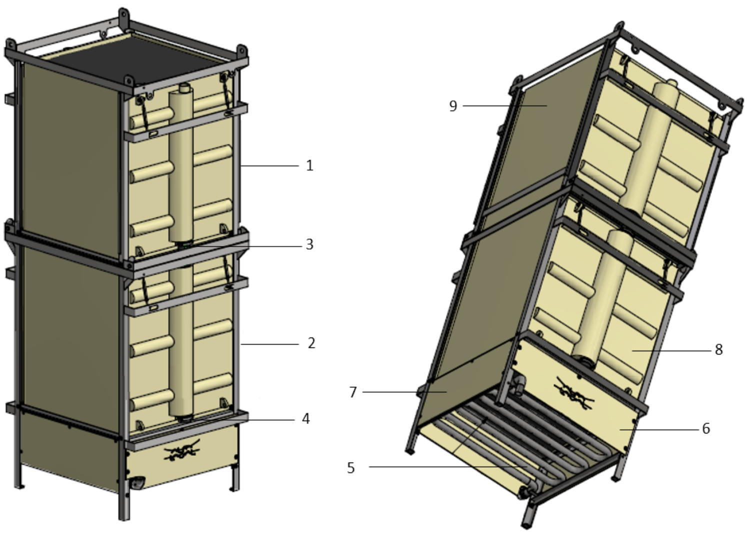
*The units specified for the air diffusers include one replacement during the estimated lifetime.

4.1.4 Membrane Bioreactor

The system contains four MBR tanks, which each holds five membrane modules (MFM240). The floor and the walls of the tanks consist of reinforced concrete with a thickness of 0.4 metres. The length, width and height of each of the tanks are 6.3, 2.0 and 5.1 meters and the water depth is 4.5 meters[5].

MBR Module MFM240

Figure 4.2 points out the visible components of the MBR module. Each MBR module consists of two parts standing on each other, also known as a pack[7]. The packs are constructed in the same way. Each pack consists of 85 membranes, which means that each MBR module consists of 170 membranes[7]. The modules consist mainly of stainless steel and polypropylene (PP). The suppliers of the material can all be derived from Europe, mainly Denmark and Poland[7]. A description of all materials, weights, supplier location and type of transport can be found in Appendix 1. The lifetime of the membranes is set to ten years, and one replacement needs to be done during the estimated lifetime of this study.



1	Frame assembly top	2	Frame assembly bottom	3	Permeate box flexible connection
4	Permeate box bottom seal	5	S-Aerator	6	Cover with notch (S-Aerator)
7	Cover (S-Aerator)	8	Permeate box	9	Endplate

Figure 4.2: Visible components of the MBR Module MFM240 (source: Alfa Laval).

[7] Bengtsson, Jessica; Global Sales Manager – Membrane Water and Food Components, Alfa Laval. 2019. Personal Communication

Manufacturing of the MBR Module MFM240

The manufacturing of the MBR modules is made in the factory of Alfa Laval in Nakskov (Denmark). Today there is a low degree of automation in the factory, and the MBR module is assembled mostly by hand. When manufacturing the MBR modules, energy is required. Figure 4.3 illustrates the energy steps that are required in the factory of Alfa Laval. A total electricity consumption of 20 MBR modules is estimated to 20 380 kWh[7]. A more detailed description of the electricity consumption of the manufacturing steps of the MBR modules is given in table A1.8 in Appendix 1.

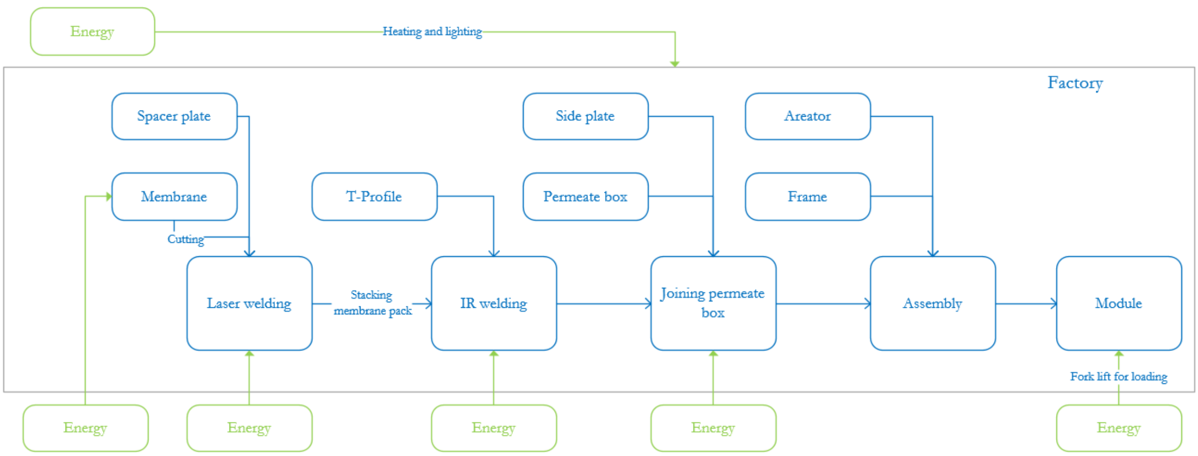


Figure 4.3: The manufacturing process of the MBR module.

As a first step in the manufacturing process, the membranes are put together with the spacer plates. The spacer plates that are made of PP are manufactured in Italy, and thereafter transported to France to make many tiny holes mechanically in each plate for the water to pass through[7]. The polyvinylidene fluoride (PVDF) membrane is produced in Nakskov. The membrane has the form of a thin white fabric. In order to put the membrane and spacer plate together, laser is used, where the edges and eight lines are welded together, see figure 4.4. The eight welding lines are done in order to make the membranes able to withstand the cleaning that is done four times a year during operation[7]. Since the cleaning with chemicals is pushed into the opposite direction compared to the water direction, the thin fabric will expand. In order not to break, the membrane is co-welded through the eight different lines into the spacer plate[7].

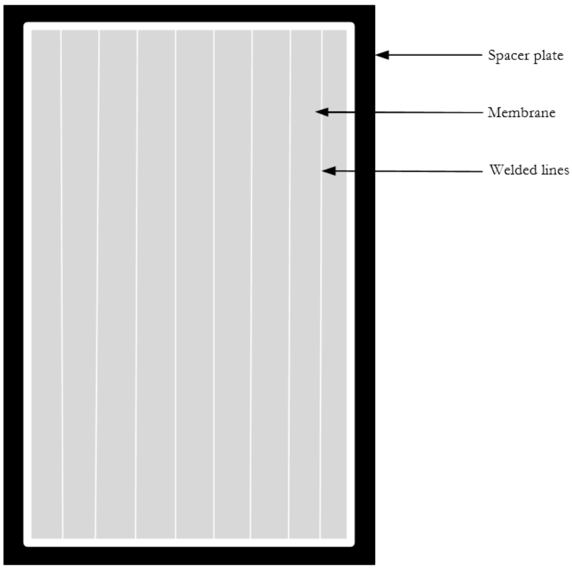


Figure 4.4: The spacer plate and PVDF membrane welded together.

To hold the membranes and spacer plates together, a T-profile (consisting of PP and fiberglass) merges the membranes together[7]. Ultrasonic heating is used in order to merge the T-profile with the membranes. A person joins the permeate box to the pack using a jointing machine. The warehouse of the modules is in proximity to the factory.

Gate

Two gates for each MBR tank is required, which each has the size of one square meter. The gates consist of stainless steel, and the total weight of eight gates is 190 kg[5]. The gates are used to recirculate the flow from the MBR tank to the biological tank instead of using recirculation pumps. The gates are creating an airlift effect, taking the sludge from the MBR tank through the bottom gate and returning it through the top gate[7].

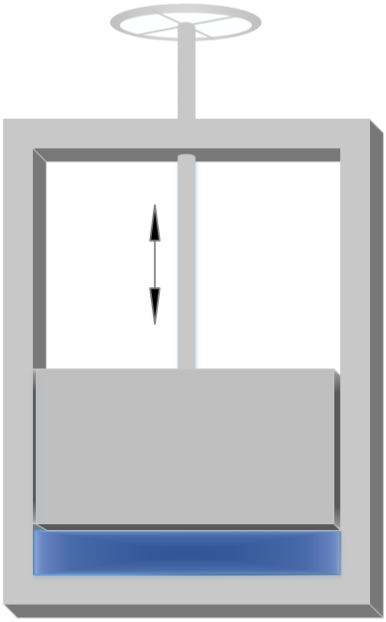


Figure 4.5: The gate that recirculate the flow from the MBR tank to the biological tank.

4.1.5 Summary of the Inventory of the Membrane Bioreactor

In addition to the components above, piping is needed, which has been estimated to a total length of 240 meters, consisting of both stainless steel and PVC[5], see table A1.4 in Appendix 1. Angles bars and mounting points are included in order to connect the MBR modules into the concrete walls[5]. Further, pressure transmitters and flow meters are required in order to measure flow and pressures in permeate, CIP, air and membrane tanks[5]. In table 4.3 the inventory findings are summarized.

Table 4.3: Material input of the Membrane Bioreactor.

Component category	Unit	Total weight (kg)
Tank	5 pieces	353 86
Piping (including piping support)	240 meters	2 862
MBR module	20 pieces	29 223
Gate	8 pieces	190
Valve (including electric actuator)	37 pieces	456
Pump	5 pieces	230
Blower (including engine)	3 pieces	1 890
Pressure transmitter	9 pieces	4
Flow meter	5 pieces	257
Angles bars + mounting points	-	33

4.1.6 Transport

Transport is divided into transport from the suppliers to Alfa Laval's factory in Nakskov, and thereafter from the factory to the wastewater treatment plant located in Copenhagen.

Transport from Supplier to the Alfa Laval Factory in Nakskov

Suppliers from different European countries supply the needed materials and components for manufacturing the MBR modules. The transport is done by truck and is assumed to start in each country's capital city where the product is manufactured unless the specific city is appointed. For more details, see table A1.6 in Appendix 1.

Transport to Wastewater Treatment Plant

The transport of the MBR modules from the factory in Nakskov is calculated from the base case, in which the treatment plant is located in Copenhagen. The transport is done by truck (172 km) and for each transport it is assumed that all 20 MBR modules are transported; see table A1.7 in Appendix 1 for a more detailed description.

4.1.7 Operation

Table 4.4 shows the power consumption and operational time of the MBR system. The table is divided into components that concern the mechanical-, biological- and membrane treatment.

Table 4.4: Power consumption and operational time for the MBR system.

Component category	Unit (operational/standby)	Operational energy use (kW)[1]	Operational time (h/day)
Mechanical			
Fine screen	4	0.31	24
Biological			
Recycle pump	2/0	9.35	24
Mixer	2/0	0.64	24
Blower	1/1	11.31	24
Membrane			
Blower	2/1	16.66	24
WAS pump	2/0	2.55	0.33
CIP pump	1/0	1.28	0.06
Dosing pump	2/0	0.20	0.06

[1]The operational energy use is set to 85 % of the peak value.

Cleaning in Place

During the operation, the MBR system requires chemicals to stay clean. The amount of chemicals required throughout a period of 20 years can be found in table 4.5. The cleaning of the MBR is done four times a year. For the cleaning of the membranes two different chemicals are used; sodium hypochlorite (NaClO) and citric acid[7]. For the cleaning process two dosing pumps (Grundfos DME) are needed, one for each chemical. The dosing pumps are connected to a tank made of polyethylene with a weight of 115 kg. The volume of the tank is 4 m^3. Between the polyethylene tank and the four MBR tanks, a pump (Grundfos CRE 15) is connected[5].

Table 4.5: The type of chemicals and the required amount for a 20 year period.

Chemicals	Amount (kg)
12 % w/w sodium hypochlorite solution	60 060
40 % w/w citric acid solution	90 080

4.2 Iso-Disc Technology

Figure 4.6 illustrates an overview of the Iso-Disc system, of which the study intends to map out the environmental impact. According to the flowchart and the scope of the study, the grey-marked steps will not be included. The system consists of two anoxic and aerobic tanks designed for a biological nitrogen removal process, one secondary clarifier tank and one tertiary filtration tank with the Iso-Disc. For material specifications of the tanks, see table A2.1 in Appendix 2. The anoxic and aerobic tanks are larger compared to the MBR system. More material is therefore required for production of the tanks. With larger volumes in the biological tanks, mixers and pumps with higher operational effects compared to the MBR system are needed. The Iso-Disc technology is a part of a conventional activated sludge (CAS) system, and a secondary clarifier tank therefore follows the biological tanks.

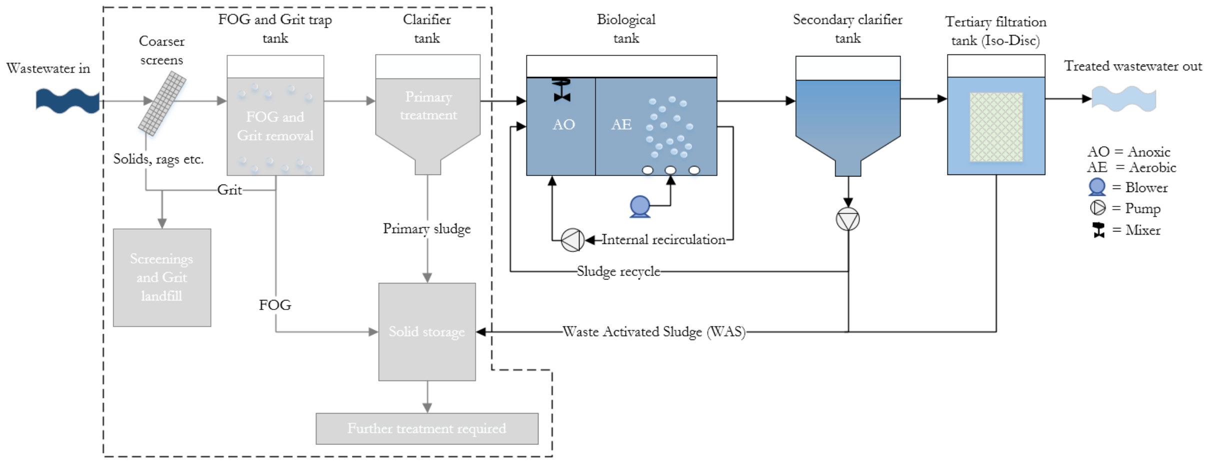


Figure 4.6: The Iso-Disc system where the grey-marked steps are excluded from this study.

4.2.1 Biological Wastewater Treatment

The biological wastewater treatment is divided into two different categories; anoxic denitrification and aerobic nitrification[8].

Anoxic Denitrification

The anoxic treatment takes place in two tanks, where the floor and walls are made of reinforced concrete with a thickness of 0.4 meters. The length, width and height of each of the tanks are 5.0, 4.4 and 5.1 meters. Each tank has a water depth of 4.5 meters[8]. For the anoxic denitrification two anoxic mixers are used (Grundfos AMG), one in each tank with an operational effect of 1.28 kW each. The total weight of each mixer is 78 kg and consists mostly of stainless steel and cast iron (Grundfos Holding A/S, n.d.d).

Aerobic Nitrification

Just like the anoxic treatment, the aerobic treatment occurs in two tanks, where the floor and the walls are made up of reinforced concrete with a thickness of 0.4 meters. The length, width and height of each of the tanks are 12.0, 4.4 and 5.1 meters and the tanks have a water depth of 4.5 meters[8]. The system needs two internal recycle pumps (Grundfos CRE 120-1) with an operational effect of 15.73 kW, one for each aerobic tank. The recycle pump mainly consists of stainless steel and cast iron and has a weight of 248 kg (Grundfos Holding A/S, n.d.b).

Air requirements of each tank are 503 mbar[8]. Two blowers are needed for the aerobic nitrification and 48 units of air diffusers are required[8]. The lifespan of the air diffusers is estimated between ten to fifteen years[9], which means that one replacement needs to be done during the lifespan of 20 years. Further, 14 valves are required for air blower and diffuser isolation[8]; see table A2.2 in Appendix 2 for more details.

[8] Gurieff, Nicholas; Global Sales Business Development – Membranes & Wastewater, Alfa Laval. 2019. Personal Communication
[9] Buhmann, Philip; Project Engineer, Jäger Umwelt-Technik GmbH. 2019. Communication via email 25th of March

4.2.2 Summary of the Inventory of the Biological Wastewater Treatment

In addition to the components above, piping is needed, which is estimated to a total length of 205 meters, consisting of both stainless steel and PVC[8], see table A2.2 in Appendix 2. In table 4.6 the inventory findings are summarized.

Table 4.6: Material input of the biological treatment.

Component category	Unit	Total weight (kg)
Tank	4	622 723
Mixer	2	156
Air diffuser	96*	206
Blower (including engine)	2	1 158
Recycle pump	2 pieces	496
Valve (including electric actuator)	14 pieces	333
Piping (including piping support)	205 meters	1 697

*The units of the air diffusers include one replacement during the estimated lifetime

4.2.3 Secondary Clarifier

After the biological treatment, a conventional rotary scraped clarifier is used. Figure 4.7, points out the different parts of the clarifier. The clarifier consists of one reinforced concrete tank. The tank has a wall thickness of 0.4 meters, a diameter of 12.7 meters and a tank depth of 5.1 meters[8]. Two pumps are needed for waste and sludge recycle (CRE 32-2-1), where each pump has a total weight of 91 kg and mainly consists of cast iron and stainless steel (Grundfos Holding A/S, n.d.b). In order to transport mixed liquor suspended solids (MLSS) to the clarifier and thereafter transport the thickened sludge and the effluent from the clarifier, 30 meters of piping is estimated[8]. The piping consists of carbon steel[8]. The gangway is used for operators as well as support for the scrapers. It consists of aluminium and has a total weight of 780 kg[8].

The rubber scrapers, which scrape the bottom of the clarifier and moves the sludge to the central sump, consist of rubber and has a total weight of 60 kg. The rubber scrapers need to be replaced annually[8]. In order to rotate the gangway and scrapers a drive engine is needed, which has a total weight of 23 kg. Around the edges of the clarifier 'shark teeth' are installed in order to improve the clarity of the water. The 'shark teeth' have a total weight of 220 kg and consist of stainless steel[8]. Right at the inlet of the clarifier, there is an energy dissipating barrier (in figure 4.7 called skirt). The flow will enter the top near the water surface in the centre. The goal with the energy dissipating barrier is to have the water velocity as low as possible, and the path the water takes as long as possible. This gives the solids as much time as possible to settle in the tank[8]. The total weight of the skirt is 80 kg and consists of stainless steel[8].

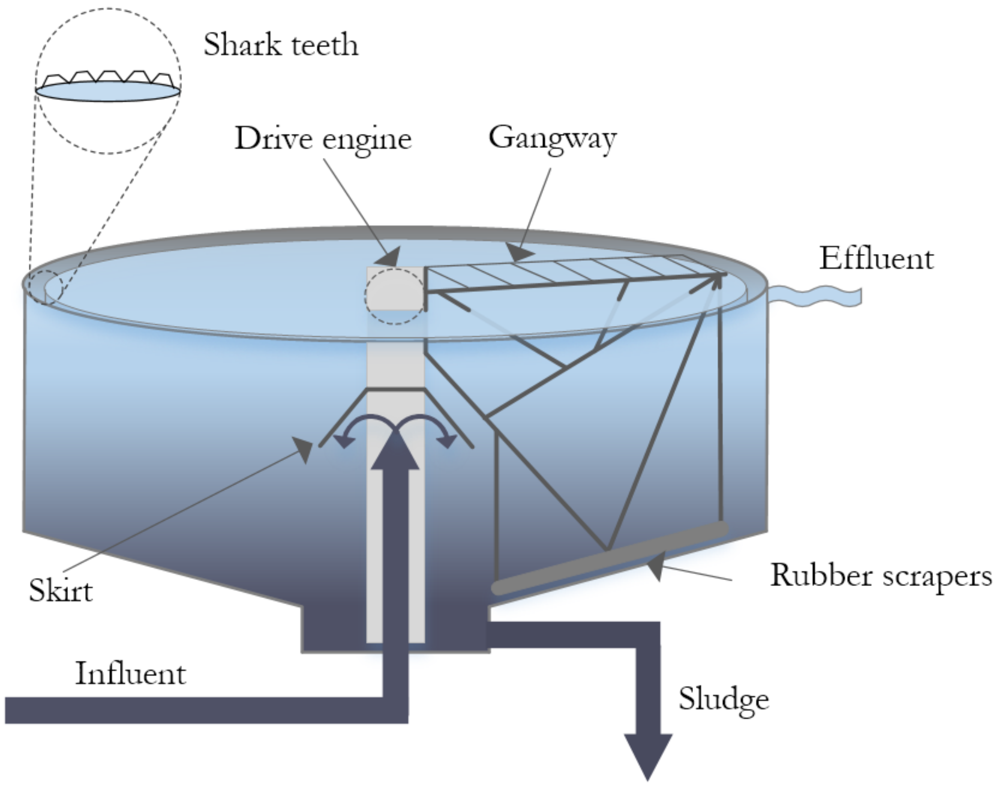


Figure 4.7: Conventional rotary scraped clarifier.

In table 4.7 the inventory findings are summarized.

Table 4.7: Material input of the secondary clarifier treatment.

Component category	Unit	Total weight (kg)
Tank	1 pieces	301 288
WAS/RAS pump	2 pieces	182
Skirting (including attachments)	1 pieces	80
Sharks teeth	1 pieces	220
Gangway	1 pieces	780
Rubber scraper	20*	1 200
Drive engine	1 pieces	23
Piping	30 meters	695

*The rubber scrapers are annually replaced, thereby the unit of 20

4.2.4 AS-H Iso-Disc Cloth Media Filter

The tank of the Iso-Disc is made of reinforced concrete and the length, width and height are 4.5, 1.5 and 2.8 meters each with a thickness of 0.4 meters. The system only requires one Iso-Disc[8]. Figure 4.8 shows a schematic illustration of the Iso-Disc and the visible parts are pointed out. The Iso-Disc can be divided into three parts; the Assembly, Vacuum Assembly and Disk Assembly. All parts mostly consist of stainless steel, for a more detailed material list, see table A2.5 in Appendix 2. The filter cloth, made of polyester, needs to be replaced every fifth year[10].

[10] Bengtsson, Jessica; Global Sales Manager – Membrane Water and Food Components, Alfa Laval. 2019. Personal Communication

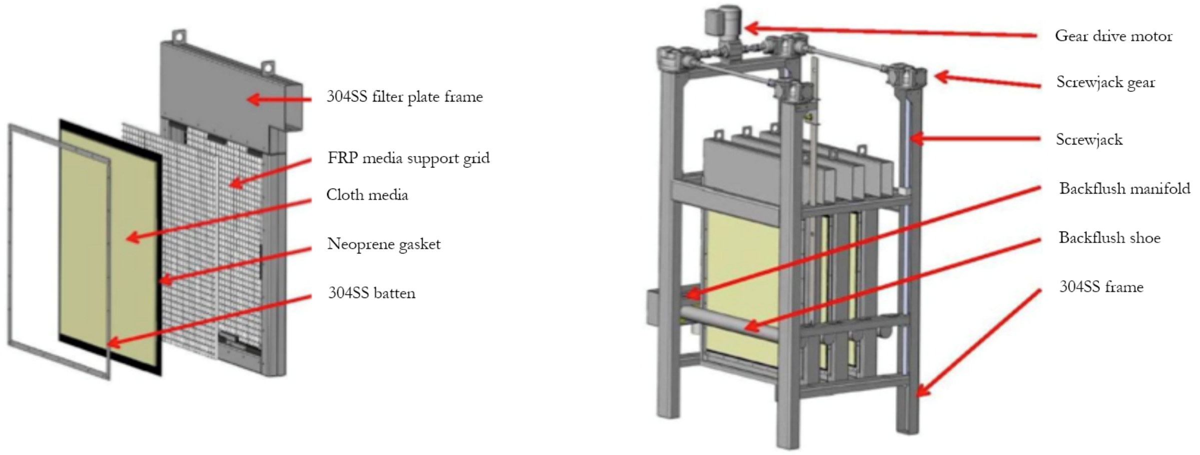


Figure 4.8: Schematic illustration of the AS-H Iso-Disc Cloth Media Filter (source: Alfa Laval).

In figure 4.9, the Iso-Disc is illustrated in a wider perspective, along with the backwash pump and piping. Three backwash pumps are needed for the system[8]. Further, piping is required, which has been estimated to 65 meters, consisting of both stainless steel and PVC[8]. The total weight of the piping includes support to hold the pipes in the right place. The influent shows the ingoing wastewater to the Iso-Disc, and the effluent shows where the treated wastewater goes out.

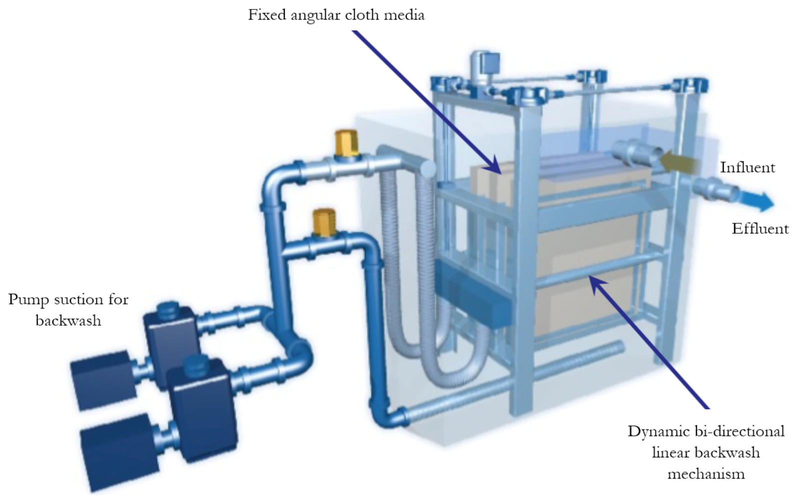


Figure 4.9: Schematic illustration of the AS-H Iso-Disc Cloth Media Filter integrated with pumps and piping (source: Alfa Laval).

Assembling and Testing of the AS-H Iso-Disc Cloth Media Filter

The assembling and testing of the Iso-Disc are made in Stoke, UK. The assembling process includes energy in form of lightning and heating of the building. Energy is used for cranes to lift the components and loading of the completed filter. Energy is used for forklifts to unload and stage the components ready for assembly. Energy is also used for different machines such as wrenches, drills and grinders to assemble the Iso-Disc. Furthermore, energy to test run the Iso-

Disc is included in the required energy to assemble the Iso-Disc in the factory. Figure 4.10 illustrates the energy steps that are required in Alfa Laval's factory. A total electricity consumption is estimated to 1 515 kWh/Iso-Disc[10].

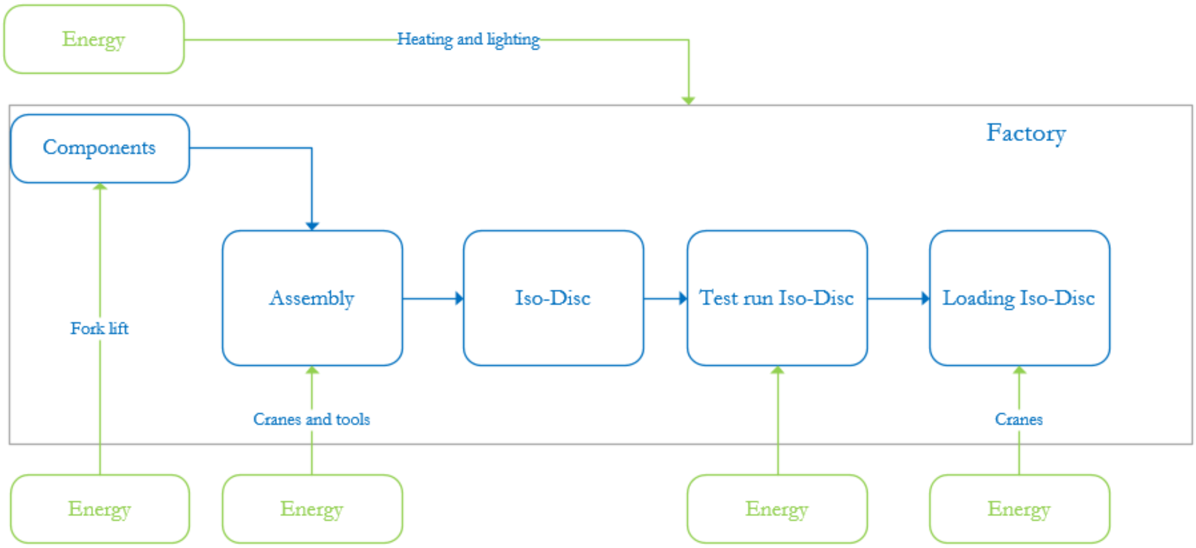


Figure 4.10: Assembling and testing of the Iso-Disc.

4.2.5 Summary of the Inventory of the Iso-Disc

In table 4.8, the inventory findings are summarized. In order to determine the height of the water in the tank, a pressure transmitter is needed[8]. Seven valves are required, consisting of ductile iron and stainless steel[8], for more details see table A2.4 in Appendix 2.

Table 4.8: Material input of the Iso-Disc treatment.

Component category	Unit	Total weight (kg)
Tank	1 pieces	31 403
Iso-Disc	1 pieces	1 224
Valve (including electric actuator)	7 pieces	49
Pump	3 pieces	117
Pressure transmitter	1 pieces	0.41
Piping (including support)	65 meters	842

4.2.6 Transport

Transport is divided into transport from the suppliers to Alfa Laval's factory in Stoke, and thereafter from the factory to the wastewater treatment plant located in Copenhagen.

Transport from Supplier to the Alfa Laval Factory in Stoke

Suppliers in different countries around the world (mainly Houston in US and Beijing in China) supply the needed materials and components for manufacturing the Iso-Disc[10]. The transport is done mostly by sea freight[10] and is assumed to start in each country's capital city where the product is manufactured, unless the specific city is appointed. For further details, see table A2.6 in Appendix 2.

Transport to Wastewater Treatment Plant

The transport of the Iso-Disc from the factory in Stoke is calculated from the base case, in which the treatment plant is located in Copenhagen. The transport is done by sea freight, with an estimated distance of 2 500 km, see table A2.7 in Appendix 2.

4.2.7 Operation

Table 4.9 shows the power consumption and operational time of the Iso-Disc system. The table is divided into components that concern the biological treatment, the clarifier and the Iso-Disc.

Table 4.9: Power consumption and operational time for the Iso-Disc system.

Component category	Pieces (operational/standby)	Operational energy use (kW)[1]	Operational time (h/day)
Biological			
Recycle pump	2/0	15.73	24
Mixer	2/0	1.28	24
Blower	1/1	11.31	24
Clarifier			
WAS/RAS pump	2/0	4.68	24
Drive engine	1/0	1.50	24
Iso-Disc			
Backwash pump	2/1	1.87	4
SEW drive engine	1/0	1.28	4

[1]The operational energy use is set to 85 % of the peak value.

5 Impact Assessment

In the following chapter, the environmental impact of the MBR and Iso-Disc technologies is shown. All the graphs are using the unit kilogram per FU, in accordance with the numbers presented in the database of Ecoinvent.

5.1 Environmental Impact of the Systems

The environmental impact of the systems includes transport, production and operation. In figure 5.1 - 5.4 the impact categories are shown in more detail. According to transport, production and operation, the Iso-Disc technology shows the lowest environmental impact for all categories compared to the MBR technology. The Iso-Disc shows between 18-56 % lower impact compared to the MBR system, depending on the category. The impact category terrestrial ecotoxicity potential, shows the highest percentage difference between the two systems. Terrestrial acidification potential shows the lowest percentage difference in environmental impact between the two systems.

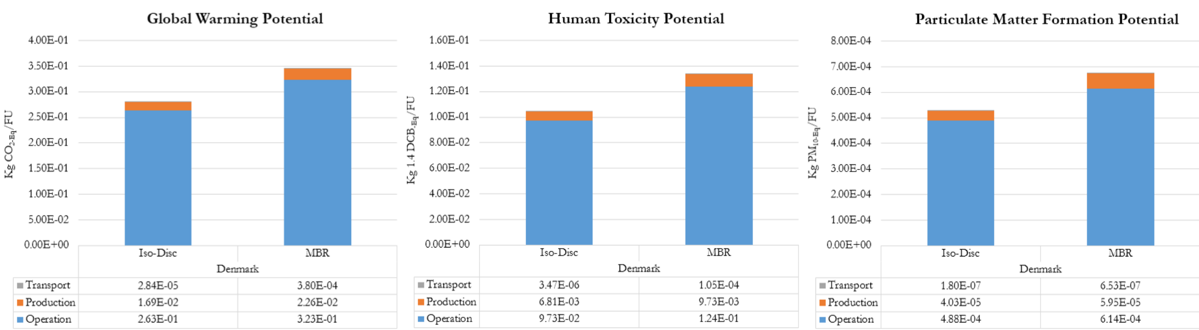


Figure 5.1: The impact of global warming potential, human toxicity potential and particulate matter formation potential.

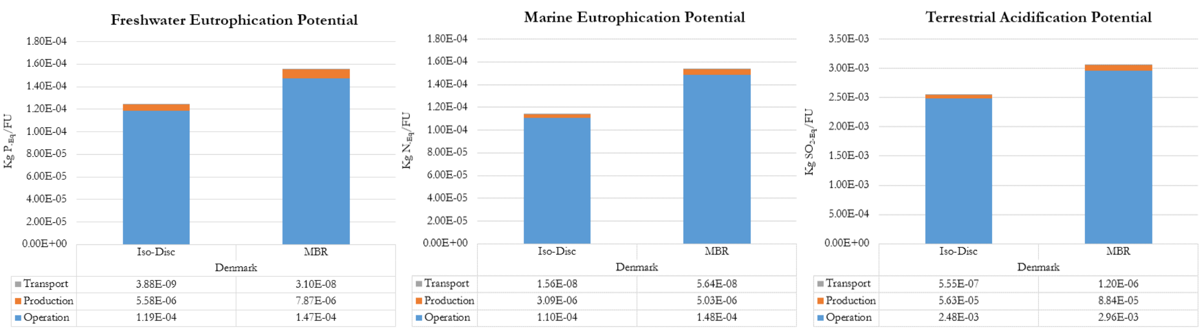


Figure 5.2: The impact of freshwater eutrophication potential, marine eutrophication potential and terrestrial acidification potential.

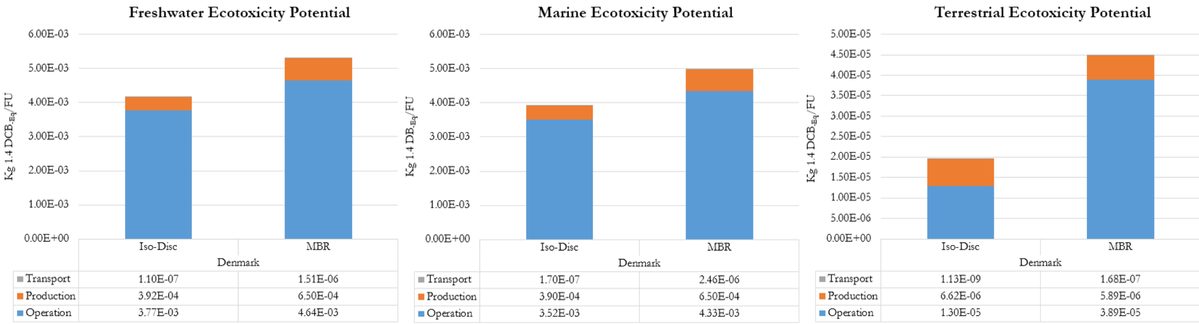


Figure 5.3: The impact of freshwater ecotoxicity potential, marine ecotoxicity potential and terrestrial ecotoxicity potential.

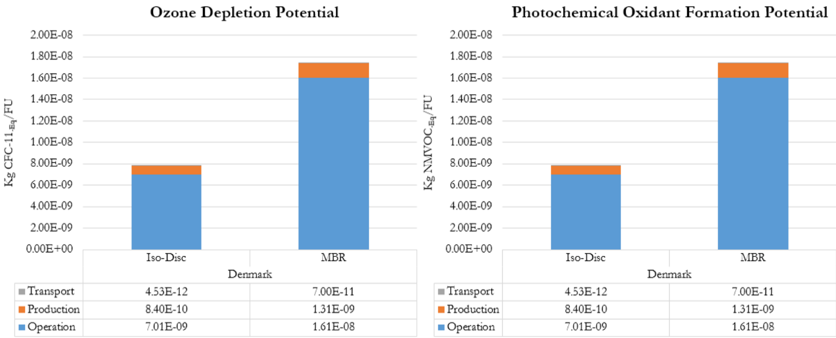


Figure 5.4: The impact of ozone depletion potential and photochemical oxidant formation potential.

The operation phase is by far the biggest contributor to all eleven impact categories, for both the Iso-Disc and the MBR system. According to the MBR system, the operation phase is responsible for about 87 - 97 % of the total environmental impact, depending on category. According to the Iso-Disc system, the operation phase contributes to 89-98 %, except for terrestrial ecotoxicity potential, which is down to 66 %. The impact of the transport is insignificant for both systems, and is barely visible in the bars. Transport is responsible for about $2.65 \cdot 10^{-5}$ - $9.4 \cdot 10^{-1}$ % for the Iso-Disc system, and $4.04 \cdot 10^{-7}$ - $4 \cdot 10^{-3}$ % for the MBR system.

In figure 5.5, the primary energy of the systems is shown. In the left graph, the total primary energy is shown for the Iso-Disc and MBR system. The MBR system requires more primary energy compared to the Iso-Disc system, in which the operation phase plays a more significant role. In the right graph, the operation, production and transport are divided into different bars. Here, the primary energy is divided into fossil and non-fossil energy. The production of the MBR system also requires more primary energy compared to the Iso-Disc system. The primary energy of the transport is insignificant.

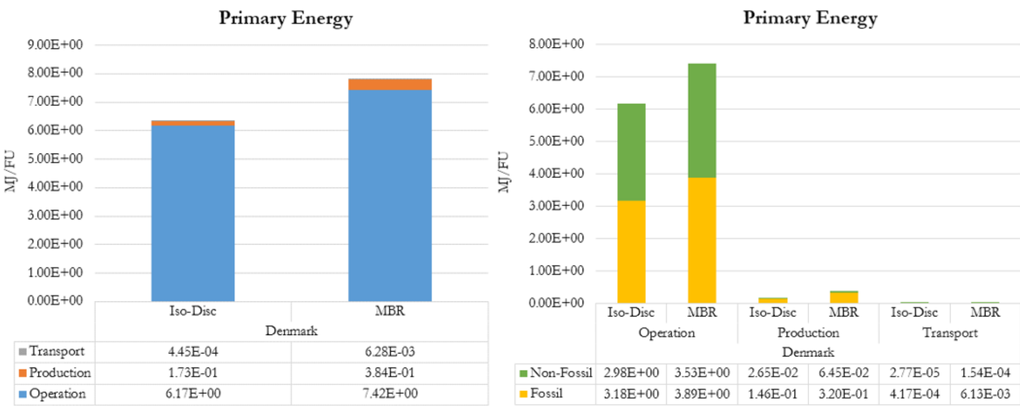


Figure 5.5: Primary energy.

5.2 The Operation Phase

In figure 5.6 - 5.9, the environmental impact during the operation phase is shown. The required electricity is divided into fossil and non-fossil electricity. The two systems are distinguished by the MBRs need of chemicals due to cleaning. According to the graphs, the impact category terrestrial ecotoxicity potential for MBR stands out, since the citric acid is taking up 60 % of the impact. Similarly, the category ozone depletion potential stands out, since the sodium hypochlorite stands for 40 % of the total impact.

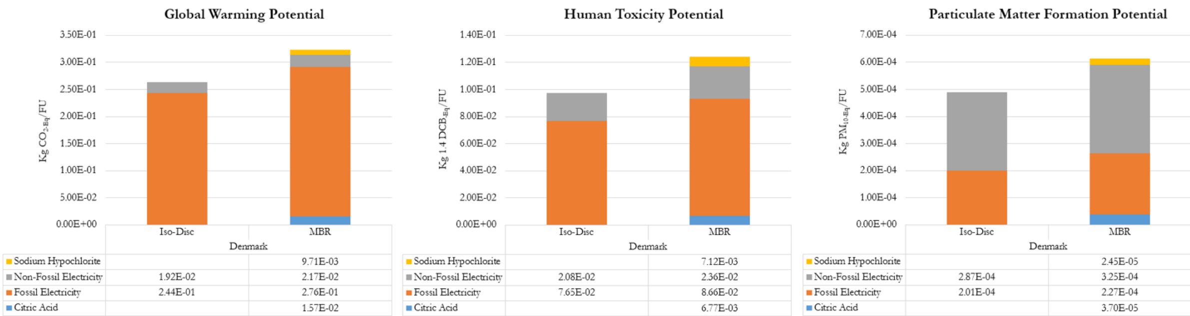


Figure 5.6: The impact of global warming potential, human toxicity potential and particulate matter formation potential.

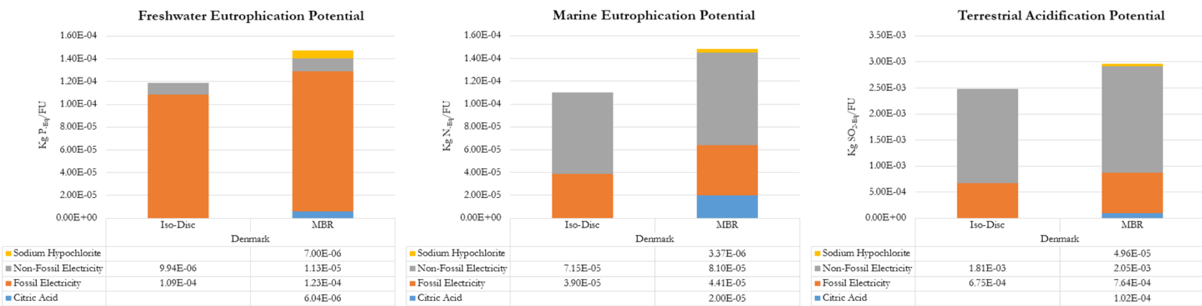


Figure 5.7: The impact of freshwater eutrophication potential, marine eutrophication potential and terrestrial acidification potential.

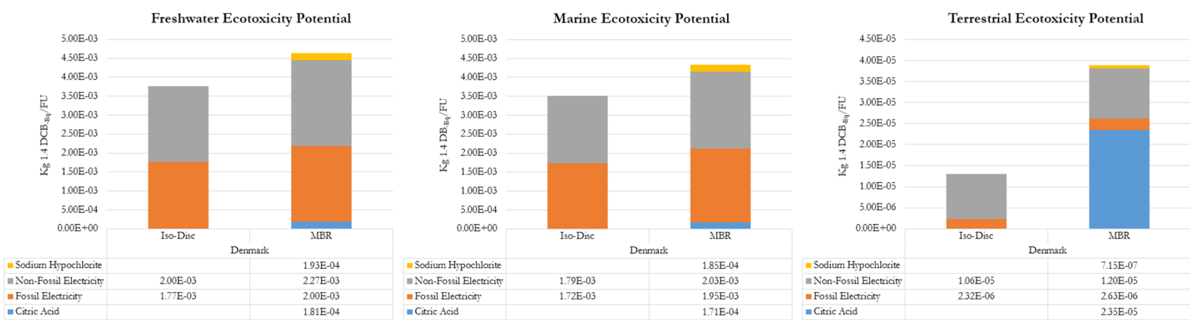


Figure 5.8: The impact of freshwater ecotoxicity potential, marine ecotoxicity potential and terrestrial ecotoxicity potential.

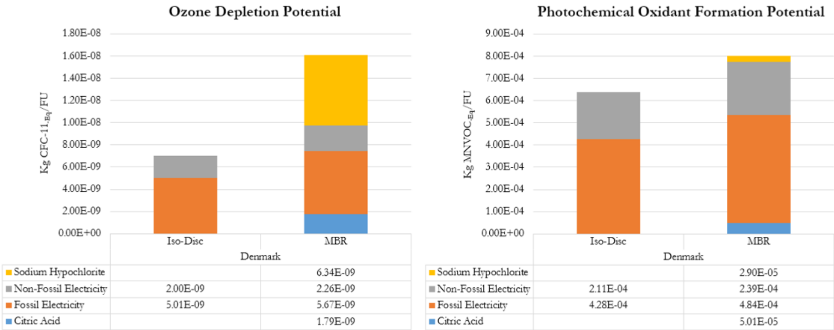


Figure 5.9: The impact of ozone depletion potential and photochemical oxidant formation potential.

5.3 Production

In figure 5.10 - 5.13, the environmental impact of the production phase for both systems is shown. The figures list the various components into different categories. The production of the MBR modules shows the highest impact in ten out of eleven impact categories. It is only terrestrial ecotoxicity potential that differs, in which the anoxic and aerobic tanks for both systems and the clarifier tank of the Iso-Disc, show a higher impact compared to the MBR modules. For specific numbers to the impact of each component, see Appendix 3.

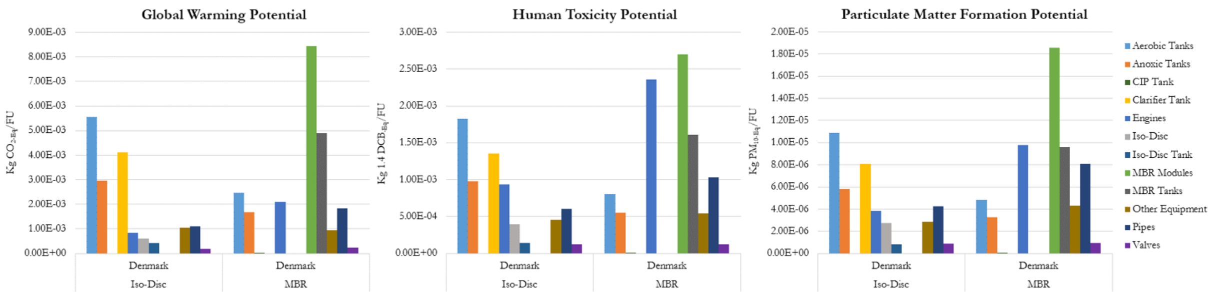


Figure 5.10: The impact of global warming potential, human toxicity potential and particulate matter formation potential.

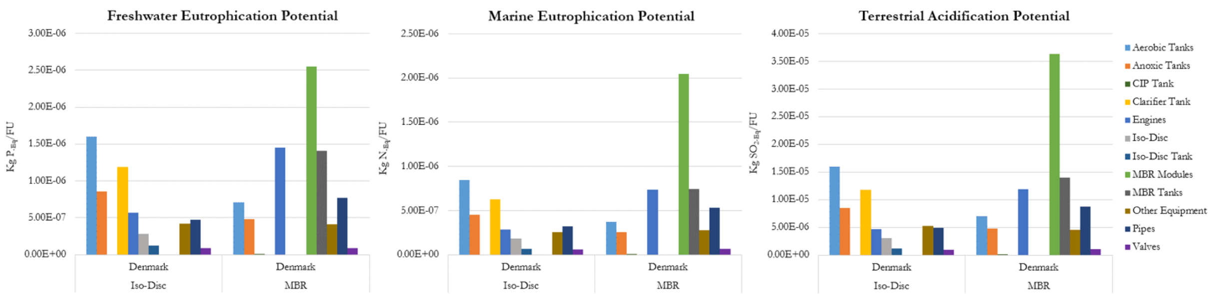


Figure 5.11: The impact of freshwater eutrophication potential, marine eutrophication potential and terrestrial acidification potential.

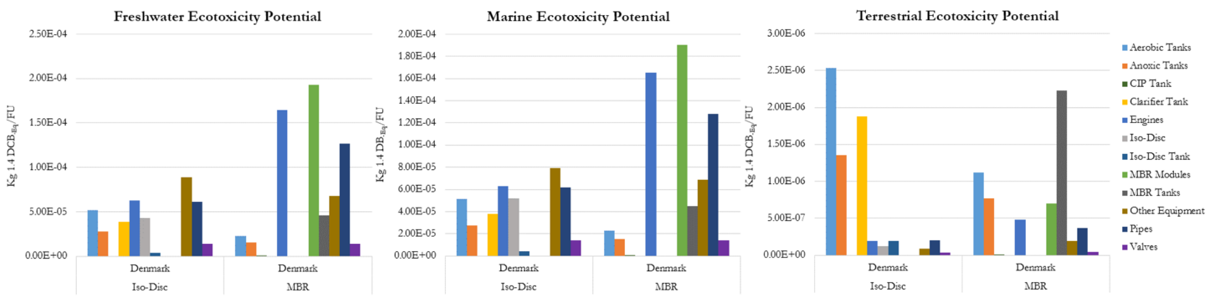


Figure 5.12: The impact of freshwater ecotoxicity potential, marine ecotoxicity potential and terrestrial ecotoxicity potential.

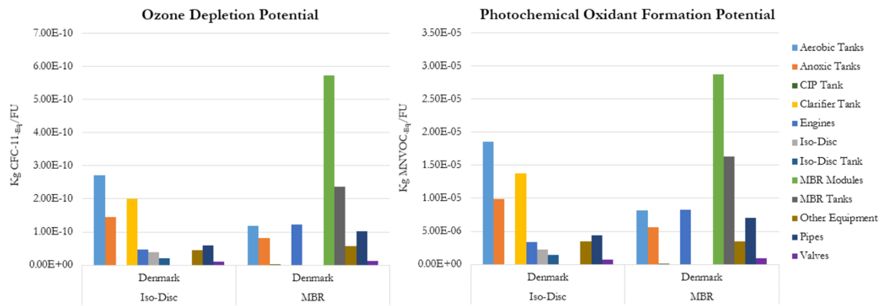


Figure 5.13: The impact of ozone depletion potential and photochemical oxidant formation potential.

5.4 Production of the MBR Modules

Since the MBR modules show the highest impact in ten out of eleven impact categories according to the production phase, the MBR modules are more closely evaluated in this section. Figure 5.14-5.17 shows the environmental impact when 20 modules are manufactured per FU. Stainless steel, polypropylene (PP) and polyvinylidene fluoride (PVDF) membrane contributed the most to the environmental impact of the different categories. For specific numbers to the impact of each component, see Appendix 4.

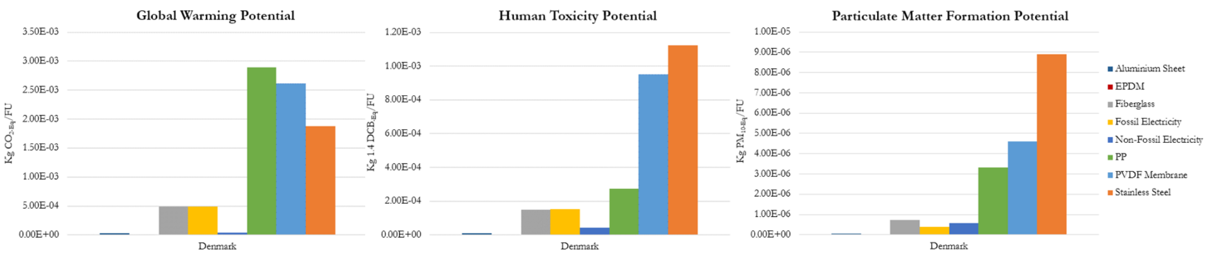


Figure 5.14: The impact of global warming potential, human toxicity potential and particulate matter formation potential.

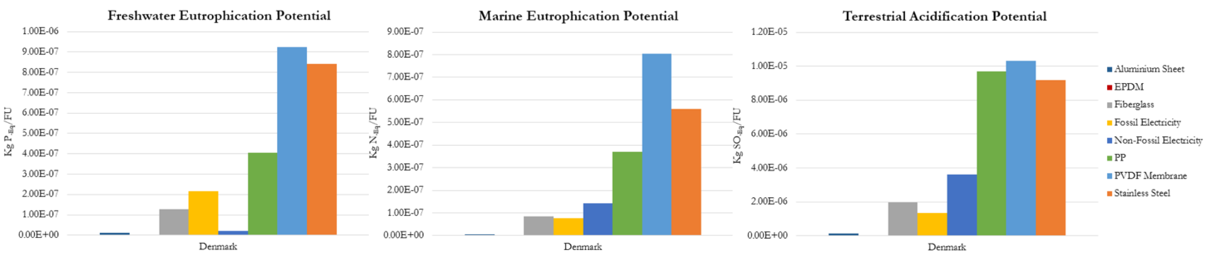


Figure 5.15: The impact of freshwater eutrophication potential, marine eutrophication potential and terrestrial acidification potential.

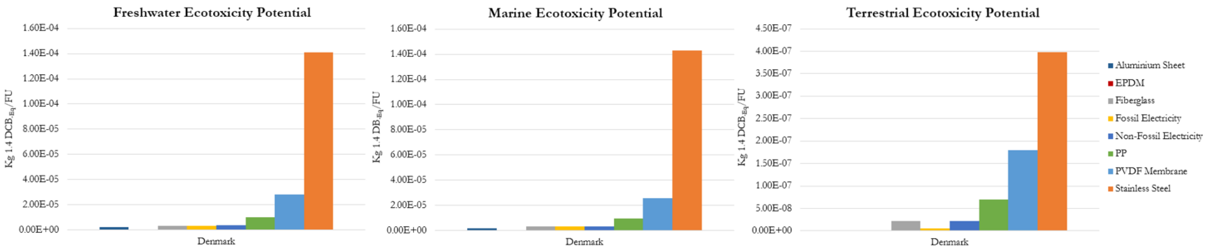


Figure 5.16: The impact of freshwater ecotoxicity potential, marine ecotoxicity potential and terrestrial ecotoxicity potential.

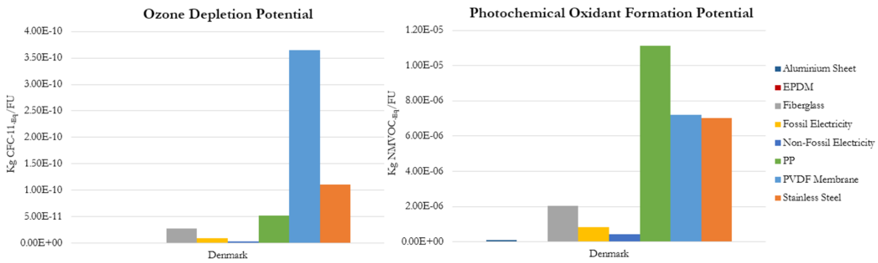


Figure 5.17: The impact of ozone depletion potential and photochemical oxidant formation potential.

6 Interpretation

Based on the result, the operation phase contributed the most to the environmental impact of all categories and was found to be a 'hot spot' for both systems. Therefore, detailed sensitivity analyses were performed for the operation phase, which consists of cleaning and electricity consumption. For the sensitivity analysis of the electricity consumption, three different cases have been established. These include the base case Denmark (358 g $CO_{2\text{-Eq}}$/kWh), a 'best' case Sweden (29.4 g $CO_{2\text{-Eq}}$/kWh) and a 'worst' case Australia (886 g $CO_{2\text{-Eq}}$/kWh), where each of the electricity mixes have been evaluated. The choice of Australia and Sweden is because of the different electricity mixes for each country. Sweden has one of the best electricity mixes in the world regarding low greenhouse gas emissions per kWh according to Energiföretagen (2018). In the same way, Australia shows one of the worst electricity mixes regarding high greenhouse gas emissions per kWh electricity according to Energiföretagen (2018). Further, the choice of Australia is to include different continents, since Alfa Laval operates in a global market and the wastewater treatment technologies are used all over the world.

6.1 Sensitivity Analysis

6.1.1 Location of the Systems

In figure 6.1, the three different cases, which are the basis for the sensitivity analysis, are shown. In the polar charts, the production, transport and operation are included for all cases. The different cases include the different electricity mixes. Further, the transport includes the transport from the factory to the capital of each country, where the plant is assumed to be located. In the polar chart, in figure 6.1, the eleven impact categories in the log scale are shown. These illustrate that there is a clear difference between the countries in many of the categories.

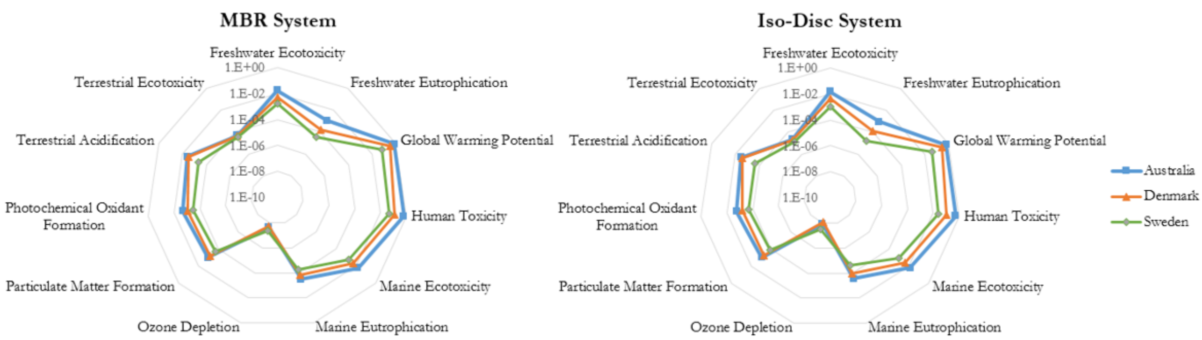
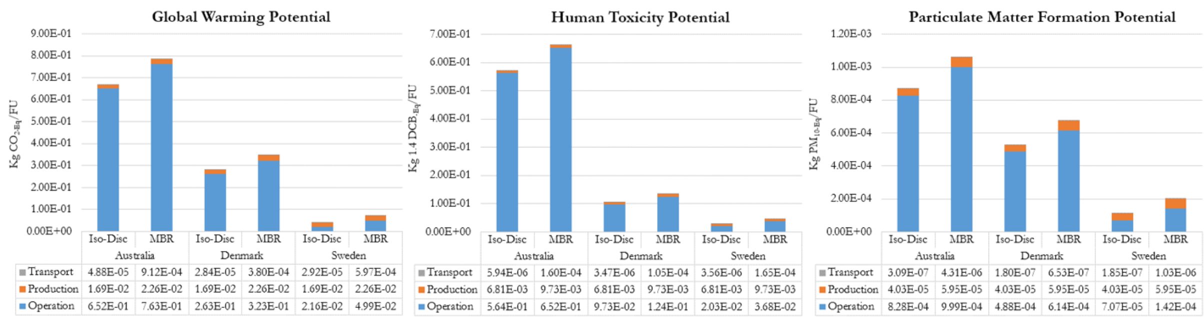


Figure 6.1: Differences between the cases, depending on the location of the wastewater treatment plant (the polar charts are shown in log scale).

In order to illustrate the environmental impact of each category in more detail, figure 6.2 - 6.5 show the eleven categories for the three cases, where transport, production and operation are displayed. The majority of the charts show that Australia has the highest values in all three cases, whereas Sweden shows the lowest. This applies both to the MBR and Iso-Disc systems. However, when it comes to ozone depletion, Sweden shows the highest value followed by Australia and Denmark. This is due to the large share of nuclear power in Sweden, see figure 6.6.



Global Warming Potential

	Australia Iso-Disc	Australia MBR	Denmark Iso-Disc	Denmark MBR	Sweden Iso-Disc	Sweden MBR
Transport	4.88E-05	9.12E-04	2.84E-05	3.80E-04	2.92E-05	5.97E-04
Production	1.69E-02	2.26E-02	1.69E-02	2.26E-02	1.69E-02	2.26E-02
Operation	6.52E-01	7.63E-01	2.63E-01	3.23E-01	2.16E-02	4.99E-02

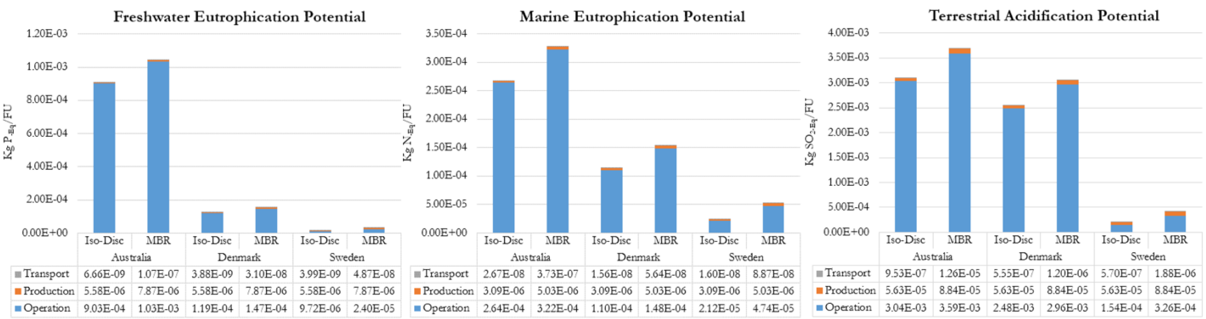
Human Toxicity Potential

	Australia Iso-Disc	Australia MBR	Denmark Iso-Disc	Denmark MBR	Sweden Iso-Disc	Sweden MBR
Transport	5.94E-06	1.60E-04	3.47E-06	1.05E-04	3.56E-06	1.65E-04
Production	6.81E-03	9.73E-03	6.81E-03	9.73E-03	6.81E-03	9.73E-03
Operation	5.64E-01	6.52E-01	9.73E-02	1.24E-01	2.03E-02	3.68E-02

Particulate Matter Formation Potential

	Australia Iso-Disc	Australia MBR	Denmark Iso-Disc	Denmark MBR	Sweden Iso-Disc	Sweden MBR
Transport	3.09E-07	4.31E-06	1.80E-07	6.53E-07	1.85E-07	1.03E-06
Production	4.03E-05	5.95E-05	4.03E-05	5.95E-05	4.03E-05	5.95E-05
Operation	8.28E-04	9.99E-04	4.88E-04	6.14E-04	7.07E-05	1.42E-04

Figure 6.2: Global warming potential, human toxicity potential and particulate matter formation potential.



Freshwater Eutrophication Potential

	Australia Iso-Disc	Australia MBR	Denmark Iso-Disc	Denmark MBR	Sweden Iso-Disc	Sweden MBR
Transport	6.66E-09	1.07E-07	3.88E-09	3.10E-08	3.99E-09	4.87E-08
Production	5.58E-06	7.87E-06	5.58E-06	7.87E-06	5.58E-06	7.87E-06
Operation	9.03E-04	1.03E-03	1.19E-04	1.47E-04	9.72E-06	2.40E-05

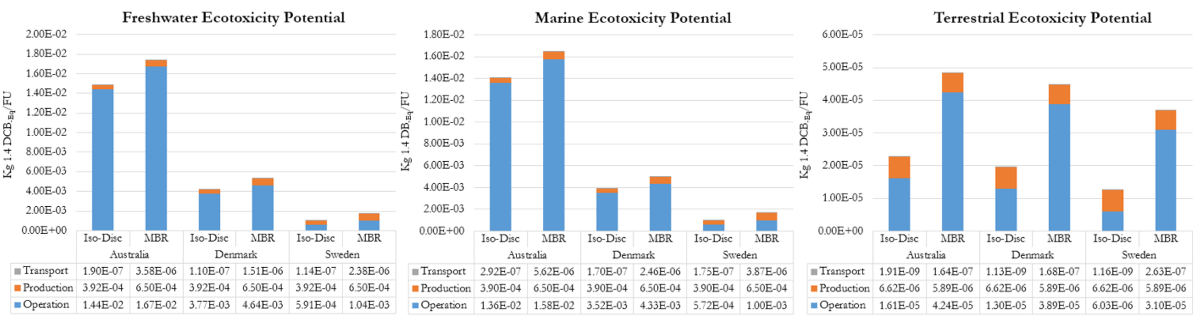
Marine Eutrophication Potential

	Australia Iso-Disc	Australia MBR	Denmark Iso-Disc	Denmark MBR	Sweden Iso-Disc	Sweden MBR
Transport	2.67E-08	3.73E-07	1.56E-08	5.64E-08	1.60E-08	8.87E-08
Production	3.09E-06	5.03E-06	3.09E-06	5.03E-06	3.09E-06	5.03E-06
Operation	2.64E-04	3.22E-04	1.10E-04	1.48E-04	2.12E-05	4.74E-05

Terrestrial Acidification Potential

	Australia Iso-Disc	Australia MBR	Denmark Iso-Disc	Denmark MBR	Sweden Iso-Disc	Sweden MBR
Transport	9.53E-07	1.26E-05	5.55E-07	1.20E-06	5.70E-07	1.88E-06
Production	5.63E-05	8.84E-05	5.63E-05	8.84E-05	5.63E-05	8.84E-05
Operation	3.04E-03	3.59E-03	2.48E-03	2.96E-03	1.54E-04	3.26E-04

Figure 6.3: Freshwater eutrophication potential, marine eutrophication potential and terrestrial acidification potential.



Freshwater Ecotoxicity Potential

	Australia Iso-Disc	Australia MBR	Denmark Iso-Disc	Denmark MBR	Sweden Iso-Disc	Sweden MBR
Transport	1.90E-07	3.58E-06	1.10E-07	1.51E-06	1.14E-07	2.38E-06
Production	3.92E-04	6.50E-04	3.92E-04	6.50E-04	3.92E-04	6.50E-04
Operation	1.44E-02	1.67E-02	3.77E-03	4.64E-03	5.91E-04	1.04E-03

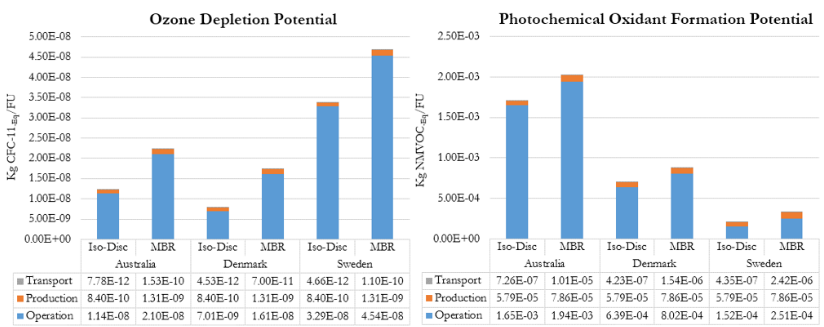
Marine Ecotoxicity Potential

	Australia Iso-Disc	Australia MBR	Denmark Iso-Disc	Denmark MBR	Sweden Iso-Disc	Sweden MBR
Transport	2.92E-07	5.62E-06	1.70E-07	2.46E-06	1.75E-07	3.87E-06
Production	3.90E-04	6.50E-04	3.90E-04	6.50E-04	3.90E-04	6.50E-04
Operation	1.36E-02	1.58E-02	3.52E-03	4.33E-03	5.72E-04	1.00E-03

Terrestrial Ecotoxicity Potential

	Australia Iso-Disc	Australia MBR	Denmark Iso-Disc	Denmark MBR	Sweden Iso-Disc	Sweden MBR
Transport	1.91E-09	1.64E-07	1.13E-09	1.68E-07	1.16E-09	2.63E-07
Production	6.62E-06	5.89E-06	6.62E-06	5.89E-06	6.62E-06	5.89E-06
Operation	1.61E-05	4.24E-05	1.30E-05	3.89E-05	6.03E-06	3.10E-05

Figure 6.4: Freshwater ecotoxicity potential, marine ecotoxicity potential and terrestrial ecotoxicity potential.



Ozone Depletion Potential

	Australia Iso-Disc	Australia MBR	Denmark Iso-Disc	Denmark MBR	Sweden Iso-Disc	Sweden MBR
Transport	7.78E-12	1.53E-10	4.53E-12	7.00E-11	4.66E-12	1.10E-10
Production	8.40E-10	1.31E-09	8.40E-10	1.31E-09	8.40E-10	1.31E-09
Operation	1.14E-08	2.10E-08	7.01E-09	1.61E-08	3.29E-08	4.54E-08

Photochemical Oxidant Formation Potential

	Australia Iso-Disc	Australia MBR	Denmark Iso-Disc	Denmark MBR	Sweden Iso-Disc	Sweden MBR
Transport	7.26E-07	1.01E-05	4.23E-07	1.54E-06	4.35E-07	2.42E-06
Production	5.79E-05	7.86E-05	5.79E-05	7.86E-05	5.79E-05	7.86E-05
Operation	1.65E-03	1.94E-03	6.39E-04	8.02E-04	1.52E-04	2.51E-04

Figure 6.5: Ozone depletion potential and photochemical oxidant formation potential.

Even though transport did not have any significant impact on the systems, a sensitivity analysis of the three different cases (Denmark, Sweden and Australia) was conducted. This was done in order to see if longer distances would get a different result. The transport distance differs a lot depending on the location of the plant. In the MBR case, the transport distance differs by a factor of 31, depending if the end location is Stockholm or Canberra. With a distance more than 31 times greater, the impact of the transport to Canberra is still only twice as large compared to the Stockholm case regarding the impact category global warming potential. The impact categories of human toxicity potential and terrestrial ecotoxicity potential showed emissions that are larger from 800 km of truck transport compared to 25 000 km of ship transport. In the remaining categories, the ship transport has higher emissions compared to the truck transport, due to larger distances.

6.1.2 The Operation Phase

During the operation phase, the environmental impact will differ depending on where the wastewater treatment plant is located. This is due to the electricity mix of the selected country. Figure 6.6 shows the electricity mix in Sweden, Denmark and Australia, based on the percentage number of 2016 given by IEA (2019). As can be seen in the figure, the electricity mix in Sweden mostly consists of hydropower and nuclear power. The electricity mix in Denmark mainly consists of wind, coal and biofuels whereas Australia primarily depends on coal and gas. In figure 6.7, the electricity mixes are divided into fossil and non-fossil electricity based on the year of 2016 (IEA, 2019). In Sweden, non-fossil includes nuclear power, and in Australia and Denmark non-fossil only refers to renewable electricity.

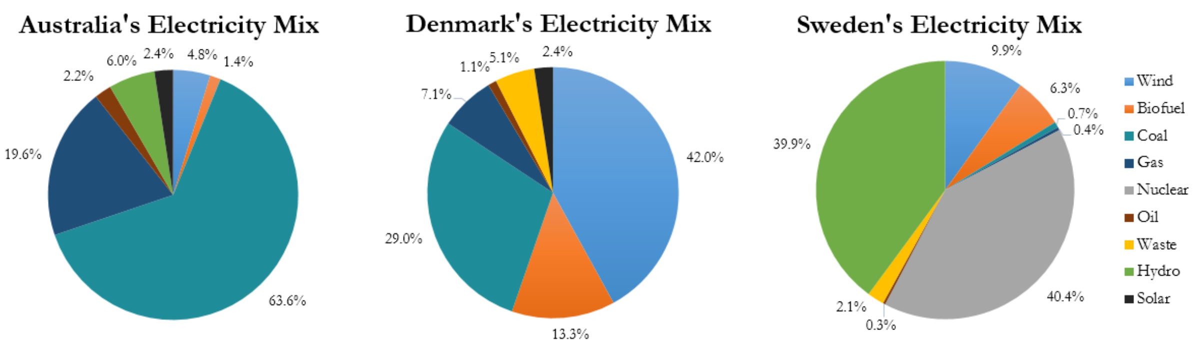


Figure 6.6: The electricity mix in Australia, Denmark and Sweden based on the year of 2016 (IEA, 2019).

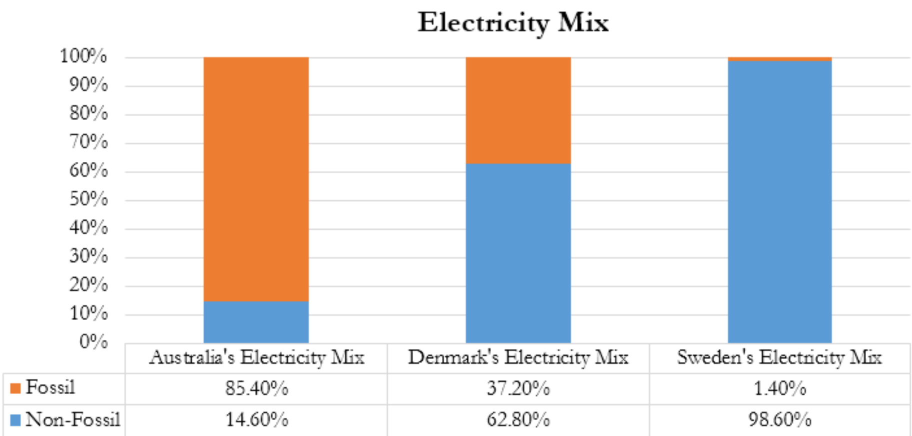


Figure 6.7: The electricity mixes divided into fossil and non-fossil electricity in Australia, Denmark and Sweden based on the year of 2016 (IEA, 2019).

Since the operation phase turned out to be the biggest contributing factor in all of the environmental impact categories, a deeper analysis on the content of this phase was performed. The operation phase consists of cleaning and electricity consumption during operation. In figure

6.8 -6.11, all eleven impact categories are shown. The electricity is divided into non-fossil and fossil electricity. In the majority of the cases, Australia has the highest emissions, which can be explained by Australia's high proportion of fossil electricity.

The terrestrial ecotoxicity and ozone depletion are distinguished from the rest, see figure 6.10 and figure 6.11. In the case of terrestrial ecotoxicity, the cleaning with the citric acid has a huge impact on the MBR system, which in this case results in high values independent of which country the treatment plant is located. In the case of ozone depletion, Sweden distinguishes itself significantly compared to Australia and Denmark and deviates from the observed trends by showing high emissions. This is derived from the non-fossil electricity, which has a big impact on the ozone depletion of Sweden. Nuclear power is one of the most dominating electricity sources in Sweden and accounts for 41 % of the total production. Nuclear power has significant higher emissions for ozone depletion per kWh compared to coal, which is the dominating electricity source in Australia consisting 64 % of the total production. The electricity mix affects both the MBR and the Iso-Disc systems. However, there is a difference between the systems, since the cleaning of the MBR requires sodium hypochlorite, which in this case has a great environmental impact. In Denmark the impact of sodium hypochlorite contributes to the ozone depletion by 39 %. The effects from the sodium hypochlorite in Sweden are less significant because of the nuclear power, which already contributes heavily.

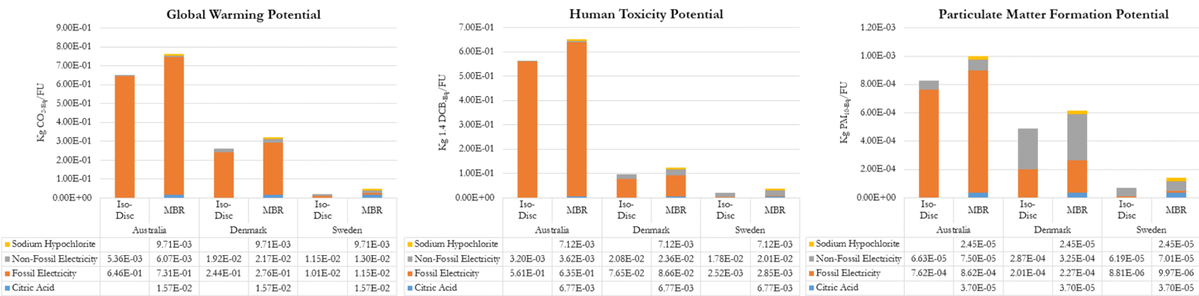


Figure 6.8: Global warming potential, human toxicity potential and particulate matter formation potential.

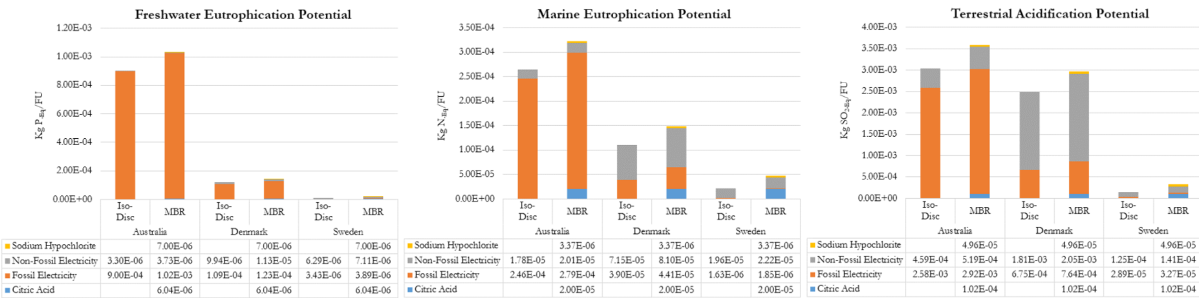


Figure 6.9: Freshwater eutrophication potential, marine eutrophication potential and terrestrial acidification potential.

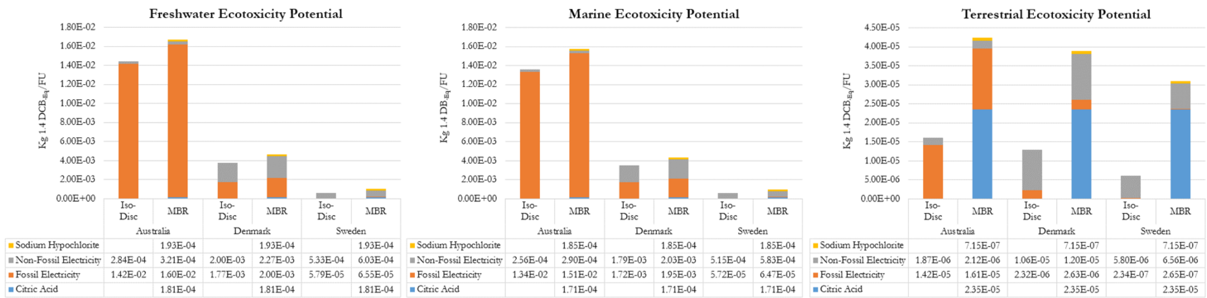


Figure 6.10: Freshwater ecotoxicity potential, marine ecotoxicity potential and terrestrial ecotoxicity potential.

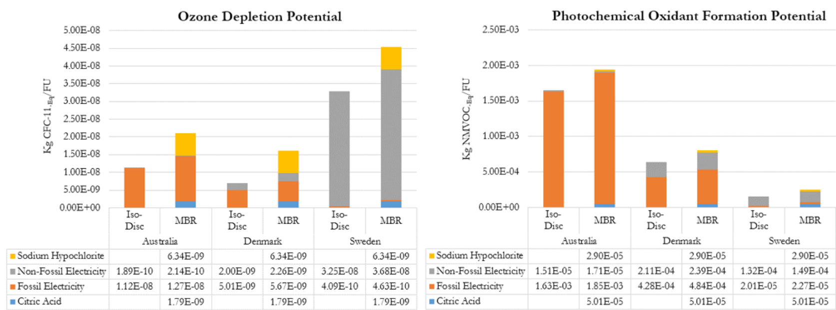


Figure 6.11: Ozone depletion potential and photochemical oxidant formation potential.

6.1.3 The Operation Phase in Sweden

Since the emissions of Australia and Denmark mostly originate from each country's electricity mix, there is no need for any further analysis. The Swedish case differs from the others because of the difficulties to interpret the analysis. The values are simply too small in the graphs compared to the other cases, and are therefore hard to analyse. In figure 6.12 - 6.15 the operation phase in Sweden is illustrated where all eleven impact categories are shown. In Sweden, 1.4 % of the electricity comes from fossil sources. Despite the small percentage, it still contributes to global warming by 13.8 g $CO_{2\text{-}Eq}$/kWh. Non-fossil electricity on the other hand, which takes up 98.6 % of Sweden's electricity mix, only contributes to climate change by 15.6 g $CO_{2\text{-}Eq}$/kWh. This shows the great effects of the fossil electricity despite its low percentage. This is clearly illustrated in figure 6.12.

Citric acid and sodium hypochlorite contribute to 50.98 % of the category global warming of the operation phase in Sweden, seen in figure 6.12. Thanks to the low impact of the electricity in Sweden, the cleaning chemicals have a large percentage impact on the total result.

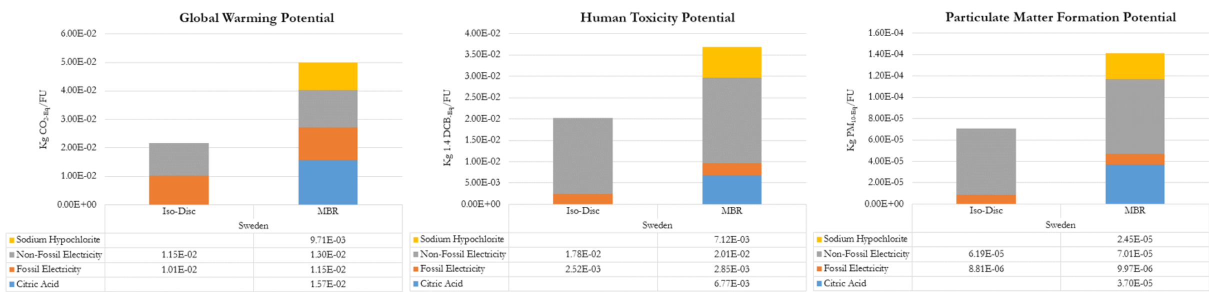


Figure 6.12: Global warming potential, human toxicity potential and particulate matter formation potential

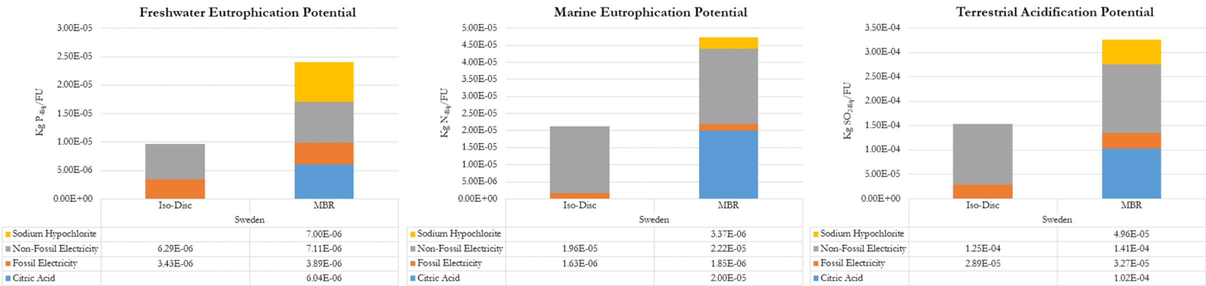


Figure 6.13: Freshwater eutrophication potential, marine eutrophication potential and terrestrial acidification potential

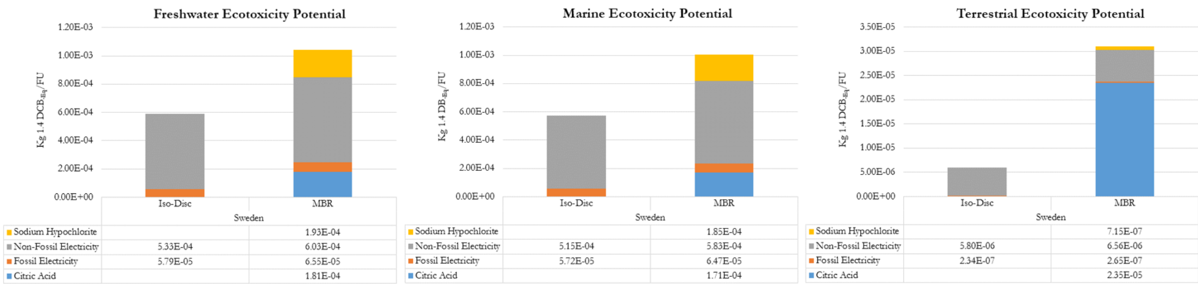


Figure 6.14: Freshwater ecotoxicity potential, marine ecotoxicity potential and terrestrial ecotoxicity potential

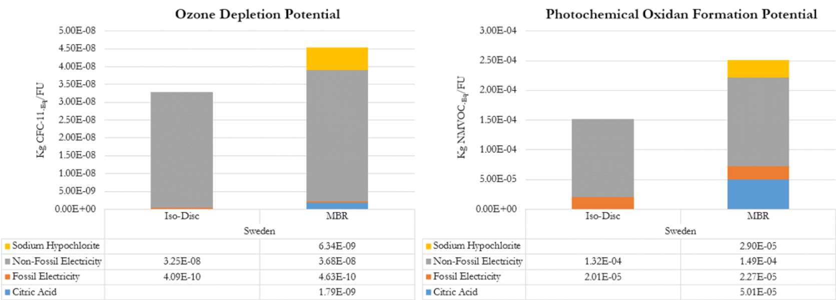


Figure 6.15: Ozone depletion potential and photochemical oxidant formation potential

6.1.4 Chemicals

The chemicals have a big impact on the MBR system due to the low emissions from the electricity mix in Sweden. A sensitivity analysis of the chemicals was therefore done, based on the assumption of the plant being located in Sweden. In figure 6.16 - 6.19, the impact of a change in chemicals is shown. Case 1 shows the base case, where the chemical citric acid (global production) is used. In case 2, the production of citric acid is now being produced in Europe only.

A shift from a global production of citric acid to a European production causes a decrease of all the environmental impact categories. The total impact of the categories can decrease between 2 - 29 % in Sweden depending on the category. Terrestrial ecotoxicity potential shows the highest percentage difference and ozone depletion the lowest percentage difference when a change of chemicals is done.

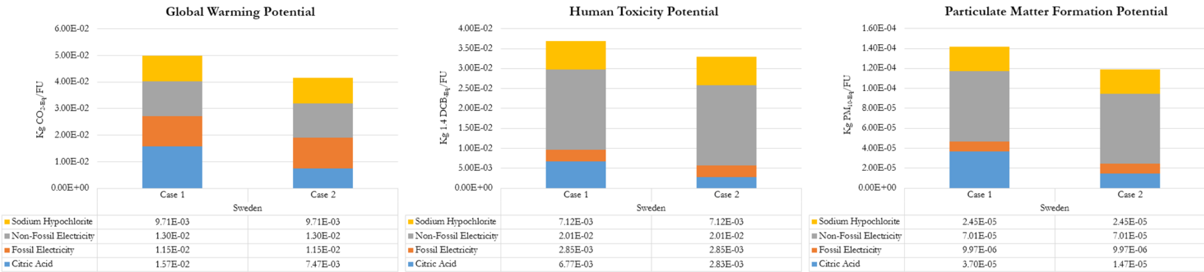


Figure 6.16: Global warming potential, human toxicity potential and particulate matter formation potential

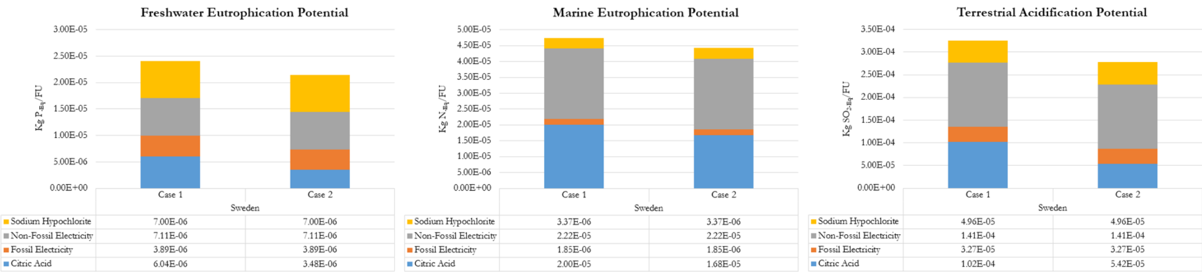


Figure 6.17: Freshwater eutrophication potential, marine eutrophication potential and terrestrial acidification potential

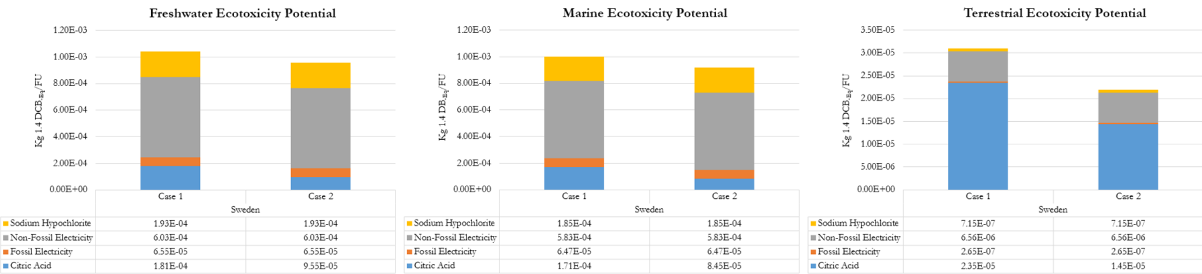


Figure 6.18: Freshwater ecotoxicity potential, marine ecotoxicity potential and terrestrial ecotoxicity potential

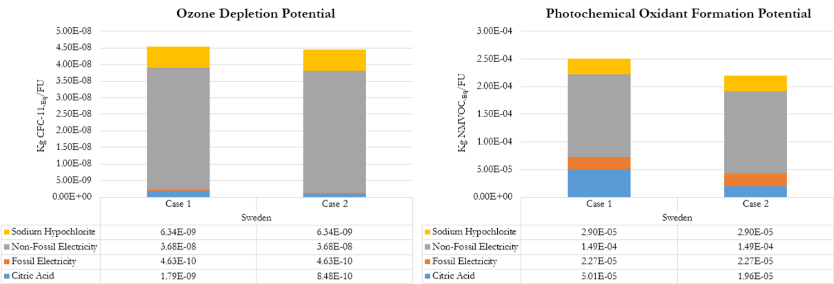


Figure 6.19: Ozone depletion potential and photochemical oxidant formation potential

It is possible to change citric acid to oxalic acid and sodium hypochlorite to hydrogen peroxide[11]. However, problems arose when modelling oxalic acid, since it was not available in the database of Ecoinvent. For this reason, oxalic acid did not replace citric acid. Neither sodium hypochlorite was replaced by hydrogen perioxide, due to difficulties in finding the right chemical.

[11] Bengtsson, Jessica; Global Sales Manager – Membrane Water and Food Components, Alfa Laval. 2019. Personal Communication

6.1.5 The Lifespan

If the lifespan of the plant increases from 20 to 30 years, the emission per FU decreases for all categories in both systems. The reason for this is because of categories such as tanks, piping and engines, which are not replaced. The emissions are therefore spread out over larger amounts of cubic meters of water. However, the operation phase will not make any difference if the lifespan changes, since the amount of electricity and water per FU remain the same. If the lifespan increases by ten years, the membranes need to be replaced one more time and the filter cloth of the Iso-Disc need to be replaced two more times. The MBR system needs to operate ten more years than the Iso-Disc to have similar emissions per FU in six out of eleven categories.

6.1.6 Differences in Purification Quality

It is important to keep in mind while analysing the different technologies that they have different purification quality. The MBR technology shows higher emissions compared to the Iso-Disc technology in all of the impact categories of the systems, presented in section 5.1. The Iso-Disc can be considered as the best alternative according to the result of the study. However, it may not be the best alternative, since the emissions from the effluent are not considered in the presented result. It is far more complex than to only consider the emissions derived from the production, transport and operation of each technology and not the indirect emissions that occur due to lower purification level. The total suspended solids (TSS) concentration in the effluent is considered to 1 mg/litre for the MBR and 5 mg/litre for the Iso-Disc[12]. Thus, the MBR has a higher level of purification than the Iso-Disc, since the treated water has smaller amount of suspended solids in the effluent. It is interesting to see how the eutrophication potential changes when the indirect emissions from the two technologies are taken into account. Except from the emissions in the TSS, small amounts of BOD, N and P are drained with the wastewater that has not been removed in the wastewater treatment process. However, these amounts can be considered the same for the Iso-Disc and the MBR process[12]. Therefore, the only difference in the eutrophication potential of the effluent is the TSS content[12]. The assumed TSS content in the effluent and calculations can be found in Appendix 5.

In figure 6.20 the freshwater- and marine eutrophication potential are shown. The figure shows how the impact categories of eutrophication change when indirect emissions in the TSS from the effluent are included. The blue bars show the impact of production, transport and operation. In the orange bars also the indirect emissions of nitrogen and phosphorus in the TSS of the effluent are included.

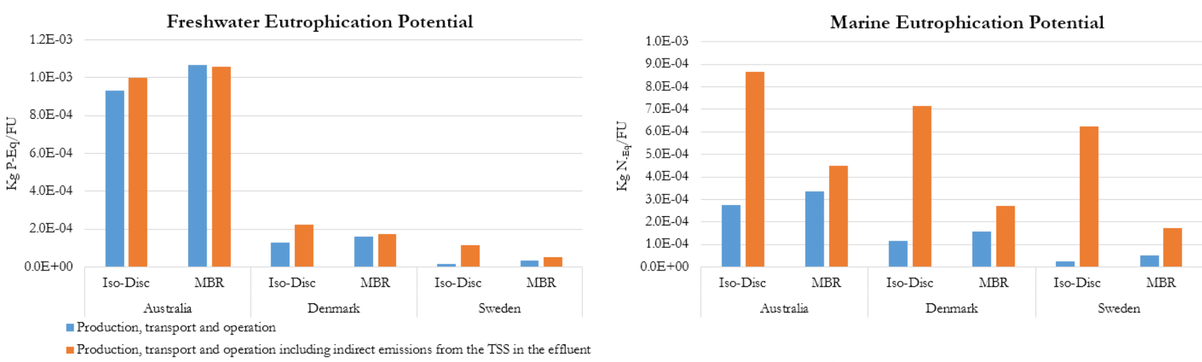


Figure 6.20: Differences in freshwater- and marine eutrophication potential.

[12] Gurieff, Nicholas; Global Sales Business Development – Membranes & Wastewater, Alfa Laval. 2019. Personal Communication

The Iso-Disc technology turned out to be the best alternative when the total of production, transport and operation was evaluated. Independent of country, the Iso-Disc shows a lower environmental impact for both freshwater- and marine eutrophication. When indirect emissions from the TSS in the effluent are included the result changes. From marine eutrophication potential, the MBR technology shows a lower environmental impact independent of the plants location, whether it is in Australia, Denmark or Sweden. When studying freshwater eutrophication, the MBR technology is the better alternative when the plant is located in Sweden or Denmark. The only case where the Iso-Disc is the better alternative in comparison to the MBR technology from an eutrophication aspect, is for freshwater eutrophication assuming the plant is located in Australia. However, the Iso-Disc showed only small improvements in emission reduction compared to the MBR technology. The reason why the Iso-Disc is a better alternative in Australia is due to the Australian electricity mix. The technology with a low energy demand beats the better purification quality in terms of reducing the emissions according to freshwater eutrophication. In countries with a low share of fossil fuels in the electricity mix, a better purification level can reduce the total emissions according to eutrophication more than the increased emissions that a more energy demanding technology would contribute with.

7 Conclusion

The purpose of this study was to compare an MBR system with an Iso-Disc system in terms of environmental impact and primary energy consumption. When only production, transport and operation in Denmark are studied, the Iso-Disc system shows a lower environmental impact compared to the MBR system for all eleven impact categories. The MBR system requires more primary energy input (7.8 MJ/FU) compared to the Iso-Disc system (6.3 MJ/FU) for production, transport and operation. Further, the purpose of this study was to identify which parts contributed most to the environmental impact of the result. What is clear for both systems, is that the operating phase has the greatest effect in all impact categories. The operating phase accounts for 87-97 % of the MBR system depending on the impact category. Similarly, the operating phase accounts for 89-98 % of the Iso-Disc system, with the exception of terrestrial ecotoxicity potential, where the operating phase drops to 66 %. Since the operating phase contributes the most to the emissions, the type of electricity that is used will play an important role regarding the result.

An improvement to reduce the environmental impact would be to use more non-fossil electricity. In a sensitivity analysis comparing Australia's and Sweden's electricity mixes, large differences were shown. If a wastewater treatment plant is located in Sweden instead of Australia, there is a reduction in ten out of eleven impact categories. For the MBR system, the emissions from production, transport and operation were reduced by up to 97 %. The Iso-Disc system showed a reduction of up to 98 %. It was only the emissions of ozone depletion potential that increased if the plant was located in Sweden. The increase is related to Sweden's large share of nuclear power, which has a major impact on ozone depletion. In cases where an electricity mix with a low share of fossil electricity is available, the chemicals become an important parameter to look at when the MBR technology is studied. When global production of citric acid was replaced by local production in Europe, the emissions of all impact categories were reduced. The environmental impact was reduced between 2 – 29 % of the emissions from the operating phase in Sweden.

Both systems are designed to treat 1 900 m^3 wastewater per day. What distinguishes the two technologies is their level of purification, since the MBR purifies down to an effluent concentration of 1 mg TSS/litre and the Iso-Disc purifies down to 5 mg TSS/litre. This different level of purification creates difficulties in comparing the various technologies entirely based on production, transport and operation. In cases where the level of purification is taken into account and the amount of phosphorus and nitrogen in the TSS in outgoing water is included, the MBR technology is shown to be the better alternative, for freshwater- and marine eutrophication in both Sweden and Denmark, and in Australia for marine eutrophication. It is interesting to see how the environmental impacts rapidly change when indirect emissions of phosphorus and nitrogen are included. This clearly shows the big impact the purification level of the effluent has based on eutrophication. The results of this study show that it may be a better alternative to use the Iso-Disc technology in countries with a large share of fossil-based electricity mixes based on the category freshwater eutrophication. This is due to the fact that a large share of fossil-based electricity mix contributes more to the freshwater eutrophication potential than an improved level of purification may reduce it. The choice of technology should therefore take the location of the plant into consideration. It also shows the importance of including indirect emissions of phosphorus and nitrogen when a comparison of wastewater treatment technologies with different effluent concentrations is evaluated.

Toxic intermediate products such as dinitrogen oxide (N_2O) are emitted to a larger extent from the biological tanks if the system is stressed. However, the plant is considered to work properly and eventual indirect emissions from dinitrogen oxide will not be considered. Further, the biological tanks emit carbon dioxide during the operation phase. Problems arise when trying to measure how large these emissions actually are. It can be assumed that there are no larger quantities of carbon dioxide that are emitted from the biological tanks and that the difference between the two systems is irrelevant. Any consideration of indirect emissions of carbon dioxide and dinitrogen oxide are assumed to have no significant impact when comparing these technologies from global warming potential.

The indirect emissions from the amount of pharmaceuticals in the effluent, that are expected to be purified to a greater extent in the MBR technology compared to the Iso-Disc technology, were not included in the study. This may have an impact on the categories of human toxicity potential and freshwater-, marine- and terrestrial ecotoxicity. If the choice of technology depends on these categories, further studies need to be performed.

In the presented result, recycling has not been included. This would have affected the emission values associated with production, which would have been minimized to some extent. Since the production did not have any major impact on the system, any recycling would not have resulted in any major impact on the overall result.

The results of this study also showed the importance of updating the percentage of the countries electricity mixes while these are included in an LCA. Rapid changes in a country's electricity mix are taking place today. These changes may occur on an annual basis, where the electricity mix of United Kingdom is a good example. In one year, the carbon dioxide emissions from coal fell more than 50 %, due to the closure of coal-fired power plants. These changes caused major improvements in the electricity mix of the United Kingdom. This shows the importance of updating the data in order not to receive an incorrect result.

The MBR technology is gaining market share, but to some extent it is still held back due to economical reasons, since it is still seen as an expensive technology compared to a CAS system with an Iso-Disc. However, thanks to the by-products such as minerals that can be sold as fertilizers, wastewater treatment plants may be able to generate revenues higher than the operational costs in the future. Since the MBR technology has a better purification level compared to a CAS system with an Iso-Disc, it may also be able to collect larger amounts of nutrients that will generate larger revenues. These larger revenues may compensate for at least a part of the higher operating cost of the MBR.

In future research, it would be interesting to see how oxalic citric and hydrogen peroxide would affect the system if citric acid and sodium hypochlorite were replaced. It would also be interesting to include the sludge disposal in the technical system boundaries and make a system expansion of the sludge that may replace other sources of energy production.

Whether the Iso-Disc or MBR technology is the best from an environmental point of view may be discussed. To some extent it may be a question of values, where some people prefer one environmental impact category over another. For example if global warming is considered a bigger threat, then the Iso-Disc would be favoured. Others may say that eutrophication of very sensitive ecosystems such as the Baltic Sea is the most important impact category and then the MBR system would be chosen. Finally it is also important when choosing a technology to compare the pros and cons of each technology, to consider the electricity mix of the country where the plant is operating and to know the ecosystem where the wastewater is released.

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Appendix 1

The following Appendix presents data of the wastewater treatment process based on MBR technology.

Tanks

Of the total volume of the reinforcing concrete tank an assumption of 0.8 % is calculated to reinforced steel and the rest to concrete[13]. In table A1.1, a summary of all tank material for the process is specified.

Table A1.1: Summary of the tank material input of the MBR system.

Component category	Material	Weight (kg)	Unit	Total weight (kg)
Anoxic tank	Concrete	59 710	2	119 420
	Reinforced steel	1 565	2	3 130
Aerobic tank	Concrete	87 309	2	174 618
	Reinforced steel	2 288	2	4 576
MBR tank	Concrete	86 909	4	347 636
	Reinforced steel	2 278	4	9 112
CIP tank	Polyethylene	115	1	115

Screens

Table A1.2: Summary of the equipment material input of the screens of the MBR system.

Equipment	Purpose	Material	Weight per component (kg)	Unit	Total weight (kg)
Fine Screen (including engine)	To remove all particles above 2 mm in size	Stainless steel[1]	270	4	1 080

[1]The fine screen is assumed to solely consist of stainless steel, since the documentation of the screen (RS-22 RotoSieve) mainly consists of the assumed material (Läckeby products, n.d).

[13] Aronsson, Fredrik; Building constructor. 2019. Communication via email March 5th

Biological Treatment of MBR

Table A1.3: Summary of the equipment material input of the biology process of the MBR system.

Equipment	Purpose	Material	Weight per component (kg)	Unit	Total weight (kg)
Ball valve[1]	Air blower and diffuser isolation	Stainless steel	26.6	10 pieces	266
Electric actuator[2]	Electric actuators to the valves	Carbon steel	0.86	10 pieces	8.6
		Aluminium	0.29	10 pieces	2.9
		Copper	0.15	10 pieces	1.5
Mixer[3]	Maintain complete mixing of MLSS in the anoxic tank	Stainless steel	10.8	2 pieces	21.6
Air diffusers[4]	Aeration of the biological reactor	EPDM	0.72	96 pieces[8]	69.12
		PP	1.43	96 pieces[8]	137.28
Blower[5]	Aeration of the biological reactor	Stainless steel	396.8	2 pieces	793.6
		Carbon steel	49.6	2 pieces	99.2
		Cast iron	49.6	2 pieces	99.2
Engine[6]	Engine for the blowers	Carbon steel	54.78	2 pieces	109.56
		Aluminium	18.68	2 pieces	37.36
		Copper	9.55	2 pieces	19.1
Pump[7]	Recycle	Cast iron	66	2 pieces	132
		Stainless steel	66	2 pieces	132
Piping	32 meters of stainless steel piping estimated per tank.	Stainless steel	16.06 kg/meter	64 meters	1 027.84
Pipe support	Clamps to hold the pipes	Stainless steel	2.06	1 unit	2.06
Piping	50 meters of PVC piping estimated	PVC	6.07 kg/meter	50 meters	303.5
Pipe support	Clamps to hold the pipes	PVC	0.61	1 unit	0.61

[1]The valve comes from the supplier Johnsons valves (Johnsons & Sons LTD, 2019). From the data sheet, an assumption has been made, where steel accounts for the entire weight of the valve.

[2]All the valves consist of an electric actuator from Johnson valves, model JVE05 (Johnson & Sons LTD, 2018). In order to dimension the material set, an assumption was made, where the engine consists of 66 % carbon steel, 22.5 % aluminium and 11.5 % copper. The assumption was based on a study from Legarth et al (2000), in which they have made the percentage distribution of an engine for their LCA of an air-handling unit.

[3]The mixer is assumed to consist of stainless steel, since the documentation of the used mixer of the study (Grundfos AMD.05-08) mainly consists of stainless steel (Grundfos Holding A/S, n.d.a).

[4]The air diffusers are based on the tube diffuser TD90-2-G1-1000 from the manufacturer Jäger Umwalt-Technik GmbH. The diffuser has a total weight of 2.15 kg and consists of 1/3 EPDM and 2/3 Polypropylene[14].

[5]The blower is of the size GM 10S/DN 100 and needs a flow of 9.76 m^3/minute (AERZEN, n.d). Based on the data sheet, the following material structure has been adopted; 80 % stainless steel, 10 % carbon steel and 10 % cast iron.

[6]For the blower, an engine (160M) was used from ABB (ABB, 2019a). In order to dimension the material set, an assumption was made, where the engine consists of 66 % carbon steel, 22.5 % aluminium and 11.5 % copper. The assumption was based on a study from Legarth et al (2000), where they have made the percentage distribution of an engine for their LCA of an air-handling unit.

[7]The CIP pump (CRE64-1) comes from the supplier Grundfos (Grundfos Holding A/S, n.d.b). Based on the product information of the supplier, the total weight of the pump is allocated to stainless steel (50 %) and cast iron (50%).

[8] The units of the air diffusers include one replacement during the expected lifetime of 20 years.

[14] Buhmann, Philip; Project Engineer, Jäger Umwelt-Technik GmbH. 2019. Communication via email March 5th

Membrane Bioreactor Treatment

Table A1.4: Summary of the equipment material input.

Equipment	Purpose	Material	Weight per component (kg)	Unit	Total weight (kg)
Ball valve[1]	Permeate train isolation, CIP isolation	PVC	12.10	10 pieces	121.00
Ball valve[1]	Permeate isolation	PVC	5.90	8 pieces	47.20
Ball valve[1]	Permeate sampling	PVC	0.50	2 pieces	1.00
Ball valve[2]	Air	Stainless steel	26.60	1 pieces	26.60
Ball valve[2]	Air blower isolation	Stainless steel	8.90	3 pieces	26.70
Ball valve[1]	Chemical dosing, CIP tank drain	PVC	3.70	3 pieces	11.10
Ball valve[1]	Recirculation	PVC	12.10	5 pieces	60.50
Butterfly valve[3]	Relaxation valve, CIP water control valve	Ductile iron	11.41	3 pieces	34.23
		Stainless steel	4.89	3 pieces	14.67
Gate valve[4]	Permeate flow regulation	Ductile iron	22.75	2 pieces	45.50
		Stainless steel	9.75	2 pieces	19.50
Electric actuator[5]	Electric actuators for the valves	Carbon steel	0.86	37 pieces	31.82
		Aluminium	0.29	37 pieces	10.73
		Copper	0.15	37 pieces	5.55
Blower[6]	Air scour of membranes	Stainless steel	408.80	3 pieces	1 226.40
		Carbon steel	51.10	3 pieces	153.30
		Cast iron	51.10	3 pieces	153.30
Engine[7]	Engine for the blower	Carbon steel	78.54	3 pieces	235.62
		Aluminium	26.78	3 pieces	80.34
		Copper	13.69	3 pieces	41.07
Flow meter [8]	Measure flow of permeate, CIP solution, CIP water	Stainless steel	51.30	5 pieces	256.50
Gate (1m x1 m)	To allow the isolation of membrane tanks and air lift recycle of sludge from membrane tanks	Stainless steel	23.76	8 pieces	190.08
Pressure transmitter[9]	Measure pressure in permeate, CIP, air, membrane tanks	Stainless steel	0.41	9 pieces	3.69
Pump[10]	Dosing chemical concentrates for CIP	Stainless steel	22.50	2 pieces	45.00
Pump[11]	CIP	Cast iron	23.50	1 pieces	23.50
		Stainless steel	23.50	1 pieces	23.50
Pump[12]	WAS pump	Cast iron	34.50	2 pieces	69.00
		Stainless steel	34.50	2 pieces	69.00
Piping	100 meters of PVC piping estimated	PVC	6.07 kg/m	100 meters	607.00
Pipe support	Clamps to hold the pipes	PVC	1.20	1 unit	1.20
Piping	140 meters of stainless steel piping estimated	Stainless steel	16.06 kg/m	140 meters	2 248.40
Pipe support	Clamps to hold the pipes	Stainless steel	4.50	1 unit	4.50

Angles bars	In order to connect the MBR modules to the tank	Stainless steel	2.30 kg/meter	10 meters	23.00
Mounting points	Mounting points on the wall of the concrete tanks	Stainless steel	0.25	40	10.00

[1]The valve comes from the supplier ASAHI and is available in many different plastic materials (ASAHI, 2018). In this case the valve is modelled in PVC. Based on the data sheet a simplification has been made, where the entire valve is assumed to only consist of PVC.

[2]The valve comes from the supplier Johnsons valves (Johnsons & Sons LTD, 2019). From the datasheet an assumption has been made, where steel accounts for the entire weight of the valve.

[3]The valve comes from the supplier Johnsons valves (Johnsons & Sons LTD, 2017a). Based on the datasheet a simplification has been made, where the valve is assumed to consist of 70 % ductile iron and 30 % stainless steel. The percentage of material is likely to become higher for the iron and lower for the steel. Since the environmental impact of steel is higher compared to iron, the made assumption is made to not underestimate the environmental impact of the valve.

[4]The valve comes from the supplier Johnsons valves (Johnsons & Sons LTD, 2017b). Based on the datasheet a simplification has been made, where the valve is assumed to consist of 70 % ductile iron and 30 % stainless steel. The percentage of material is likely to become higher for the iron and lower for the steel. Since the environmental impact of steel is higher compared to iron, the assumption is made from a standpoint not to underestimate the environmental impact of the valve.

[5]All the valves consist of an electric actuator from Johnson valves, model JVE05 (Johnson & Sons LTD, 2018). In order to dimension the material set, an assumption was made, where the engine consists of 66 % carbon steel, 22.5 % aluminium and 11.5 % copper. The assumption was based on a study from Legarth et al (2000), where they have made the percentage distribution of an engine for their LCA of an air-handling unit.

[6]The blower of the membranes is of the size GM 15L/DN 100 and needs a flow of 14.5 m^3/minute (AERZEN, n.d). Based on the data sheet, the following material structure has been adopted; 80 % Stainless steel, 10 % carbon steel and 10 % cast iron.

[7]For the blower of the membranes, an engine (180M) was used from ABB (ABB, 2019b). In order to dimension the material set, an assumption was made, where the engine consists of 66 % carbon steel, 22.5 % aluminium and 11.5 % copper. The assumption was based on a study from Legarth et al (2000), where they have made the percentage distribution of an engine for their LCA of an air-handling unit.

[8]The flow meter that is used (Proline Promag W 400) comes from the supplier Endress+Hauser (Endress+Hauser AB, n.d.b). For this study a simplification has been made, where the total flow meter is assumed to consists of stainless steel, since the technical description of the flow meter mainly consist of stainless steel.

[9]Based on the data sheet from the supplier, an assumption has been made where all weight is based on stainless steel, since the main part of the product consists of the assumed material (Endress+Hauser AB, n.d.c).

[10]The dosing pumps are assumed to consist of stainless steel, where the total weight of the pumps are allocated to stainless steel, and no other material. The dosing pumps come from the supplier Grundfos (Grundfos Holding A/S, n.d.c).

[11]The CIP pump (CRE15-1) comes from the supplier Grundfos (Grundfos Holding A/S, n.d.b). Based on the product information of the supplier, the total weight of the pump is assumed to consist of stainless steel (50 %) and cast iron (50%).

[12]The WAS pump (CRE32-1) comes from the supplier Grundfos (Grundfos Holding A/S, n.d.b). Based on the product information of the supplier, the total weight of the pump is assumed to consist of stainless steel (50 %) and cast iron (50%).

MBR Module MFM240

Table A1.5: Components for the MBR Module (MFM240).

Component category	Material	Weight per MFM240 (kg)	Weight of 20 units of MFM240 (kg)
Assembly**	Stainless Steel	165.11	3 302.2
	EPDM	1.61*	32.16
S-Aerator**	Stainless Steel	20.37	407.4
	PP	8.7	174
Pack***	PP	840*	16 800
	PP + fiberglass	103.2*	2 064
PVDF Membrane	Confidential	20.38*	407.62
		106.61*	2 132.2
		81.29*	1 625.83
		109.66*	2 193.2
Packaging	Aluminium	1.6	32
	PP	2.32	46.4

*The weight specified for each MFM240 includes one replacement of the component during the lifetime of 20 years.
**The Assembly and S-Aerator each consist of six different components, which were separately evaluated for the study. Due to confidential reasons, the components in the table are clustered together, where only the material and total weight is given for the total components and not on an individual basis.
***The Pack consists of five different components, which were separately evaluated for the study. Due to confidential reasons, the components in the table are clustered together, where only the material and total weight is given for the total components and not on an individual basis.

Transport

Transport from Supplier to the Factory of Alfa Laval in Nakskov

Table A1.6: Transport from supplier to Nakskov.

Component	Material	Start location	End location	Transport	Load weight (kg)	Distance (km)
Assembly	Stainless steel	Copenhagen	Nakskov	Truck (16-32 ton)	3 302.20	172
	EPDM	Copenhagen	Nakskov	Truck (16-32 ton)	32.16	172
S-Areator	Stainless steel	Warszawa	Nakskov	Truck (16-32 ton)	407.40	932
	PP	Copenhagen	Nakskov	Truck (16-32 ton)	174.00	172
Pack	PP	Rome	Nakskov	Truck (16-32 ton)	12 240.00	1 906
	PP	Copenhagen	Nakskov	Truck (16-32 ton)	4 560.00	172
	PP, fiberglass	Copenhagen	Nakskov	Truck (16-32 ton)	2 064.00	172
PVDF Membrane	Confidential	Berlin	Nakskov	Truck (16-32 ton)	1 601.50	354
		Copenhagen	Nakskov	Truck (16-32 ton)	2 238.80	172
		Paris	Nakskov	Truck (16-32 ton)	517.24	1 017
		Haslev	Nakskov	Truck (16-32 ton)	1 003.60	107
Packaging	Aluminium	Copenhagen	Nakskov	Truck (16-32 ton)	32.00	172
	PP	Copenhagen	Nakskov	Truck (16-32 ton)	46.40	172

Transport to Wastewater Treatment Plant

Table A1.7: Transport of MBR modules from Nakskov to wastewater treatment plant.

MFM240	Sweden	Denmark	Australia
Start location	Nakskov	Nakskov	Nakskov
End location	Stockholm	Copenhagen	Canberra
Transport type	Truck (16-32 ton)	Truck (16-32 ton)	Sea Freight
Load weight (ton)	28.22	28.22	28.22
Distance (km)	800	172	25 000

Energy Consumption

Manufacturing of the MBR Module

In table A1.8, the required energy in the factory of Alfa Laval is shown in order to produce membranes and assemble the modules. The heat and lightning of the factory are included in the different parts; laser welding, IR welding and joining the permeate box. Since the membranes need to be replaced once during the expected lifespan of 20 years, the manufacturing of membranes, laser welding, and IR welding, seen in table A1.8, need to be multiplied by two, in order to count for the total energy consumption of the system. The total energy consumption in the factory of Alfa Laval will be 20 380 kWh.

Table A1.8: Energy consumption of manufacturing of membranes and assembling the module.

Activity	**Energy consumption per module (kWh)**	**Energy consumption of 20 modules (kWh)**	**Total energy consumption (kWh)**
Manufacturing of membranes	386	7 720	15 440
Laser welding	48	960	1 920
IR welding	64	1 280	2 560
Joining permeate box	23	460	460
Total	521	10 420	20 380

Appendix 2

Following Appendix presents data of the wastewater treatment process based on Iso-Disc technology.

Tanks

Of the total volume of the reinforcing concrete tank an assumption of 0.8 % is calculated to reinforced steel and the rest to concrete[15]. In table A2.1, a summary of all tank material for the process is specified.

Table A2.1: Summary of the tank material input of the Iso-Disc system.

Component category	Material	Weight (kg)	Pieces	Total weight (kg)
Anoxic tank	Concrete	105 707.52	2	211 415.04
	Reinforced steel	2 770.56	2	5 541.12
Aerobic tank	Concrete	197 701.63	2	395 403.26
	Reinforced steel	5 181.70	2	10 363.40
Clarifier tank	Concrete	293 592.96	1	293 592.96
	Reinforced steel	7 694.98	1	7 694.98
Iso-Disc	Concrete	30 600.58	1	30 600.58
	Reinforced steel	802.03	1	802.03

[15] Aronsson, Fredrik; Building constructor. 2019. Communication via email March 5th

Biology Treatment of the Iso-Disc

Table A2.2: Summary of the simplified equipment material input of the biology process of the CAS system.

Equipment	Purpose	Material	Weight per component (kg)	Unit	Total weight (kg)
Mixer[1]	Maintain complete mixing of MLSS in the anoxic tank	Stainless steel	39.00	2 pieces	78.00
		Cast iron	39.00	2 pieces	78.00
Air diffuser[2]	Aeration of the biological reactor	EPDM	0.72	96 pieces[9]	69.12
		PP	1.43	96 pieces[9]	137.28
Blower[3]	Aeration of the biological reactor	Stainless steel	396.80	2 pieces	793.60
		Carbon steel	49.60	2 pieces	99.20
		Cast iron	49.60	2 pieces	99.20
Engine[4]	Engine for the blower	Carbon steel	54.78	2 pieces	109.56
		Aluminium	18.68	2 pieces	37.36
		Copper	9.55	2 pieces	19.10
Recycle pump[5]	Internal recycle of sludge	Cast iron	124.00	2 pieces	248.00
		Stainless steel	124.00	2 pieces	248.00
Ball valve[6]	Air blower and diffuser isolation	Stainless steel	26.60	10 pieces	266.00
Ball valve[7]	Switch flow from RAS (return to plant) to WAS (wasted sludge from plant).	PVC	12.10	4 pieces	48.40
Electric actuator[8]	Electric actuators for the valves	Carbon steel	0.86	14 pieces	12.04
		Aluminium	0.29	14 pieces	4.06
		Copper	0.15	14 pieces	2.10
Piping	160 meters of PVC piping estimated.	PVC	6.07 kg/m	160 meters	971.20
Pipe support	Clamps to hold the pipes	PVC	1.94	1 piece	1.94
Piping	45 meters of stainless steel estimated.	Stainless steel	16.06 kg/m	45 meters	722.70
Pipe support	Clamps to hold the pipes	Stainless steel	1.46	1 piece	1.46

[1]The mixer (AMG.15.55.339) is assumed to consist of stainless steel (50 %) and cast iron (50 %), since the documentation of the used mixer of the study mainly consists of these materials (Grundfos Holding A/S, n.d.d).
[2]The air diffusers is based on the tube diffuser TD90-2-G1-1000 from the manufacturer Jäger Umwalt-Technik GmbH. The diffuser has a total weight of 2.15 kg and consists of 1/3 EPDM and 2/3 Polypropylene[16].
[3]The blower is of the size GM 10S/DN 100 and needs a flow of 9.76 m^3/minute (AERZEN, n.d). Based on the data sheet, the following material structure has been adopted; 80 % Stainless steel, 10 % carbon steel and 10 % cast iron.
[4]For the blower, an engine (160M) was used from ABB (ABB, 2019a). In order to dimension the material set, an assumption was made, where the engine consists of 66 % carbon steel, 22.5 % aluminium and 11.5 % copper. The assumption was based on a study from Legarth et al (2000), where they have made the percentage distribution of an engine for their LCA of an air-handling unit.
[5]The recycle pump (CRE 120-1) comes from the supplier Grundfos (Grundfos Holding A/S, n.d.b). Based on the product information of the supplier, the total weight of the pump is allocated to stainless steel (50 %) and cast iron (50%).
[6]The valve comes from the supplier Johnsons valves (Johnsons & Sons LTD, 2019). From the datasheet an assumption has been made, where steel accounts for the entire weight of the valve.
[7]The valve comes from the supplier ASAHI and is available in many different plastic materials (ASAHI, 2018). In this case the valve is modelled in PVC. Based on the datasheet a simplification has been made, where the entire valve is assumed to only consist of PVC.
[8]All the valves, consists of an electric actuator from Johnson valves, model JVE05 (Johnson & Sons LTD, 2018). In order to dimension the material set, an assumption was made, where the engine consists of 66 % carbon steel, 22.5 % aluminium and 11.5 % copper. The assumption was based on a study from Legarth et al (2000), where they have made the percentage distribution for an engine for their LCA of an air-handling unit.
[9]The units of the air diffusers include one replacement during the expected lifetime of 20 years.

[16] Buhmann, Philip; Project Engineer, Jäger Umwelt-Technik GmbH. 2019. Communication via email March 5th

Clarifier Treatment

Table A2.3: Summary of the simplified equipment material input of the clarifier process of the Iso-Disc system.

Equipment	Purpose	Material	Weight per component (kg)	Unit	Total weight (kg)
WAS/RAS pump*	Return activated sludge and waste activated sludge	Cast iron	45.50	2	91.00
		Stainless Steel	45.50	2	91.00
Skirting (including attachments)	Improves settling of incoming MLSS. Installed around the central pillar	Stainless Steel	80.00	1	80.00
Sharks teeth	This is installed around the edge of the clarifier. Improves the clarity of the effluent	Stainless Steel	220.00	1	220.00
Gangway	Allow access for operators and acts as support for the scrapers	Aluminium	780.00	1	780.00
Rubber scraper	Scrapers the bottom of the clarifier, moving sludge to the central sump	Rubber	60.00	20**	1 200.00
Drive engine***	To rotate the gangway and scrapers	Carbon steel	14.98	1	14.98
		Aluminium	5.12	1	5.12
		Copper	2.61	1	2.61
Piping	To transport MLSS to the clarifier, thickened sludge and effluent from the clarifier.	Carbon steel	30 meters	1	695.00

*The WAS/RAS pump (CRE 32-2-1) comes from the supplier Grundfos (Grundfos Holding A/S, n.d.b). Based on the product information of the supplier, the total weight of the pump is allocated to stainless steel (50 %) and cast iron (50%).

**Replaced annually, thereby the unit of 20.

***In order to dimension the material set, an assumption was made, where the engine consists of 66 % carbon steel, 22.5 % aluminium and 11.5 % copper. The assumption was based on a study from Legarth et al (2000), where they have made the percentage distribution of an engine for their LCA of an air-handling unit.

Iso-Disc Technology

Table A2.4: Summary of the equipment material input.

Equipment	Purpose	Material	Weight per component (kg)	Unit	Total weight (kg)
Butterfly valve[1]	Manual	Ductile iron	3.78	2	7.56
		Stainless steel	1.62	2	3.24
Butterfly valve[1]	Sludge	Ductile iron	3.78	2	7.56
		Stainless steel	1.62	2	3.24
Butterfly valve[1]	Backwash	Ductile iron	4.27	3	12.81
		Stainless steel	1.83	3	5.49
Electric actuator	Electric actuators for the valves	Carbon steel	0.86	7	6.02
		Aluminium	0.29	7	2.03
		Copper	0.15	7	1.05
Pump[3]	Backwash	Stainless steel	19.50	3	58.50
		Cast iron	19.50	3	58.50
Pressure transmitter[4]	Determining the height of the water in the tank	Stainless Steel	0.41	1	0.41
Effluent connection pipes	Piping to connect the Iso-Disc to the plant effluent outlet	304 Stainless Steel	42.51 kg/meter	10 meters	425.10
Backwash drop pipes	Piping for the backwash	304 Stainless Steel	11.28 kg/meter	25 meters	282.00
Sludge withdrawal piping	Piping to collect solids settling to the bottom and connected to pumps etc.	PVC	3.33 kg/meter	40 meters	133.20
Backwash manifold support	Clamps to hold the pipes	PVC	0.30	1	0.30
Drop pipe support	Metal clamps to hold the pipes	304 Stainless Steel	0.30	1	0.30
Backwash manifold support	Metal clamps to hold the pipes	304 Stainless Steel	0.30	3	0.90

[1]The valve comes from the supplier Johnsons valves (Johnsons & Sons LTD, 2017a). Based on the data sheet a simplification has been made, where the valve is assumed to consist of 70 % ductile iron and 30 % stainless steel. In real life, the percentage of material is likely to become higher for the iron and lower for the steel. Since the environmental impact of steel is higher compared to iron, the assumption is made from a standpoint of not underestimating the environmental impact of the valve.

[2]All the valves consist of an electric actuator from Johnson valves, model JVE05 (Johnson & Sons LTD, 2018). In order to dimension the material set, an assumption was made, where the engine consists of 66 % carbon steel, 22.5 % aluminium and 11.5 % copper. The assumption was based on a study from Legarth et al (2000), where they have made the percentage distribution of an engine for their LCA of an air-handling unit.

[3]The backwash pump (CRE3-17) comes from the supplier Grundfos (Grundfos Holding A/S, n.d.b). Based on the product information of the supplier, the total weight of the pump is assumed to consist of stainless steel (50 %) and cast iron (50%).

[4]Based on the data sheet from the supplier, an assumption has been made where all weight is based on stainless steel, since the main part of the product consist of the assumed material (Endress+Hauser AB, n.d.c).

AS-H Iso-Disc Cloth Media Filter

Table A2.5: Summary of the equipment material input of the Iso-Disc.

Component category	Material	Weight per Iso-Disc
Assembly[1]	Cast Iron	10.96
	Stainless Steel	622.22
	UHMWPE	13.49
	EPDM	15.00
	Rubber	3.00
	PP	3.48
	PVC	0.52
Vacuum assembly[2]	Neoprene	0.54
	UHMWPE	10.88
	Stainless Steel	322.70
Disk assembly[3]	Stainless Steel	102.94
	UHMWPE	16.46
	Polyester[4]	16.00
Drive engine[5]	Carbon Steel	14.98
	Aluminium	5.11
	Copper	2.61
Gearbox dual[6]	Cast Iron	15.90
	Stainless Steel	15.90
Gearbox single[6]	Cast Iron	15.90
	Stainless Steel	15.90

[1]The Assembly consist of 24 different components, which were separately evaluated for the study. Due to confidential reasons, the components in the table are clustered together, where only the material and total weight is given for the total components and not on an individual basis.
[2]The Vacuum Assembly consists of five different components, which were separately evaluated for the study. Due to confidential reasons, the components in the table are clustered together, where only the material and total weight is given for the total components and not on an individual basis.
[3]The Disk Assembly consists of seven different components, which were separately evaluated for the study. Due to confidential reasons, the components in the table are clustered together, where only the material and total weight is given for the total components and not on an individual basis.
[4]The weight includes replacement every fifth year of the material.
[5]In order to dimension the material set, an assumption was made, where the engine consists of 66 % carbon steel, 22.5 % aluminium and 11.5 % copper. The assumption was based on a study from Legarth et al (2000), where they have made the percentage distribution of an engine for their LCA of an air-handling unit.
[6]The material of the gearbox was estimated to cast iron (50 %) and stainless steel (50 %). The estimation was based on an LCA of Vestas where they described the construction of a gearbox, which mainly consisted of cast iron and stainless steel (Vestas, 2006).

Transport

Transport from Supplier to the Factory of Alfa Laval in Stoke

Table A2.6: Transport from supplier to Stoke.

Component	Material	Start location	End location	Transport	Load weight (kg)	Distance (km)
Assembly	304 Stainless Steel	Houston	Stoke	Sea Freight	80.00	9 300
	PVC	Stoke	Stoke	Truck (16-32 ton)	0.52	-
	PP	Houston	Stoke	Sea Freight	3.48	9 300
	304 Stainless Steel	Beijing	Stoke	Sea Freight	574.02	29 800
	EPDM w/PE	Houston	Stoke	Sea Freight	15.00	9 300
	UHMWPE	Stoke	Stoke	Truck (16-32 ton)	13.49	-
	Cast iron	Houston	Stoke	Sea Freight	10.96	9 300
	Cast iron	Beijing	Stoke	Sea Freight	31.80	29 800
	Rubber	Stoke	Stoke	Truck (16-32 ton)	3	-
Vacuum assembly	Neoprene	Houston	Stoke	Sea Freight	0.54	9 300
	UHMWPE	Stoke	Stoke	Truck (16-32 ton)	10.88	-
	304 Stainless Steel	Beijing	Stoke	Sea Freight	322.70	29 800
Disk assembly	UHMWPE	Stoke	Stoke	Truck (16-32 ton)	16.46	-
	304 Stainless Steel	Beijing	Stoke	Sea Freight	102.94	29 800
	Polyester	Houston	Stoke	Sea Freight	16.00	9 300
Drive engine	Various	London	Stoke	Truck (16-32 ton)	22.70	100

Transport to Wastewater Treatment Plant

Table A2.7: Transport of Iso-Disc from Stoke to the wastewater treatment plant.

Iso-Disc	Sweden	Denmark	Australia
Start location	Stoke	Stoke	Stoke
End location	Stockholm	Copenhagen	Canberra
Transport type	Sea Freight	Sea Freight	Sea Freight
Load weight (ton)	1.22	1.22	1.22
Distance (km)	3 300	2 500	23 000

Energy Consumption

Manufacturing of the Iso-Disc

Table A2.8: Energy consumption.

Activity	Energy consumption (kWh/Iso-Disc)	Unit	Total energy consumption (kWh)
Manufacturing of Iso-Disc	1 515	1	1 515

Appendix 3

Table A3.1: Global warming potential, human toxicity potential and particulate matter formation potential.

	Global Warming Potential (kg $CO_{2\text{-}Eq}$)		*Human Toxicity Potential (kg 1.4 $DCB_{\text{-}Eq}$)*		*Particulate Matter Formation Potential (kg $PM_{10\text{-}Eq}$)*	
	Iso-Disc	**MBR**	**Iso-Disc**	**MBR**	**Iso-Disc**	**MBR**
Aerobic Tanks	5.56E-03	2.46E-03	1.83E-03	8.07E-04	1.09E-05	4.82E-06
Anoxic Tanks	2.97E-03	1.68E-03	9.77E-04	5.52E-04	5.84E-06	3.30E-06
CIP Tank	-	1.92E-05	-	1.87E-06	-	2.31E-08
Clarifier Tank	4.13E-03	-	1.36E-03	-	8.11E-06	-
Engines	8.39E-04	2.11E-03	9.36E-04	2.36E-03	3.87E-06	9.81E-06
Iso-Disc	6.15E-04	-	3.95E-04	-	2.72E-06	-
Iso-Disc Tank	4.30E-04	-	1.41E-04	-	8.45E-07	-
MBR Modules	-	8.44E-03	-	2.70E-03	-	1.86E-05
MBR Tanks	-	4.89E-03	-	1.61E-03	-	9.60E-06
Other Equipment	1.06E-03	9.38E-04	4.52E-04	5.46E-04	2.84E-06	4.32E-06
Pipes	1.11E-03	1.84E-03	6.02E-04	1.03E-03	4.27E-06	8.12E-06
Valves	1.97E-04	2.31E-04	1.20E-04	1.25E-04	8.94E-07	9.33E-07

Table A3.2: Freshwater eutrophication potential, marine eutrophication potential and terrestrial acidification potential.

	Freshwater Eutrophication Potential (kg $P_{\text{-}Eq}$)		*Marine Eutrophication Potential (kg $N_{\text{-}Eq}$)*		*Terrestrial Acidification Potential (kg $SO_{2\text{-}Eq}$)*	
	Iso-Disc	**MBR**	**Iso-Disc**	**MBR**	**Iso-Disc**	**MBR**
Aerobic Tanks	1.60E-06	7.05E-07	8.44E-07	3.73E-07	1.59E-05	7.03E-06
Anoxic Tanks	8.54E-07	4.82E-07	4.52E-07	2.55E-07	8.51E-06	4.81E-06
CIP Tank	-	2.42E-09	-	2.27E-09	-	6.76E-08
Clarifier Tank	1.19E-06	-	6.27E-07	-	1.18E-05	-
Engines	5.65E-07	1.45E-06	2.87E-07	7.38E-07	4.67E-06	1.19E-05
Iso-Disc	2.83E-07	-	1.80E-07	-	2.99E-06	-
Iso-Disc Tank	1.24E-07	-	6.53E-08	-	1.23E-06	-
MBR Modules	-	2.55E-06	-	2.05E-06	-	3.63E-05
MBR Tanks	-	1.40E-06	-	7.42E-07	-	1.40E-05
Other Equipment	4.16E-07	4.12E-07	2.54E-07	2.74E-07	5.30E-06	4.54E-06
Pipes	4.73E-07	7.74E-07	3.23E-07	5.32E-07	4.93E-06	8.70E-06
Valves	8.58E-08	9.04E-08	5.70E-08	6.38E-08	9.40E-07	1.05E-06

Table A3.3: Freshwater ecotoxicity potential, marine ecotoxicity potential and terrestrial ecotoxicity potential.

	Freshwater Ecotoxicity Potential (kg 1.4 $DCB_{\text{-}Eq}$)		*Marine Ecotoxicity Potential (kg 1.4 $DB_{\text{-}Eq}$)*		*Terrestrial Ecotoxicity Potential (kg 1.4 $DCB_{\text{-}Eq}$)*	
	Iso-Disc	**MBR**	**Iso-Disc**	**MBR**	**Iso-Disc**	**MBR**
Aerobic Tanks	5.21E-05	2.30E-05	5.13E-05	2.27E-05	2.53E-06	1.12E-06
Anoxic Tanks	2.78E-05	1.57E-05	2.74E-05	1.55E-05	1.36E-06	7.66E-07
CIP Tank	-	7.03E-08	-	6.55E-08	-	4.76E-10
Clarifier Tank	3.87E-05	-	3.81E-05	-	1.88E-06	-
Engines	6.26E-05	1.64E-04	6.29E-05	1.65E-04	1.90E-07	4.78E-07
Iso-Disc	4.27E-05	-	5.17E-05	-	1.23E-07	-
Iso-Disc Tank	4.03E-06	-	3.97E-06	-	1.96E-07	-
MBR Modules	-	1.93E-04	-	1.90E-04	-	6.97E-07
MBR Tanks	-	4.58E-05	-	4.51E-05	-	2.23E-06
Other Equipment	8.90E-05	6.79E-05	7.92E-05	6.87E-05	8.96E-08	1.92E-07
Pipes	6.15E-05	1.27E-04	6.17E-05	1.28E-04	2.07E-07	3.66E-07
Valves	1.36E-05	1.38E-05	1.38E-05	1.40E-05	4.07E-08	4.29E-08

Table A3.4: Ozone depletion potential and photochemical oxidant formation potential.

	Ozone Depletion Potential (kg CFC-11-Eq)		*Photochemical Oxidant Formation Potential (kg MNVOC-Eq)*	
	Iso-Disc	**MBR**	**Iso-Disc**	**MBR**
Aerobic Tanks	2.70E-10	1.19E-10	1.85E-05	8.18E-06
Anoxic Tanks	1.44E-10	8.16E-11	9.90E-06	5.59E-06
CIP Tank	-	3.58E-13	-	8.34E-08
Clarifier Tank	2.01E-10	-	1.38E-05	-
Engines	4.82E-11	1.22E-10	3.35E-06	8.29E-06
Iso-Disc	3.88E-11	-	2.27E-06	-
Iso-Disc Tank	2.09E-11	-	1.43E-06	-
MBR Modules	-	5.73E-10	-	2.88E-05
MBR Tanks	-	2.38E-10	-	1.63E-05
Other Equipment	4.60E-11	5.64E-11	3.51E-06	3.51E-06
Pipes	5.97E-11	1.03E-10	4.42E-06	7.01E-06
Valves	1.12E-11	1.20E-11	7.55E-07	9.16E-07

Appendix 4

Table A4.1: Global warming potential, human toxicity potential and particulate matter formation potential.

	Global Warming Potential (kg $CO_{2\text{-}Eq}$)	*Human Toxicity Potential (kg 1.4 $DCB_{\text{-}Eq}$)*	*Particulate Matter Formation Potential (kg $PM_{10\text{-}Eq}$)*
Aluminium Sheet	2.88E-05	1.17E-05	6.99E-08
EPDM	5.37E-06	2.11E-06	9.39E-09
Fiberglass	4.86E-04	1.48E-04	7.34E-07
Fossil Electricity	4.87E-04	1.53E-04	4.01E-07
Non-Fossil Electricity	3.83E-05	4.16E-05	5.74E-07
PP	2.89E-03	2.73E-04	3.31E-06
PVDF Membrane	2.62E-03	9.50E-04	4.60E-06
Stainless Steel	1.88E-03	1.12E-03	8.89E-06

Table A4.2: Freshwater eutrophication potential, marine eutrophication potential and terrestrial acidification potential.

	Freshwater Eutrophication Potential (kg $P_{\text{-}Eq}$)	*Marine Eutrophication Potential (kg $N_{\text{-}Eq}$)*	*Terrestrial Acidification Potential (kg $SO_{2\text{-}Eq}$)*
Aluminium Sheet	1.11E-08	5.71E-09	1.48E-07
EPDM	2.11E-09	1.06E-09	2.62E-08
Fiberglass	1.27E-07	8.40E-08	1.97E-06
Fossil Electricity	2.17E-07	7.78E-08	1.35E-06
Non-Fossil Electricity	1.98E-08	1.43E-07	3.61E-06
PP	4.04E-07	3.71E-07	9.68E-06
PVDF Membrane	9.24E-07	8.03E-07	1.03E-05
Stainless Steel	8.43E-07	5.60E-07	9.19E-06

Table A4.3: Freshwater ecotoxicity potential, marine ecotoxicity potential and terrestrial ecotoxicity potential.

	Freshwater Ecotoxicity Potential (kg 1.4 $DCB_{\text{-}Eq}$)	*Marine Ecotoxicity Potential (kg 1.4 $DB_{\text{-}Eq}$)*	*Terrestrial Ecotoxicity Potential (kg 1.4 $DCB_{\text{-}Eq}$)*
Aluminium Sheet	2.31E-06	2.02E-06	8.66E-10
EPDM	6.13E-08	5.77E-08	2.56E-10
Fiberglass	3.56E-06	3.33E-06	2.19E-08
Fossil Electricity	3.53E-06	3.44E-06	4.64E-09
Non-Fossil Electricity	4.00E-06	3.58E-06	2.12E-08
PP	1.01E-05	9.48E-06	6.96E-08
PVDF Membrane	2.80E-05	2.57E-05	1.80E-07
Stainless Steel	1.41E-04	1.43E-04	3.98E-07

Table A4.4: Ozone depletion potential and photochemical oxidant formation potential.

	Ozone Depletion Potential (kg $CFC\text{-}11_{\text{-}Eq}$)	*Photochemical Oxidant Formation Potential (kg $MNVOC_{\text{-}Eq}$)*
Aluminium Sheet	9.78E-13	9.51E-08
EPDM	1.25E-12	2.66E-08
Fiberglass	2.82E-11	2.03E-06
Fossil Electricity	1.00E-11	8.54E-07
Non-Fossil Electricity	3.99E-12	4.21E-07
PP	5.25E-11	1.11E-05
PVDF Membrane	3.65E-10	7.21E-06
Stainless Steel	1.11E-10	7.01E-06

Appendix 5

The following Appendix presents the calculations of the total eutrophication potential that has been made, where the phosphorus and nitrogen in the TSS are considered.

The assumed TSS content in the effluent, listed in table A5.1, is retrieved from Tchobanoglous et al. (2013).

Table A5.1: Assumed composition of TSS of the effluent.

TSS composition of the effluent	Percentage (%)
Carbon	50
Oxygen	22
Nitrogen	12
Hydrogen	9
Phosphorus	2
Sulphur	1
Potassium	1
Sodium	1
Calcium	0.5
Magnesium	0.5
Chlorine	0.5
Iron	0.2
Other trace elements	0.3

Iso-Disc Technology

Q = 1 900 000 litre/day

Effluent concentration = 5 mg TSS/litre

Emissions from the TSS of Phosphorus (P)

Kg-P/day = 1 900 000 l· 5 mg/l· 0.02 = 190 000 mg P/day

Kg-P/lifespan = 190 000 mg P· 365· 20 = 1 387 000 000 mg P

Emissions from the TSS of Nitrogen (N)

Kg-N/day = 1 900 000 l· 5 mg/l· 0.12 = 1 140 000 mg N/day

Kg-N/lifespan = 1 140 000 mg N· 365· 20 = 8 322 000 000 mg N

MBR Technology

Q = 1 900 000 litre/day

Effluent concentration = 1 mg TSS/litre

Emissions from the TSS of Phosphorus (P)

Kg-P/day = 1 900 000 l· 1 mg/l· 0.02 = 38 000 mg P/day

Kg-P/lifespan = 38 000 mg P· 365· 20 = 277 400 000 mg P

Emissions from the TSS of Nitrogen (N)

Kg-N/day = 1 900 000 l· 1 mg/l· 0.12 = 228 000 mg N/day

Kg-N/lifespan = 228 000 mg N · 365· 20 = 166 400 000 mg N

Table A5.2: The total emissions of phosphorus (P) and nitrogen (N) in Denmark

	Iso-Disc		***MBR***	
	P (kg)	**N (kg)**	**P (kg)**	**N (kg)**
Emissions from TSS	1 387	8 322	277.4	1 664.4
Emissions from production, transport and operation	1 722	1 576	2 151	2 129
Total	3 109	9 898	2 428.4	3 793.4

Table A5.3: The total emissions of phosphorus (P) and nitrogen (N) in Australia

	Iso-Disc		***MBR***	
	P (kg)	**N (kg)**	**P (kg)**	**N (kg)**
Emissions from TSS	1 387	8 322	277.4	1 664.4
Emissions from production, transport and operation	12 603	3 707	14 465	4 545
Total	13 990	12 029	14 742.4	6 209.4

Table A5.4: The total emissions of phosphorus (P) and nitrogen (N) in Sweden

	Iso-Disc		***MBR***	
	P (kg)	**N (kg)**	**P (kg)**	**N (kg)**
Emissions from TSS	1 387	8 322	277.4	1 664.4
Emissions from production, transport and operation	212	337	443	728
Total	1 599	8 659	720.4	2 392.4

Table A5.5: Differences in freshwater eutrophication potential

	Freshwater Eutrophication Potential (kg P_{-Eq}/FU)					
	Australia		***Denmark***		***Sweden***	
Emission source	**Iso-Disc**	**MBR**	**Iso-Disc**	**MBR**	**Iso-Disc**	**MBR**
Production, transport and operation	9.32E-04	10.68E-04	1.28E-04	1.59E-04	1.57E-05	3.27E-05
Production, transport and operation including indirect emissions from the TSS in the effluent	1.00E-03	1.06E-03	2.24E-04	1.75E-04	1.15E-04	5.19E-05

Table A5.6: Differences in marine eutrophication potential

	Marine Eutrophication Potential (kg N_{-Eq}/FU)					
	Australia		***Denmark***		***Sweden***	
Emission source	**Iso-Disc**	**MBR**	**Iso-Disc**	**MBR**	**Iso-Disc**	**MBR**
Production, transport and operation	2.74E-04	3.36E-04	1.16E-04	1.57E-04	2.5E-05	5.38E-05
Production, transport and operation including indirect emissions from the TSS in the effluent	8.67E-04	4.48E-04	7.14E-04	2.73E-04	6.24E-04	1.72E-04

Appendix 6

Below is the modelling of materials, electricity mixes and transport presented.

Modelling of Materials

Table A6.1: Summary of the material required for the study and their modulation in Ecoinvent.

Material	Modelled as	Activity	Region	Data reference
Aluminium	Market for aluminium, wrought alloy	Raw material	Global	Ecoinvent 3.5
	Sheet rolling, aluminium	Manufacturing	Europe	Ecoinvent 3.5
Aluminium	Market for aluminium, wrought alloy	Raw material	Global	Ecoinvent 3.5
	Metal working, average for aluminium product manufacturing	Manufacturing	Europe	Ecoinvent 3.5
Carbon steel	Market for reinforcing steel	Raw material	Global	Ecoinvent 3.5
	Metal working, average steel production manufacturing	Manufacturing	Europe	Ecoinvent 3.5
Cast iron/ductile iron	Cast iron production	Raw material/ manufacturing	Europe	Ecoinvent 3.5
Citric acid	Market for citric acid production	Raw material/ manufacturing	Global	Ecoinvent 3.5
Citric acid	Citric acid production	Raw material/ manufacturing	Europe	Ecoinvent 3.5
Copper	Market for copper	Raw material	Global	Ecoinvent 3.5
	Metal working, average for copper product manufacturing	Manufacturing	Europe	Ecoinvent 3.5
EPDM	Synthetic rubber production	Raw material/ manufacturing	Europe	Ecoinvent 3.5
Fiberglass and PP	Market for chemical, organic	Raw material	Global	Ecoinvent 3.5
	Market for glass fibre	Manufacturing	Global	Ecoinvent 3.5
	Market for polypropylene, granulate	Raw material	Global	Ecoinvent 3.5
	Injection moulding	Manufacturing	Europe	Ecoinvent 3.5
Confidential				
PVDF*	Market for polyvinylfluoride	Raw material	Global	Ecoinvent 3.5
	Extrusion, plastic pipes	Manufacturing	Europe	Ecoinvent 3.5
Neoprene	Synthetic rubber production	Raw material/ manufacturing	Europe	Ecoinvent 3.5
Confidential				
PE	Market for polyethylene, high density, granulate	Raw material	Global	Ecoinvent 3.5
	Extrusion, plastic pipes	Manufacturing	Europe	Ecoinvent 3.5
Polyester	Market for polyethylene terephtale, granulate, bottle grade	Raw material	Global	Ecoinvent 3.5
	Extrusion, plastic pipes	Manufacturing	Europe	Ecoinvent 3.5
PP	Market for polypropylene, granulate	Raw material	Global	Ecoinvent 3.5
	Extrusion, plastic pipes	Manufacturing	Europe	Ecoinvent 3.5
PVC	Market for polyvinylchloride, bulk polymerised	Raw material	Global	Ecoinvent 3.5

	Extrusion, plastic pipes	Manufacturing	Europe	Ecoinvent 3.5
Reinforced concrete	Market for concrete, normal	Raw material/ manufacturing	Rest-of-World	Ecoinvent 3.5
	Market for reinforcing steel	Raw material / manufacturing	Global	Ecoinvent 3.5
Sodium hypochlorite	Sodium hypochlorite production, product in 15%solution state	Raw material/ Manufacturing	Europe	Ecoinvent 3.5
Stainless steel	Steel production, chromium steel 18/8, hot rolled	Raw material /semi product	Europe	Ecoinvent 3.5
	Metal working, average for chromium steel production manufacturing	Manufacturing	Europe	Ecoinvent 3.5
UHMWPE	Market for polyethylene, high density, granulate	Raw material	Global	Ecoinvent 3.5
	Extrusion, plastic pipes	Manufacturing	Europe	Ecoinvent 3.5

*Today, there is no value for polyvinylidene fluoride (PVDF) in Ecoinvent. After a thorough review of previous research, only one value for PVDF could be found. This value was presented in an environmental product declaration (EPD) from Fischer (2012), where a piping system was investigated. Based on the EPD, a value of 16.8 kg $CO_{2\text{-eq}}$/ kg for PVDF was found. However, the EPD did not contain all environmental impact categories that this study intends to present. Since there is a lack of information regarding the environmental impacts of PVDF, previous research has solved the problem in different ways, when environmental impact from PVDF is required. Zackrisson et al. (2010) replaced PVDF with 50 % each of tetrafluoroethylene (TFE) and polyethylene (PE). This replacement gives a value that corresponds to approximately 70 kg $CO_{2\text{-eq}}$/ kg in Ecoinvent. However, this replacement is four times as high compared to the value presented by Fischer (2012) and may be seen as high. Blom (2010) solved the lack of values for PVDF by replacing PVDF with emulsion polymerized PVC. This replacement gives a value that corresponds to approximately 2.5 kg $CO_{2\text{-eq}}$/ kg. This may be seen as low, as it differs by a factor of seven against the value of Fischer (2012). In this study, PVDF has been replaced by PVF, which has a value of 15 kg $CO_{2\text{-eq}}$/ kg in Ecoinvent, which is close to the value that Fischer (2012) has presented.

Modelling of Electricity Mix

Table A6.2: Summary of the electricity mixes required for the study and their modulation in Ecoinvent.

Electricity mix (2016)	Modelled as	Share of total electricity (%)[11]	Data reference
Sweden	Electricity production, hydro, run-of-river[1]	39.9	Ecoinvent 3.5
	Electricity production, hydro, reservoir, non-alpine region[1]		
	Electricity production, nuclear, boiling water reactor[2]	40.4	Ecoinvent 3.5
	Electricity production, nuclear, pressure water reactor[2]		
	Electricity production, wind, <1MW turbine, onshore[3]	9.9	Ecoinvent 3.5
	Electricity production, wind, 1-3MW turbine, onshore[3]		
	Heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014[4]	8.4	Ecoinvent 3.5
	Heat and power co-generation, hard coal	0.7	Ecoinvent 3.5
	Treatment of blast furnace gas, in power plant	0.4	Ecoinvent 3.5
	Heat and power co-generation, oil	0.3	Ecoinvent 3.5
Denmark	Electricity production, wind, <1MW turbine, onshore[5]	42	Ecoinvent 3.5
	Electricity production, wind, 1-3MW turbine, onshore[5]		
	Electricity production, wind, 1-3MW turbine, offshore[5]		
	Electricity production, wind, >3MW turbine, onshore[5]		
	Heat and power co-generation, hard coal	29	Ecoinvent 3.5
	Heat and power co-generation, biogas, gas engine	5.1	Ecoinvent 3.5
	Heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	13.3	Ecoinvent 3.5
	Heat and power co-generation, natural gas, conventional power plant, 100MW electrical	7.1	Ecoinvent 3.5
	Electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	2.4	Ecoinvent 3.5
	Heat and power co-generation, oil	1.1	Ecoinvent 3.5
Australia	Electricity production, lignite[6]	63.6	Ecoinvent 3.5
	Electricity production, hard coal[6]		
	Electricity production, natural gas, conventional power plant[7]	19.6	Ecoinvent 3.5

	Electricity production, natural gas, combined cycle power plant[7]		
	Heat and power co-generation, natural gas, conventional power plant, 100MW electrical[7]		
	Electricity production, oil	2.2	Ecoinvent 3.5
	Electricity production, solar tower power plant, 20 MW[8]	2.4	Ecoinvent 3.5
	Photovoltaic, 570kWp open ground installation, multi-Si[8]		
	Electricity production, hydro, run-of-river[9]	6	Ecoinvent 3.5
	Electricity production, hydro, pumped storage[9]		
	Electricity production, wind, 1-3MW turbine, onshore[10]	4.8	Ecoinvent 3.5
	Electricity production, wind, >3MW turbine, onshore[10]		
	Electricity production, wind, <1MW turbine, onshore[10]		
	Heat and power co-generation, biogas, gas engine	1.4	Ecoinvent 3.5
United Kingdom	Electricity production, natural gas, conventional power plant	42.2	Ecoinvent 3.5
	Electricity production, nuclear, boiling water reactor[12]	21.1	Ecoinvent 3.5
	Electricity production, nuclear, pressure water reactor[12]		Ecoinvent 3.5
	Electricity production, wind, <1MW turbine, onshore[13]	11	Ecoinvent 3.5
	Electricity production, wind, 1-3MW turbine, onshore[13]		Ecoinvent 3.5
	Electricity production, wind, >3MW turbine, onshore[13]		Ecoinvent 3.5
	Electricity production, wind, 1-3MW turbine, offshore[13]		Ecoinvent 3.5
	Heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014[4]	10.3	Ecoinvent 3.5
	Electricity production, hard coal	9.3	Ecoinvent 3.5
	Photovoltaic, 570kWp open ground installation, multi-Si	3.1	Ecoinvent 3.5
	Electricity production, hydro, run-of-river[14]	2.5	Ecoinvent 3.5
	Electricity production, hydro, pumped storage[14]		Ecoinvent 3.5
	Electricity production, oil	0.5	Ecoinvent 3.5

[1]Hydro generated electricity in Sweden is dimensioned as 80 % run-of-river and 20 % non-alpine region (Wernet et al., 2016).
[2]Nuclear generated electricity in Sweden is dimensioned as 64 % boiling water and 36 % pressure water (Uniper SE, 2019).
[3]Wind generated electricity in Sweden is dimensioned as 85 % wind turbines with an effect between 1-3 MW and 15 % wind turbines with an effect of less than 1 MW. In addition, Wernet et al. (2016) also include wind turbines offshore 1-3 MW and wind turbines onshore with an effect more than 3 MW for Sweden's wind generated electricity, but due to its low share (3.2 % and 0.037 %) this is excluded from the study.
[4]Biofuels and waste generated electricity is assumed to be produced by the same technology as 'heat and power co-generation wood chips'.
[5]Wind generated electricity in Denmark is dimensioned as 40.5 % from onshore wind turbines with an effect of less than 1 MW, 27.6 % from onshore wind turbines with an effect between 1-3MW, 22.2% from offshore wind turbines with an effect between 1-3MW and 9.8% from onshore wind turbines with an effect of more than 3MW (Wernet et al., 2016).
[6]Coal generated electricity in Australia is dimensioned as 71 % hard coal and 29 lignite (Ball et al., 2017).
[7]Natural gas generated electricity in Australia is dimensioned as 75 % combined cycle power plant, 17 % conventional power plant and 8 % heat and power co-generation, natural gas (Werner et al., 2016).
[8]Solar generated electricity in Australia is dimensioned as 92 % photovoltaic (570 kWp) and 8 % solar tower (Ball et al., 2017).
[9]Hydro generated electricity in Australia is dimensioned as 98 % hydro, run-of-river and 2 % hydro, pumped storage (Wernet et al., 2016).
[10]Wind generated electricity in Australia is dimensioned as 95 % from onshore wind turbines with an effect between 1-3 MW, 54 % from onshore wind turbine with an effect less than 3 MW and 1 % from onshore wind turbine with an effect of less than 1 MW (Wernet et al., 2016).
[11]Each country's share of electricity mix is based on the different types of energy sources that were specified in the year of 2016 and specified by the International Energy Agency (IEA). IEA specifies that the electricity mix of Sweden 2016 consisted of 0.1 % solar energy. However, the solar energy has been removed from the study due to its low share, and the percentage of 0.1 % has been put on hydropower instead. Further, IEA specifies that the electricity mix of Denmark consisted of 0.1 % hydropower. However, the hydropower has been removed from the study due to its low share, and the percentage of 0.1 % has been put on wind energy instead (IEA, 2019).
[12]Nuclear generated electricity in United Kingdom is dimensioned as 87.1 % boiling water and 12.9 % pressure water based on the electricity mix in Ecoinvent (Wernet et al., 2016).
[13]Wind generated electricity in United Kingdom is dimensioned as 6.8 % from onshore wind turbines with an effect of less than 1 MW, 56.6 % from onshore wind turbines with an effect between 1-3MW, 4 % from onshore wind turbines with an effect between more than 3MW and 32.6% from offshore wind turbines with an effect of between 1-3MW (Wernet et al., 2016).
[14] Nuclear generated electricity in United Kingdom is dimensioned as 61.9 % 'run-of-river' and 38.1 % 'pumped storage' according to the electricity mix in Ecoinvent (Wernet et al., 2016).

Modelling of Transport

Table A6.3: Summary of the transport required for the study and its modulation in Ecoinvent.

Transport by/	**Modelled as**	**Data reference**
Land	Freight, lorry> 16-32 metric ton	Ecoinvent 3.5
Sea	Market for transport, freight, sea, transoceanic ship	Ecoinvent 3.5

Appendix 7

Figure A7.1 illustrates the difference of the electricity mix that is used for this study in comparison to the predefined electricity mixes that can be found in Ecoinvent. Problems arise while using the predefined electricity mixes in Ecoinvent, if they are not updated to correct percentages for each power source. In figure A7.1, our electricity mixes differ from the one in Ecoinvent. It can be seen in the figure that the electricity mix in Sweden, which is used in the study, is modelled higher compared to the predefined one in Ecoinvent of Sweden's electricity mix. It can also be seen that the electricity mix in the United Kingdom is modelled much lower in our study compared to the one predefined in Ecoinvent. The reason why our modelled electricity mix in the UK shows significantly lower emissions than the predefined electricity mix in Ecoinvent, is because of the percentage breakdown of fuels, which is probably not updated in Ecoinvent. Since the closure of coal-fired power plants, the electricity mix in the UK has in recent years gone from a large proportion of coal to more natural gas and renewable energy (Vanlint, 2018). These closures have given rise to a great change in the electricity mix for UK. During the years 2015 and 2016, the carbon dioxide emissions from coal consumption in UK fell more than 50 % (Vanlint, 2018). This downward trend has continued and in the years 2016 and 2017 the use of coal fell even further, reducing the carbon dioxide emission from coal by an additional 24 % (Vanlint, 2018).

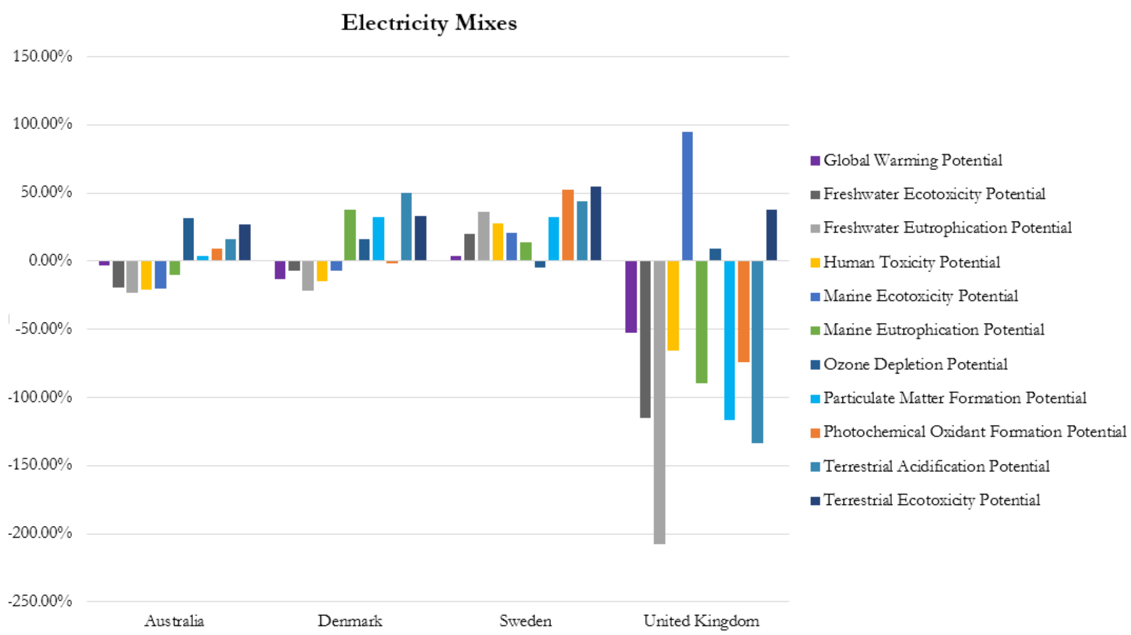

Figure A7.1: The figure illustrates how the electricity mixes that this study is based on differ compared to the predefined electricity mixes in Ecoinvent.

Emissions from countries' different electricity mixes depend on a large number of factors. One of the factors is whether fossil or non-fossil fuels are used, but also which specific fossil or non-fossil fuel acts as the basis for the electricity mixes. Changes in emissions per kWh can occur from one year to another. These changes can happen if fuel costs for a specific fuel either increases or decreases. Due to economic reasons, they can either be included or replaced (Ball et al., 2017). When it comes to hydropower, it all depends on the weather and the water levels in the water reservoirs since they are not always completely filled (Energiföretagen, 2018).