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# Cradle-to-Gate LCA of Water Treatment Alternatives

## A case study performed for Norrvatten's future waterwork expansion

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# Cradle-to-Gate LCA of Water Treatment Alternatives

## A case study performed for Norrvatten's future waterwork expansion

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# Sammanfattning

Norrvatten är en kommunförening som äger en vattenreningsanläggning som kan leverera dricksvatten av god kvalitet till konsumenterna i de angränsande grannkommunerna. Efter preliminära undersökningar för det kommande året 2050 fanns det uppskattningar som tyder på en potentiell nedbrytning av vattenkvaliteten i sjön som ger råvattnet för behandling på grund av osäkra framtida klimatförhållanden och andra former av föroreningar från omgivningen. Det finns också en prognos om framtida befolkningsökning i respektive grannkommuner i Stockholms län, vilket följaktligen ökar efterfrågan på ytterligare mängd levererat dricksvatten. För närvarande levererat Dricksvatten, som trots att det är acceptabelt enligt de standarder som fastställts av Livsmedelsverket, kräver ytterligare avancerade behandlingstekniker för att ge en förbättring av dess kvalitet. Denna ökning av vattenkvaliteten kan uppnås genom att öka de tekniska behandlingsteknikerna för avlägsnande av organiskt material i vattenreningsverket genom att implementera fler kemiska och mikrobiologiska barriärer. Norrvatten har föreslagit flera alternativa vattenreningsmetoder, varav en av dem kan implementeras i vattenreningsverket, efter en utvidgning av anläggningens kapacitet att uppnå alla ovannämnda krav.

En fallstudie har utförts vid Norrvatten i Stockholm för att utvärdera miljöprestanda för de föreslagna behandlingsalternativen. Denna studie använder livscykelanalys för att analysera alternativen. Ett uttryckligt fokus ges med valet av 15 olika miljökategorier för att bedöma relaterade miljöbördor. De olika hotspots som identifierats från analysen undersöks och identifieras för att hitta tillhörande avvägningar med alternativen som studeras. Ytterligare parameterändringar har gjorts i alternativen för att förstå hur effekterna förändras i enlighet därmed.

De olika hotspots som identifierats från resultaten av studien var användningen av grandulerat aktivt kol för filtrering, konsumtionen av aluminiumsulfat för koagulering, konsumtionen av läsk om järnklorid väljs som huvudkoaguleringsmedel, förbrukningen av el i vattenreningsverket genom nanofiltreringsprocessen , vattenkraft från pumplagring och användning av tunga lastbilar för transport av kemikalier från leverantörer till anläggningen. Andra aspekter och antaganden från att genomföra en känslighetsanalys visade att det finns möjligheter att minska effekterna genom följande förändringar. Genom att byta huvudkoaguleringsmedlet från aluminiumsulfat till järnklorid för att minska den största resursutarmningen och människors hälsoeffekter med en avvägning av effekterna från en ökad produktion av natriumkarbonat. Genom att byta det aktuella inköpet av el, från en grön energimix till den svenska nätmixen, för att kraftigt förbättra reningsverkets miljöprestanda. Denna energiförändring observerades leda till en minskning av den globala uppvärmningspotentialen från koldioxidutsläpp. Andra förändringar som kan genomföras för att minska den totala miljöpåverkan är att byta från bränslebaserade transportbilar till elektriska lastbilar och byta kemikalieleverantörer från utanför Sverige till leverantörer nära eller inom Sverige, närmare vattenreningen växt.

*Nyckelord:* Livscykelbedömning, Vattenreningsmetod, Produktion av dricksvatten, Mikrobiologisk barriär, Aktivt kol, Slamavskiljning

# Abstract

Norrvatten is a municipal association which owns a water treatment plant capable of supplying good quality drinking water to the consumers in the associated neighbouring municipalities. After preliminary investigations for the future year of 2050, there were estimates which suggest a potential water quality degradation in the lake which supplies the raw water for treatment due to uncertain future climatic conditions and other forms of pollutions from the surrounding. There is also a forecast of future population increase in the respective neighbouring municipalities of Stockholm county, which consequently increases the demand for additional quantity of supplied drinking water. The supplied drinking water, which even though is currently acceptable by the standards set by Swedish Food Agency, still requires additional advanced treatment techniques in order to provide an upscale to its quality. This increase in water quality can be achieved by increasing the natural organic matter removal treatment techniques in the water treatment plant by implementing more chemical and microbiological barriers. Norrvatten has proposed several alternative water purification methods, out of which one of them can be implemented in the water treatment plant, after an expansion in the capacity of the plant to achieve all the above-mentioned requirements.

A case study has been performed at Norrvatten in Stockholm, Sweden for evaluating the environmental performance of the proposed treatment alternatives. This study adopts a cradle-to-gate life cycle assessment methodology to analyze the alternatives using stand-alone and comparative assessment methods. An explicit focus is given with the selection of 15 different environmental categories to assess the related environmental burdens. The various hotspots identified from the analysis is investigated and identified to find the associated trade-offs with the alternatives under study. Additional parameter changes have been made in the alternatives to apprehend how the impacts change accordingly.

The various hotspots identified from the results of the study were, the utilization of granular activated carbons for filtration, the consumption of aluminium sulphate for coagulation, the consumption of soda if iron chloride is selected as the main coagulant, the consumption of electricity in the WTP by nanofiltration process, hydropower from pumped storage and the use of heavy trucks for transporting chemicals from suppliers to the site. Other aspects and assumptions from conducting a sensitivity analysis indicated that there are possibilities to decrease the impacts through the following changes. By switching the main coagulant from aluminium sulphate to iron chloride to decrease the major resource depletion and human health impacts with a trade-off increase in impacts from an increased production of soda for chemical consumption. By switching the current purchase of electricity, from a green energy mix to the Swedish grid mix, to greatly improve the environmental performance of the treatment plant. This energy change was observed to result in the reduction of global warming potential from $CO_2$ emissions. Other changes which can be implemented to reduce the overall environmental impacts are switching from fuel-based transportation trucks to electric trucks and switching chemical suppliers from outside Sweden to suppliers located near or within Sweden, closer to the water treatment plant.

*Keywords:* Life cycle assessment, Water purification method, Potable water production, Microbiological barrier, Activated carbon, Sludge separation

# Preface

This thesis marks the end of my master's degree in Environmental Engineering and Sustainable Infrastructure at KTH Royal Institute of Technology. The work comprises of 30 credits and has been ongoing since the spring of 2020 on behalf of Norrvatten. It is important to note that this thesis is an academic study performed to meet the master's degree requirement at KTH. The results obtained from this LCA study are not reviewed and approved by any third-party institutions or peers as required by the ISO standard.

The master project started as a collaboration with Rahul Aggarwal, a colleague at KTH, to study the project proposition from Norrvatten. The thesis work was split between each of us to study and analyze the specific future treatment alternatives suggested by Norrvatten. This includes activities such as data collection, contemplation of the required datasets, attending supervision meetings with the university and the company. The LCA study was conducted in the SimaPro classroom version provided by KTH in their institutional labs. The results for the study were modelled and analyzed using the provided software by the two of us in two different project databases. Two separate thesis reports were submitted by each of us for the specific alternatives chosen for our study.

The SimaPro model with the selected datasets used for the selected alternatives and the flowchart model depicting the alternatives in this study were compiled in a similar manner based on the previously created datasets and flowcharts for the other alternatives selected and studied by Rahul Aggarwal in his research. Some of the datasets were changed to fit the sensitivity models and assumptions taken for this study. For such models, proxy datasets were created from the existing datasets in the Ecoinvent database.

# Acknowledgements

This thesis was written during the pandemic time of 2020, from spring till the end of the year. It was hard to not have the necessary social contact with supervisors, friends and family. There was a lot of delay in the progress of the thesis, due to the restrictions with the ongoing pandemic. But despite all the social restrictions, this thesis was successfully completed with the help of Norrvatten and KTH.

First and foremost, I would like to express my gratitude to my supervisor Göran Finnveden and my examiner Anna Björklund for their time, patience and guidance throughout the project. They were very helpful in giving me the required feedback with their expertise in Life Cycle Assessment.

I would like to thank Daniel Hellström, my supervisor at Norrvatten for offering his time, expertise and advice regarding the required information. Thanks to Jens Forslund from Ramboll and Philip McCleaf from Uppsala Vatten och Avfall for offering their time in answering my questions through email which helped to clarify my doubts.

A special thanks to my friend Tejas LK, a fellow colleague from KTH for his immense support by patiently helping me with the complex calculations required for the project. I also appreciate the moral support from my close friends, Ashish Guhan Baskar, Araavind Sridhar, Vinoth Kumar Ponnusamy and my family throughout the hectic duration of the project. I am very much grateful to have you all around me.

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# General Abbreviations

| | |
|---|---|
| MLD | Millions of Liters per Day |
| WTP | Water Treatment Plant |
| SFA | Swedish Food Agency |
| GLO | Global dataset |
| RER | Rest of Europe dataset |
| CH | Switzerland dataset |
| GWP | Global Warming Potential |
| LCA | Life Cycle Assessment |
| LCIA | Life Cycle Impact Assessment |
| LCI | Life Cycle Inventory |
| ISO | International Organization for Standardization |
| ALG | Aluminium Sulphate |
| PIX-111 | Iron Chloride |
| pH | Potential of Hydrogen |
| CEB | Chemical Enhanced Backwashing |
| CIP | Cleaning in Place |
| $NH_2Cl$ | Ammonium Chloride or Monochloramine |
| NaOCl | Sodium Hypochlorite |
| HCl | Hydrochloric Acid |
| $H_2SO_4$ | Sulphuric Acid |
| $(NH_4)_2SO_4$ | Ammonium Sulphate |
| NF | Nanofiltration |
| UF | Ultrafiltration |
| SF | Sand Filtration |
| $O_3$ | Ozone |
| BAC | Biological Activated Carbon |
| GAC | Granular Activated Carbon |
| PAC | Powder Activated Carbon |

| | |
|---|---|
| UV | Ultraviolet disinfection |
| NOM | Natural Organic Matter |
| PES | Polyethersulfone |
| PVP | Polyvinylpyrrolidone |
| PFAS | Polyfluoroalkyl substances |
| $CO_2$ | Carbon dioxide |
| kg 1.4-DB eq. | Kilogram of dichlorobenzene equivalent |
| kg CFC-11 eq. | Kilogram of trichlorofluoromethane equivalent |
| kg. $CO_2$ eq. | Kilogram of carbon dioxide equivalent |
| kg $PM_{2.5}$ eq. | Kilogram of fine particles (diameter less than 2.5 micrometers) |
| kg $PO_4$ eq. | Kilogram of phosphate equivalent |
| kg $SO_2$ eq. | Kilogram of sulphur dioxide equivalent |
| kBq CO-60 eq. | Kilobecquerel of cobalt-60 equivalent |
| kg NOx eq. | Kilogram of nitrogen oxides equivalent |
| kg P eq. | Kilogram of phosphorus equivalent |
| kg N eq. | Kilogram of nitrogen equivalent |
| kg Cu eq. | Kilogram of copper equivalent |
| kg oil eq. | Kilogram of oil equivalent |

# Abbreviations used in Calculation

| | |
|---|---|
| cm | Centimeter |
| m | Meter |
| km | Kilometer |
| $m^2$ | Area in meter (Square meter) |
| $m^3$ | Volume in meter (Cubic meter) |
| $m^3/d$ | Cubic meter per day |
| h | hour |
| d | day |
| y | year |
| mg | Milligram |
| g | Gram |
| kg | Kilogram |
| $g/m^3$ | Gram per cubic meter |
| g/ml | Gram per milliliter |
| t | Ton |
| t/y | Ton per year |
| $t/m^3$ | Ton per cubic meter |
| tkm | Ton kilometer |
| $J/m^2$ | Joules per square meter |
| l | Liter |
| l/y | Liter per year |
| ml | Milliliter |
| kW | Kilowatts |
| MW | Megawatts |
| kWh | Kilowatt hour |
| kWh/y | Kilowatt hour per year |
| MWh | Megawatt hour |
| MWh/y | Megawatt hour per year |

| | |
|---|---|
| GWh | Gigawatt hour |
| GWh/y | Gigawatt hour per year |
| nm | Nanometer |
| p | Part or Piece |
| % | Percentage |
| μ | Micro |

# 1. Introduction

Norrvatten is a municipal association responsible for providing drinking water to consumers from its municipality and the other 14 associated member municipalities. It has its own waterwork, Görvälnverket located near Lake Mälaren in Järfälla municipality capable of supplying a maximum of 200,000 cubic meter of drinking water per day (Heldt, 2019).

The region around lake Mälaren was identified by RUS Uppsala to be one of the fastest growing regions in Europe. In the year 2019, there was a population of 3 million around the area and it is estimated to increase to 5 million by the year 2050. The population density in Stockholm county is expected to increase by 25% by the year 2050 and by 45% by the year 2060 (Hansson et al., 2019). Norrvatten has to expand the waterwork to fit the need of drinking water for the increased population in the associated municipalities.

The intake of raw water for the purification is taken from the nearby Lake Mälaren. The raw water quality from the lake is subject to change due to different seasons, climatic conditions and population increase (Ejhed, 2020). According to Hansson et al., (2019) from IVL, it is recommended to have new water treatment methods in the WTP to purify the water for drinking. Current purification processes in Norrvatten's WTP are not adapted to the challenges of the future to meet the required water quality standards.

Another challenge for Norrvatten is to improve the Natural Organic Matter (NOM) removal rate in the water from the treatment steps taken in WTP. Pilot trials are being undertaken to test new innovations in the treatment of water with ozone, carbon filters, Ultrafilters (UF), Nanofilters (NF) and ion exchange processes. The microbiological and chemical parameters in the WTP need to be expanded in order to guarantee the provision of safe drinking water which meets the standard set by the Swedish Food Agency (SFA) and EU directive (Heldt, 2019).

To address these pressing issues of drinking water meeting the potable quality targets and due to the wake of a global climate crisis, Norrvatten has to act quickly and strongly. So, to fulfil the estimated future plant capacity and water quality demands till the year 2050, nine different water treatment alternatives are proposed and investigated by Norrvatten. This has been done by commissioning four different consulting firms to do the required investigations and pilot trials, to collect data and do a feasibility check. The proposed new process solution will result in the creation of new infrastructures or expansion of the current infrastructure in Görvälnverket to meet the demand by the potential future alternative. In this study, out of the nine suggested alternatives, three alternatives are selected and studied using a cradle-to-gate life cycle perspective methodology to assess the potential environmental impacts from the selected alternatives.

Life Cycle Assessment is a process which helps to understand and evaluate the potential environmental impacts associated with a product throughout its entire life cycle from raw material extraction & processing, manufacturing, transportation & distribution, reuse and final disposal (Zbicinski et al., 2006). The LCA for this study does not take into account the distribution, reuse and disposal of the product under consideration making it a Cradle-to-gate assessment instead. Potential hotspots can be identified from the results of the study which can help to aid in the future decision-making procedure for the selection of the alternative to be implemented in Norrvatten's WTP.

## 1.1 Aim and objectives

The aim of this study is to perform a cradle-to-gate LCA assessment on three of the nine different alternatives, proposed for the future by Norrvatten municipal association for their water treatment plant, Görvälnverket. The study would be conducted to evaluate the potential carbon emissions and other significant environmental impacts related to the specific alternatives in their operational phase.

The objectives of the research study are as follows:

- To conduct stand-alone assessments of the specific alternatives to identify their significant environmental impacts.
- To conduct comparative assessments of the specific alternatives within themselves and to the current existing water treatment plant.
- To conduct sensitivity assessments by modifying the alternatives with a different coagulant and electricity mix to analyze how the environmental impacts may vary.
- To propose suggestions and recommendations on how to optimize/select the alternatives for the future.

## 1.2 Delimitations

The alternatives proposed for the water treatment plant (WTP) in this study are modelled and based on values which are estimated for a future water quality in Lake Mälaren, based on a future climatic change in the year 2050. The climate change for the future is uncertain and hence the provided data is subject to change. The result of the study may therefore be a near or reasonable approximation for the alternatives suggested for the future.

The suggested alternatives were still in their pilot phase of being tested at the time of commencement of this LCA study. The inventory data used for the use phase of the water treatment plant for the study were based on previously available data for similar alternatives proposed earlier for the same water treatment plant. Hence, modelling of the alternatives in their use phase on a real time occurring event was not possible. An exact estimation for the final water quality is not provided at start of this study, due to the previous reason (still in pilot trials), and hence it is assumed that the water quality at the end of all the future alternatives is acceptable according to the required standards based on the assurances from the parent authority. The inventory datasets from SimaPro are for an older machinery/manufacturing technology than the required technology for the future year of 2050. The future alternatives are modelled with relevant assumptions to replicate the actual intended working of the WTP in the future.

## 1.3 Disposition

The structure of the thesis is presented as the following. In chapter 1, a brief introduction is given on the water treatment plant managed by Norrvatten municipal association, the challenges faced by them, and proposition made by them for the future regarding the drinking water quality. Chapter 2 provides a background for the corresponding study regarding the various purification processes with their respective unit processes involved within. The chapter also entails the previous impact assessment studies conducted on water treatment plants. Chapter 3 provides the necessary details regarding the life cycle approach adopted for the study i.e., the goal and scope of LCA, assumptions, limitations, cut-off criteria, allocation procedure, impact assessment method and the life cycle inventory for all the mentioned alternatives. The life cycle impact assessment and a sensitivity analysis for all the alternatives, followed with the interpretation of the simulated models, the uncertainties linked to the results, recommendations for the future work and a final discussion will be presented in chapter 4. Chapter 5 would present the conclusion of the conducted LCA study. All the other supplementary information for the study is provided in the Appendix section at the end for reference.

# 2. Background

The following chapters will provide a background of the various unit processes involved in the WTP, the proposed alternatives for the year 2050, previous impact assessment studies conducted for a WTP. Other supplementary background information like the history of Norrvatten and its WTP, the water quality in lake Mälaren which supplies the raw water for the WTP, the current purification process in Görvälnverket are included in Appendix 1 for reference. Appendix 1 also includes the background information for the adopted LCA methodology for this study.

## 2.1 Unit Processes Involved in the WTP

There are various treatment methods proposed to be implemented in the WTP. This chapter will provide a brief description on the various unit processes involved, their function, estimated water loss (if any) and their energy consumption in the WTP.

### 2.1.1 Micro-screen

Micro-screens are initial filters shaped like basket belt strainers which are used to reduce the zooplanktons from the raw water intake (Forsberg, 2019). According to Forsberg (2019), an 80% reduction of zooplankton can be achieved during micro-screening. A strainer with a mesh size of 250 µm was assessed to be suitable for Görvälnverket by Ramboll. There is an estimated 1% water loss from this process (Lindgren, 2020) according to Ramboll. This water is washed back to Lake Mälaren (Lindgren, 2020). The pumping of raw water to the micro-screen has an energy consumption of 1.8 GWh per year. The micro-screen has an energy consumption of 0.1 GWh per year. (Forslund, personal communication, 2020).

### 2.1.2 Flocculation

Flocculation is a process where a chemical coagulant is added to the water to aid in bonding between the particles, which creates larger aggregates for easier separation. Coagulation and flocculation are used in the treatment process to separate the suspended solids from the raw water. A flocculation chamber follows the micro-screen, where the main coagulant is added for chemical precipitation (Forsberg, 2019). The water is led to five different flocking lines parallel to each other. After addition of the main coagulant, activated sulphuric acid is added for aiding flocculation in the first chamber of the respective flocking line. Both ALG and PIX-111 are considered to be used as the main coagulant in the future alternatives by Norrvatten (Lindgren, 2020).

### 2.1.3 Sedimentation & Lamellar Separation

After flocculation, the water is led to the sedimentation basin consisting of nine basins parallel to each other (Forsberg, 2019). An auxiliary coagulant called activated silica is added to aid in making the flocks bigger. These bigger flocks can settle well in the sedimentation basins. According to Forsberg (2019), a 90% reduction of zooplankton can be achieved during flocculation and sedimentation. Lamellar separation was selected to be one of the unit process over Floatation process by Ramboll (Forsberg, 2019). Lamellar separation tank follows the sedimentation tank, where the sedimented sludge is removed through lamellar modules. The sediments from lamellar modules go to the sludge separation chamber where they require polymer for thickening the sludge (Forsberg, 2019). The energy consumption for sedimentation followed by Lamellar separation is 0.4 GWh per year (Forslund, personal communication, 2020).

### 2.1.4 Sand filtration (SF)

After sedimentation, the water is led to 18 different sand filters parallel to each other. The sand filters act as a gravity filter where the water is filtered through coarse sand to remove the particles and impurities. The impurities in the sand are backwashed once a day and the backwash of water is led to the sludge tank for treatment. The water loss from the sand filters is reported to be 5.4% by Ramboll (Lindgren, 2020). The energy consumption by the sand filters is 0.4 GWh per year (Forslund, personal communication, 2020).

### 2.1.5 Ultrafiltration (UF)

Ultrafiltration is a membrane filtration process used to remove particulates and macromolecules in water through a semipermeable membrane. The proposed UF filter to be used in the future is from Pentair X-flow, named XIGA (Forsberg, 2019). The UF pumps placed before the UF filter units, pump the water to the filters for treatment. There are a total of 27 filter units for a total of 27 filter pumps. Each filter unit has an attached peripheral equipment to perform a chemical cleaning without dismantling the unit. This cleaning process is called Chemical Enhanced Backwashing (CEB) (Lindgren, 2020). The water for backwash is taken from an intermediate reservoir and this results in a water loss of 5.5 or 5.6% depending on the filter equipment used in the proposed alternatives (See ***Table 24*** for more details). The energy consumption by the UF filter unit is 0.05 kWh per cubic meter of permeate flow (Pentair, 2019).

### 2.1.6 Nanofiltration (NF)

Nanofiltration is a membrane filtration process used to remove particulates and nanometer sized molecules in water through a semipermeable membrane. The proposed NF filter to be used in the future is from Pentair X-flow, named HFW1000 (Pentair, 2019). Each NF filter unit, same as the UF filter unit, has an attached peripheral equipment to perform a chemical cleaning without dismantling the unit (Lindgren, 2020). The water for backwash is taken from an intermediate reservoir and this results in a water loss of 7% or 8% depending on the filter equipment used in the proposed alternatives (See ***Table 24*** for more details). In the NF process, there is an initial rejection of water with concentrate which is sent back to the lake, unlike an UF membrane (Norrvatten, 2019b). This concentrate flow is 17% or 25% depending on the type of NF filter unit. The energy consumption by the NF filter units are either 0.29 or 0.3 kWh per cubic meter of permeate flow (Pentair, 2019) depending on the used filter unit for the specific future alternative.

### 2.1.7 Ozonation

Liquid ozone is prepared in an ozone generator onsite for the ozonation process. This prepared ozone is unstable in nature and is added to disinfect the water of its odor and taste. This disinfection process is called as ozonation. The ozone generator is placed outside the chemical terminal. The chemical terminal is the contact tank where the ozone is dosed with water to disinfect it. There are a total of 9 ozone generators for 9 contact tanks (Lindgren, 2020). The energy consumption for generating and dosing ozone is 1.5 GWh per year (Forslund, personal communication, 2020).

### 2.1.8 GAC filtration

Activated carbons in granular forms are used as filters to remove the contaminants. The carbons have a high adsorption potential to remove Polyfluoroalkyl substances (PFAS) from the water. The activated carbons are reactivated after they become saturated to get back the efficient filtration potential (Mimna, 2020). Reactivation of GAC is done in Norrvatten instead of buying more activated carbons. The carbons with the filtered sediments need a backwash with water to remove the contaminants. The estimated water loss is an average value of 1.5% reported by Ramboll (Lindgren, 2020). In the study conducted by Ramboll, Carbon filters preceded by Ozone are called Biological Activated Carbon (BAC) (Forsberg, 2019). With BAC, an increased reduction of the contaminants can be achieved from 95 to 100% compared to GAC where it is >90%. (Lindgren, 2020) There is no energy consumption for GAC/BAC (Forslund, personal communication, 2020).

## 2.1.9 UV disinfection

UV disinfection is the process where ultraviolet rays are used to disinfect the water before distribution. In Görvälnverket, the drinking water is treated with UV to inactivate any germs in the water before distribution. This disinfection is after GAC filtration where most of the remaining contaminants are removed. The energy consumption by the UV unit is 0.55 GWh per year (Norrvatten, 2019a).

## 2.1.10 Sludge separation

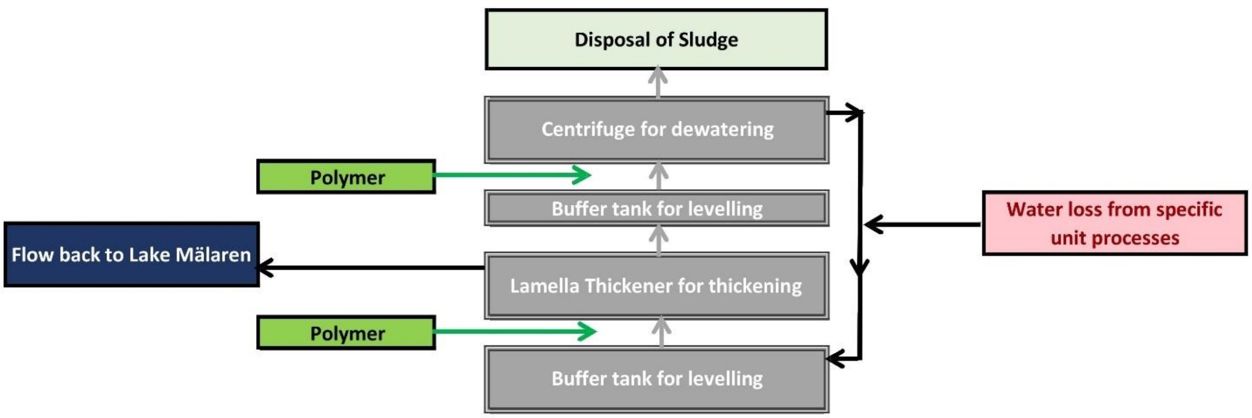


**Figure 1:** A basic flow diagram representing the sludge separation in the WTP.

Management of the produced sludge is performed in all the alternatives in a separate building. Sludge collection and management can differ for different alternatives. The sludge separation tank (See ***Figure 1*** above) includes two buffer tanks for levelling the sludge, a lamella thickener for thickening the sludge and two centrifuges at the end for dewatering the sludge. Polymer is dosed after each of the buffer tanks, one for thickening and one for dewatering. After the lamella thickener, the water with removed sludge is sent back to lake Mälaren. After the final sludge is dewatered from the centrifuge, the removed water is sent back to the initial buffer tank. The sludge is separated at each stage in the sludge tank until 18% of the total solid content is removed after the centrifuge (Lindgren, 2020). See ***Table 25*** in Appendix 6 for more details on the sludge separation. The energy consumption for handling the sludge is 1.7 GWh per year (Forslund, personal communication, 2020).

## 2.2 Proposed future alternatives and existing treatment process in the WTP

The following chapters deal with the description of the various water treatment alternatives considered for the study. These alternatives form the basis for the stand-alone and comparative assessment to be conducted for this study.

The selected process solutions for this study are named Alternatives 7, 8 & 9 and are suggested amongst the other alternatives (See ***Figure 51***) for the future year 2050 by Norrvatten based on investigations and recommendations from Ramboll. These selected future alternatives are modified versions of the previous alternatives, N1, N2 and N3 investigated earlier by Norrvatten (See ***Table 23*** in Appendix 6). Hence an assumption is made as mentioned in chapter 2.4 that the inventory data for the future alternatives are adopted from the similar inventory data for N1, N2 and N3 after performing few calculations. Also included is the treatment process currently used in the WTP named Alternative 0 for comparison during assessment.

**Table 1:** Process solutions suggested by Norrvatten for the future year 2050.

| Alt. | Sieving + emergency chemical barrier | NOM-removal<br>μ-biological barrier | Particle removal | (NOM-removal)<br>μ-biological barrier | Chemical barrier / taste and odor<br>μ-biological barrier | μ-biological barrier | Post treatment |
|---|---|---|---|---|---|---|---|
| **7** | Micro-screen & PAC | Precipitation (ALG/PIX-111)<br>Lamella/sedimentation | SF | NF<br>UF | BAC ($O_3$ + GAC) | UV | Soda & $NH_2Cl$ |
| **8** | Micro-screen & PAC | Direct precipitation in UF (ALG/PIX-111) | | - | BAC ($O_3$ + GAC) | UV | Soda & $NH_2Cl$ |
| **9** | Micro-screen & PAC | NF without pre-treatment | | - | BAC ($O_3$ + GAC) | UV | Soda & $NH_2Cl$ |
| **0** | Micro-screen & PAC | Precipitation (ALG)<br>Lamella/sedimentation | SF | - | GAC | UV | Lime & $NH_2Cl$ |

(Light purple indicates unit processes in the new infrastructure after waterwork expansion
Dark purple indicates unit processes in the old infrastructure)

These process solutions were developed by Norrvatten and investigated by Ramboll to provide the data regarding the water intake, water loss, chemical consumption, energy consumption, produced sludge and other concerned information. Each process solution (as seen in the above ***Table 1***) has an initial sieving process, followed by chemical and microbiological barriers and ends with a post treatment for the potable water and pipe network.

An expanded description of the treatment process will be given in the following chapters. The inventory data provided for these future alternatives are attached in Appendix 3 (Page **70**) for reference.

### 2.2.1 Alternative 0

Alternative 0 is indicative of the existing treatment process in the WTP to achieve an average/sustained water production of 160,000 $m^3$ per day (Lavonen, 2018, pp.9).

**Table 2:** The average and maximum capacity for the existing water treatment plant (Hellström, personal communication, 2020).

| Parameter | Drinking Water Capacity | Unit |
|---|---|---|
| Average production in 2019 | 160,000 | $m^3/d$ |
| Maximum capacity in 2019 | 200,000 | $m^3/d$ |

The process solution includes the following:

- ❑ Raw water intake from Lake Mälaren with three intake pipes at two different depths depending on the season.
- ❑ Reserve water intake from Lake Mälaren with two different intake pipes.
- ❑ Micro-sieves to remove zooplankton. There is a 1% water loss from this process back to the lake.
- ❑ Raw water pumps to control the flow of water into the consequent purification processes.
- ❑ Possibility for an emergence dosage of Powdered Activated Carbon (PAC).
- ❑ Dosage of sulphuric acid for optimizing the pH during chemical precipitation.
- ❑ Dosage of ALG for NOM separation in the mixing channel.
- ❑ Flocculation chamber to collect the flocks with NOM.
- ❑ Dosing of activated silica or sodium metasilicate as an auxiliary coagulant to make the flocks bigger.
- ❑ Lamellar separator/sedimentation to collect the concentrated NOM sediments. There is a 0.38% water loss with the collected sediments to the sludge chamber.
- ❑ Sludge separation chamber to collect and treat the sludge from the lamella chamber.
- ❑ Dosage of soda for adjusting the pH to 7.0 and the alkalization to >60 mg $HCO_3$ / l.
- ❑ Sand filter acting as a gravity filter to remove contaminants. The backwash from the sand filter (5.4%) is sent to Lake Mälaren.
- ❑ Intermediate Reservoir 1 included to collect the rinsing water from sand filtration and to provide water for chemical preparation.

- ❑ GAC filters prepared for 20 minutes for a water residence time of 12 minutes. The water loss from the filters is 1.5% of the specific intake.
- ❑ Ultraviolet radiation treatment of the water dosed with 400 J / $m^2$ of UV light.
- ❑ Intermediate reservoir 2 provided to divert water from the UV process to use as a flush water for GAC filters. It also provides water for chemical preparation.
- ❑ Dosage of Lime to adjust the final pH to 8.3.
- ❑ Dosage of Monochloramine ($NH_2Cl$) to counteract the biofilm growth in the plumbing network. This is a prerequisite for achieving the drinking water with a high biostability.
- ❑ A lower reservoir to collect the drinking water followed by distribution pumps to pump the water onto the distribution network.

See ***Figure 22*** attached in Appendix 2 for reference.

## 2.2.2 Alternative 7

Alternative 7 was designed similar to the previous alternative N2, to withstand an average/sustained water production of 208,000 $m^3$ per day in 2050 according to Ramboll.

**Table 3:** The assumed Average and maximum plant capacity for Alternative 7 in the year 2050 (Forsberg, 2019, pp.6).

| Parameter | Drinking Water Capacity | Unit |
|---|---|---|
| Average production in 2050 | 208,000 | $m^3/d$ |
| Maximum capacity in 2050 | 280,000 | $m^3/d$ |

The process solution includes the following:

- ❑ Raw water intake from Lake Mälaren with three intake pipes at two different depths depending on the season.
- ❑ Reserve water intake from Lake Mälaren with two different intake pipes.
- ❑ Micro-sieves to remove zooplankton. There is a 1% water loss from this process back to the lake.
- ❑ Raw water pumps to control the flow of water into the consequent purification processes.
- ❑ Possibility for an emergence dosage of Powdered Activated Carbon (PAC).
- ❑ Dosage of sulphuric acid for optimizing the pH during chemical precipitation.

- Dosage of ALG/PIX-111 for NOM separation in the mixing channel.
- Flocculation chamber to collect the flocks with NOM.
- Dosing of activated silica or sodium metasilicate as an auxiliary coagulant to make the flocks bigger.
- Lamellar separator/sedimentation to collect the concentrated NOM sediments. There is a 0.38% water loss with the collected sediments to the sludge chamber.
- Sludge separation chamber to collect and treat the sludge from the lamella chamber.
- Dosage of soda for adjusting the pH to 7.0 and the alkalization to >60 mg $HCO_3$ / l.
- Sand filter acting as a gravity filter to remove contaminants. The backwash from the sand filter (5.4%) is sent to the sludge tank.
- Intermediate Reservoir 1 to collect the rinsing water from sand filtration and to provide water for chemical preparation.
- An intake basin to collect the water from sand filtration.
- Ultrafiltration and Nanofiltration pumps to take in 50% of the capacity for each filtration process from the intake basin.
- The Ultrafiltration filters are backwashed with Chemicals for cleaning the filters and then sent for neutralization. The loss of water from UF to the lake is 5.6% from the specific intake.
- There is an initial concentrate flow (25%) from NF before an overall recovery, back to the lake.
- The Nanofiltration filters are backwashed with Chemicals for cleaning the filters and then sent for neutralization. The loss of water from NF to the lake is 7% from the specific intake.
- Ozone generators and contact tanks prepared for treating the water taken from both the previous filters with liquid ozone.
- Dosage of soda for adjusting the pH to 7.5 for the removal of residual iron and to optimize the pH in water for any further chemical barriers.
- GAC filters prepared for 20 minutes for a water residence time of 12 minutes. The water loss from the filters is 1.5% of the specific intake.
- Ultraviolet radiation treatment of the water dosed with 400 J / $m^2$ of UV light.

- ❏ Intermediate reservoir 2 to divert water from the UV process to use as a flush water for UF, NF and GAC filters. It also provides water for chemical preparation.
- ❏ Dosage of soda to adjust the final pH to 8.3.
- ❏ Dosage of Monochloramine ($NH_2Cl$) to counteract the biofilm growth in the plumbing network. This is a prerequisite for achieving the drinking water with a high biostability.
- ❏ A lower reservoir to collect the drinking water followed by distribution pumps to pump the water onto the distribution network.

See ***Figure 23*** attached in Appendix 2 for reference.

### 2.2.3 Alternative 8

Alternative 8 was designed similar to N3, to withstand an average/sustained water production of 208,000 $m^3$ per day in 2050 according to Ramboll.

**Table 4:** The assumed average and maximum capacity for Alternative 8 in the year 2050 (Forsberg, 2019, pp.6).

| Parameter | Drinking Water Capacity | Unit |
|---|---|---|
| Average production in 2050 | 208,000 | $m^3/d$ |
| Maximum capacity in 2050 | 280,000 | $m^3/d$ |

The process solution includes the following:

- ❏ Raw water intake from Lake Mälaren with three intake pipes at two different depths depending on the season.
- ❏ Reserve water intake from Lake Mälaren with two different intake pipes.
- ❏ Micro-sieves to remove zooplankton. There is a 1% water loss from this process back to the lake.
- ❏ Raw water pumps to control the flow of water into the consequent purification processes.
- ❏ Possibility for an emergence dosage of Powdered Activated Carbon (PAC).
- ❏ Dosage of sulphuric acid for optimizing the pH during chemical precipitation.
- ❏ Dosage of ALG/PIX-111 for NOM separation in the mixing channel.
- ❏ Flocculation chamber to collect the flocks with NOM.
- ❏ Dosage of soda for adjusting the pH to 7.0 and the alkalization to >60 mg $HCO_3$ / l.

- ❑ Ultrafiltration pump is provided to collect the water with the flocks and sediments and pump it to the UF filters.
- ❑ The Ultrafiltration filters are backwashed with Chemicals for cleaning the filters and then sent for neutralization. The loss of water from UF to the lake is 5.5% from the specific intake.
- ❑ Intermediate Reservoir 1 to collect and divert the rinsing water from Ultrafiltration onto the ozonation chamber. It also serves to provide water for chemical preparation.
- ❑ Intermediate Reservoir 2 to collect the backwash from UF to supply to the secondary UF.
- ❑ A secondary UF filter unit is provided near the sludge tank to treat and send back 85% of the treated water back to the treatment process through a distribution channel.
- ❑ A sludge separation chamber is provided after the secondary UF to treat the 15% permeate flow.
- ❑ Ozone generators and contact tanks prepared for treating the permeate water taken from UF with liquid ozone.
- ❑ Dosage of soda for adjusting the pH to 7.5 for the removal of residual iron and to optimize the pH in water for any further chemical barriers.
- ❑ GAC filters prepared for 20 minutes for a water residence time of 12 minutes. The water loss from the filters is 1.5% of the specific intake.
- ❑ Ultraviolet radiation treatment of the water dosed with 400 J / $m^2$ of UV light.
- ❑ Intermediate reservoir 3 provided to divert water from the UV process to use as a flush water for GAC filters. It also provides water for chemical preparation.
- ❑ Dosage of soda to adjust the final pH to 8.3.
- ❑ Dosage of Monochloramine ($NH_2Cl$) to counteract the biofilm growth in the plumbing network. This is a prerequisite for achieving the drinking water with a high biostability.
- ❑ A lower reservoir to collect the drinking water followed by distribution pumps to pump the water onto the distribution network.

See ***Figure 24*** attached in Appendix 2 for reference.

## 2.2.4 Alternative 9

Alternative 9 was designed similar to N1, to withstand an average/sustained water production of 208,000 $m^3$ per day in 2050 according to Ramboll.

**Table 5:** The assumed average and maximum capacity for Alternative 9 in the year 2050 (Forsberg, 2019, pp.6).

| Parameter | Drinking Water Capacity | Unit |
|---|---|---|
| Average production in 2050 | 208,000 | $m^3/d$ |
| Maximum capacity in 2050 | 280,000 | $m^3/d$ |

The process solution includes the following:

- ❑ Raw water intake from Lake Mälaren with three intake pipes at two different depths depending on the season.
- ❑ Reserve water intake from Lake Mälaren with two different intake pipes.
- ❑ Micro-sieves to remove zooplankton. There is a 1% water loss from this process back to the lake.
- ❑ Raw water pumps to control the flow of water into the consequent purification processes.
- ❑ Possibility for an emergence dosage of Powdered Activated Carbon (PAC).
- ❑ Dosage of Soda for adjusting the pH to 7.0 and the alkalization to >60 mg $HCO_3$ / l.
- ❑ A Nanofiltration pump is provided to collect the raw water and pump it to the NF filters.
- ❑ There is an initial concentrate flow (25%) from NF before an overall recovery, back to the lake.
- ❑ The Nanofiltration filters are backwashed with Chemicals for cleaning the filters and then sent for neutralization. The loss of water from NF to the lake is 8% from the specific intake.
- ❑ Intermediate Reservoir 1 to collect and divert the rinsing water from Nanofiltration onto the ozonation chamber. It also serves to provide water for chemical preparation.
- ❑ Intermediate Reservoir 2 to collect the backwash from UF to supply to the secondary UF.
- ❑ A secondary UF filter unit is provided near the sludge tank to treat and send back 85% of the treated water back to the treatment process through a distribution channel.
- ❑ A sludge separation chamber is provided after the secondary UF to treat the 15% permeate flow.
- ❑ Ozone generators and contact tanks prepared for treating the permeate water taken from UF with liquid ozone.

- ❑ Dosage of soda for adjusting the pH to 7.5 for the removal of residual iron and to optimize the pH in water for any further chemical barriers.
- ❑ GAC filters prepared for 20 minutes for a water residence time of 12 minutes. The water loss from the filters is 1.5% of the specific intake.
- ❑ Ultraviolet radiation treatment of the water dosed with 400 J / $m^2$ of UV light.
- ❑ Intermediate reservoir 3 provided to divert water from the UV process to use as a flush water for GAC filters. It also provides water for chemical preparation.
- ❑ Dosage of soda to adjust the final pH to 8.3.
- ❑ Dosage of Monochloramine ($NH_2Cl$) to counteract the biofilm growth in the plumbing network. This is a prerequisite for achieving the drinking water with a high biostability.
- ❑ A lower reservoir to collect the drinking water followed by distribution pumps to pump the water onto the distribution network.

See ***Figure 25*** attached in Appendix 2 for reference.

## 2.3 Previous Impact Assessment Studies

A few studies have been made earlier to determine the environmental impacts from the water treatment plant. The operation stage of a conventional water treatment plant is found to be the major contributor to the total environmental impacts (81 to 98%), when compared with the other stages like the construction and decommissioning of the WTP (Saad et al., 2019). Although there are GHG emissions from the WTP leading to environmental impacts, LCA research from Van der Helm (2007) reports that the environmental impacts from the operation of a drinking water treatment plant is relatively small compared to other activities like driving a car. There are a lot of studies available for wastewater treatments than water treatments because of a lower emission from water treatment plants (Jutterström, 2015).

Author Wallén (1999) in his report stated that the production of chemicals is the major hotspot for the greenhouse gas emissions in Sweden. This estimation is backed by the research from Jutterström (2015), where the author reported that chemical consumption in Norrvatten's waterwork is the major hotspot for the environmental impacts. Aluminium sulphate and slaked Lime which were used in the water treatment was found to be the major contributors to the total carbon footprint.

Other studies from outside Sweden (Presura & Robescu, 2017) have reported that a major impact on the climate is due to energy consumption contributing to GHG emissions. The energy consumed by the various equipments running 24/7 in the water treatment plant is one of the largest consumers of energy in a community and hence the biggest contributor to total GHG emissions from the said community (Presura & Robescu, 2017). Author Jutterström (2015) in her report, argued that the source of electricity which contributes to a majority of environmental impacts was found to be lower in Sweden, in case of an average Swedish electricity mix and a green energy mix. Use of a green energy like wind power generated from wind turbines instead of the grid mix will result in a 29 to 84% impact reduction in all the impact categories (Saad et al., 2019). According to the International Energy Agency (2002), use of a green energy like hydropower, will have no direct emissions of pollutants but will result in emission due to production and transportation of building materials for the hydroelectric power plant. The size and type of the used power plant will be the factors that influence the amount of emissions. $CO_2$ emissions from a concrete dam will be higher than that from a dam made from earth and rock fills (IEA, 2002).

According to Mohamed-Zine et al., (2013) in a drinking water plant, the highest environmental burdens are due to the coagulant preparation leading to depletion in mineral resources and atmospheric ozone. The pretreatment methods with a coagulant requirement upstream have a high GHG emission potential compared to the rest of the process (Mohamed-Zine et al., 2013). Aluminium sulphate which is usually the main coagulant in a conventional drinking water treatment plant is found to be the highest contributor to the mineral resource depletion. It also leads to ozone layer depletion due to tetrachloromethane emissions from aluminium sulphate production (Mohamed-Zine et al., 2013).

Authors Sombekke et al., (1997) mentioned in their report, that even though the unit process nanofiltration contributes to a higher environmental impact due to high energy consumption, more raw water intake and concentrate deposit to the surface water, it has a slight preference over conventional treatment due to a higher water quality score leading to a better human health. This analysis is supported by the research from the author Keucken (2017) where he reported that nanofiltration achieves a NOM reduction of 90% compared to conventional flocculation and sedimentation. The justification given for the use of NF in a WTP by author Sombekke et al., (1997) is to use green sourced energy for its energy consumption instead of the grid mix to reduce the environmental impacts.

According to author Keucken (2017), UF must be combined with pretreatment either with flocculation and sedimentation or direct coagulation, to achieve an efficient NOM removal. UF combined with direct coagulation requires lower chemical dosages leading to a lower sludge when compared with conventional pretreatment followed by UF where chemical dosages and sludge formation are higher.

Author Bergström (2020) from her research on the previous alternatives N2 and N1 from Norrvatten, reported that global warming was the highest contributor followed by acidification and eutrophication. Ozone depletion from the atmosphere was comparatively lower from the previous alternatives. A normalized result indicated that acidification was the highest contributor, followed by eutrophication and lastly global warming within acceptable emission level in Sweden. In her research, the parameter of chemical production showed the highest impact followed by transportation of the chemicals. Author Karlsson (2020), who also recently did an LCA research on the proposed nanofiltration process for Norrvatten, reported that NF has a very high energy consumption of 130% in comparison to the conventional treatment methods. This estimate corroborates the research by Sombekke et al., (1997) for NF as previously declared. Although there is a drastic increase in energy consumption, using NF decreases the need for upstream chemical usage which results in a lower environmental impact. Karlsson (2020) also did a sensitivity analysis, from which he reported that switching the electricity usage from a Swedish mix to a Nordic mix resulted in an even smaller carbon footprint for NF.

# 3. LIFE CYCLE ASSESSMENT OF WATER TREATMENT PLANT

This chapter will cover the goal and scope of the LCA which includes functional unit taken for the system, system boundaries, cut-off criteria, assumptions and other limitations, followed by the chosen Impact assessment method and the Life Cycle Inventory for this study. The background for the LCA methodology with the incorporated steps for this study is provided in Appendix 1 (page **58**) for reference.

## 3.1 Goal and Scope Definition

The goal of the study is to conduct an attributional life cycle assessment (ALCA) to identify and evaluate the potential environmental impacts of the WTP, with different future alternatives consisting of various water treatment processes. To get a different perspective on the environmental burdens, the future alternatives are also compared with each other and with the current existing WTP in Görvälnverket. The results obtained from the study is to serve Norrvatten's future decision making for implementing the proper alternative instead of the current existing treatment process in order to meet the future water treatment requirement in the year 2050.

Norrvatten has stated that their objective is to find the emissions from the proposed alternatives related to Global Warming Potential (GWP) to make appropriate improvements to the existing WTP. Hence, this assessment is also to inform Norrvatten on how to improve the treatment process with change in key inputs like electricity, chemical or the mode of transport to limit the global warming potential. Apart from GWP, several other impact categories are also selected and used to analyze the alternatives to aid as supplementary information for Norrvatten's decision making.

Additionally, a sensitivity analysis will also be done to analyze how the environmental impacts change with a different input for the key elements in the study, like chemical usage and electricity consumption. These results are compared with the base results to estimate the impact change and this also has the potential to aid in the decision making for Norrvatten.

### 3.1.1 Functional unit

The reference measure to which the environmental burdens are expressed is called the functional unit. The functional unit used as a calculation base for this study is 1 $m^3$ of produced drinking water. The stated drinking water is in reference to the water which has been purified at the Norrvatten waterwork. The water distributed to the consumers in the associated municipalities is not within the scope of this functional unit.

All requirements and conditions are considered for satisfying the functional unit of 1 $m^3$ of purified drinking water with respect to the water quality. In Sweden, all drinking water must meet the requirement according to the SFA (Wallén, 1999). In this study, all the treatment measures necessary to meet the standard are included in the form of the required treatment process/chemical.

### 3.1.2 System Boundary

The system boundary for drinking water production by Norrvatten is limited to just the operational phase in the water treatment plant, from the raw water intake from lake Mälaren to the production of 1 $m^3$ of drinking water before its distribution to the associated municipalities through the distributional pipes. The system does not include the distribution of the water to the consumer including construction & decommissioning of the water treatment plant. For all the future alternatives and the existing water treatment, the same system boundaries are taken as they are all limited to the same water treatment plant. The expansion of the WTP infrastructure and the drinking water network to fit the future alternatives is not included in this study.

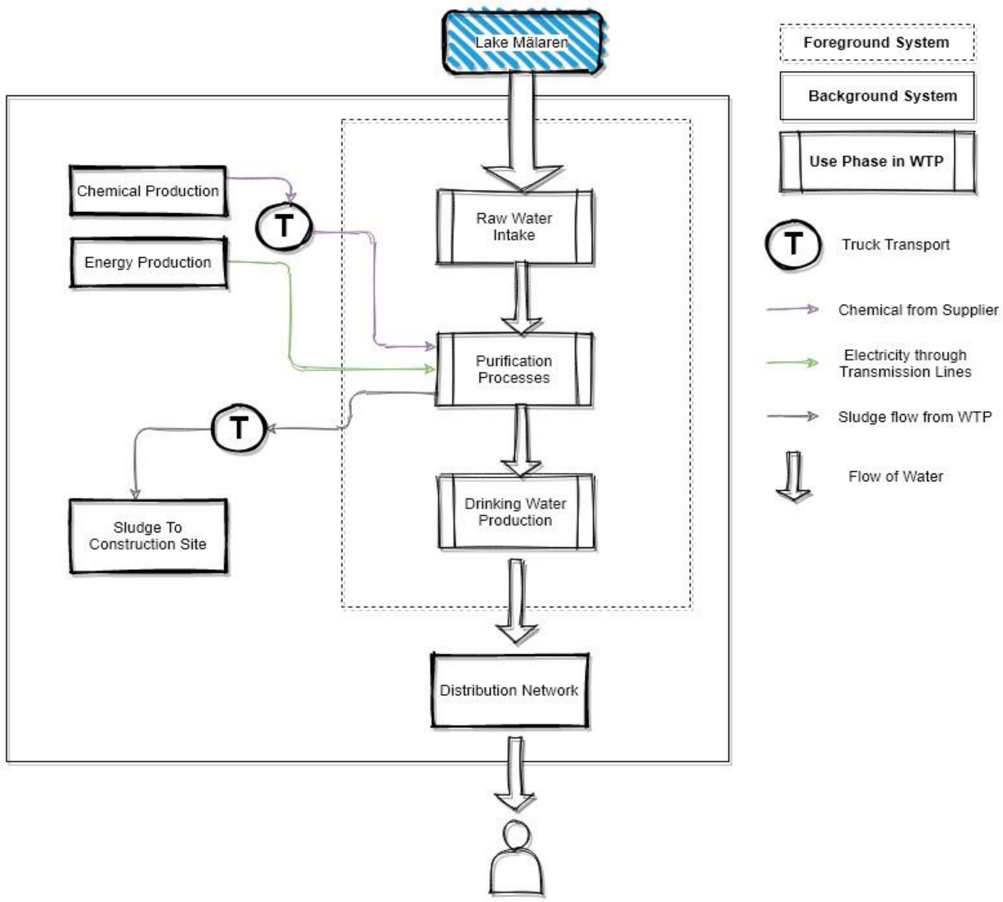


**Figure 2:** Basic flow chart indicating the system boundary considered for the LCA study. The foreground and background system boundaries for the LCA study has been marked in the diagram.

## Foreground System

The foreground system (see ***Figure 2*** above) consists of the system boundaries which can be controlled and affected by the decision maker (Curran, 2015), which in this case is the municipality of Norrvatten. This involves the intake of raw water from lake Mälaren, the treatment process using unit processes inside the water treatment plant and the final production of 1 $m^3$ of drinking water before distribution of the purified drinking water to the consumers. The intake pumps, treatment processes and distribution pumps are all managed by Norrvatten in their own waterwork, Görvälnverket. In the use phase, the water is purified by various unit processes like micro-screening, flocculation, sedimentation, sand filtration, nanofiltration, ultrafiltration, filtration through activated carbon, ozonation, UV disinfection and sludge treatment. The chemical and energy requirements needed per unit process are also taken into consideration in the use phase of the WTP. The foreground system boundary ends before the distribution network to consumers which satisfies the cradle-to-gate criteria.

### Background System

The background system (see ***Figure 2*** above) consists of the system boundaries which lie outside the ownership and responsibility (Curran, 2015) of Norrvatten. The background system in this study involves the production of the required chemicals and energy, transportation of the chemicals and the energy to the site through trucks and transmission lines respectively, and the transportation required for the disposal of the sludge from the WTP to the construction site. The background system ends by incorporating the final pumping required for the distribution of the water to the consumers. In Norrvatten, the drinking water network is composed of several different pipes which also requires treatment with chemicals before distribution. These chemicals are also added within the boundaries.

## 3.1.3 Geographical Boundary

The use phase of the water treatment plant taken for the study is set within the geographical area of Stockholm in Sweden. The background system however involves the production and transportation of the chemicals and sludge from/to locations outside Sweden. Depending on the nature of the emissions, the environmental impact can take place at both the global level and a local level. All the levels have been included in this study to analyze the emissions.

Global (GLO), Rest of Europe (RER) and Switzerland (CH) datasets from SimaPro are used in this study to represent the region/country specific data which are unavailable in the Ecoinvent database (Wernet et al., 2016). Activities occurring in the specific geographic areas inside/outside Sweden for the chemical and energy production, transportation of chemicals and energy to the WTP and the transportation of the sludge from the WTP are associated with these available datasets instead to account for uncertainty. The closest dataset with a low degree of uncertainty is RER which is linked with the European region where every activity in the study is based on.

## 3.1.4 Time Horizon

The time horizon taken for this specific study is limited to the use phase of the WTP, with the proposed alternative to create a sustained drinking water capacity per day. The water treatment plant which has a lifetime of 50 years is assumed to be the temporal horizon for this study to assess the environmental impacts. The study is intended to apply the usage of the WTP until the year 2050. Any technological developments made within those years can lead to major changes in the environmental impacts and hence the actual temporal validity of the study is quite difficult to predict (Bergström, 2020). The uncertain change in water quality in the lake and the drinking water quality requirements are also factors that can affect the temporal validity of the study (Bergström, 2020).

The various processes and materials modelled in SimaPro have a certain time period and are dependent on the data provided in Ecoinvent database v3.5. The data representing a time period from 2020-2050 were preferred for this study as the future WTP is proposed to be designed to meet the requirements for the year 2050. Most of the data taken for this study were from an older time period of 2015-2018. Older datasets in SimaPro have been extrapolated by PreConsultants to make them valid until the year 2018 in most cases. One such example is the Raw Sewage Sludge dataset, which was extrapolated and made valid until 2018 from the initial year 2013 after adjusting for uncertainties (Ecoinvent, 2013). The older datasets have been taken with an assumption that there is no major technological improvement to the unit processes, manufacturing and transportation of chemicals and energy. If such innovations are made in recent years, this may result in a reduced environmental impact to a high extent. Since technology becomes more efficient with time, using these older datasets might result in an overestimation of the environmental impacts in a few cases of the study.

## 3.2 Assumptions and Limitations

The following points are the assumptions taken for the study when there is lack of data or to limit the uncertainty.

- Water loss percentage for each unit process per the maximum production of drinking water is the same for the average production of drinking water.
- The chemical and energy requirements for Alternative 7, 8 and 9 are the same as the previous Alternatives N2, N3 and N1 suggested by Norrvatten, respectively.
- The secondary UF near the sludge tank in Alternatives 7 and 9 is the same UF unit as taken for the future Alternatives 7.
- The sludge properties for the previous alternative N2 from Norrvatten report is assumed to be the constant sludge property for all the alternatives including the existing WTP. It is also the same for ALG/PIX-111 utilization.
- Energy requirement for Lime dosage is similar to the reported energy requirement of soda dosage in existing WTP.
- Energy requirement for NF from the Intermediate reservoir is assumed to be similar to the energy requirement taken for SF and UF.
- The Sulphuric acid and Ammonium sulphate doses in a solution state of 96% and 13% is assumed to be in 100% solution state.
- A 100% Hydropower electricity usage purchased from Vattenfall is split 40% from Reservoir, 30% from Flow-by-water and 30% from pumped storage.
- The extrapolated dataset for the Swedish energy mix in SimaPro is assumed to have the same percentage of the included energy sources as mentioned in the studied literature.
- Direct precipitation in ultrafiltration has the same coagulant usage as ultrafiltration with pre-treatment, except the usage of the auxiliary coagulant activated silica.
- 100% of the activated carbons are reactivated after their saturation in the use phase of the WTP.
- The technology used in the WTP unit processes, chemical & energy production, and type of transportation used are similar to the technology used in the selected Ecoinvent datasets in SimaPro.
- EURO-6 standard trucks are utilized for transporting the chemicals from supplier to site.
- The probability for any unexpected leaks, malfunctions or other disruptions by human labor in the WTP is not considered.
- Each water treatment process alternative is able to achieve an acceptable level of drinking water quality requirement, according to SFA, at the end before distribution.

## 3.3 Cut-off Criteria

The following points are excluded from the study.

- Powdered Activated Carbon (PAC) usage in the WTP is neglected due to its utilization only in emergency situations.
- The production and usage of sand in the sand filters is neglected due to lack of data regarding the type and amount of sand used within the WTP.
- The chemicals taken in granular form are considered as they are for impact assessment. The preparation of the granules into a solution state is not considered as there was a lack of data on the exact preparation.
- The neutralization and disposal of hazardous waste from CEB is neglected due to lack of data.
- The transports made by WTP employees and other staff to and from the workplace is not included in this study.

## 3.4 Allocation Procedure

Allocation is the division of environmental burdens of a product in a system, which fulfills two or more functions. In case of multi-input/output, the total emission should be attributed to each of the specific products (Zbicinski et al., 2006). In this study, a closed-loop allocation method is used to attribute the burden from Activated Carbon usage. A closed-loop allocation applies to an open-loop allocation where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of a secondary material replaces the use of the primary material (Goedkoop et al, 2016). In this study, activated carbon is the only material which needs an allocation procedure. Once the granular carbon is saturated or the treatment objective is reached, the carbon can be recycled for reuse by thermal reactivation (Chemviron, 2010). The re-usage of activated carbon has helped to avoid the initial burden from production of the activated carbon. Only the environmental impact from the reactivation of carbon is considered. This reuse of carbon will be considered by SimaPro as being recycled in a closed loop model. 100% of the Carbon is reused after reactivation in the system and they are appropriately allocated inside the system to be modelled with SimaPro.

## 3.5 Impact Assessment Method

This LCA study is carried out using the software SimaPro 9.0.0.47 with Ecoinvent v3.5 database. A priority is given for an LCA assessment of characterization results at mid-point level in SimaPro and hence the method Midpoint 2016 ReCipe (H) V1.03 is selected from the software for the purpose of LCIA. For a selected number of impact categories, ReCipe 2016 offers the characterization factors at both midpoint and endpoint level in the cause-effect chain (environmental mechanism) (Bare et al., 2000 as cited in Mujkic & Kesavan, 2020). The main impact categories selected for this study are Global Warming, Stratospheric Ozone Depletion, Ionizing Radiation, Fine Particulate Matter Formation, Ozone Formation - Terrestrial Ecosystem, Ozone Formation - Human Health, Freshwater Eutrophication, Terrestrial Acidification, Marine Eutrophication, Terrestrial Ecotoxicity, Freshwater Ecotoxicity, Marine Ecotoxicity, Human Carcinogenic Toxicity, Mineral Resource Scarcity and Fossil Resource Scarcity. A brief assessment of the normalized results is given for reference in Appendix 5. Weighting and Grouping are neglected from consideration. To assess whether the selected alternative performs better or worse with altered input parameters, a sensitivity analysis is performed at the end.

**Table 6:** The structure of impact categories in ReCipe Midpoint (H) (Source: Golsteijn, 2017).

| Midpoint Impact Category | Area of effect | Damage indication | Unit |
|---|---|---|---|
| Global Warming | Human Health & Ecosystem | Increase in Malnutrition | kg $CO_2$ eq |
| Stratospheric Ozone Depletion | Human Health | Increase in various types of cancer & other types of diseases | kg $CFC_{11}$ eq |
| Ionizing Radiation | Human Health | Increase in various types of cancer & other types of diseases | kBq CO-60 eq |
| Ozone Formation (Human Health) | Human Health | Increase in respiratory diseases | kg NOx eq |
| Fine Particulate Matter Formation | Human Health | Increase in respiratory diseases | kg $PM_{2.5}$ eq |
| Ozone Formation (Terrestrial Ecosystem) | Ecosystem | Damage to terrestrial species | kg $NO_x$ eq |

| | | | |
|---|---|---|---|
| Terrestrial Acidification | Ecosystem | Damage to terrestrial species | kg $SO_2$ eq |
| Freshwater Eutrophication | Ecosystem | Damage to freshwater species | kg P eq |
| Marine Eutrophication | Ecosystem | Damage to marine species | kg N eq |
| Terrestrial Ecotoxicity | Ecosystem | Damage to terrestrial species | kg 1,4-DCB |
| Freshwater Ecotoxicity | Ecosystem | Damage to freshwater species | kg 1,4-DCB |
| Marine Ecotoxicity | Ecosystem | Damage to marine species | kg 1,4-DCB |
| Human Carcinogenic Toxicity | Human Health | Increase in various types of cancer | kg 1,4-DCB |
| **Human Non-carcinogenic Toxicity** | Human Health | Increase in other diseases/causes | kg 1,4-DCB |
| **Land Use** | Ecosystem | Damage to terrestrial species | m2a crop eq |
| Mineral Resource Scarcity | Resource Availability | Increase in extraction costs | kg Cu eq |
| Fossil Resource Scarcity | Resource Availability | Increase in extraction costs | kg oil eq |
| **Water Consumption** | Human Health & Ecosystem | Increase in malnutrition | $m^3$ |

*(The colour coded impact categories are neglected from the study)

There are a few impact categories which are neglected from the study (see in above ***Table 6***). **Water Consumption** which seems to be a major indicator to this study is neglected because the impact of water intake from Lake Mälaren is considered to be very low as the lake is reported to be one of the largest lakes in Sweden. The lake is reported by Bergström (2015) to have had a risk of flooding due to very high inflow. The lake is mostly always saturated, and it can be assumed that the environmental impact towards the consumption of water from the lake is negligible for the study. **Land Use** is neglected as there is no agricultural need for extraction of materials (Matilda et al, 2011) and also because the associated infrastructures from the waterwork which can account for land use is also not a major focus in this study. Out of the two human health indicators to assess the damage to human health by cancer or non-cancerous diseases, the minor one is neglected, which is **Human Non-carcinogenic Toxicity**.

Norrvatten's objective from this study is to mainly analyze & evaluate the environmental burden of the WTP with the global warming potential. Other selected impact categories are also calculated and analyzed in addition to assess the potential environmental burdens from the WTP. This will act as supplementary information to Norrvatten to aid them in their decision making for a future potential selection of the proposed alternatives.

## 3.6 Life Cycle Inventory for the main study

This chapter will cover the LCA inventory required for the operation of the Alternatives in the main LCA study. The inventory is divided into chemicals, energy and transport requirements for the use phase of the WTP. The provided data are taken from the previous alternatives suggested by Norrvatten. All these inventory data are described with the details on where they are utilized in the use phase of the system. Details regarding the calculations and the inventory datasets used in the study are attached in the Appendix 7 (page **120**) and Appendix 3 (page **70**), respectively for reference.

### 3.6.1 Chemicals

The description of the chemicals required for all the future alternatives and the existing WTP and the selected Ecoinvent dataset for entry in SimaPro is included in this chapter. The information regarding the exact chemical inventory data taken in the system for assessment is given from ***Table 8*** to ***Table 10*** in Appendix 3. The information regarding the supplier for the chemicals is provided in ***Table 11*** in the same appendix.

#### Aluminium Sulphate (ALG)

Aluminium sulphate is used as the main coagulant in the precipitation process. The main coagulant will help to separate Natural Organic Matter (NOM) from the raw water. It is produced as a powder in its anhydrous form (Bergström, 2020). The data used in SimaPro is for the production of *Aluminium sulphate (RER)* (Ecoinvent, 2013).

#### Activated Silica

Activated silica is an auxiliary coagulant which helps to make the flocks with NOM bigger in the flocculation chamber. This helps to better settle them in the sedimentation tank which follows flocculation. Activated silica is prepared with sodium metasilicate and then activated by ammonium sulphate and water (Lindgren, 2020). From SimaPro, the Ecoinvent dataset selected for Activated silica production is *Activated silica (GLO)* (Ecoinvent, 2013).

#### Sulphuric acid

Sulphuric acid in a solution state of 96% is added in the precipitation chamber for optimizing the pH in the initial intake of raw water. It is also added during Chemical Enhanced Backwashing (CEB) of the UF and NF filters (Lindgren, 2020). The Ecoinvent dataset selected in SimaPro is the production of *Sulphuric acid (RER)* (Ecoinvent, 2013). The dataset selected is for a 100% solution state of sulphuric acid and is assumed to be the case for this study.

#### Lime

Lime dosage is given at the end of the process before monochloramine to adjust the alkalization / pH in the water and prevent corrosion in the pipe network. Dosing the treated water with Lime is the current employed means of optimizing the final pH in the WTP. Lime is cheaper, but its preparation is quite cumbersome (Hellström, personal communication, 2020) compared to Soda, an alternative to adjust the pH. In case of Lime, the calcium from it has a potential risk of depositing on the UF/NF membranes and on the activated carbon. SFA has recommended that calcium must lie over 20mg/l in water from a corrosion point of view (Forsberg, 2019). The selected Ecoinvent dataset from SimaPro is production of *Quicklime, milled, loose (CH)* (Ecoinvent, 2013).

#### Soda

Dosing with soda is proposed for the future alternatives instead of lime to optimize the pH, based on investigations by Ramboll. Soda dosage is given at various points throughout the treatment process to adjust the alkalization / pH in the water. It is taken in a granular form for the dosage (Lindgren, 2020). Even though Lime is cheaper, Soda is chosen* for future alternatives as it is easier to prepare and does not contain calcium. The calcium in water is reported to be usually above the level recommended by SFA (26 mg/l on an average), (Forsberg, 2019) and hence soda was chosen over Lime due to these reasons. The Ecoinvent dataset selected from SimaPro is production of *Soda ash, light, crystalline, heptahydrate (RER)* (Ecoinvent, 2013). The soda ash is produced by the Solvay process as it is the common method in Europe and Globally (Bergström, 2020).

*See ***Figure 49*** for an independent sensitivity analysis for comparison between impacts from Soda vs Lime.

## Hypochlorite

Hypochlorite or sodium hypochlorite is used in the treatment process for the preparation of Monochloramine ($NH_2Cl$) and for CEB for UF and NF filters. The hypochlorite dosage for monochloramine is in 15% of solution state and the dosage for CEB is in 12.5% of solution state (Pentair, 2019). Data for sodium hypochlorite is based on hypochlorite production from chlorine emission captured in a 50% sodium hydroxide solution (Ecoinvent, 2013). The Ecoinvent dataset selected from SimaPro for both the dosage is *Sodium hypochlorite, without water, in 15% of solution state (RER)* (Ecoinvent, 2013). Calculation is made for converting the input values from 12.5% to 15% of solution state.

## Sodium hydroxide

Sodium hydroxide is used in CEB for UF and NF filters. The sodium hydroxide dosage in 25% of solution state (Pentair, 2019) and the only closest available Ecoinvent dataset selected in SimaPro is *Sodium hydroxide, without water, in 50% solution state (RER)* (Ecoinvent, 2013). Calculation is made for converting the input values from 25% to 50% of solution state.

## Hydrochloric acid

Hydrochloric acid is used in CEB for UF and NF filters. The Hydrochloric acid dosage in 25% of solution state (Pentair, 2019) and the only closest available Ecoinvent dataset in SimaPro is for *Hydrochloric acid, without water, in 30% solution state (RER)* (Ecoinvent, 2013). Calculation is made for converting the input values from 25% to 30% of solution state.

## Ammonium sulphate

Ammonium sulphate is used in the preparation of Monochloramine ($NH_2Cl$). It is in granular form and is combined with hypochlorite in a solution state to create monochloramine for the treatment of the distribution network to counteract biofilm growth (Forsberg, 2019). The Ecoinvent dataset selected from SimaPro is the production of *Ammonium sulphate, as N (RER)* with a nitrogen content of 21% (Ecoinvent, 2013).

## Ozone

Ozone is an unstable colorless gas. Ozone treatment is to reduce any odor and taste and to form a microbiological safety barrier against micro-contaminants (Forsberg, 2019). It also has the potential to eliminate a wide variety of organic, inorganic and microbiological problems. Ozone is produced in a liquid form (Lindgren, 2020) on- site in the ozonation chamber with oxygen and energy (Oram, n.d). There is no additional chemical addition during ozonation. The Ecoinvent dataset taken in SimaPro is the production of *Ozone Liquid (RER)* (Ecoinvent, 2013).

## Polymer

Polymer is needed in the sludge separation tank for thickening and dewatering the sludge (Forsberg, 2019). The polymer is taken in a granular form. The selected Ecoinvent dataset from SimaPro is the production of *Polyacrylamide (GLO)* (Ecoinvent, 2013). This dataset represents the combined production of acrylamide and its polymerization to polyacrylamide from basic chemical reactants (acrylonitrile and water) (Ecoinvent, 2013).

## 3.6.2 Energy

This chapter includes the selected energy source to provide for the energy consumption by the unit processes and other equipment in all the future alternatives and the existing WTP. This chapter also includes the selected Ecoinvent dataset for entry in SimaPro. The specific energy requirement for each of the unit processes in each of the alternatives is given in Appendix 3 for reference.

Each of the alternatives share a common energy consumption from Micro-screen, Raw water pump, UV disinfection, Construction electricity, sludge handling, distribution, chemical precipitation downstream. There are other requirements like the provision of intermediate reservoirs, UF, NF, SF, additional UF near Sludge tank which are dependent on the requirement for the specific treatment process of the specific alternatives (See Chapter 2.2 in page **6** for details on the requirement).

Norrvatten has reported that the electricity usage in the WTP is from 67% of Hydropower and 33% of Wind power (Hellström, personal Communication, 2020). The hydropower is purchased from Vattenfall, Sweden (Bergström, 2020) and the wind power are produced from wind turbines owned by Norrvatten onshore in a wind farm on Fallåsberget in Ockelbo municipality / Gävleborg county, Sweden (Ekholm, 2012).

**Figure 3:** Wind power generated from onshore wind turbines (Byman, 2016b).

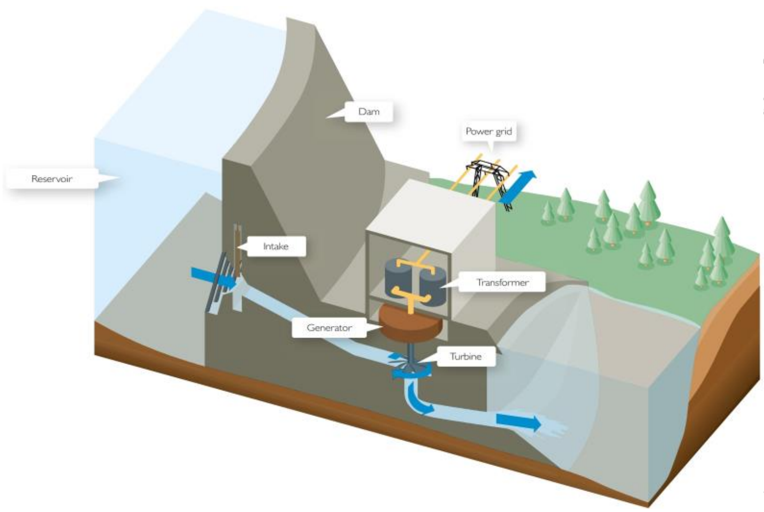


**Figure 4:** Diagram representing how a hydroelectric power plant works in Sweden (Source: Byman, 2016).

In SimaPro, the Ecoinvent dataset selected for electricity from Hydropower consists of three different sources: *Electricity, high voltage, hydro, Pumped storage, Reservoir non-alpine region, run-of-river (SE)* (Ecoinvent, 2013). As there is a lack of data from where the hydropower is taken from all three is taken into consideration with an assumption that *Reservoir non-alpine region* has a 40% share and each of *Pumped storage* and *run-of-river* have a 30% share to the total production of hydropower to the WTP. The dataset selected for electricity from Wind power is 100% from *Electricity, high voltage, wind, >3 MW turbine, onshore (SE)* (Ecoinvent, 2013).

## 3.6.3 Transport

The transportation required by all the future alternatives and the existing WTP and the selected Ecoinvent datasets for each entry in SimaPro is included in this chapter. The specific transport requirement for each of the chemicals and sludge in each of the alternatives is given in Appendix 3 for reference.

Transport includes the transportation of the various chemicals used in the WTP, from the distributor/supplier to Görvälnverket and also the removed sludge to be disposed of from the WTP. According to Bergström (2020) and Karlsson (2020), two different truck capacities are considered for this study. A *light truck* is considered to transport the chemicals needed for CEB, the auxiliary coagulant activated silica, chemicals for Monochloramine preparation (hypochlorite and ammonium sulphate) and polymer for sludge thickening and dewatering. A *heavy truck* is considered to transport the main coagulant (ALG/PIX-111), sulphuric acid and soda for alkalization, GAC for filtration purpose (Bergström, 2020) (Karlsson, 2020).

The stated transport distances are in reference to the total km of transport from the supplier to the WTP, calculated from Google maps based on round-trip travels. The shortest distance was chosen for travel of the trucks regardless of the traffic situation (Bergström, 2020).

From SimaPro, the selected Ecoinvent datasets are *Transport, freight, lorry >32 metric ton, EURO6 (RER)* for the *heavy truck* and *Transport, freight, lorry 3.5-7.5 metric ton, EURO6 (RER)* for the *light truck*. In Sweden, EURO6 is the considered standard for air pollution by vehicles used for transport and other purposes (Govt. of Sweden, 2018).

## 3.6.4 Other Inputs

Apart from chemicals, energy and transports other inputs like the infrastructure, machinery, inflow and outflow of water, disposed sludge are also part of the use phase in the WTP. The other inputs required for all the future alternatives and the existing WTP and the selected Ecoinvent datasets for each entry in SimaPro is included in this chapter.

### a) Infrastructure and other equipments inside the WTP

For this study, information regarding the WTP infrastructure and the machinery used inside for each process was not available. Hence datasets from the Ecoinvent database were chosen as close to the actual WTP in Görvälnverket and the equipment used within each unit process.

- **Water Treatment Plant Infrastructure**

The dataset from Ecoinvent chosen to represent the WTP is *Water works, capacity, 1.1E$^{10}$ l/year, conventional treatment (Europe without Switzerland)* (Ecoinvent, 2013). This dataset represents the construction of a medium-sized potable water treatment plant with a conventional treatment method. The conventional treatment technique includes Coagulation, decantation, filtration and disinfection (Ecoinvent, 2013). The mentioned plant capacity in the Ecoinvent dataset is smaller compared to the WTP in this study and hence adjustments have been made to implement the proper value to fit the capacity of the WTP in our study. This varies for each of the selected capacity for this study; 160 MLD and 208 MLD (See ***Table 33*** in appendix 7 for reference).

▪ **Nanofiltration Modules**

**Figure 5:** The cross section of a HFW1000 Nanofilter module (Karlsson, 2020).

The Nanofiltration filter unit proposed to be used in the WTP is HFW1000, an NF module developed for commercial use by Pentair X-flow (Pentair, 2019). This module was previously used in the pilot trials at Görvälnverket. It is of a hollow fiber type made from a modified Polyethersulfone (PES). It is hydrophilic and can be backwashed with chemicals including chlorine (Norrvatten, 2019b). One module is 1.5m long and 0.2m in diameter and consists of 1000 spaghetti like fibers encased within a PVC pipe. Each fiber has an inner diameter of 0.8 mm. The surface area per NF module is 40 m$^2$ and can treat the molecules in water above the molecular weight of 1000 Daltons. The membrane is designed to separate the NOM without affecting the hardness of the water. The NF filter has a lower permeability with a higher energy consumption (Pentair, n.d.a).

**Figure 6:** Representation of the setup of the HFW1000 membrane modules for the process of nanofiltration in the WTP (Karlsson, 2020).

The NF filter unit is proposed to be used in Alternative 7 and in Alternative 8 as one of the main unit processes. In the current WTP there are no unit processes with NF filter usage.

As there was not any specific dataset for an NF module available in SimaPro, a proxy dataset is created from SimaPro from the existing UF module dataset, *Ultrafiltration module, hollow fiber (GLO)*. The surface area for this UF hollow fiber is given as 50 m$^2$ (Ecoinvent, 2013). The NF module for this study has a surface area of 40 m$^2$ per module for a total of 120 membrane modules. See additional details in Appendix 6 (page **114**). Hence, adjustments have been made to fit the proper value to meet the requirement of the actual NF module to be used in the future WTP.

▪ **Ultrafiltration Modules**

**Figure 7:** Cross section of the UF module in X-flow XIGA (Pentair, n.d.b).

The Ultrafiltration filter unit proposed to be used in the WTP is Pentair XIGA 64, developed by Pentair X-flow (Forsberg, 2019). XIGA modules are hydrophilic hollow-fiber membranes composed of a blend of both PES/PVP. It has an excellent chemical resistance and a high chlorine stability. It allows for a higher permeability than NF filters at a lower energy consumption (Pentair, n.d.b). The XIGA membranes consist of a large number of fibers with a pore size of 20 nm and a surface area per module of 64 m$^2$ (Dahlberg, 2019).

**Figure 8:** Representation of the setup of Ultrafilter modules for the process of ultrafiltration in the WTP (Forsberg, 2019).

The UF filter unit is proposed to be used in Alternative 7 in the main unit process, in Alternative 8 for both the main unit process and an additional unit process near the sludge separation chamber, in Alternative 9 for an additional unit process near the sludge separation chamber. There are no UF filters in the existing WTP.

The specific dataset selected for the UF module is *Ultrafiltration module, hollow fiber (GLO)* same as the one selected for the NF module. The surface area for this specific UF hollow fiber is given as 50 $m^2$ (Ecoinvent, 2013). The UF module in our study has a surface area of 64 $m^2$ per module for a total of 22 membrane modules. See Appendix 6 for more details (page **114**). Hence, adjustments have been made to fit the proper value to meet the requirement of the actual UF module.

- **Ultraviolet lamp**

Ultraviolet lamp is used at the end of the water purification process before distribution to disinfect the water. It acts to inactivate germs in the drinking water before the distribution. There is a UV chamber in the existing WTP, where the water is passed through UV light. In Görvälnverket, the UV dosage employed for the UV reactors is 400 $J/m^2$ (Dahlberg, 2017). There are a total of 9 UV units (Lindgren, 2020).

The selected Ecoinvent dataset in SimaPro is the production of *Ultraviolet Lamp, for water disinfection (GLO).*

### b) Granular Activated Carbon (GAC)

Activated carbon is used in the purification process as a filter to remove micropollutants in the presence of high concentration of NOM through the process of adsorption. In this process, substances in liquid phase are adsorbed and accumulated to a solid phase, which results in its exclusion from the liquid (Östlund, 2015). GAC are normally produced from bituminous coal, lignite coal, wood and coconut shells. They are used to reduce compounds causing concentration of organic contaminants, odor and taste and NOM. GAC is different from PAC, where it is a fixed bed acting as a filter membrane for the liquid to pass through whereas PAC is added directly to the liquid in a powder form and is removed using filtration or sedimentation (Östlund, 2015).

The GAC used in Norrvatten is *Filtrasorb 400* imported from Belgium. *Filtrasorb 400* carbons are produced by steam activation of bituminous coal that has been pulverized and then agglomerated. The activated carbons should have a high adsorption capacity for a high efficiency of micropollutant removal. *Filtrasorb 400* is reported to have a high adsorption capacity and excellent reactivation performances. It is eligible for multiple reactivations and is of a consistent high quality throughout its lifetime (Chemviron, 2010).

Granular activated carbon is produced in Belgium and imported to the WTP through truck transport. The selected dataset in SimaPro is the production of *Activated carbon, granular from hard coal (RER).* This dataset represents the production of GAC from hard coal which is typical for Central Europe. The production is where hard coal undergoes carbonization and partial gasification (Ecoinvent, 2013). The chosen dataset is assumed to be similar to the production of *Filtrasorb 400.* For this study, in SimaPro, GAC is taken under chemical consumption initially to introduce the impacts from the production of the activated carbons. It is also added under the other inputs for the WTP to remove the initial burden and introduce the burden from its reactivation due to its reuse (Goedkoop et al.,

2016) within the WTP. As mentioned in the assumptions (See chapter 3.2 in page **18**), it is considered that 100% of the activated carbon is reused in the WTP by reactivation.

GAC is also reactivated and used again onsite for the same quantity. The dataset selected for this reactivation process is *Activated carbon, granular from hard coal, treatment of spent activated carbon, reactivation (RER)*. This dataset represents the emissions from reactivation of spent activated carbon without including the contaminants (Ecoinvent, 2013).

### c) Sewage

The sludge waste is formed from the sedimented contaminants in the various water losses after the specific unit processes which goes to the sludge chamber. The sludge content varies for each treatment process depending on the amount of water inflow and the type of unit process employed to remove the contaminants (See water balance diagrams in **Appendix 2: Flow diagrams**). After the sludge is dewatered in the centrifuge of the Sludge separation tank it is disposed of by transporting it to Ragn-Sells, which is a construction site, to be used as a construction material in fixed assets (Bergström, 2020).

The selected Ecoinvent dataset from SimaPro for the disposal of sludge is *Raw sewage sludge, drying (CH)* (Ecoinvent, 2013). This dataset is added in 'Outputs to Technosphere: Waste and emissions to treatment to indicate that the sludge goes out of the system (Goedkoop et al., 2016). The dataset represents thermal drying of the sludge after mechanical dewatering. This sewage can be used as a raw material in the clinker production (Ecoinvent, 2013).

### d) Water Consumption

There are three different water requirements which are considered for this study.

- **Raw Water Intake**

The raw water intake for each alternative is different due to the various different unit processes within each alternative, with all their different water losses. See ***Figure 26***, ***Figure 27***, ***Figure 28*** & ***Figure 29*** in Appendix 2 for reference. The intake is added in 'Inputs from nature' with a selected dataset from Ecoinvent *Water, lake, SE* (Ecoinvent, 2013). This will account as a resource taken from nature (Goedkoop et al., 2016).

- **Produced Drinking water**

The produced drinking water from the WTP for each future alternative is the same, which is a sustained/average capacity of 208 MLD. The average/sustained production of drinking water in the existing WTP or Alternative 0 is 160 MLD.

The drinking water which is the produced product in the LCA is added under 'Outputs to Technosphere: Products and Co-products' as a quantity in mass. The quantity of water in cubic meters is converted to Ton to meet the dataset requirement.

- **Flow back to lake**

In the WTP, there are certain water losses from each unit processes which are sent back to the lake with the initial contaminants/concentrates. These water losses are different for each alternative, due to the various different unit processes within each alternative, with all their different water losses. See ***Figure 26, Figure 27, Figure 28*** & ***Figure 29*** in Appendix 2 for reference.

## 3.7 Life Cycle Inventory for the Sensitivity Analysis

This chapter will cover the LCA inventory phase for the sensitivity analysis of the LCA study. The inventory taken for the study is for a change in main coagulant and energy mix in the WTP. Details regarding the calculations and the inventory datasets used in the study are attached in **Appendix 7: Calculations** and **Appendix 3: Inventory data** respectively, for reference.

### 3.7.1 Coagulant Change

**Iron Chloride (PIX-111)**
Iron chloride or PIX-111 as it is called in Norrvatten is an alternative main coagulant which can be used in the precipitation process. PIX-111 is not currently used in the current WTP but is suggested to be used in the future due to its significant potential to reduce 30% of chemical oxygen demand (COD) compared to ALG (Forsberg, 2019). The dosage suggested to be used in the WTP is in 40% of the solution state. The Ecoinvent dataset used in SimaPro is the production of *Iron chloride in 40% of the solution state (CH)* (Ecoinvent, 2013).

### 3.7.2 Electricity Mix Change

For the sensitivity analysis, a Swedish electrical mix is taken instead of the energy used currently. This is done to assess the difference between impacts from the electricity change for an informed decision making if the Norrvatten authority considers implementing it in the future.

According to Swedish energy Agency (2020), the electricity mix in Sweden as reported in the year 2018 consists of 39% Hydropower, 10% Wind power, 41% Nuclear power, 0.2% Solar power and a majority of the remaining 9% from Combustion based power which includes combined heat and power plants and industrial processes. There is also electricity imported from neighboring countries like Norway and Denmark and electricity exported to Finland, Poland, Lithuania and Germany (Swedish Energy Agency, 2020).

The Ecoinvent dataset selected from SimaPro is the production of *Electricity, medium voltage* (SE). This dataset represents the production of 1kWh of energy produced with the various electricity sources in Sweden including the imported energy from neighboring countries. The included inputs are Hydropower from pumped storage, reservoir and run-of-water, Nuclear power, power from Oil, power from Peat, Wind power (Onshore and offshore turbines), Imported energy from Germany (DE), Denmark (DK), Norway (NO), Poland (PL), Co-generation of heat and power from Biogas, Hard Coal, Natural gas, Oil and woodchips (Ecoinvent, 2013).

# 4. ANALYSIS OF MODELLED RESULTS

The assessment of the results from the conducted LCA study followed by a discussion is included in this chapter. The impacts from various selected impact categories are assessed with respect to the specific alternatives in the WTP. The environmental impacts represented under each impact category is in reference to the functional unit, that being the use of the WTP to produce 1 $m^3$ of drinking water. It is the case for both the stand-alone assessment and the comparative assessment for both the main assessment and the sensitivity analysis. The future Alternatives and the currently used process solution in the WTP (Alternative 0) is assessed to find how they contribute to the selected impact categories. All the results are for a cradle-to-gate analysis which is just the use phase of the WTP from the extraction of the raw water till the production of 1 $m^3$ of drinking water before distribution to consumers as stated in the system boundaries. The main modelled results are attached in the following chapters and the modelled supplementary results are attached in the **Appendix 5: Other Models from SimaPro** for reference. Additionally, the absolute emission data from the analyzed results are attached in **Appendix 8: Emission data from results** for reference.

## 4.1 Results from LCIA

### 4.1.1 Stand-alone Assessment of the Alternatives

The modelled results for each alternative include the contribution of environmental impacts from each aspect in the use phase of the WTP like chemical consumption, energy consumption, transportation and the other inputs for the WTP. The other WTP inputs include the capital goods/ infrastructure from the WTP, water consumption, avoided burden of initial production of GAC and reactivation of the GAC for reuse in the WTP. The positive environmental impacts are mentioned as a percentage value with a negative sign as opposed to the negative environmental impacts. Positive environmental impacts are impacts which contribute to benefit the nature/environment by including avoided burdens or by including processes which can benefit nature. Also, to be noted is that the mentioned impacts from energy consumption in all the assessments is indicative of the energy consumed by the unit processes in their respective alternatives in the WTP and not the energy from the total life cycle of the alternatives.

#### Alternative 7

The results from the analysis of Alternative 7 (See ***Figure 9*** below) shows the various contributions to the environmental impacts from the previously mentioned key aspects. It was observed that chemical consumption has a major contribution from terrestrial acidification (86%) followed by fine particulate matter formation (81%), ozone formation (terrestrial ecosystem) (78%), human carcinogenic toxicity, ozone formation (human health) & fossil resource scarcity (77%) and global warming (66%). The energy consumption in the WTP by the alternative has major contributions from ionizing radiation (83%), freshwater ecotoxicity (73%) and marine ecotoxicity (71%) followed by global warming with a minor contribution (25%). The impact contributions for transportation and WTP other inputs are quite lower compared to chemical and energy consumption. For transportation, the major contributions are from terrestrial ecotoxicity (24%), fossil resource scarcity (13%) followed by global warming (9%) with a minor contribution. The major contributions for the other inputs in the WTP are mostly the positive impacts (mentioned as a percentage value with a negative value) due to the avoided burden from GAC. The major contributing impact categories are fossil resource scarcity (-37%), ozone formation (human health and terrestrial ecosystem) (-35%), terrestrial acidification (-31%), global warming (-30%), terrestrial acidification (-30%) and marine eutrophication (-24%). The only negative impact contribution is from mineral resource scarcity (3%) which is a very small amount.

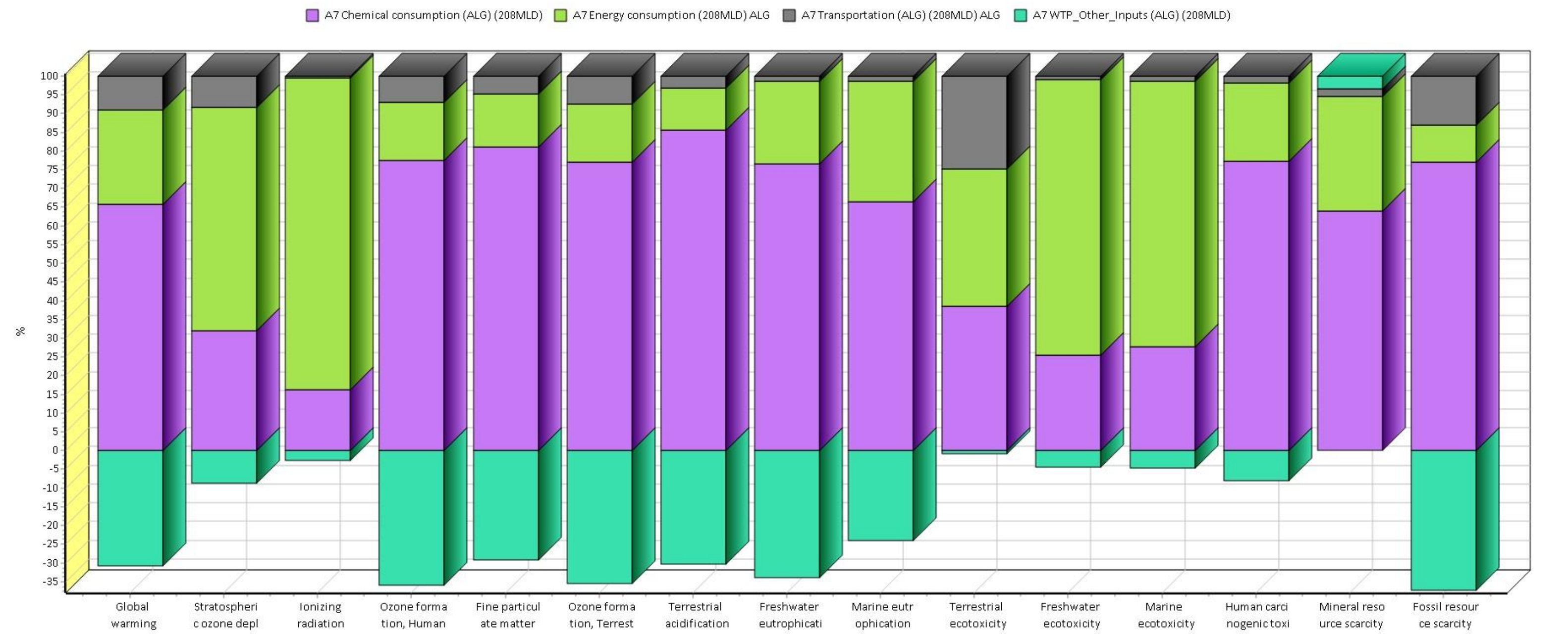


**Figure 9:** Characterized results of the environmental impacts from chemical consumption, energy consumption, transportation and other inputs in Alternative 7.

- **Chemical**

The major impact contributing chemicals in chemical consumption are GAC, ALG and Soda, respectively. The following observed contributions are due to the production and consumption of the specific chemical in the WTP. For GAC, the major contributions are from global warming (55%), fossil resource scarcity (55%), ozone formation (human health and terrestrial ecosystem) (53%) and freshwater eutrophication (49%). For Soda, the major contribution is from terrestrial ecotoxicity (38.5). For ALG, the major contribution is mineral resource scarcity (71%) and human carcinogenic toxicity (69%). Other chemicals like Liquid ozone contribute for Ionizing radiation (29%) and stratospheric ozone depletion (11%); and Polymer contributes for marine eutrophication (14%). See ***Figure 34*** in Appendix 5 for reference.

- **Energy**

The different energy sources used for energy consumption in the WTP are from Hydropower (67%) and Wind power (33%) (as mentioned in chapter 3.6.2). The following contributions are for the total energy production including distribution, which is common for all the alternatives 7, 8, 9, 0 (28 GWh/year). The wind power electricity generation and consumption was observed to have major contributions from freshwater and marine ecotoxicity (85%) followed by freshwater eutrophication (65%), mineral resource scarcity (61%), human carcinogenic toxicity (60%), fine particulate matter formation (54%), terrestrial acidification (53%) with a minor contribution from global warming (20%). The hydropower electricity generation and consumption had major contributions from ionizing radiation (99%) followed by global warming (80%), marine eutrophication & fossil resource scarcity (65%) and ozone formation (human health and terrestrial ecosystem) (59%). See ***Figure 38*** in Appendix 5 for reference. The proportion of the characterized results for energy consumption from all the modelled alternatives (7, 8, 9, 0) was observed to be the same as they all use the same electricity consumption from the same power source with the same percentages. The only difference will be in the actual characterized emission values from the impact categories as each of the alternatives have been modelled with a different value of energy consumption due to the variation in their process solutions. See the emission results attached in Annexure 8 from **Table *40*** to ***Table 45*** for reference on the energy consumption in the WTP by Alternatives 7, 8, 9 & 0 including and excluding Distribution as a common factor.

- **Transport**

The different classification of transportation vehicles used for transporting the chemicals to the WTP are *Heavy truck* and *Light truck* (as mentioned in chapter 3.6.3). There is also the inclusion of the transport of sludge from the WTP using a *heavy truck* which only has a very low impact contribution compared with the others. The use of *heavy trucks* resulted in major emission contributions from terrestrial ecotoxicity (88%), Ozone formation (human health and terrestrial ecosystem) (82%), fine particulate matter formation (80%) and fossil resource scarcity (79%). See ***Figure 39*** in Appendix 5 for reference.

## Alternative 8

The results from the analysis of Alternative 8 (See ***Figure 10*** below) shows the various contributions to the environmental impacts from the previously mentioned key aspects. The chemical consumption has major contribution from terrestrial acidification (83%) followed by fine particulate matter formation (78%), fossil resource scarcity (76%), ozone formation (human health) (76%) and ozone formation (terrestrial ecosystem) (75%), human carcinogenic toxicity (72%) and global warming (63%). The energy consumption in the WTP has major contribution from ionizing radiation (84%) followed by freshwater ecotoxicity (77%) and marine ecotoxicity (75%) followed by a minor contribution from global warming (29%). The contributions from transportation and WTP other inputs are quite lower compared to chemical and energy consumption. The use of transportation has major contributions from terrestrial ecotoxicity (22%), fossil resource scarcity (11%) followed by a minor contribution from global warming (8%). The major contributions from the use of other inputs for the WTP are mostly the positive impacts due to the avoided burden from GAC. The major contributing impacts are fossil resource scarcity (-42%), ozone formation (human health and terrestrial ecosystem) (-39%), terrestrial acidification (-35%), fine particulate matter formation & global warming (-33%) and marine eutrophication (-28%). The only negative impact contribution is from mineral resource scarcity (5%) which is a very small amount.

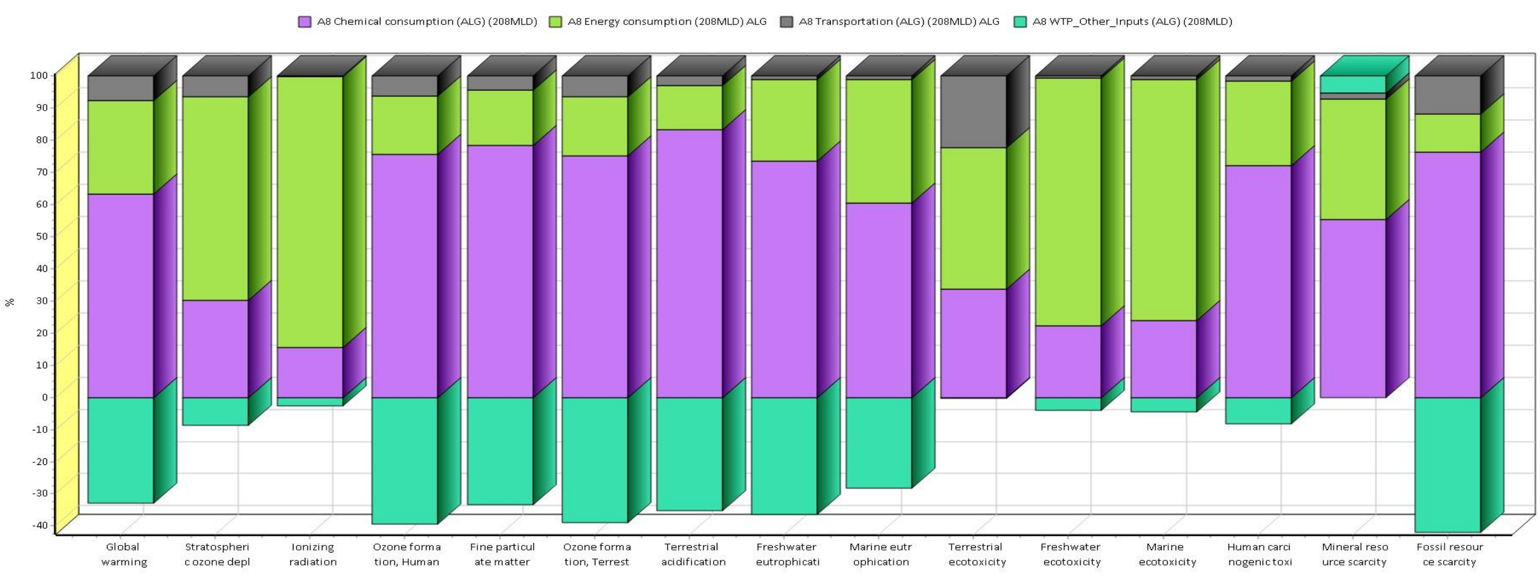


**Figure 10:** Characterized results of the environmental impacts from chemical consumption, energy consumption, transportation and other inputs in Alternative 8.

- **Chemical**

The major impact contributing chemicals from chemical consumption are GAC, ALG and Soda, respectively. For GAC, the major contribution is from fossil resource scarcity (62.8%) followed by global warming (62.5%), ozone formation (human health and terrestrial ecosystem) (61%) and freshwater eutrophication (56%). For Soda, the major contribution is from terrestrial ecotoxicity (38.5). For ALG, the major contribution is from mineral resource scarcity (71%) and human carcinogenic toxicity (69%). Other chemicals like Liquid ozone contribute for Ionizing radiation (29%) and stratospheric ozone depletion (11%); and Polymer contributes for marine eutrophication (14%). See ***Figure 34*** in Appendix 5 for reference.

- **Transport**

The major impacts are observed to be from the use of the *Heavy truck* resulting in major contributions from terrestrial ecotoxicity (87%), Ozone formation (human health and terrestrial ecosystem) (81%), fine particulate matter formation (80%) and fossil resource scarcity (78%). See ***Figure 40*** in Appendix 5 for reference.

## Alternative 9

The results from the analysis of Alternative 9 (See ***Figure 11*** below) shows the various contributions to the environmental impacts from the previously mentioned key aspects. The chemical consumption has major contribution from terrestrial acidification (78%) followed by fossil resource scarcity (74%), fine particulate matter formation (72%), ozone formation (human health & terrestrial ecosystem) (72%), human carcinogenic toxicity (46%) and global warming (59%). The energy consumption in the WTP has a major contribution from ionizing radiation (90%) followed by freshwater ecotoxicity (84%), marine ecotoxicity (82%) and a minor contribution from global warming (35%). The contributions from transportation and WTP other inputs are quite lower compared to chemical and energy consumption. The used transportation has major contributions from terrestrial ecotoxicity (18%) followed by fossil resource scarcity (10%) and global warming (6%). The major contributions from the other inputs for the WTP are mostly the positive impacts (mentioned as a percentage value with a negative value) due to the avoided burden from GAC. The major contributing impacts are from fossil resource scarcity (-52%), ozone formation (human health and terrestrial ecosystem) (-47%), terrestrial acidification (-45%), fine particulate matter formation (-43%), global warming (-37%) and marine eutrophication (-31%). The only negative impact contribution is from mineral resource scarcity (7%) which is a very small amount.

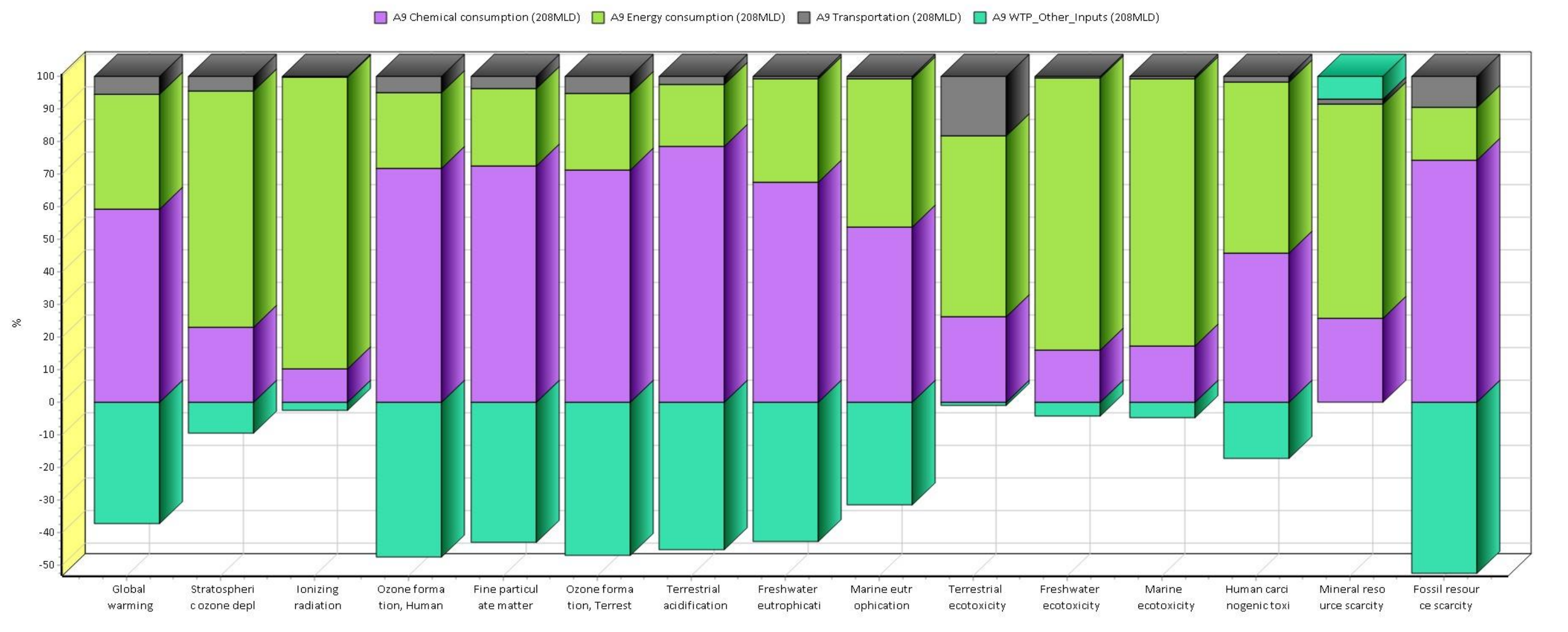


**Figure 11:** Characterized results of the environmental impacts from chemical consumption, energy consumption, transportation and other inputs in Alternative 9.

- **Chemical**

The major impact contributing chemicals from chemical consumption are GAC, Soda and Ozone liquid, respectively. There is no coagulant usage for precipitation upstream in Alternative 9. For GAC, the major contribution is from fossil resource scarcity (80%) followed by ozone formation (human health and terrestrial ecosystem) (76%), global warming (75%), freshwater eutrophication (70%) and marine eutrophication (67%). For Soda, the major contribution is from marine resource scarcity (68%) and terrestrial ecotoxicity (65%). For Liquid ozone, the major contribution is from Ionizing radiation (47%) followed by freshwater ecotoxicity (29%), marine ecotoxicity (27%), stratospheric ozone depletion & mineral resource scarcity (17%). Other chemicals like Polymer have minor contributions from marine eutrophication (5%). See ***Figure 36*** in Appendix 5 for reference.

- **Transport**

The use of *Heavy trucks* has major contributions from terrestrial ecotoxicity (95%), Ozone formation (human health and terrestrial ecosystem) (93%), fine particulate matter formation (92%) and fossil resource scarcity (91%). See ***Figure 41*** in Appendix 5 for reference.

## Alternative 0

The results from the analysis of Alternative 0 (See ***Figure 12*** below) shows the various contributions to the environmental impacts from the previously mentioned key aspects. The chemical consumption has major contribution from terrestrial acidification (88%) followed by human carcinogenic toxicity (87%), fine particulate matter formation (85%), ozone formation (human health and terrestrial ecosystem) (83%), fossil resource scarcity (83%) and global warming (75%). The energy consumption in the WTP has major contributions from ionizing radiation (81%), freshwater ecotoxicity (72%) and marine ecotoxicity (69%) followed by a minor contribution from global warming (19%). The contributions from transportation and WTP other inputs are quite lower compared to chemical and energy consumption. The transportation used has major contributions from terrestrial ecotoxicity (24%), fossil resource scarcity (10%) followed by a minor contribution from global warming (6%). The major contributions from the other inputs for the WTP are mostly the positive impacts (mentioned as a percentage value with a negative value) due to the avoided burden from GAC. The major contributing impacts are fossil resource scarcity (-39%), ozone formation (human health and terrestrial ecosystem) (-38%), terrestrial acidification (-34%), marine eutrophication (-32%) and global warming (-30%). The only negative impact contribution is from mineral resource scarcity (4%) which is a very small amount.

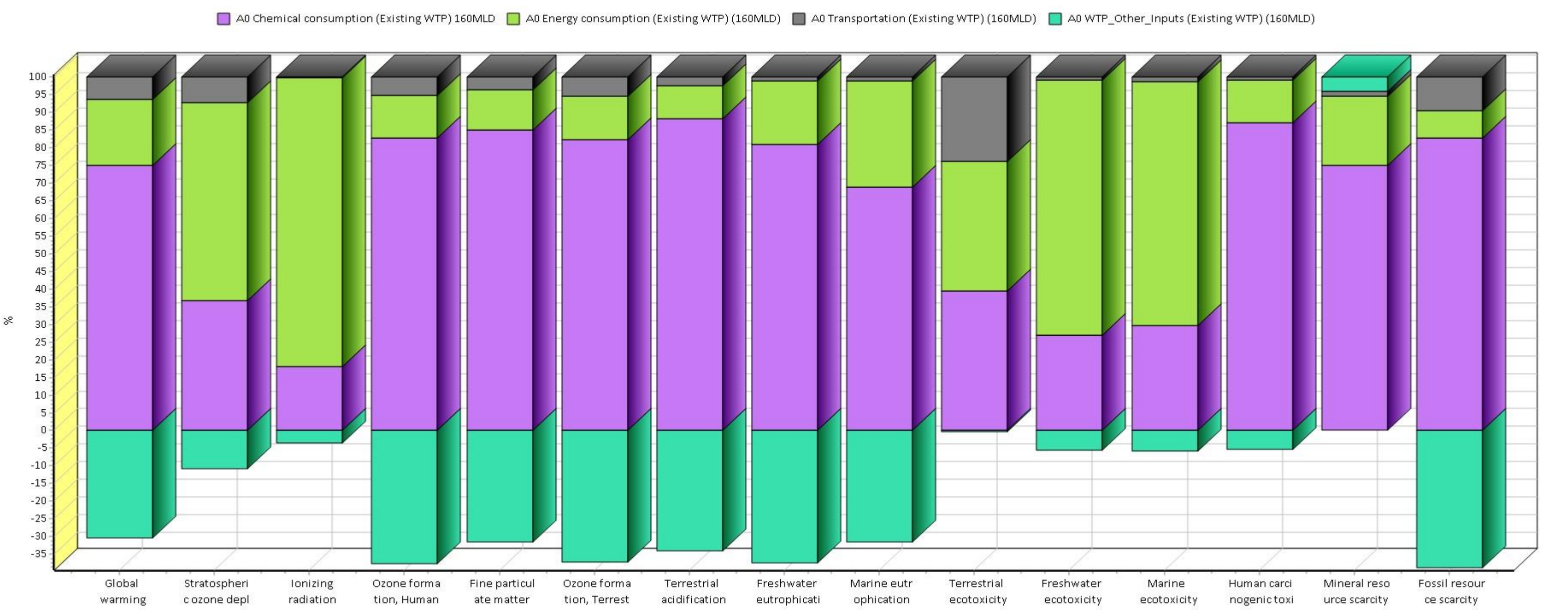


**Figure 12:** Characterized results of the environmental impacts from chemical consumption, Energy consumption, Transportation and other inputs in Alternative 0.

- **Chemical**

The major impact contributing chemicals in chemical consumption are ALG, GAC and Quick lime, respectively. For ALG, the major contribution is observed to be from mineral resource scarcity (95%), human carcinogenic toxicity (86%) and terrestrial ecotoxicity (74%). For GAC, the major contributions are from fossil resource scarcity (54%), marine eutrophication (54%), ozone formation (human health and terrestrial ecosystem) (53%) freshwater eutrophication (52%) and global warming (49%). For Lime, the major contributions are from global warming (18%), fossil resource scarcity (6%), stratospheric ozone depletion (5%) and ozone formation (human health and terrestrial ecosystem) (4%). Other chemicals like polymer contribute to marine eutrophication (2%) and sodium hypochlorite contribute to all the impact categories from 0.8% to 8.7%. See ***Figure 37*** in Appendix 5 for reference.

- **Transport**

The use of *Heavy trucks* has shown major contributions from terrestrial ecotoxicity (89%), Ozone formation (human health and terrestrial ecosystem) (83%) and fossil resource scarcity (81%). See ***Figure 42*** in Appendix 5 for reference.

### 4.1.2 Comparative Assessment of the Alternatives

The modelled characterized results for the comparative assessment of each alternative includes the contribution of environmental impacts from each utilized aspect from cradle-to-gate of the WTP, like chemical, energy consumption, transportation and the other inputs for the WTP. An overall assessment is made for each alternative along with an assessment for each mentioned aspect in **Appendix 5: Other Models from SimaPro**. A brief normalized result assessment is also provided for the overall alternatives to aid in understanding the result distribution in the above-mentioned Appendix. As mentioned before, the mentioned impacts from energy consumption in all the assessments is indicative of the energy consumed by the unit processes in their respective alternatives in the WTP and not the energy from the total life cycle of the alternatives.

From an overall perspective of the modelled characterized result for all the alternatives (see ***Figure 13*** below), it was seen that Alternative 7 contributes to a majority of the environmental impact categories. This is due to the high consumption of energy and chemicals as mentioned before. This is the case for most of the impact categories except in Ionizing radiation where Alternative 9 contributes higher followed closely by Alternative 7. As previously mentioned in the standalone assessment for each alternative, Ionizing radiation impact category shows the highest contribution for alternatives with unit processes requiring high energy consumption. This specific peak in Ionizing radiation is due to the inclusion of hydropower from pumped storage which requires electricity to function the reservoir from pumped storage. This required electricity is taken from the Swedish grid mix, which has nuclear power. The ionizing radiation is indicative of the chemical radioactive decay which is due to the said inclusion of nuclear power. Alternative 9 has the highest energy consumption (see ***Figure 30*** and the following figures for the respective alternatives from Appendix 5 or ***Table 30*** for reference) out of all the alternatives and hence the reason for maximum contribution to ionizing radiation.

In other impact categories like mineral resource scarcity and fossil resource scarcity which depend on the depletion of the resource from nature, Alternative 9 scores the lowest as it has the lowest chemical consumption out of all the alternatives. Mineral resource scarcity is the depletion of mineral ores like aluminium, iron, zinc, nickel etc. from nature. Fossil resource scarcity is the depletion of resources like crude oil, coal, peat, gas etc. from nature. As seen from the stand-alone assessment, the resource scarcity is the major contributing impact category in Alternative 7 compared to other alternatives, due to the high ALG and coal consumption combined with a relatively high degree of energy production. The second dominant alternative is Alternative 0 due to a high ALG consumption coupled with a high coal consumption. It trails behind Alternative 7 because of its relatively lower energy consumption.

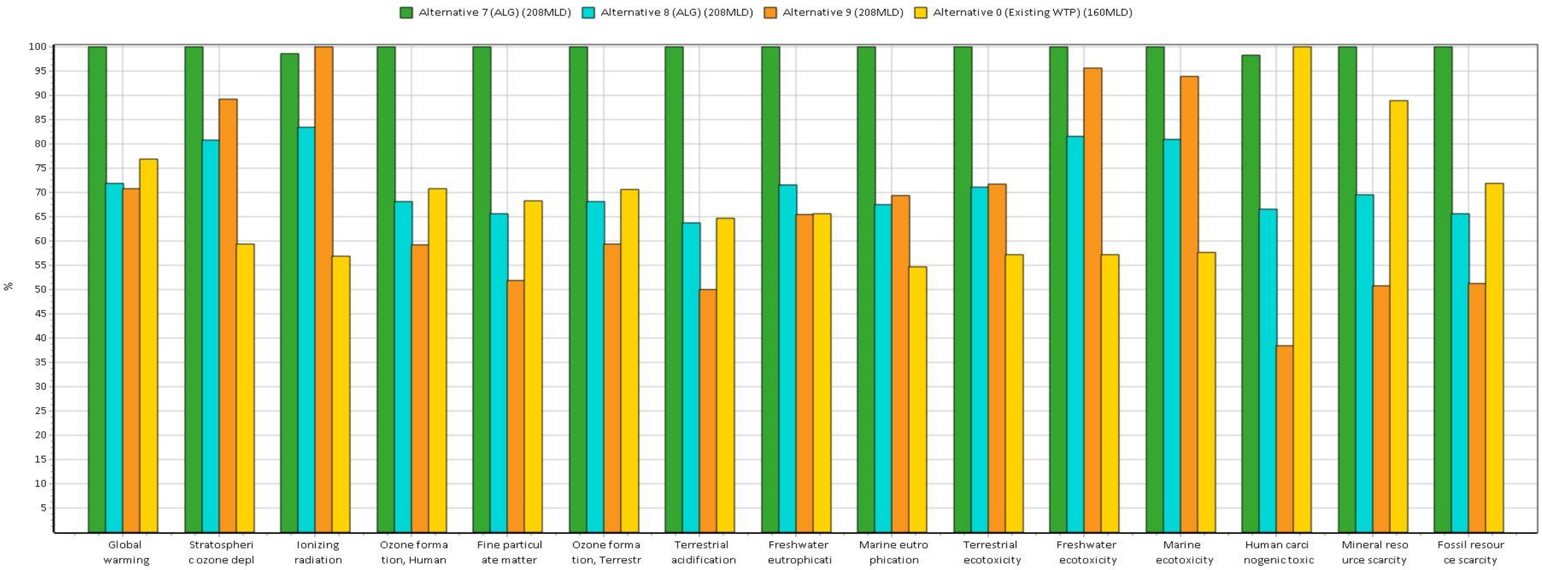


**Figure 13:** Characterized results from the Comparative assessment of Alternative 7, Alternative 8, Alternative 9 with 208 MLD as plant capacity vs Alternative 0 with 160 MLD as plant capacity.

Freshwater and marine ecotoxicity is higher in Alternative 7 followed by Alternative 9 due to the high electricity usage provided by wind turbines and the high consumption of ALG. Alternative 9 is second dominant compared to Alternative 7 due to the absence in consumption of ALG. Even though alternative 8 has both ALG and wind energy consumption, it trails behind Alternative 9 due to a lower consumption of energy. Wind turbines contribute majorly to marine, terrestrial and human ecotoxicity impacts due to the impacts from the steel content in the turbine's foundation (Greening & Azapagic, 2013).

Assessing the major air emission impact indicators like global warming potential, ozone formation (human health and terrestrial ecosystem), fine particulate matter formation, and human carcinogenic toxicity from the alternatives, it was inferred that a majority of the emissions are from energy consumption by hydropower from pumped storage & reservoir followed by chemical preparation (ALG) and the transportation of the chemicals in all the future Alternatives 7, 8, 9. In alternative 0, the related emissions are lower due to lesser energy consumption but in comparison to Alternative 8 and 9 it is higher due to more consumption of chemicals (especially ALG) and consequently their transportation. Alternative 0 is seen to have the highest contribution in human carcinogenic toxicity compared to the other alternatives due to the high ALG consumption. International Agency for Research on Cancer (IARC) has classified the production of aluminium and other forms of aluminium as carcinogenic to humans (Krewski et al., 2007) and its preparation in the form of ALG for the WTP contributes adversely to the human health majorly from Alternative 0. Hydropower is observed to contribute a lot to GHG emissions due to the use of reservoir-based dams. According to Song et al. (2018), reservoir-based dams seemingly have higher contribution to GHG emissions as opposed to other sources of dams. Reservoir creation and its management contributes to a lot of Greenhouse gas emissions (GHG). One of the other energy sources added to the hydropower mix is electricity from flow by water. For this study it was assessed and observed that it had a very limited environmental impact compared to the other two reservoir-based power sources.

## 4.2 Sensitivity Analysis Assessment

A sensitivity analysis is performed to analyze how the various hotspots in the WTP would change with a different input of key parameters like the use of a different coagulant or a different electricity mix. The following chapters will include each of the above-mentioned parameter changes in a comparative assessment of all the future alternatives with their main parameters. The future alternatives 7, 8 and 9 with changed parameters for the sensitivity analysis are named sensitive alternatives for this study.

### 4.2.1 Sensitivity Analysis 1: Coagulant Change

The main coagulant ALG used during flocculation is replaced with a different coagulant called PIX-111 (see chapter 3.7.1 in page **28**). PIX-111 is reported by Forsberg (2019) to have a better NOM removal rate compared to ALG. For this study, only two of the future alternatives use main coagulant, Alternative 7 and Alternative 8. Both the alternatives are taken under this sensitivity analysis for assessing how these process solutions contribute to a different environmental impact with a change in the main coagulant usage. This change in main coagulant also changes the dosage of other chemicals used in the WTP, like sulphuric acid used upstream along with the main coagulant and also to the soda dosage used throughout the process solution (See inventory ***Table 8*** & ***Table 9*** in Appendix 3 for reference). It was observed that PIX-111 has a lower consumption than ALG, but it influences the dependent chemical dosages for soda and sulphuric acid to increase drastically. Other dosages of the required chemicals provided under the aspect chemical consumption (see chapter 3.6.1 in page **21**) remain the same for both the actual alternative and the sensitive alternative.

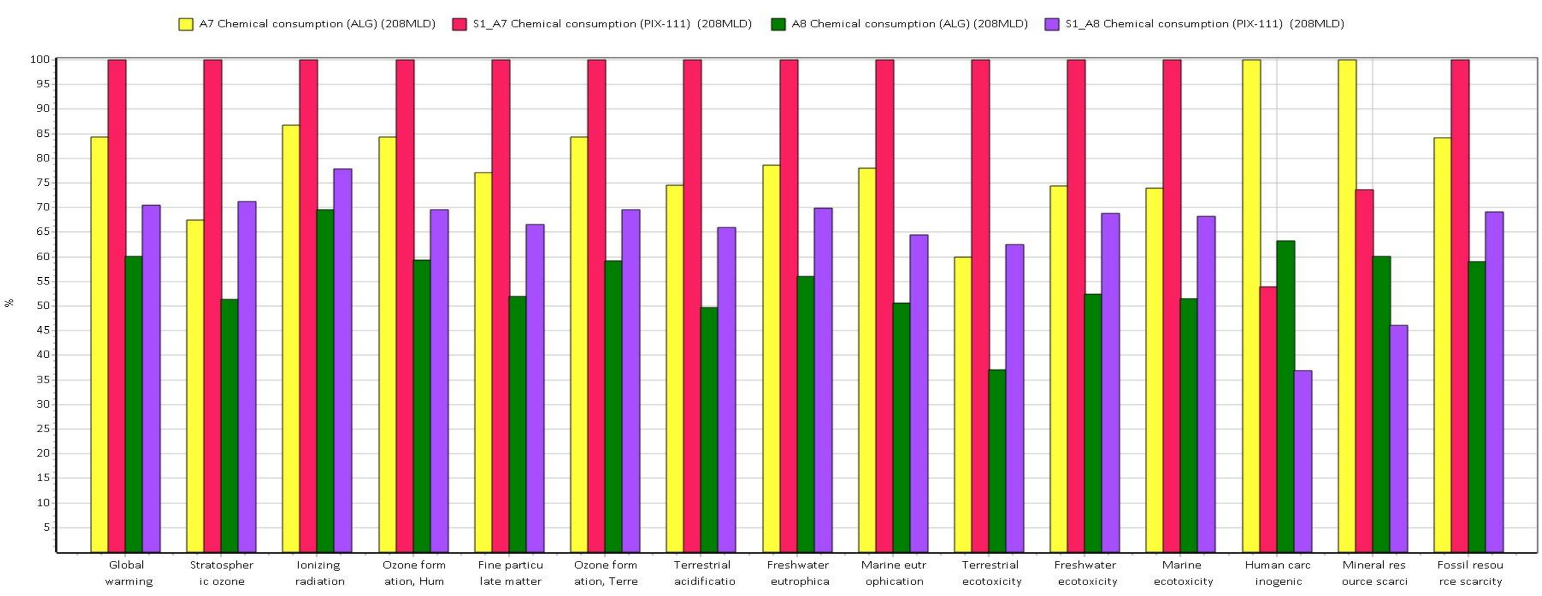


**Figure 14:** Characterized results of sensitivity analysis for comparisons between main alternatives 7 and 8 using ALG as main coagulant vs sensitive alternatives 7 and 8 using PIX-111 as main coagulant.

From the overall sensitivity analysis of Alternative 7 and 8 with different coagulants, (See ***Figure 14*** above), it was observed that the sensitive alternatives using PIX-111 had higher impacts. The major contributions to influence the change in the various impact categories are from the higher soda and sulphuric acid consumption in Sensitive Alternative 8 and the higher ALG consumption in Alternative 7. The major contribution across the impact categories like stratospheric ozone depletion and terrestrial ecotoxicity was from sensitive alternative 7 (100%), followed by sensitive alternative 8 (71% and 62% respectively) as the second dominant contributor. It was followed by Alternative 7 (67% and 60%) and Alternative 8 (51% and 37% respectively). Stratospheric ozone depletion is an impact indicator representing the emission of different methane and ethane variants to the atmosphere. From the analysis, preparation and consumption of PIX-111 was found to be the major contributing factor, followed by ALG, soda and then sulphuric acid for the impact indicator stratospheric ozone depletion. This is due to more methane and ethane emissions from the preparation and consumption of the mentioned respective chemicals in their required dosages. It was the same for terrestrial ecotoxicity, which is indicative of the deposition of chemical emissions to the atmosphere (air and water) like copper, zinc, nickel etc. which is higher due to the production of the said chemicals in the respective alternatives.

The major contributions across impact indicators like mineral resource scarcity and fossil resource scarcity varies for each alternative. The depletion of aluminium from nature in the main alternative assessment was observed to be higher than the iron depletion from nature in the sensitive alternative assessment, due to their respective higher and lower consumption for the process solutions. Hence for mineral resource scarcity, the impact contribution is the highest from Alternative 7 (100%) & sensitive alternative 7 (74%) followed by Alternative 8 (60%) & sensitive alternative 8 (46%) as seen in ***Figure 14***. For the impact indicator of fossil resource scarcity, the highest contribution is from activated carbon usage which is higher in both Alternative 7 and sensitive alternative 7, followed by Alternative 8 and sensitive alternative 8. Overall, with all the other chemicals included, the major contribution is from sensitive alternative 7 (100%) followed by alternative 7 (84%), sensitive alternative 8 (70%) and Alternative 8 (60%). The activated carbons as mentioned before in chapter 3.6.4, are produced from hard coal consumed in large amounts by both the main and sensitive Alternative 7, compared with the other alternatives.

Other impact indicators like global warming, ionizing radiation, ozone formation (human health and terrestrial ecosystem), terrestrial acidification, freshwater and marine (eutrophication and ecotoxicity) have the same respective contributions, which is, sensitive alternative 7 with the major contribution, followed by Alternative 7, sensitive alternative 8 and Alternative 8 respectively (as seen in ***Figure 14***). These contributions are similar to the contributions from fossil resource scarcity, where the affiliated major contribution is due to the high use of activated carbons in both alternative 7 and sensitive alternative 7. Activated carbons being made from hard coal, which is a natural fossil, results in major emissions to the atmosphere from $CO_2$, $NO_X$, $SO_X$ etc. Coupled with the fossil resource usage is the use of a high amount of chemicals in Alternative 7 and sensitive alternative 7, as compared to Alternative 8 and sensitive alternative 8, which also leads to more contribution from the said impact indicators.

See ***Figure 47*** and ***Figure 48*** in Appendix 5 for reference on the standalone assessment results from the utilization of PIX-111 in Alternative 7 and 8.

### 4.2.2 Sensitivity Analysis 2: Energy Change

The electricity mix was switched from just hydropower (67%) and wind power (33%) to the whole Swedish mix to assess the change in impacts (See chapter 3.7.2 in page **28**). The Swedish electricity mix has energy from nuclear power, industrial heat sources, fossil resources and imported energy from neighboring countries.

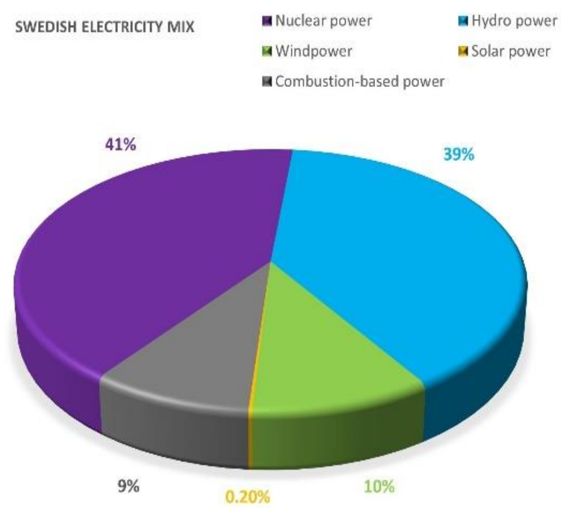


**Figure 15:** The Swedish electricity mix with various sources of electricity.

From the overall sensitivity analysis of all the future alternatives with different energy mixes (see ***Figure 16*** below), it was inferred that the inclusion of nuclear power in the Swedish mix results in a lower amount of $CO_2$ emissions in the sensitive alternatives. Nuclear power has the potential to reduce greenhouse gas emissions (Lee et al., 2017) and Carbon dioxide which is one of the major GHG contributor is not a byproduct in nuclear power production. It was observed that the major contribution is from both main and sensitive alternative 9, due to the high consumption of electricity required for the treatment processes in the alternative. Impact indicators like global warming, freshwater eutrophication, human carcinogenic toxicity, mineral resource scarcity, freshwater and marine ecotoxicity are noticed to contribute more to the main alternatives compared to the sensitive alternatives. This is due to the higher amount of emission potential from the hydropower pumped storage and the turbine used for acquiring wind energy.

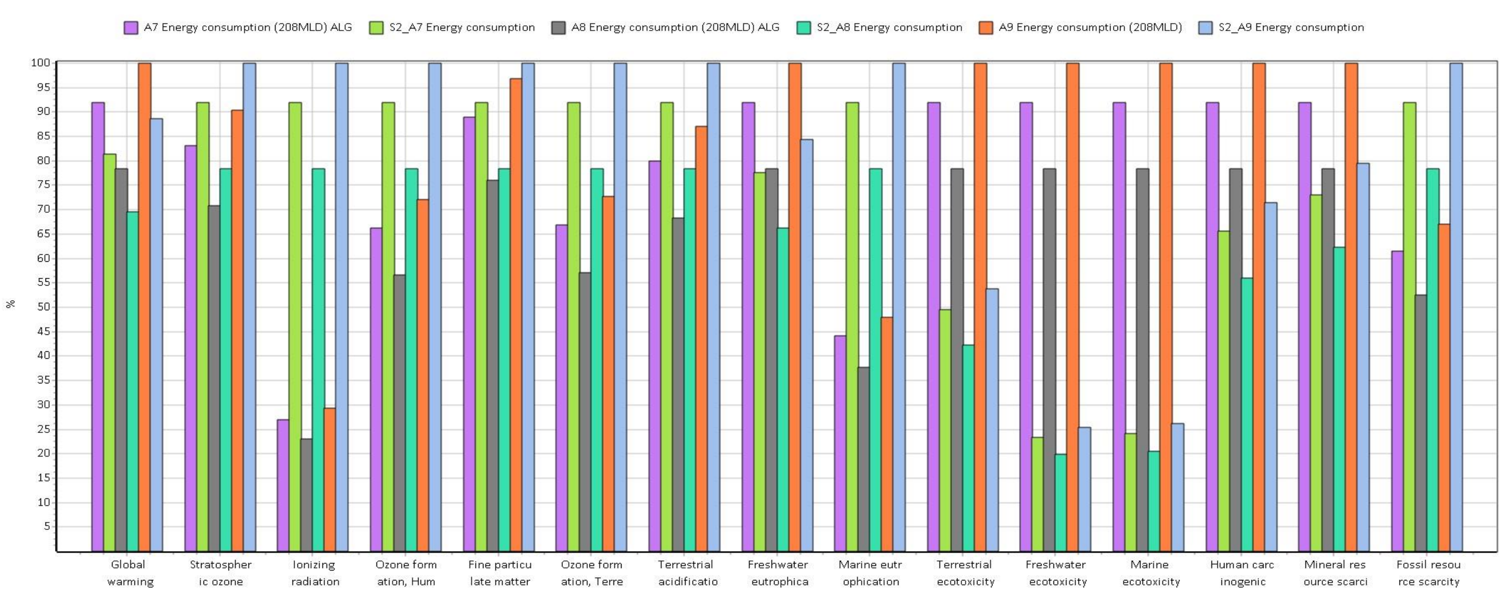


**Figure 16:** Characterized results of sensitivity analysis for comparisons between main alternatives 7, 8 and 9 using hydropower (67%) and wind power (33%) as the main energy mix vs the sensitive alternatives 7, 8 and 9 using the Swedish electricity mix.

Human carcinogenic toxicity was noticed to be higher in the main alternatives, due to the higher GHG emissions when compared to the sensitive alternatives (nearly 30% lower) because of the absence of nuclear power. Global warming potential was found to be 10 to 12% higher in the main alternatives when compared with the sensitive alternatives due to higher $CO_2$ emissions. Also, from the modelled results it is observed that impact indicators like ozone formation (human health and terrestrial ecosystem), terrestrial acidification, stratospheric ozone depletion, fine particulate matter formation, Ionizing radiation, marine eutrophication and fossil resource scarcity contribute more to the sensitive alternatives compared to the main alternatives. This is due to inclusion of nuclear power and an increase in other fossil fuel-based energy usages in the Swedish electricity mix. Ozone and particulate matter emissions are higher (30% and 3% respectively) due to more use of fossil fuel-based energy in the Swedish mix. This also leads to depletion of fossil resources from nature and more deposition of chemicals to the atmosphere. The main tradeoff is noticed in the impact indicator ionizing radiation where nuclear power usage will have a high contribution (50 to 70% higher) majorly due to the decay/emission of radon-222, carbon-14, cesium-137 and other respective radioactive gases from the nuclear plant.

## 4.3 Discussion

From the conducted LCIA, it was inferred that Alternative 7 has the highest contribution to most of the environmental impacts due to its high chemical consumption coupled with a high energy consumption in the WTP. The Chemical consumption in the WTP, as seen from the previous research studies (See chapter 2.3 in page **13**) was observed to have the highest contribution from the major impact categories. Alternative 7 has a larger chemical consumption upstream than the other alternatives, with consumption of soda, sulphuric acid, the main coagulant ALG and activated silica as auxiliary coagulant. Alternative 8 has no consumption of activated silica due to the absence of a sedimentation tank, where it is normally added for aiding the settlement of flocs from the flocculation chamber. This is due to chemical precipitation done directly in the UF process, without requiring settling tanks. Alternative 9 has the least impact with regards to chemical consumption, due to the absence of upstream chemical usage. The NF process in Alternative 9 has the potential to remove higher concentrations of NOM, without utilizing any main coagulant (Karlsson, 2020). It also has a lower impact on the alkalinity in the raw water intake, hence requiring much less soda dosage for alkalization/pH adjustment as compared to the other alternatives (Hellström, personal communication, 2020).

It should be noted that Alternative 7 has a lot more filtration processes than the other alternatives, utilizing UF, NF and SF. This contributes to a better removal of NOM content, due to the presence of numerous microbiological barriers, but also to negative impacts due to a high energy consumption utilized by all the filtration units. Nanofiltration process has the highest consumption of electricity and it is present in both Alternative 7 and Alternative 9. Alternative 8 utilizes only UF with the absence of SF and NF (See ***Table 30*** from Appendix 6) and hence the impacts due to electricity usage is moderately lower, compared to Alternative 7 (as seen from ***Figure 44*** in Appendix 5). Alternative 9 was observed to have the highest impact in terms of electricity consumption with just NF utilization in the WTP. The energy consumption is very much higher due to a large intake of raw water to satisfy the average water production of 208 MLD. In Alternative 7, only 50 percent of the specific intake is treated with NF, hence utilizing a lower amount of electricity than in Alternative 9 (See ***Figure 26*** and ***Figure 28*** in Appendix 5). Additionally, there is a utilization of a secondary UF before the sludge tank in Alternative 8 and 9, but it consumes very low amounts of electricity due to small quantities of specific sludge flow to tank (See Figure 61 in page **123**). In Alternative 0, there is just SF and no application of UF and NF. This coupled with the low plant capacity (160 MLD), results in lower specific intakes for treatment in comparison with the future alternatives and hence the reason for the low energy consumption. There is also the absence of the ozonation process in Alternative 0, which negates the need for $O_3$ and the required energy.

From this LCA, it was observed that production of ALG and coal contributes to major impacts in terms of both ecosystem and human toxicity. ALG requirement in an alternative is based on the effectiveness of the treatment of suspended impurities in the water with the included chemical and microbiological barriers. Direct precipitation on UF required a relatively lower consumption of coagulant dosage as opposed to pretreatment followed by UF and NF in Alternative 7. As stated before, there is no coagulant usage for NF in Alternative 9. Alternative 0, even with a lower specific intake required the highest ALG consumption, due to the absence of additional chemical barriers in the form of auxiliary upstream chemical dosages like soda and sulphuric acid. The amount of coal requirement is based on the specific dimensioning of activated carbon filters used in the process solution. The amount of coal used is higher for BAC, due to a smaller dimensional flow of water through it and vice versa for GAC (Forslund, personal communication, 2020). All the future alternatives use BAC as they all have an ozonation process preceding the GAC filters. Alternative 0 has just GAC due to the absence of ozonation and hence the least amount of coal consumption out of all the alternatives. Coal is a fossil fuel resource which contributes heavily to GHG emissions from its production. Its depletion from the earth due to heavy consumption is also an environmental impact which needs to be taken into account.

A better treatment of sludge is another aspect considered in the proposed process solutions. The amount of disposed sludge is higher in Alternative 7 due to the backwash sediments from both sand filtration and lamellar separation chambers being sent for sludge treatment (See ***Figure 23*** or ***Figure 26*** in Appendix 2). In Alternative 8 and 9, the backwash water loss from UF and NF respectively and their respective UF before the sludge tank are taken for the sludge treatment (See ***Figure 24*** and ***Figure 25*** in Appendix 2). Alternative 9 has a relatively more sludge content than Alternative 8 due to the high amount of backwash water loss from NF process. It is observed that the backwash from SF in Alternative 0, is not sent to the sludge tank, but back to the lake to limit the sludge content (See ***Figure 22*** in Appendix 2). This is the currently followed practice in the existing water treatment plant. To limit the environmental impact due to its disposal back in the lake, Alternative 7 has a modified process solution with SF where the sludge from SF is treated instead of disposed of in the lake as in the case of Alternative 0.

The aforementioned chemical requirement for the alternatives and the sludge disposed from the respective alternatives requires transportation which leads to environmental emissions from the use of *Heavy* and *Light trucks*. Alternative 7 has the highest emission from transportation followed by Alternative 8, Alternative 0 and finally Alternative 9 with the least amount of transportation impacts due to low chemical consumption. Transportation of the chemicals from the respective suppliers to the WTP in Sweden is done with the previously classified *Heavy* and *Light trucks*, both with a EURO-6 standard which significantly reduces the emissions as compared to previous standards like EURO-4 and EURO-5 (Vierth et al., 2017). EURO-6 standard trucks have the potential to reduce $CO_2$, $NO_X$ and particulate emissions on a large scale (Vierth et al., 2017) and hence total emissions from transportation are observed to be trailing behind emissions from chemical and energy consumption in the WTP.

From the conducted sensitivity analysis, the change in coagulant from ALG to PIX-111, was observed to increase the environmental impacts across all the alternatives. PIX-111 has a better removal rate of NOM from the raw water than ALG (Forsberg, 2020). However, as mentioned before (see chapter 4.2.1 in page **37**), the other dependent chemical dosages like soda and sulphuric acid increases, even with a decreased PIX-111 dosage when compared with ALG. This increased dosage for the aforementioned chemicals is for adjusting the pH. Using PIX-111 as the precipitating chemical requires a specific pH between 5 and 5.5 and hence more soda and sulphuric acid is needed upstream to adjust the pH in the specific water intake. For the case of ALG, a lower amount of soda and sulphuric acid is needed as it requires a pH level just below 7 (Hellström, personal communication, 2020). This increase in the required soda dosage for when PIX-111 is used as the main coagulant, poses a potential problem for PIX-111 selection over ALG, as soda is the second dominant impact contributor in chemical consumption after coal for the respective process solutions. This consequently leads to increased emissions from transportation, due to higher amount of chemical consumption from alternatives with PIX-111 as main coagulant over ALG. Despite these factors, it was observed from the results that production of Iron contributes to a lower emission than aluminum. The human health impact indicator human carcinogenic toxicity is lower for PIX-111 over ALG, due to its lower carcinogenicity potential. Also, Iron depletion as a mineral resource is lower than aluminium due to its relatively low consumption/production.

The change in energy mix from a green electricity mix (hydro and wind power) to the Swedish mix (Nuclear power, wind power, hydropower, combustion based power and solar power) resulted in an increase of environmental impacts to most of the impact indicators (see chapter 4.2.2 in page **39**). The inclusion of a certain percentage of nuclear power and combustion-based power in the sensitivity analysis has decreased the sole majority of percentage from hydropower in the main analysis for comparison, which resulted in most of the environmental impacts. According to the International Energy Agency (2019), nuclear power has the potential to play an important part in the future electricity production as a clean source of energy which can reduce the $CO_2$ emissions. It is reported to be the lowest carbon source of electricity, which in recent years have seen a decline in its rate of usage. This is due to new developments in solar and wind power electricity mixes and the financial constraints in construction of the nuclear plants (IEA, 2019). After 2020, nuclear power in Sweden is expected to run only in 6 of the 12 reactors as there was an economic threat for meeting its safety requirements (IEA, 2019, pp.50). Hydropower is outstripped by one-third of a percentage by nuclear power to be the cleanest source of energy with lower $CO_2$ emissions. IEA (2019) has declared that nuclear power is reportedly ten times cleaner than the total output of wind and solar power combined. Over the last 50 years, it was reported to help slow the long-term increase in the $CO_2$ emissions. From this LCA assessment, this was confirmed with the impact indicator GWP, where the associated $CO_2$ emissions are quite lower in the sensitive alternatives. The Swedish mix also has the utilization of fossil fuel resources which are used as energy by the process of combustion. The major effects from this is observed only in fossil resource scarcity and its contribution to GHG emissions are quite negligible due to the inclusion of a higher percentage of power consumption from nuclear sources.

## 4.4 Uncertainties

As previously mentioned in chapter 3.2, this study has assumptions and limitations and therefore it comes with a degree of uncertainty. A review of the various uncertainties in the study is done in this chapter to let the audience better understand the extent to which results of the study are altered from what they could have been. According to Røyne (2016), “Uncertainty in LCA results stems from the attempt to convert the variability of the real world into results through parameters, models and choices”. In the entirety of this LCIA study, the uncertainties are spread in different stages from the proposed assumptions for the process solutions, choice of modelling, the used method of impact assessment, dataset availability & reliability, inventory data depending on the future climatic conditions, and other related criteria.

The methodology of LCA strongly depends on the quality of the data, which is usually extremely hard to find and calculate (Zbicinski et al., 2006, pp.105). Firstly, the inventory data comes from various sources, estimates, assumptions and theoretical calculations (Zbicinski et al., 2006, pp.105) which are quite uncertain at the moment as Norrvatten is still undergoing pilot trials for their proposed treatment techniques. The exact required doses of chemicals are still being investigated as it depends on the climate conditions for the future which is quite uncertain. Secondly, any LCA which involves the inclusion of subjective choices which cannot be avoided becomes a study where uncertainty is a part of the model (Zbicinski et al., 2006, pp.105). The included system boundaries, characterization models and allocation rules all have uncertainty as part of their definition. Classification and characterization of many input items are neglected due to their lack of sufficient data, which ultimately results in their exclusion from the inventory table for the study (Zbicinski et al., 2006, pp.97). While classifying the impacts, there is an uncertainty on the universally accepted appropriate list of environmental impacts which should be considered for the LCA study. A list of environmental impacts which are considered to be “standard” are selected (Zbicinski et al., 2006, pp.97) from the Ecoinvent database, which are frequently used previously for earlier LCA studies to evaluate the WTP. These impact indicators are the related to the generally recognized environmental problems such as global warming, ozone depletion, toxicity, resource depletion, acidification, eutrophication etc., and the choice of selecting from these indicators is subjective based on the related product associated with the LCA study (Zbicinski et al., 2006, pp.97). There are other impact categories which could have been included amidst the selected indicators like noise, smell and landscape degradation (Zbicinski et al., 2006, pp.97).

There were some specific assumptions made for the alternatives to analyze and compare them on a common ground. The water losses for the unit process as mentioned in in Appendix 6 were calculated by Ramboll based on the maximum production of drinking water in the treatment plant. In this study those values were assumed to be the same for the considered average production of drinking water. This is not certain and can change depending on the efficiency and the functioning of the specific infrastructure selected for a specific unit process in the future. The chemical requirement for the alternatives is based on the previously proposed alternatives and this assumption can lead to an uncertainty regarding the water quality as every alternative is considered to produce drinking water with the same or an accepted level of quality. The quality of water at the end of every alternative can be different from one another and this results in an uncertainty in the validity of the estimated results. However, process engineers in Norrvatten and data estimators from Ramboll have agreed and assured that the water quality at the end of the proposed alternatives would be acceptable according to the SFA standard with the considered chemical assumption. The sludge separation chamber parameters are different for alternatives utilizing different coagulants. But in this study, it is assumed to be similar for ALG and PIX-111 as the percentage difference for each unit process in the sludge chamber with their sludge removing property was observed (Forsberg, 2019) to be minute. The data for the secondary UF unit near the sludge tank was taken from Norrvatten, with no specific information of its type and efficiency. Hence, it is assumed to be the same UF unit for all the alternatives as the primary UF unit in Alternative 8, but with a different removal efficiency as it is the only available data from the documents.

The ambition for this study is to estimate the impacts from the data representative of the method of chemical production, technology of the treatment and transportation units for the current time period 2020 until 2050. But due to the inability to find recent data, older datasets from 2018 were deemed acceptable for the study with an assumption that no innovation in technology is made. This is probably not the case in the real world as every day there is technological advancements to overthrow the outdated technologies.

The exact European emission standard and the used fuel for the transportation vehicle is unknown. Hence, the assumption is taken from literature backing that the *Heavy* and *Light trucks* assumed for this study utilize EURO-6 standard. They are assumed to utilize petrol/diesel as normal trucks do while modelling them. But in reality, there is a possibility that the trucks used for transporting the chemicals may be electric and hence the impacts for an electric vehicle can be much lower than the predicted impacts from this study. Another uncertainty in the study, is the unavailability of specific datasets regarding the required infrastructure for unit processes like UF and NF. Hence proxy datasets were created by incorporating the data taken from literature. For NF, proxy datasets were created with the available datasets from UF. The dataset for creation of liquid ozone was edited to implement the green electricity mix as it is produced in-site. This is done to limit the uncertainty.

The chosen green energy mix currently used in Norrvatten had no available literature to back up its exact requirement. The major energy impact was from Hydropower, which was purchased from Vattenfall. As there was no proper literature reference to pinpoint the specific sources and emissions for the utilized hydropower, assumptions were made from the available datasets in Ecoinvent database. The hydropower source from pumped storage was given an assumed lower value of 30% and it resulted in a major impact across the impact indicators in all the alternatives. It is not exactly certain if in reality there is usage of electricity from a pumped hydropower storage, and hence this is one of the uncertainties for this study. To limit this uncertainty an individual assessment was performed with just the hydropower energy source from reservoir assumed to provide the total 67% (See Page **109**). The wind power is generated from a wind turbine owned by Norrvatten, but there was no proper literature to back up its energy production and emission results, and hence assumptions were made from the available datasets in the Ecoinvent database. The Swedish energy mix from various literatures, was observed to change over the years. The selected Swedish mix from literature was from a literature in 2019. The selected dataset for utilizing the Swedish mix from Ecoinvent database was observed to be last extrapolated and adjusted for uncertainties until the year 2018 (Ecoinvent, 2013). This results in an uncertainty where the exact energy mix needed may not be properly implemented in the simulation.

It should be taken into account that using the LCA method to assess the alternatives has certain restrictions, like the aforementioned, that can prove to be shortcoming while evaluating the results. The results from the LCA study gives us a simplified perspective on the extent of the emissions and the potential environmental threat but does not consider the consequences that the threat can give rise to. To assess the human health & well-being impacts on a much bigger perspective, a social life cycle analysis is needed with consultations from all the related stakeholders. It is important to include more parameter variations to assess the process solutions, otherwise there is a risk of running into an assessment where a process solution is prematurely approved to be better than how it really is.

## 4.5 Recommendations for Future research

Based on the results, there are some recommendations suggested for Norrvatten's future research on the proposed alternatives.

- Expand the LCA assessment from a cradle-to-gate analysis to a cradle-to-grave analysis for an even better assessment on the full lifecycle of the drinking water.
- Perform a cost-benefit analysis for the alternatives with their required chemicals and energy to assess the financial investment needed to implement any change in the future which can be afforded by Norrvatten.
- Adopt a social lifecycle methodology with a focus on assessing the impact on human health & wellbeing associated with the drinking water production in the WTP and its consumption by the consumers. This can include assessing the impacts after the water reaches the consumers and also the behavior of Norrvatten as an organization using a stakeholder assessment.
- Conduct more studies to estimate the exact required chemical dosage in the suggested alternatives for the future year 2050, to limit the current uncertainty in case further LCA studies are proposed to be done for the same alternatives.
- Conduct more research to assess whether Lime can still be used instead of the proposed Soda, or any other alternative to mitigate the impacts.
- Investigate the exact specific environmental impact in each unit process in the alternatives i.e., the specific impact in SF, UF, NF etc. This investigation could be interesting for future comparisons.

# 5. Conclusion

The environmental performance of the various proposed future alternatives has been evaluated through an attributional cradle-to-gate life cycle assessment in this study. The key aspect which has the biggest contribution to the environmental impacts from the alternatives is the consumption of chemicals, followed by energy consumption and finally transportation. There are some hotspots observed in the main alternatives which play a major role in promoting higher impacts. These hotspots include the use of coal for GAC resulting in fossil resource scarcity, the use of ALG as the main coagulant resulting in carcinogenicity & resource scarcity, the utilization of NF process in the WTP with a high energy consumption, hydropower from pumped storage and the utilization of heavy trucks to transport the chemicals. The observed hotspots from the sensitivity analysis are the increase in use of soda in case of using PIX-111 as main coagulant and the use of nuclear power from the Swedish grid mix resulting in reduced $CO_2$ emissions. The preference for switching from ALG to PIX-111 should be based on the water treatment requirement by Norrvatten. The Swedish energy mix presents a better solution compared to the green energy mix due to the drastic reduction in $CO_2$ emissions and a much lower freshwater, marine and human ecotoxicity impacts. The major deciding factors for the choice of the change in electricity mix for the future, if considered by Norrvatten, is based on the requirement of switching to a cleaner energy source and the required financial investments.

Out of all the future alternatives, both Alternative 7 and Alternative 9 have a high trade-off, where even though they contribute to a better removal of NOM concentrations, Alternative 7 contributes to environmental burdens from high chemical consumption followed by Alternative 9 through high energy utilization. If NOM reduction in the WTP gains a priority over the potential environmental impacts, then PIX-111 can be used as the main coagulant instead of ALG in Alternative 7 to reduce a majority of the emissions. In an alternate scenario, Alternative 9 can be selected after switching to the Swedish grid mix for improving the environmental performance of the WTP with a reduced global warming potential. If reducing the environmental emission potential from the WTP gains a priority over a better NOM reduction potential, then selecting Alternative 8 is recommended. From another perspective, it is recommended to select Alternative 8 which can have a good synergy, if a decision was made to utilize PIX-111 as the main coagulant and energy from the Swedish grid mix in that alternative to further reduce the potential environmental impacts.

Furthermore, other changes can be implemented in the WTP to increase the environmental performance. Changing the chemical supplier from outside Sweden to within Sweden near the WTP, has the potential to limit the impacts from transportation with reduced distances. Utilize electric trucks to transport the chemicals instead of fuel-based trucks. More follow-up investigations can be taken by Norrvatten based on the given recommendations to further improve the environmental performance.

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# 7. Appendix

## Appendix 1: Other Background Information

### A1.1: Norrvatten Background

Norrvatten is a municipal association that produces and distributes high-quality drinking water to 14 member municipalities in Sweden. The other member municipalities which are dependent on Norrvatten's water are Danderyd, Järfälla, Knivsta, Norrtälje, Sigtuna, Sollentuna, Solna, Sundbyberg, Täby, Upplands-Bro, Upplands Väsby, Vallentuna, Vaxholm and Österåker. Norrvatten's current waterwork Görvälnverket was built as early as the end of 1920s and is located by Lake Mälaren in the Järfälla municipality of Sweden produces a maximum of 200,000 $m^3$ of drinking water per day (Norrvatten, 2020a).


**Figure 17:** The 14 member municipalities in Sweden which depend on Norrvatten's waterwork for drinking water supply (Norrvatten, 2020b).

Norrvatten is responsible for a guaranteed supply of healthy drinking water to nearly 700,000 people, several hospitals and Arlanda airport depending on it. It is the fourth largest drinking water producer in Sweden capable of producing 1600 liters of drinking water per second. Annually, the waterwork produces a total of approximately 50 million cubic meters of drinking water (Norrvatten, 2020a). The drinking water is produced in the waterwork and delivered to the consumers via Norrvatten's main water pipes to the municipalities water supply network. Each municipality is then responsible for delivering the water to households and businesses in the corresponding municipality (Norrvatten, 2020b).

**Figure 18:** Aerial photo of Norrvatten's Water treatment plant, Görvälnverket near Lake Mälaren (Source: Lavonen et al., 2018).

Norrvatten's drinking water is continuously checked with the regulation set by the Swedish Food Agency and is carefully controlled and monitored to produce in high quality. The produced water is medium hard (5-6 dH), has a pH value of 8.2 to 8.4, has a low fluoride content less than 0.20 mg / l and a low chlorine content as per the guideline value (Norrvatten, 2020d).

Initially, Görvälnverket had a water purification process which consists of only rapid filtration and chlorination. Due to increase in water and quality demands, the water treatment plant has been expanded and the treatment processes have become more advanced than before. The last expansion was made in the mid-1960s. Since then, there was not a need for an expansion as even though the population increased, the water consumption was lower due to development of water efficient technologies such as low flush toilets (Norrvatten, 2020d). The trend reports from Norrvatten reported that since 2014, the water consumption from different municipalities had increased by 18 percent. Norrvatten's recent forecast reports show that the water consumption will increase steadily until 2050. Therefore, Norrvatten is once again planning for an expansion of the production capacity and the treatment processes to fit the future needs (Norrvatten, 2020d).

## A1.2: Lake Mälaren and its future water quality change

Lake Mälaren is the third largest freshwater lake in Sweden having an expansive area of 1140 square kilometers and a maximum depth of 64 meters. The lake's water consists mainly of shallow groundwater that flows into streams and rivers and onto the lake. On its way through the soil layers and further in streams and rivers to Lake Mälaren, many useful salts are added to the water, such as magnesium, calcium and potassium, but also pollutants. The lake drains from south-west to north-east, into the Baltic sea. Mälaren is supplied with water from ten larger rivers and several smaller watercourses. The supply of water is very large, and only a fraction of Lake Mälaren's outflow to the Baltic Sea is purified into drinking water. (Norrvatten, 2020c).

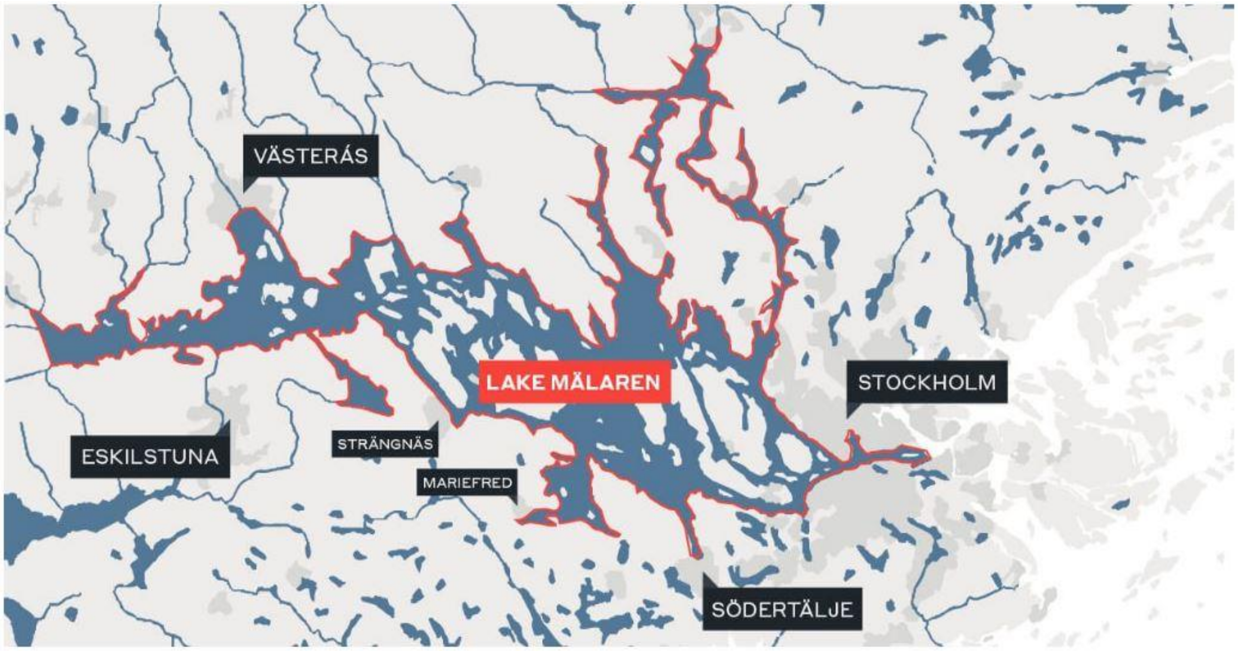



**Figure 19:** Lake Mälaren's location and spread around Sweden covering many municipalities (Source: Bergström, 2015).

Lake Mälaren, which supplies the raw water to the water treatment plant has a constant change of water quality due to the change in climate as years progress and due to population increase leading to pollution in the lake (RUFS 2050). The climate is forecasted to change extremely in the future with an average global temperature increase of 2.6-4.8 °C by the year 2100. Until the end of the century, the climate scenarios in Stockholm county is forecasted to change with a mean increase in temperature by 3-5 °C, along with an increased number of heat waves. There will be an increased torrential rainfall in the county with an increased precipitation from 20-40% across many seasons (Hansson et al., 2019).

During winter, according to Hansson et al., (2019) there will be an increase in the inflow of water to the lake by 75% while it will gradually decrease during the summer, due to evaporation. This increased inflow results in an increase in leakage of pollutants and other humic substances. With these changes in climatic conditions in the future, there will also be an increased stormwater and drainage water (Hansson et al., 2019). Lake Mälaren is reported to have an increase in saltwater intrusion after 2050, due to an increase in sea level. Currently, there is construction of barriers and dikes underway in the archipelago to prevent this saltwater intrusion.

Due to a warmer climate in the future, the lake's water temperature is expected to increase. The ice cover on the surface of water will decrease, affecting the lake's raw water quality and the surrounding ecosystem. This also leads to a decreased oxygen deficiency in the bottom layer of the lake (Hansson et al., 2019). Mälaren's water quality is also vulnerable from leakage of nutrients from the nearby contaminated land, pollution from boat traffic, industries & stormwater drainages (Ejhed, 2020).

The future water quality of Lake Mälaren is forecasted by Norrvatten with the help of expert support from Swedish University of Agricultural sciences or Sveriges lantbruksuniversitet (SLU), Swedish Meteorological and Hydrological Institute (SMHI), IVL Svenska Miljöinstitutet, and Chalmers (Ejhed, 2020). The following forecasts are compiled from the synthesis report made by the author Helene.

1. Lake Mälaren is reported to have a slight increase in natural organic content materials as well as higher microbial and chemical loads in the future.
2. There will be faster variations in the flow and level of substances/particulates in the future.
3. Emissions of microbial and chemical pollutants and algal blooms resulting in the formation of algal toxins are some additional risky events which are expected to occur in the future.

The factors involved in the change in lake water quality are Natural Organic Matter (NOM), Temperature, Overfertilization, Polyfluoroalkyl substances (PFAS), Pesticides and Drug residues. NOM increase over a long period of time has resulted in reduced acidification and this can result in the disruption of the disinfection process in the WTP and formation of byproducts. Temperature increase will result in a stronger stratification in the lake. This would lead to a deficiency in oxygen in groundwater, an increased risk for algal blooms in surface water and growth of bacteria in the pipe networks. The lake is affected by PFAS but is well within the guideline value as per measurements made from the beginning of 2010. The use of pesticides for agricultural purposes will increase in relation to the climatic adaptation in the future. This would lead to toxic chemicals to seep through to the groundwater leading back to the lake. As population is expected to increase in the future, this would increase drug consumption and the residue from such drugs can affect the lake's water quality (Ejhed, 2020).

There are certain other risky events which are also associated with the water quality of the lake.

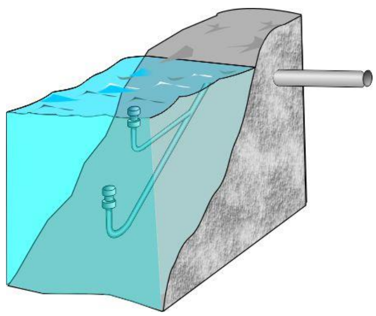
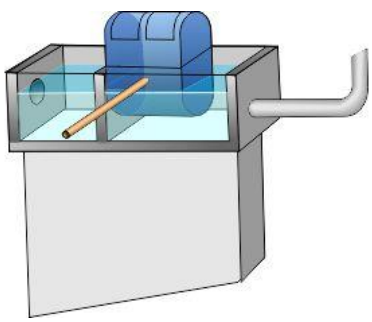
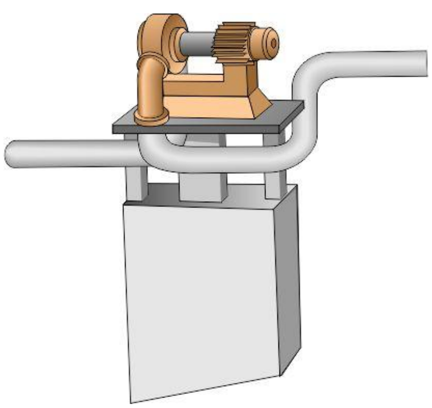
1. The fuel emissions from shipping and traffic around Lake Mälaren.
2. The algal blooms which produce toxins in the surface water.
3. The crude sewage emissions which have the potential to spread microbial infection and cause chemical pollution.
4. Microbial infection from beach baits, sewage ponds and stormwater drainage.
5. Emissions from construction work or contaminated land mass surrounding the lake.
6. Saltwater intrusion due to rise of sea level could result in a long-term risk if no measures are taken.

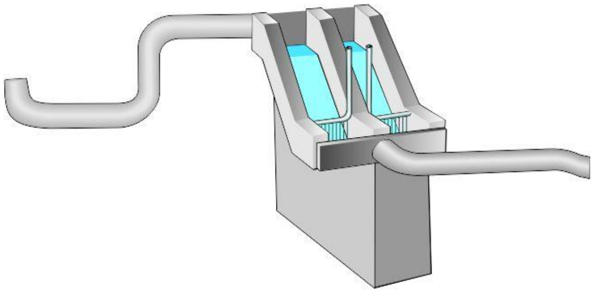
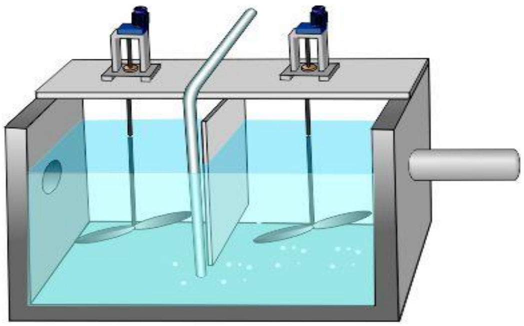
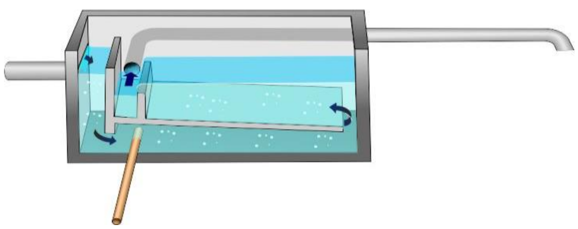
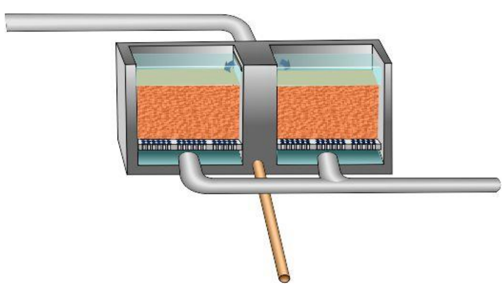
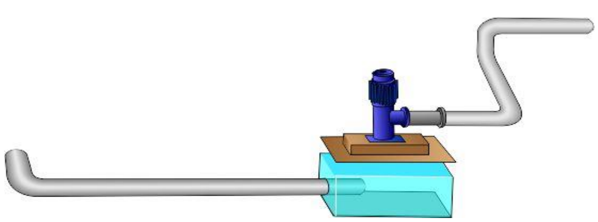
Out of all the listed factors and risky events, NOM, fuel emissions, algae toxins and crude sewage emissions are prioritized by Norrvatten in the short term. The knowledge of effects from the future climatic change is constantly evolving and hence constant monitoring is needed from Norrvatten to assess the lake as a proper drinking water source (Ejhed, 2020).

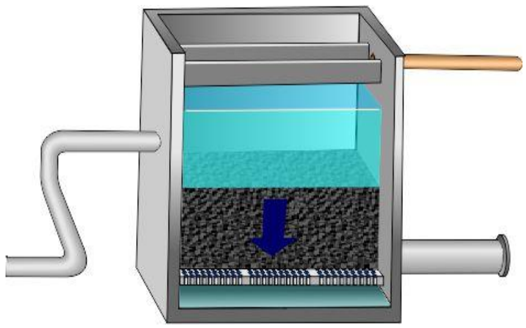
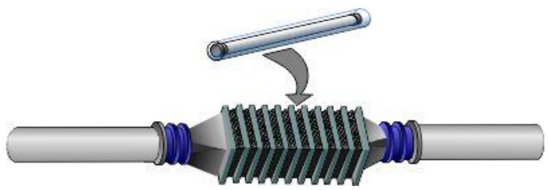
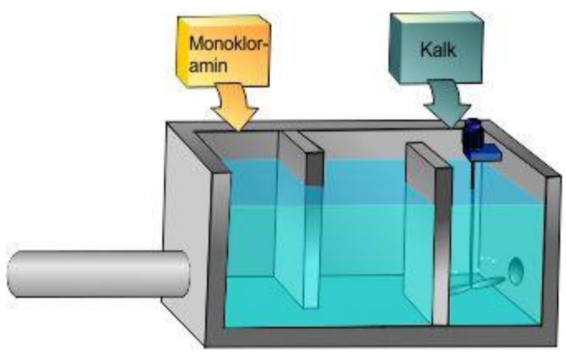
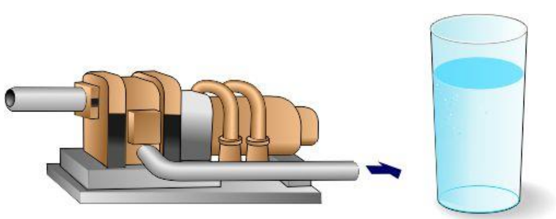
## A1.3: Water purification in Görvälnverket

The raw water intake from the lake has different water quality parameters, which requires different treatment methods to purify and meet the standards set by Swedish Food Agency (SFA). The water treatment currently used in Görvälnverket is a step-by-step process where the raw water is taken from lake Mälaren and then subsequently filtered, purified both physically and chemically and then disinfected before being pumped out into the pipe network to the consumers. The table provided below will describe each purification process step by step.

**Table 7:** The water purification process in Görvälnverket (Norrvatten, 2020f).

| S.no | Figure of the specific purification step | Description of the process |
|---|---|---|
| 1 |  | The raw water for purification is taken from lake Mälaren. The water is taken from two different locations, close to the surface or from hypolimnion depending on the season and the quality of water. |
| 2 |  | A large micro-strainer or a so-called basket strainer is used to filter the raw water from fish, algae or other substances (Zooplankton). |
| 3 |  | A pumping station ensures that the right amount of water is pumped onto the purification process. |

| | | |
|---|---|---|
| 4 |  | A mixing channel to add the proper coagulant dosage. |
| 5 |  | A flocculation chamber where the coagulant forms flocks and binds to humic substances, clay particles, microorganisms and other particulates. An auxiliary coagulant called Activated silica/Sodium metasilicate is added to make the flocks larger. |
| 6 |  | A sedimentation basin is next to the flocking chamber where the flocks sink to the bottom and settle. |
| 7 |  | After passing from the sedimentation tank, the water is quickly filtered through a 1.5-meter-thick bed of sand. The sand filters will remove the last remnants of flocks. |
| 8 |  | The water passing through after the sand filter is clear and colorless and can still have a certain smell and taste. For an additional improvement of water quality, it is pumped to a carbon filter through this tank. |

| | | |
|---|---|---|
| 9 |  | The water is filtered with a 2.5-meter-thick bed of granular activated carbon, which improves the smell and taste of the water. This filtration also helps to reduce the NOM content and protects against contamination. |
| 10 |  | After filtration with activated carbon the water is treated with a UV assembly where the water is disinfected with the help of ultraviolet light. |
| 11 |   | After purification, the water is treated with a dosage of monochloramine ($NH_2Cl$) which is a mild form of chlorine and a Lime/Soda dosage. The chlorine dosage is to prevent bacterial growth in the pipe network and the lime dosage is to adjust the pH/alkalinity, which can reduce the risk of corrosion in the pipe network. |
| 12 |  | The final drinking water is then led to a reservoir from where it is pumped out to the pipe network and subsequently distributed to the consumers. |

## A1.4: LCA Research Design and Method

To achieve the aim and objectives of the study, a six-step procedure is followed. See **Figure 20** which illustrates the chosen methodologies.

**Step 1:** A pre-study is conducted to understand the working of the WTP in Norrvatten. This is done through video conference interviews and emails with the people working in Norrvatten's treatment plant. Only qualitative data is collected at this stage.

**Step 2:** The required quantitative data is collected by conducting interviews with Norrvatten and Ramboll through email and video conference meetings, contacting chemical suppliers through email. The supplementary data are acquired by conducting literature reviews of various previously made internal research by Norrvatten and other external research of Norrvatten's WTP.

**Step 3:** The modelling of the stand-alone and comparative assessments (LCA) of the WTP is conducted in SimaPro by utilizing the information acquired from following Step 1 and 2.

**Step 4:** The modelling of the sensitivity analysis is carried out as proposed in the objectives, with the information collected in Step 2, to identify how the WTP performs with the declared parameter changes.

**Step 5:** Other literature reviews are made to support the results from the initial analysis made from the acquired models from SimaPro.

**Step 6:** A complete analysis is made from the modelled life cycle impact assessment results and a discussion is followed to interpret the conducted research to answer the study's aim and objectives.

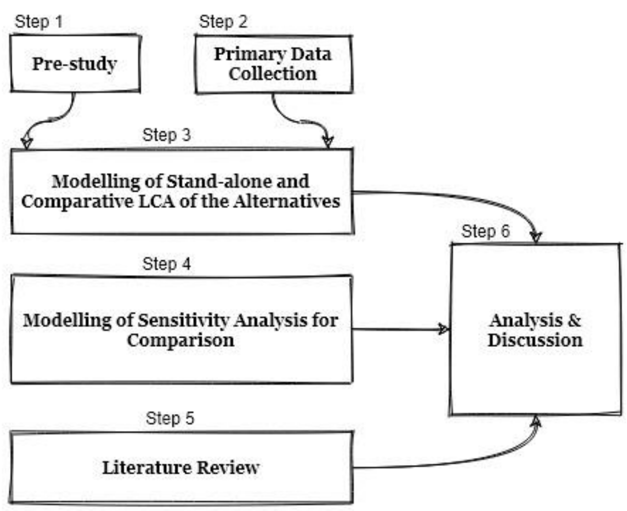



**Figure 20:** The six-step research methodology as implemented in the study.

## ❖ Life Cycle Assessment

Life Cycle Assessment methodology is used as a tool to examine and identify and quantify the potential cumulative environmental impacts and the consumption of the resource from the earth as a result of the usage of the product, process or service throughout the entirety of its lifetime (Curran, 2015). An entire life cycle would include raw material extraction, manufacture or the preparation of the product/system, transportation involved in distribution of raw materials/product, use of the product/system followed by a safe disposal or recycling of the product/system at the end of its lifetime. This form of life cycle is called a Cradle-to-grave method (Sadhukhan et al., 2014). A cradle-to-gate method is a partial assessment of the product's lifetime from the resource extraction (Cradle) till the end of the factory gate. This does not include its transportation to the consumers (Cao, 2017).

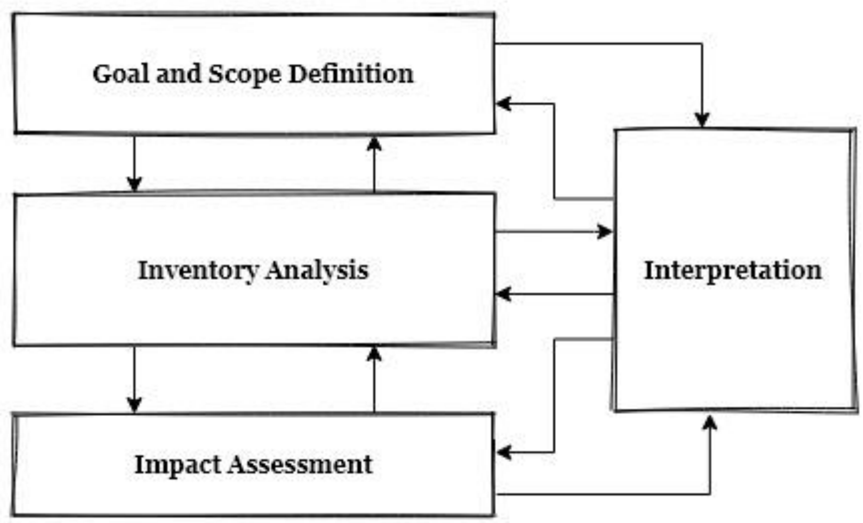



**Figure 21:** Life Cycle Assessment framework as adapted from ISO 14044:2006.

The LCA methodology is internationally standardized according to ISO 14040:2006 (European Commission JRC, 2011). The ISO 14040 series of international standards is the adopted framework (see **Figure 21** above) which covers the four stages: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and the interpretation (Curran, 2015). A new product can be developed, or an existing product can be improved using the results of the LCA study, by organizations. The results can assist policy makers to help them strategize a futuristic plan for a long-lasting impact (Sadhukhan et al., 2014).

### ▪ Goal and Scope

The first phase of an LCA is to define the goal and scope for the study. The phase also includes, product and co-product definition, waste utilization routes (if any), utilized allocation methods (if any), geographical and temporal boundaries for the study with clear justifications. (Sadhukhan et al., 2014).

The product is defined using the Functional Unit which is taken as the unit of analysis for the study. If more than one alternative is studied in a LCA study, the functional unit stands as a basis for comparison (Sadhukhan et al., 2014). While defining a system, the assumptions, limitations, availability and quality of data taken for the study is acknowledged for the audience. The various impact categories used for the impact assessment are recognized. The impacts can vary for the components supplied from various regions and hence this should be attributed to a geographical location for the assessment (Sadhukhan et al., 2014).

There are two main types of LCA studies based on their goal and scope: Attributional and Consequential. An Attributional LCA investigates into the description of the physical flows (to and from) of the system that are imperative in environmental terms, while a Consequential LCA investigates into the description of how the physical flows are transformed as a reaction to a different choice in the system (Pérez & Yalavarthy, 2020). In this study, an attributional LCA is carried out due to the objective of the LCA which states to identify the environmental impacts of the system.

- **Life Cycle Inventory Analysis**

The compilation and quantification of the various materials used, energy consumed, transportation done with their environmental releases in each stage of the life cycle is involved in the Life Cycle Inventory Analysis (LCI). All the inventory data are quantified based on the defined functional unit. The data provided for the foreground system and the background system are different. Some of the data is given by the producer, which in this case study is Norrvatten, while some data is taken from different databases in SimaPro. The provided data should be best representative for the time period and geographical area of reference taken for the study (Klöpffer, 2013 as cited in Mujkic & Kesavan, 2020). The collected data is implemented inside the system after following the assumption, allocation and cut-off rules as defined in the goal and scope for the study. It should be noted that if any allocation problems arise due to multi-input, multi-output and open loop recycling due to material reuse, it should be handled by employing various allocation solutions and if possible, a potential sensitivity analysis (Finnveden et al., 2009 as cited in Mujkic & Kesavan, 2020).

- **Life Cycle Impact Assessment**

The Life Cycle Impact Assessment (LCIA) is the process to assess the possible human health and environmental impacts from the environmental resources and releases acknowledged in the LCI phase. The emission flows from LCI level are transformed into the intuitive impact categories, as declared in the guidelines of ISO standards (Du, 2015, pp.6). The included inventory data is analyzed and translated into its potential contribution across a range of environmental impact category indicators. The assessment is done to acquire a better understanding of the potential impact areas that need to be placed under protection by the society (Finnveden & Potting, 2014 as cited in Mujkic & Kesavan, 2020).

The LCIA is carried out by either focusing the impacts at a problem-oriented level (midpoint) or a damage-oriented level (endpoint) (Du, 2015, pp.6). In this study, the LCIA is carried out at a midpoint level which according to author Du (2015, pp.6), is an assessment where the complex emission list is interpreted into an easier and commonly accepted group of emission indicators (Global warming, Acidification, Eutrophication etc.) as opposed to the endpoint level assessment where it focuses primarily on the broader overall effects, such as the consequences of production of the product for human health, resource depletion or the quality of ecosystem.

The required criteria in LCIA according to Guinée (2001); SAIC (2006); ILCD (2010) (as cited in Du, 2015) is Selection of the impact indicators, Classification, Characterization followed by optional steps like Normalization, Grouping and Weighting.

*Selection of Impact Categories*: A key element in conducting a LCIA is to take into account which environmental impacts are considered for the study. The most appropriate set of impact indicators is chosen with their relevance to the goal and scope of the LCA, the selected LCIA methodology and the data availability for the required LCI (Du, 2015).

*Classification:* The LCI result parameters are sorted and assigned into different commonly recognized impact indicators. There are two ways of allocating the LCI results into different impact categories. Either assign them to all the impact categories if the effects are independent of each indicator or partition them within the impact categories for avoiding the 'double counting' when the effects are dependent on each indicator (Du, 2015).

*Characterization*: A number of chemicals are quantified on an equivalence scale to measure their contribution to the overall impact of the product in focus for a given impact category. This process is called characterization and it includes the summation of the effects of all the pertinent substances by utilizing the appropriate characterization factors. For e.g., effects of the decay of Radon-222, Carbon-14, Cesium-14 etc. for ionizing radiation. According to Hauschild (2005), characterization results will relate the impact contribution from each emission indicator in a common unit (%) to express the impact score.

*Normalization, Grouping and Weighting:* These are optional steps proposed by ISO standards through the LCA framework. Normalization results will relate the resource consumption and the impact scores to a common reference, which is usually the total activities of a society. The impact contribution is spread across a common scale with different units (Hauschild, 2005). The normalized data is based on a single geographically and temporally defined reference system as mentioned in the goal and scope section, for a whole year (Du, 2015). Grouping results are the results from characterization sorted into one of more sets for enabling the explanation of the results. Weighting is a procedure where an environmental impact category is given a relative importance over others and assessed in a qualitative and quantitative manner. The importance of the impact indicator can be assigned based on monetary values, technology abatement, authoritative panels, authorized targets, proxies etc. (Du, 2015). But the use of weighting results for product comparisons is not recommended by ISO standards due to the bias they introduce in the LCIA results (Du, 2015).

- ### Interpretation

The numerous LCA results are compiled and refined to address specific concerns with meaningful conclusions. According to author Du (2015), ISO standard 14040 defines the interpretation of LCIA as the phase in LCA where the findings of either or both the inventory analysis and impact assessment are combined consistent with the previously defined goal and scope to reach conclusions and recommendations. At this stage, the drawbacks, limitations and the uncertainty issues in the study should be illuminated clearly (Du, 2015). An example of a possible issue is the unavailability of primary data required for analysis. Acquiring the concerned data would be through other sources like conducted literature reviews, database entries in SimaPro or assuming data that is used on an average basis. The collected data may not be time specific or geographic appropriate to equate it to the environmental impacts for comparison.

# Appendix 2: Flow diagrams

## A2.1: Treatment process in Future alternatives and existing WTP

### Alternative 0

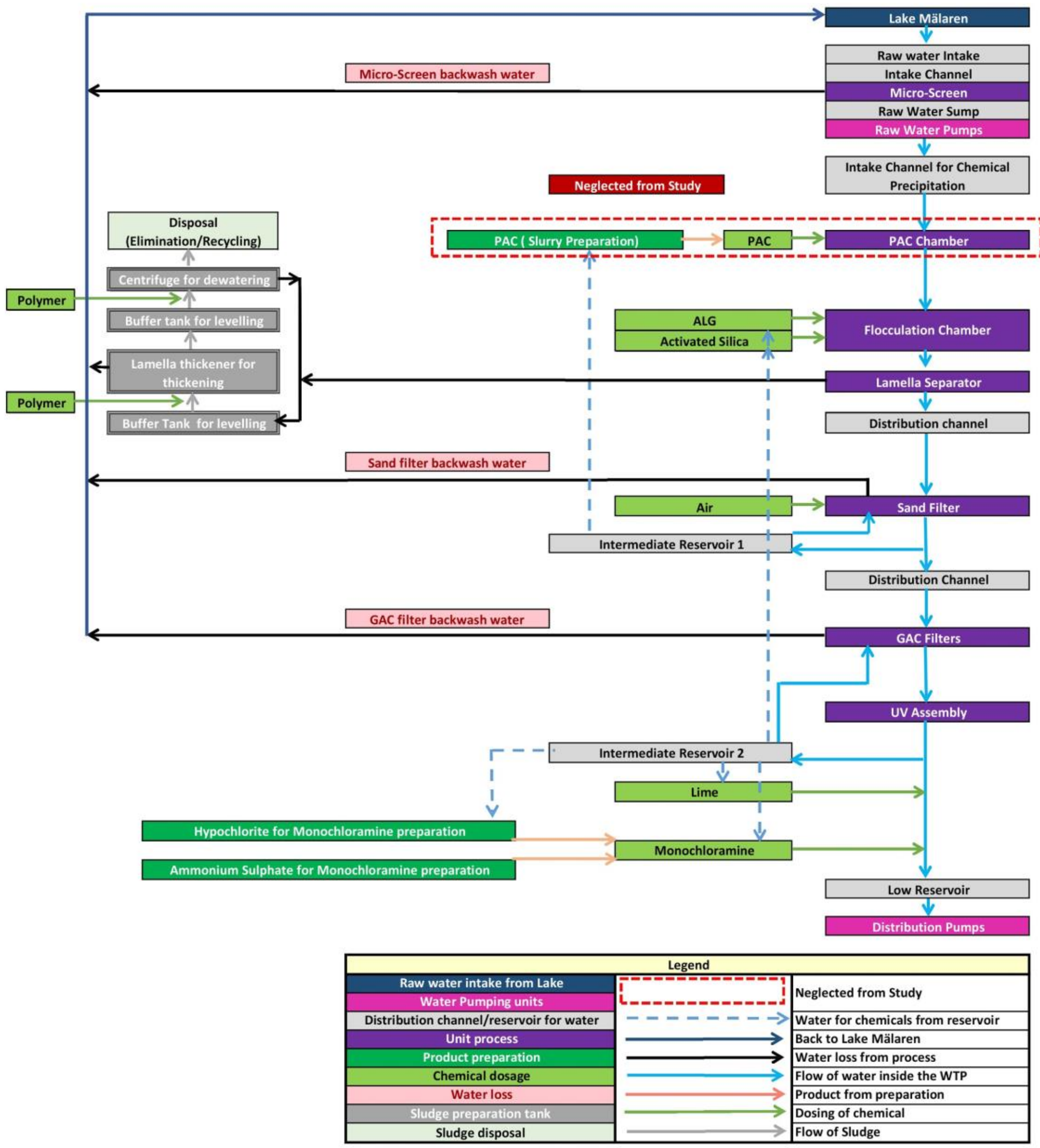



**Figure 22:** The flow diagram of all the unit processes, chemicals, water loss and other purification processes involved in the existing water treatment plant (Alternative 0).

## Alternative 7

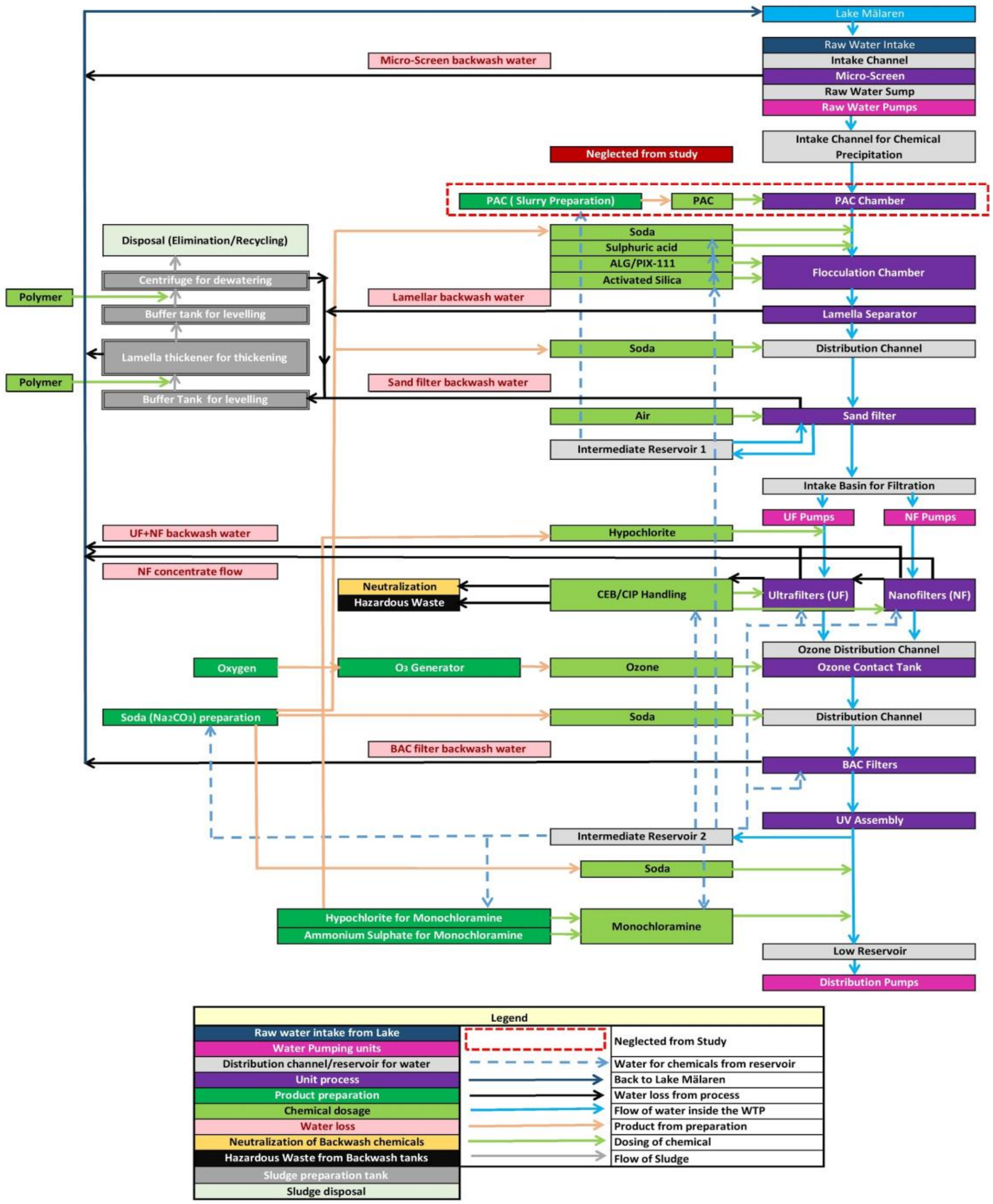



**Figure 23:** The flow diagram of all the unit processes, chemicals, water loss and other purification processes involved in the future Alternative 7.

## Alternative 8

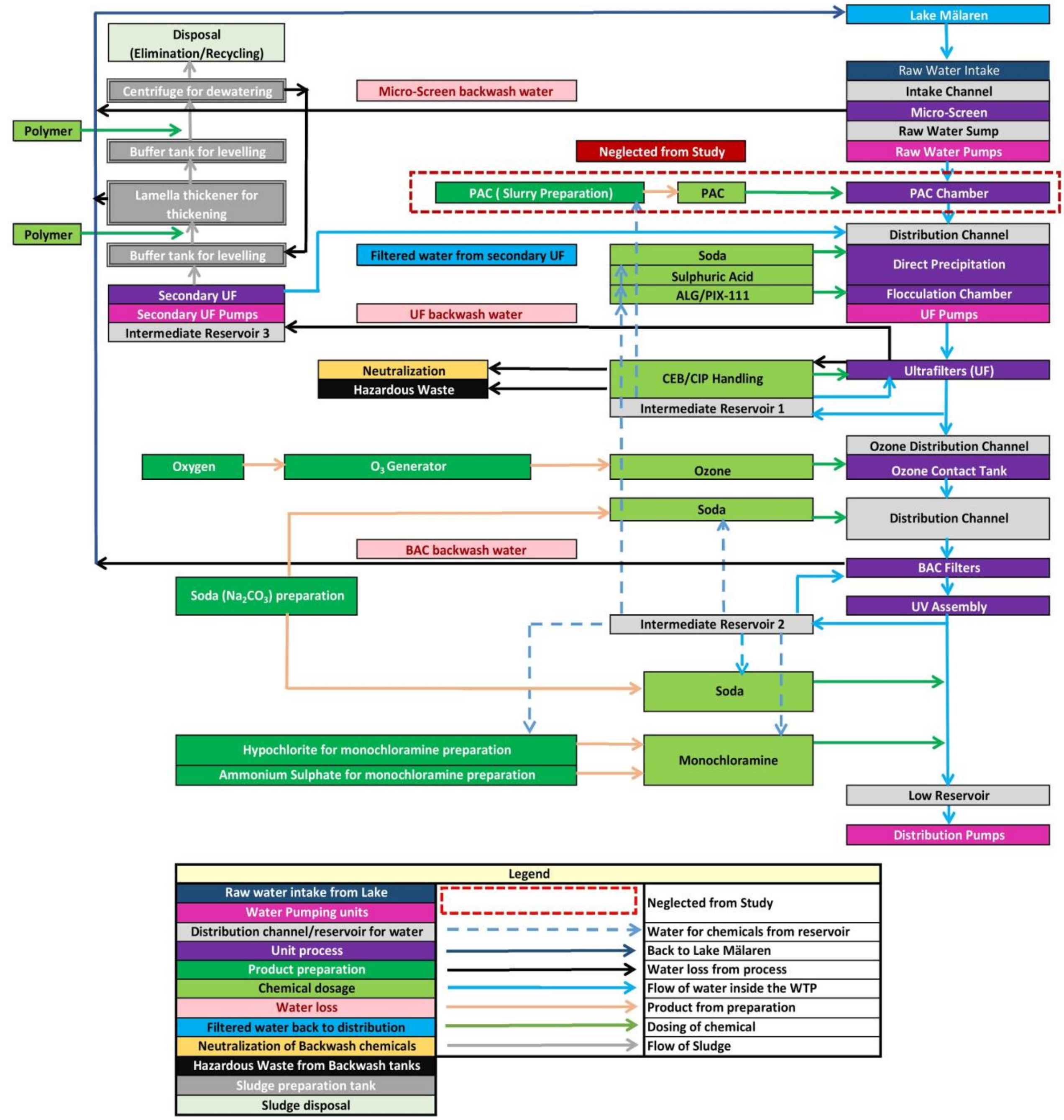



**Figure 24:** The flow diagram of all the unit processes, chemicals, water loss and other purification processes involved in the future Alternative 8.

## Alternative 9

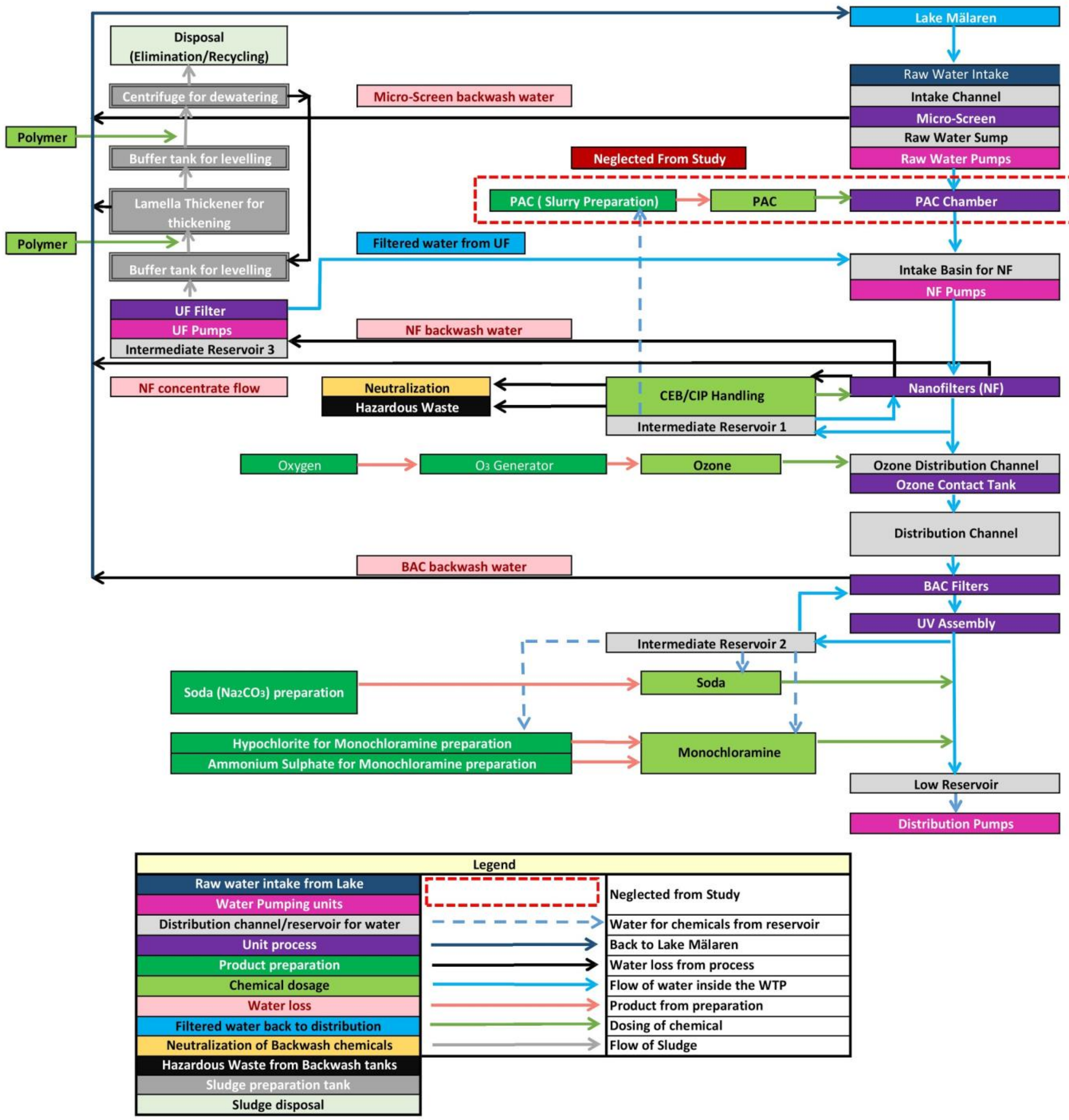



**Figure 25:** The flow diagram of all the unit processes, chemicals, water loss and other purification processes involved in the future Alternative 9.

## A2.2: Water Balance Calculated for the future alternatives and the existing WTP

## Alternative 7 - 208 MLD

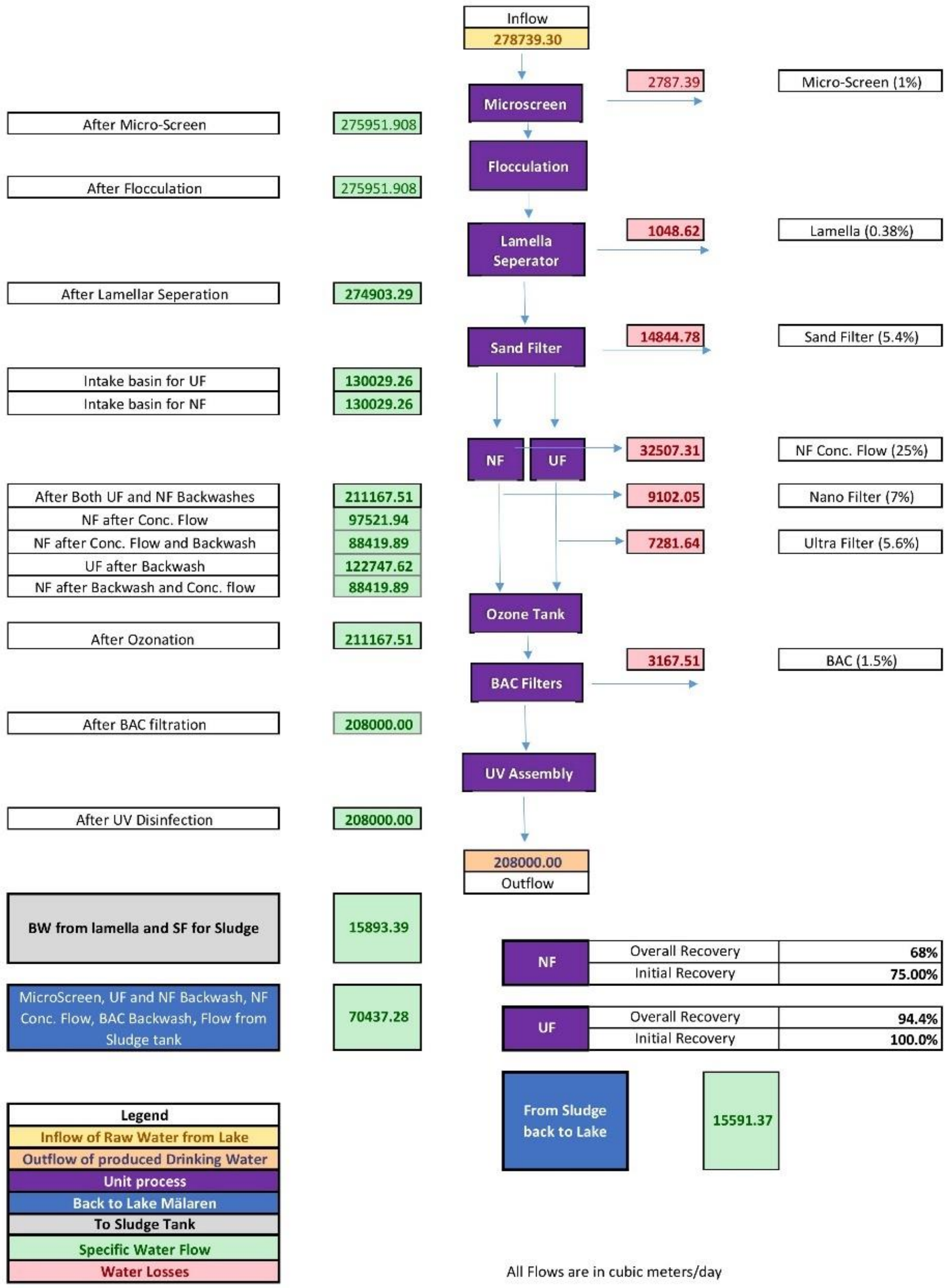



**Figure 26:** Water balance calculation for Alternative 7 with 208 MLD of average/sustained capacity.

## Alternative 8 - 208 MLD

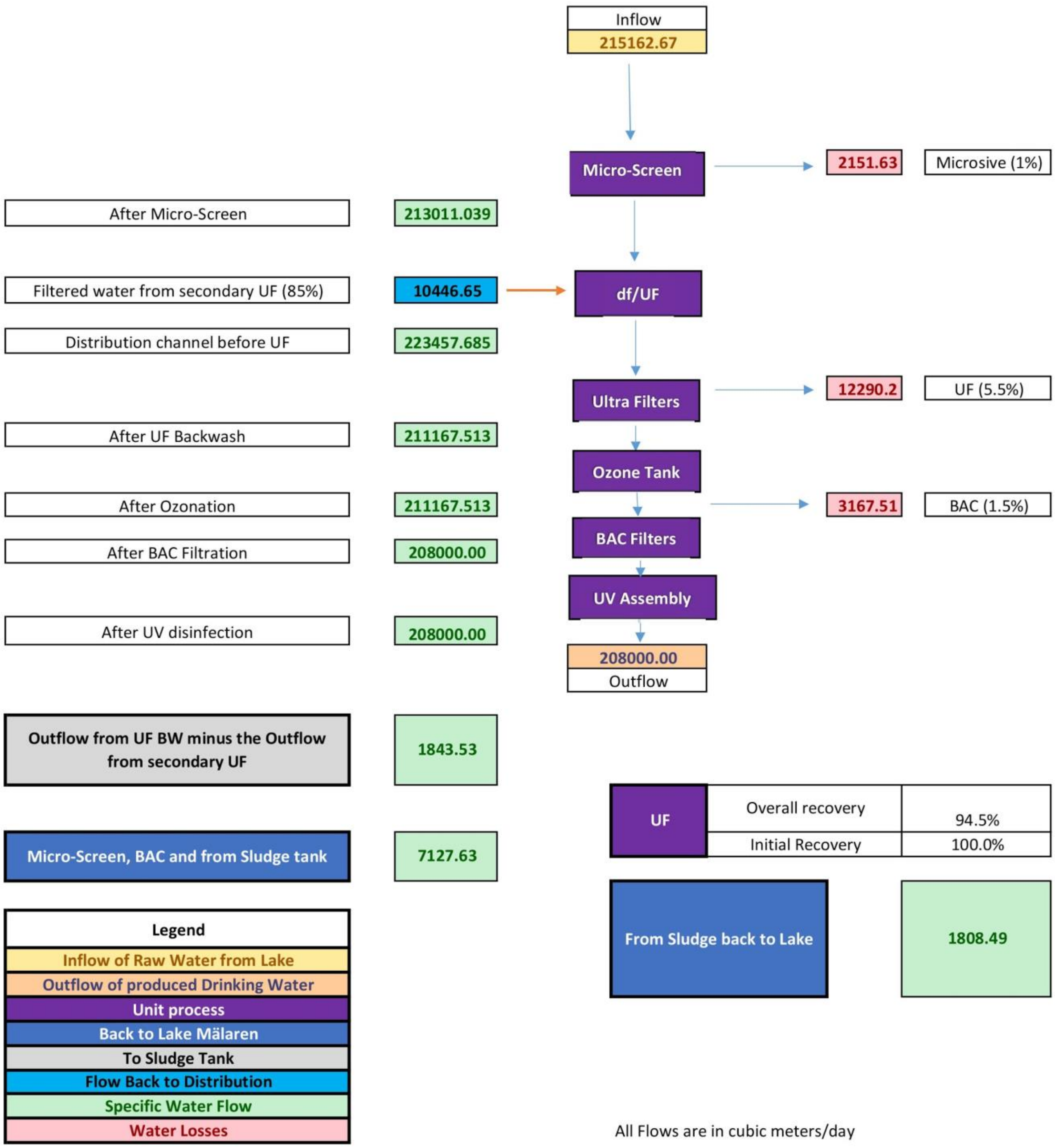



**Figure 27:** Water balance calculation for Alternative 8 with 208 MLD of average/sustained capacity.

## Alternative 9 - 208 MLD

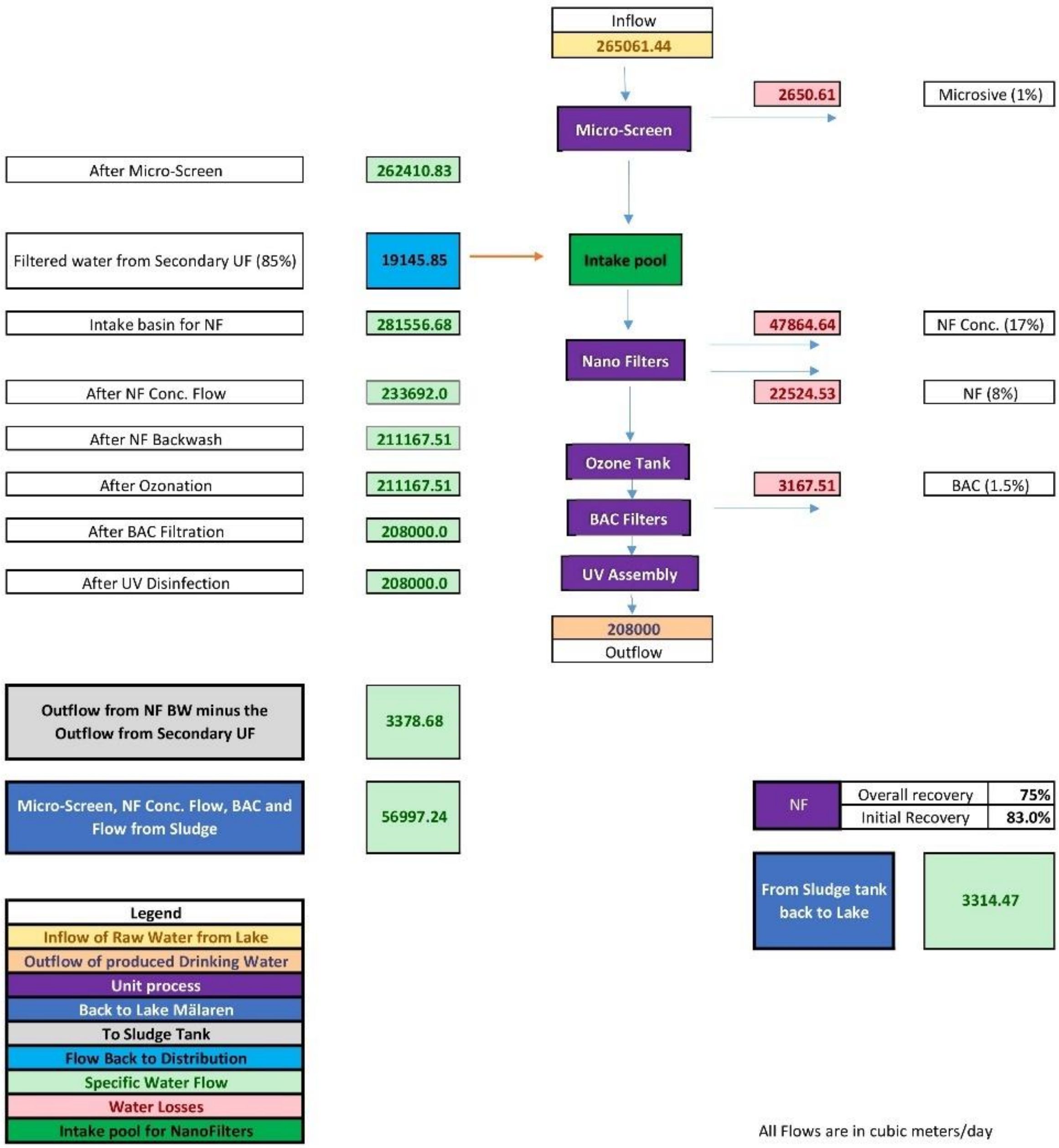



**Figure 28:** Water balance calculation for Alternative 9 with 208 MLD of average/sustained capacity.

## Alternative 0 - 160 MLD

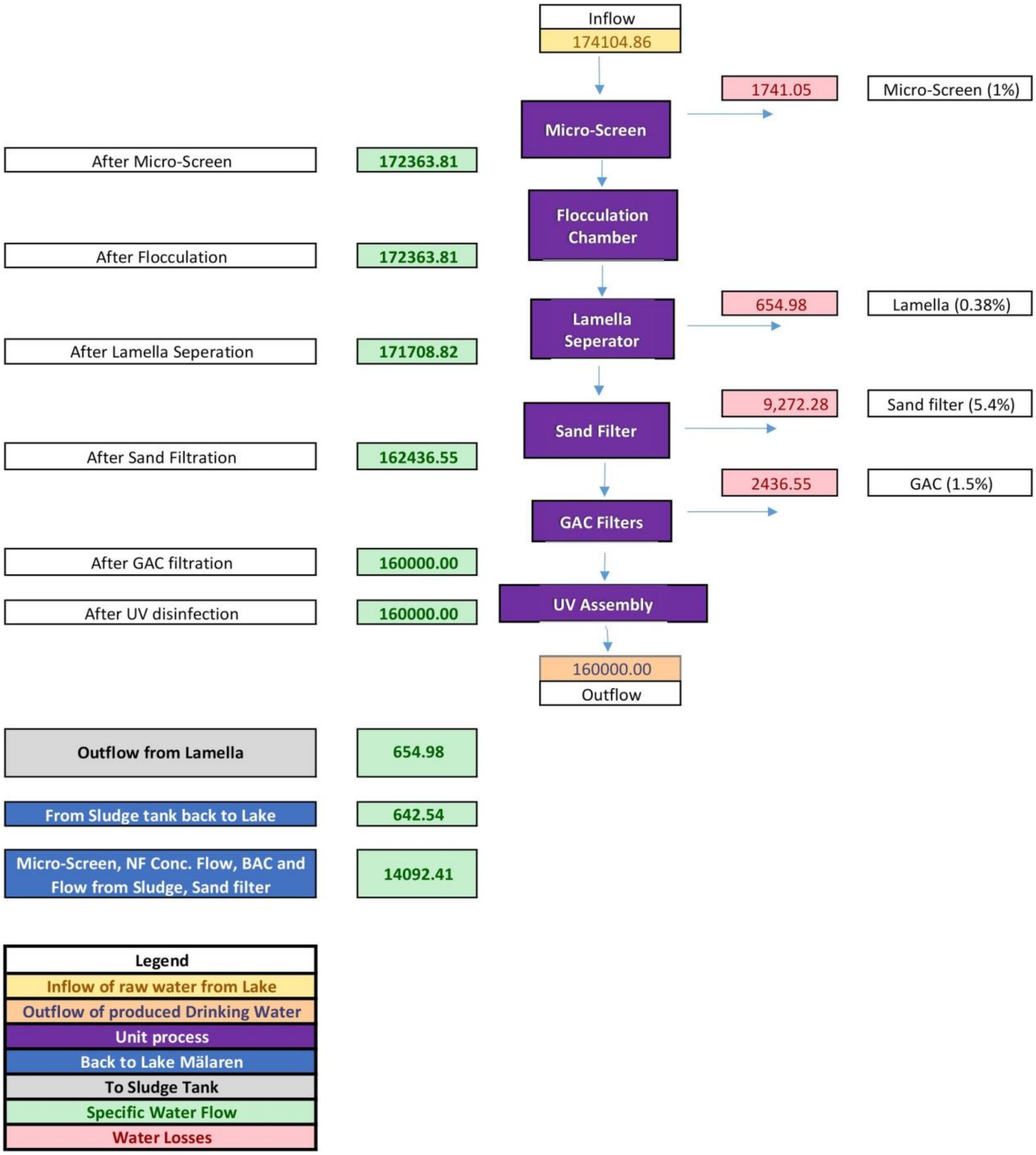



**Figure 29:** Water balance calculation for Alternative 0 or the Existing WTP with 160 MLD of average/sustained capacity.

# Appendix 3: Inventory data

All the necessary inventory data have been collected from the provided internal documents from Norrvatten and calculated for the respective alternatives and the calculation details are provided in Appendix 7 for reference. Both the inventory data for the main assessment and the sensitivity assessment are included in this appendix.

## A3.1: Chemical consumption inventory data for each alternative

**Table 8:** Chemical consumption inventory data for alternatives with 208 MLD of average capacity - ALG and other chemical doses.

| Chemical Requirement | Alternative 7 | | Alternative 8 | | Alternative 9 | | Unit |
|---|---|---|---|---|---|---|---|
| ALG | 2558.35 | | 1827.10 | | - | | t/y |
| Sulfuric acid | 594.26 | | 458.72 | | - | | t/y |
| Activated Silica | 211.52 | | - | | - | | t/y |
| Soda | 4578.29 | | 3306.30 | | 3782.82 | | t/y |
| Liquid Ozone | 308.30 | | 308.30 | | 308.30 | | t/y |
| Hypochlorite (15%) | 15.18 | | 15.18 | | 15.18 | | t/y |
| Ammonium sulfate | 45.55 | | 37.96 | | 7.59 | | t/y |
| Granular Activated Carbon | 728.18 | | 584.79 | | 692.45 | | t/y |
| Polymer | 30.01 | | 3.48 | | 6.38 | | t/y |
| **Chemicals required in CEB** | **Alternative 7** | | **Alternative 8** | | **Alternative 9** | | **Unit** |
| | **UF** | **NF** | **UF1** | **UF2** | **UF** | **NF** | |
| Hydrochloric acid (30%) | 60.74 | - | 103.63 | 5.7 | 0.36 | - | t/y |
| Sulphuric acid (100%) | - | 41.68 | - | - | - | 4.49 | t/y |
| Sodium hydroxide (50%) | 43.01 | 6.53 | 73.39 | 4.04 | 1.34 | 16.71 | t/y |
| Sodium hypochlorite (15%) | 51.59 | 13.87 | 77.65 | 4.27 | 3.51 | 43.92 | t/y |

**Table 9:** Chemical consumption inventory data for alternatives with 208 MLD of average capacity - PIX-111 and other chemical doses.

| Chemical Requirement | Alternative 7 | Alternative 8 | Alternative 9 | Unit |
|---|---|---|---|---|
| PIX-111 (40%) | 2064.81 | 1446.13 | - | t/y |
| Sulfuric acid | 2659.07 | 1904.85 | - | t/y |
| Activated Silica | 211.52 | - | - | t/y |
| Soda | 10357.12 | 7994.80 | 3782.82 | t/y |
| Liquid Ozone | 308.30 | 308.30 | 308.30 | t/y |
| Hypochlorite (15%) | 15.18 | 15.18 | 15.18 | t/y |
| Ammonium sulfate | 45.55 | 37.96 | 7.59 | t/y |
| Granular Activated Carbon | 728.18 | 584.79 | 692.45 | t/y |
| Polymer | 30.01 | 3.48 | 6.38 | t/y |

| Chemicals required in CEB | Alternative 7 | | Alternative 8 | | Alternative 9 | | Unit |
|---|---|---|---|---|---|---|---|
| | UF | NF | UF1 | UF2 | NF | UF | |
| Hydrochloric acid (30%) | 60.74 | - | 103.63 | 5.7 | - | 0.36 | t/y |
| Sulphuric acid (100%) | - | 41.68 | - | - | 4.49 | - | t/y |
| Sodium hydroxide (50%) | 43.01 | 6.53 | 73.39 | 4.04 | 16.71 | 1.34 | t/y |
| Sodium hypochlorite (15%) | 51.59 | 13.87 | 77.65 | 4.27 | 43.92 | 3.51 | t/y |

**Table 10:** Chemical consumption inventory data for alternatives with 160 MLD of average capacity - ALG and other chemical doses.

| Chemical Requirement | Alternative 0 | Unit |
|---|---|---|
| ALG | 2765.69 | t/y |
| Activated Silica | 145.76 | t/y |
| Hypochlorite (15%) | 94.92 | t/y |
| Ammonium Sulphate | 13.56 | t/y |
| Lime | 1006.47 | t/y |
| Granular Activated Carbon | 432.72 | t/y |
| Polymer | 1.24 | t/y |

## A3.2: Energy consumption inventory data for each alternative:

The energy consumption from unit processes UF, NF and UV in the WTP were calculated based on their specific flow at the unit process. See calculation under Appendix 7 for reference. Inventory data reference: Forslund, personal communication, 2020; Pentair, 2019; Bergström, 2020.

**For an average plant capacity of 208 MLD**

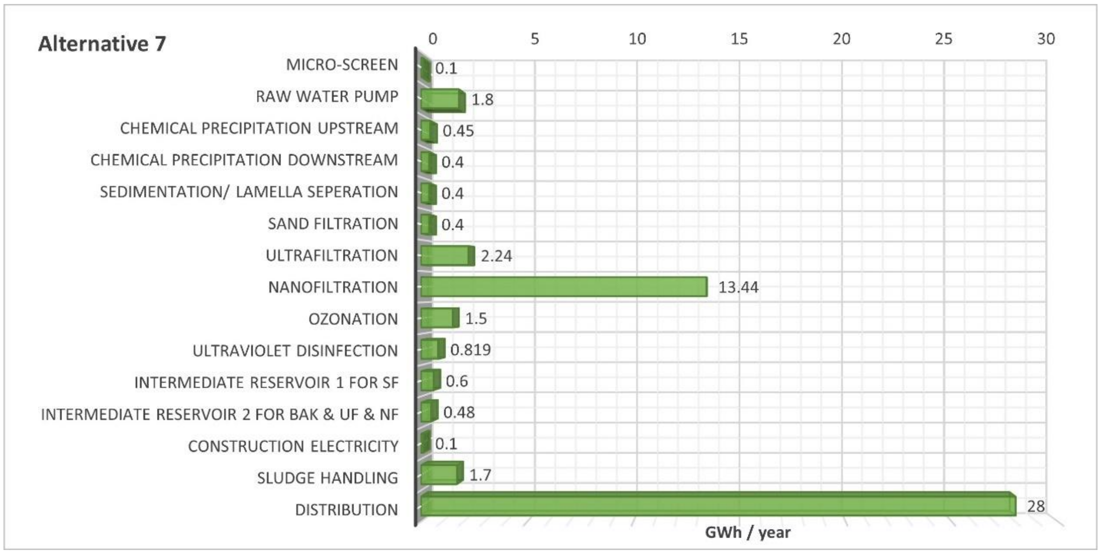



**Figure 30:** Chart representing the various energy requirements from each unit process and other equipment in Alternative 7 with 208 MLD plant capacity.

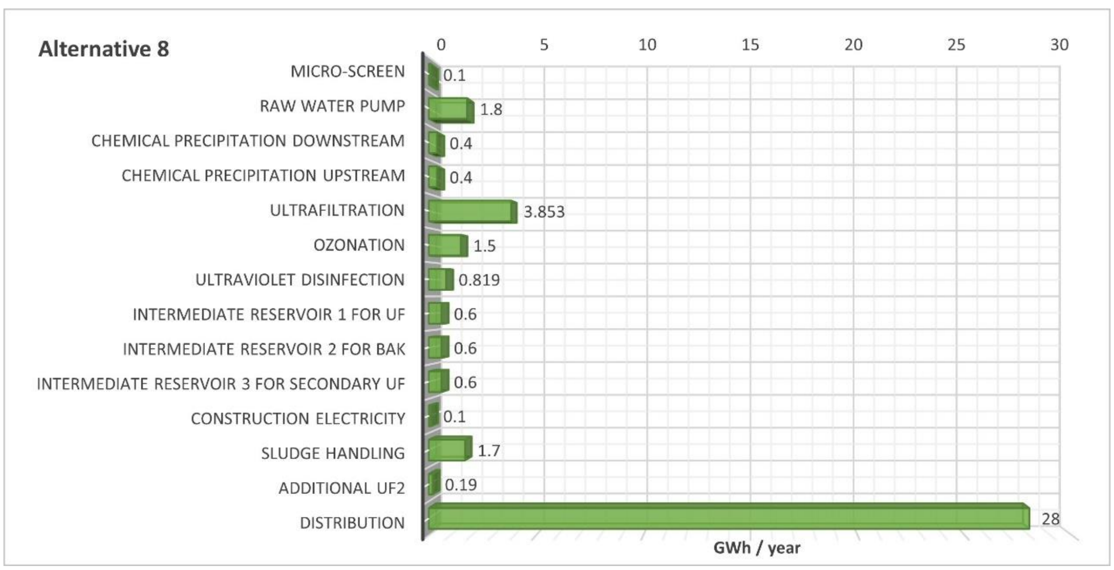



**Figure 31:** Chart representing the various energy requirements from each unit process and other equipment in Alternative 8 with 208 MLD plant capacity.

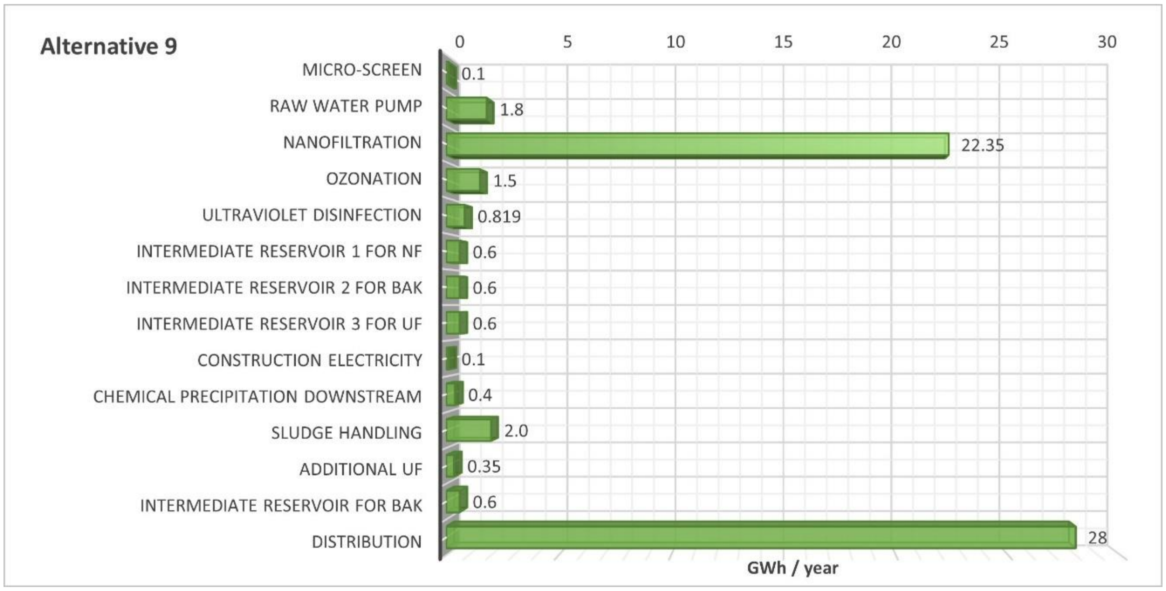



**Figure 32:** Chart representing the various energy requirements from each unit process and other equipment in Alternative 9 with 208 MLD plant capacity.

**For the existing WTP with 160 MLD of average plant capacity**

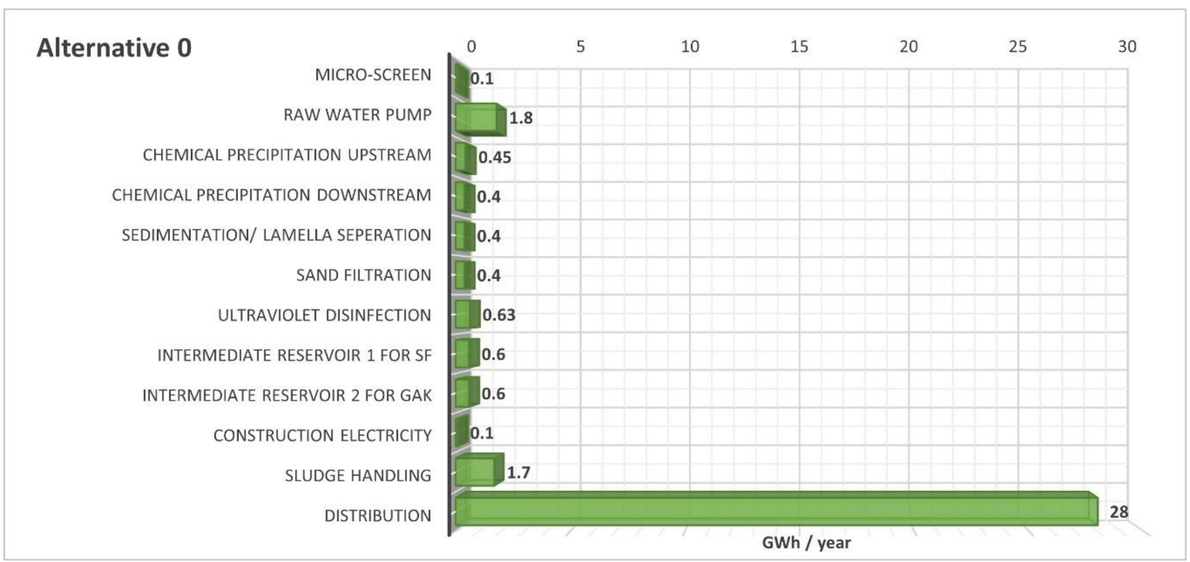



**Figure 33:** Chart representing the various energy requirements from each unit process and other equipment in Alternative 0 with 160 MLD plant capacity.

## A3.3: Transportation inventory data for each alternative

**Table 11:** Type of transportation and the round-trip distance from specific chemical suppliers to the WTP.

| Chemical | From manufacturer | Distance (Km) | Type of transport | Reference |
|---|---|---|---|---|
| ***Heavy Truck*** | | | | |
| Granular Activated Carbon | Chemviron | 3624 | *Heavy truck* | (McCleaf, personal communication, 2020) |
| Sludge | Ragn-Sells | 55.2 | *Heavy truck* | (Karlsson, 2020) |
| ALG | Kemira | 1164 | *Heavy truck* | (Bergström, 2020) |
| PIX-111 | Kemira | 1164 | *Heavy truck* | (Bergström, 2020) |
| Sulfuric acid | Kemira | 1164 | *Heavy truck* | (Bergström, 2020) |
| Soda | Kemira | 1164 | *Heavy truck* | (Bergström, 2020) |
| Lime | Nordkalk | 310 | *Heavy truck* | (Karlsson, 2020) |
| ***Light Truck*** | | | | |
| Hypochlorite | Kemira | 1164 | *Light truck* | (Bergström, 2020) |
| Activated Silica | Sibelco Nordic | 720 | *Light truck* | (Bergström, 2020) |
| Ammonium sulfate | Brenntag Nordic | 2708 | *Light truck* | (Bergström, 2020) |
| Hydrochloric acid (CEB) | Kemira | 1164 | *Light truck* | (Karlsson, 2020) |
| Sulphuric acid (CEB) | Kemira | 1164 | *Light truck* | (Karlsson, 2020) |
| Sodium hydroxide (CEB) | Kemira | 1164 | *Light truck* | (Karlsson, 2020) |
| Sodium hypochlorite (CEB) | Kemira | 1164 | *Light truck* | (Karlsson, 2020) |

**Table 12:** Inventory data for the transportation in a plant with 208 MLD as average capacity using ALG as main coagulant.

| Chemical | Alternative 7 | Alternative 8 | Alternative 9 | Unit |
|---|---|---|---|---|
| Hydrochloric acid (CEB) | 70698.32 | 127263.41 | 5642.87 | tkm |
| Sulphuric acid (CEB) | 48510.74 | - | - | tkm |
| Sodium hydroxide (CEB) | 57664.17 | 90123.95 | 21008.47 | tkm |
| Sodium hypochlorite (CEB) | 76198.26 | 95359.42 | 55209.13 | tkm |
| ALG | 2977919.56 | 2126746.94 | - | tkm |
| Sulfuric acid | 691721.47 | 533949.23 | - | tkm |
| Activated Silica | 152292.34 | - | - | tkm |
| Soda | 5329133.08 | 3848529.82 | 4403207.59 | tkm |
| Hypochlorite | 17674.18 | 17674.18 | 17674.18 | tkm |
| Ammonium sulfate | 123354.82 | 102795.68 | 20559.14 | tkm |
| Sludge | 135882.21 | 15761.41 | 28886.37 | tkm |
| Granular Activated Carbon | 2376773.88 | 1908762.81 | 2260144.56 | tkm |
| Polymer | 34928.05 | 4051.42 | 7425.14 | tkm |

**Table 13:** Inventory data for the transportation in a plant with 208 MLD as average capacity using PIX-111 as main coagulant.

| Chemical | Alternative 7 | Alternative 8 | Alternative 9 | Unit |
|---|---|---|---|---|
| Hydrochloric acid (CEB) | 70698.32 | 127263.41 | 5642.87 | tkm |
| Sulphuric acid (CEB) | 48510.74 | - | - | tkm |
| Sodium hydroxide (CEB) | 57664.17 | 90123.95 | 21008.47 | tkm |
| Sodium hypochlorite (CEB) | 76198.26 | 95359.42 | 55209.13 | tkm |
| PIX-111 | 2403439.02 | 1683297.58 | - | tkm |
| Sulfuric acid | 3095160.49 | 2217246.81 | - | tkm |
| Activated Silica | 152292.34 | - | - | tkm |
| Soda | 12055683.27 | 9305946.21 | 4403207.59 | tkm |
| Hypochlorite | 17674.18 | 17674.18 | 17674.18 | tkm |
| Ammonium sulfate | 123354.82 | 102795.68 | 20559.14 | tkm |
| Sludge | 135882.21 | 15761.41 | 28886.37 | tkm |
| Granular Activated Carbon | 2376773.88 | 1908762.81 | 2260144.56 | tkm |
| Polymer | 34928.05 | 4051.42 | 7425.14 | tkm |

**Table 14:** Inventory data for the transportation in the existing WTP with 160 MLD as average capacity using ALG as main coagulant.

| Chemical | Alternative 0 | Unit |
|---|---|---|
| ALG | 3219266.29 | tkm |
| Activated Silica | 104947.16 | tkm |
| Hypochlorite | 110481.36 | tkm |
| Ammonium Sulphate | 36718.64 | tkm |
| Lime | 312007.16 | tkm |
| Sludge | 5599.84 | tkm |
| Granular Activated Carbon | 1412387.46 | tkm |
| Polymer | 1439.42 | tkm |

## A3.4: Other inputs in the WTP inventory data for each alternative

**Table 15:** The inventory data for the other inputs required in the WTP for each alternative with 208 MLD as average plant capacity.

| Other Requirements | Alternative 7 | Alternative 8 | Alternative 9 | Unit |
|---|---|---|---|---|
| Granular Activated Carbon | 1.995 | 1.602 | 1.897 | t/d |
| Sludge | 6.74 | 4.43 | 1.43 | t/d |
| Raw water Intake | 278739.3 | 223852.69 | 265061.44 | $m^3/d$ |
| Produced drinking water | 208000 | 208000 | 208000 | t |
| Back to Lake | 70437.28 | 15654.17 | 56997.24 | $m^3/d$ |
| Water Treatment Plant (Infrastructure) | 0.0069 | 0.0069 | 0.0069 | p |
| Ultrafiltration Modules | 1 (20x22) | 2 (7x22) | 1 (7x22) | p |
| Nanofiltration Modules | 1 (44x120) | - | 1 (88x120) | p |
| Ultraviolet Lamp | 1 (9) | 1 (9) | 1 (9) | p |
| Reactivation of GAC | 1.71 | 1.6 | 1.89 | t/d |

**Table 16:** The inventory data for the other inputs required in the WTP for Alternative 0 with 160 MLD as average plant capacity.

| Other Requirements | Alternative 0 | Unit |
|---|---|---|
| Granular Activated Carbon | 1.185 | t/d |
| Sludge | 1.54 | t/d |
| Raw water Intake | 174104.86 | $m^3/d$ |
| Produced drinking water | 160000 | t |
| Back to Lake | 60278.05 | $m^3/d$ |
| Water Treatment Plant (Infrastructure) | 0.0053 | p |
| Ultraviolet Lamp | 1 (9) | p |
| Reactivation of GAC | 1.185 | t/d |

# Appendix 4: Ecoinvent datasets in SimaPro for each Alternatives

The inventory data for SimaPro is calculated from the data provided in the internal documents* provided by Norrvatten. All the mentioned *materials/assemblies* in the following tables are in their specific quantity per year. They are converted and taken by their specific parts in the respective *products* to fit the functional unit of 1 $m^3$ of produced drinking water. The calculation reference is provided in Annexure 7.

*(Forsberg (2019), Lindgren (2019) & (2020), Pentair, (2019))

**Table 17:** LCA inventory data for entry in SimaPro for Alternative 7 using ALG and PIX-111 with 208 MLD average capacity.

| | | | Comments |
|---|---|---|---|
| **Products** | | | |
| **A7 Chemical consumption (ALG)** | 1.32E-8 | p | To convert it to the functional unit. = (1p/ (208,000 * 365) |
| **Materials/assemblies** | | | |
| Sodium hypochlorite, without water, in 15% solution state {RER}\| sodium hypochlorite production, product in 15% solution state \| Cut-off, U | 65.46 | ton | Backwash Chemicals for UF/NF |
| Sodium hydroxide, without water, in 50% solution state {RER}\| chlor-alkali electrolysis, diaphragm cell \| Cut-off, U | 49.54 | ton | |
| Hydrochloric acid, without water, in 30% solution state {RER}\| hydrochloric acid production, from the reaction of hydrogen with chlorine \| Cut-off, U | 60.74 | ton | |
| Sulfuric acid {RER}\| production \| Cut-off, U | 41.68 | ton | |
| Aluminium sulfate, powder {RER}\| production \| Cut-off, U | 2558.35 | ton | Chemicals upstream |
| Sulfuric acid {RER}\| production \| Cut-off, U | 594.26 | ton | |
| Activated silica {GLO}\| production \| Cut-off, U | 211.52 | ton | |
| Soda ash, light, crystalline, heptahydrate {RER}\| soda production, solvay process \| Cut-off, U | 4578.29 | ton | Soda taken for all dosages |
| Activated carbon, granular {RER}\| activated carbon production, granular from hard coal \| Cut-off, U | 728.18 | ton | GAC for filtration |
| Ozone, liquid {RER}\| production \| Cut-off, U | 308.30 | ton | $O_3$ for Ozonation |
| Sodium hypochlorite, without water, in 15% solution state {RER}\| sodium hypochlorite production, product in 15% solution state \| Cut-off, U | 15.18 | ton | Chemicals downstream |
| Ammonium sulfate, as N {RER}\| ammonium sulfate production \| Cut-off, U | 45.55 | ton | |
| Polyacrylamide {GLO}\| production \| Cut-off, U | 30.01 | ton | Polymer for sludge |
| | | | |
| **Products** | | | |
| **A7 Energy consumption (ALG)** | 1.32E-8 | p | To convert it to the functional unit. = (1p/ (208000 * 365) |
| **Materials/assemblies** | | | |
| Distribution | 28000.00 | p | Pumping through pipes for consumers (kWh) |
| Total (excluding distribution) | 52429.62 | p | Electricity consumption in WTP by all the unit processes (kWh) |

| | | | |
|---|---|---|---|
| **Products** | | | |
| **A7 Transportation (ALG)** | 1.32E-8 | p | To convert it to the functional unit. = (1p/ (208,000 * 365) |
| **Processes** | | | |
| Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Cut-off, U | 11375547.99 | tkm | Heavy transport for Chemicals |
| Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}\| market for transport, freight, lorry 3.5-7.5 metric ton, EURO6 \| Cut-off, U | 581320.87 | tkm | Light transport for Chemicals |
| Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Cut-off, U | 135882.20 | tkm | Heavy transport for Sludge |

| | | | |
|---|---|---|---|
| **Products** | | | |
| **A7 Chemical consumption (PIX-111)** | 1.32E-8 | p | To convert it to the functional unit. = (1p/ (208,000 * 365) |
| **Materials/assemblies** | | | |
| Sodium hypochlorite, without water, in 15% solution state {RER}\| sodium hypochlorite production, product in 15% solution state \| Cut-off, U | 65.46 | ton | Backwash Chemicals for UF/NF |
| Sodium hydroxide, without water, in 50% solution state {RER}\| chlor-alkali electrolysis, diaphragm cell \| Cut-off, U | 49.54 | ton | |
| Hydrochloric acid, without water, in 30% solution state {RER}\| hydrochloric acid production, from the reaction of hydrogen with chlorine \| Cut-off, U | 60.74 | ton | |
| Sulfuric acid {RER}\| production \| Cut-off, U | 41.68 | ton | |
| Iron (III) chloride, without water, in 40% solution state {CH}\| iron (III) chloride production, product in 40% solution state \| Cut-off, U | 2064.81 | ton | Chemicals upstream |
| Sulfuric acid {RER}\| production \| Cut-off, U | 2659.07 | ton | |
| Activated silica {GLO}\| production \| Cut-off, U | 211.517 | ton | |
| Soda ash, light, crystalline, heptahydrate {RER}\| soda production, solvay process \| Cut-off, U | 10357.12 | ton | Soda taken for all dosages |
| Activated carbon, granular {RER}\| activated carbon production, granular from hard coal \| Cut-off, U | 728.18 | ton | GAC for filtration |
| Ozone, liquid {RER}\| production \| Cut-off, U | 308.30 | ton | $O_3$ for Ozonation |
| Sodium hypochlorite, without water, in 15% solution state {RER}\| sodium hypochlorite production, product in 15% solution state \| Cut-off, U | 15.18 | ton | Chemicals downstream |
| Ammonium sulfate, as N {RER}\| ammonium sulfate production \| Cut-off, U | 45.55 | ton | |
| Polyacrylamide {GLO}\| production \| Cut-off, U | 30.007 | ton | Polymer for sludge |

| | | | |
|---|---|---|---|
| **Products** | | | |
| **A7 Energy consumption (PIX-111)** | 1.32E-8 | p | To convert it to the functional unit. = (1p/ (208,000 * 365) |
| **Materials/assemblies** | | | |
| Distribution | 28000 | p | Pumping through pipes for consumers (kWh) |
| Total (excluding distribution) | 52429.62 | p | Electricity consumption in WTP by all the unit processes (kWh) |

| | | | |
|---|---|---|---|
| **Products** | | | |
| **A7 Transportation (PIX-111)** | 1.32E-8 | p | To convert it to the functional unit. = (1p/ (208,000 * 365) |
| **Processes** | | | |
| Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Cut-off, U | 19931056.66 | tkm | Heavy transport for Chemicals |
| Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}\| market for transport, freight, lorry 3.5-7.5 metric ton, EURO6 \| Cut-off, U | 581320.87 | tkm | Light transport for Chemicals |
| Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Cut-off, U | 135882.21 | tkm | Heavy transport for Sludge |

| | | | |
|---|---|---|---|
| **Products** | | | |
| **WTP Other inputs - A7** | 1 | p | 1p of 208,000 ton will fit the functional unit |
| Drinking water (208MLD) | 208000 | ton | Produced drinking water (Converted to Mass) |
| | | | |
| **Avoided products** | | | |
| Activated carbon, granular {RER}\| activated carbon production, granular from hard coal \| Cut-off, U | 1.995 | ton | To negate the burden from production (GAC per day) |
| | | | |
| **Resources** | | | |
| Water, lake, SE | 278739.30 | $m^3$ | Raw water intake |
| | | | |
| **Materials/fuels** | | | |
| Water works, capacity 1.1E$^{10}$ l/year {Europe without Switzerland} \| water works construction, capacity 1.1E$^{10}$ l/year, conventional treatment \| Cut-off, U | 0.0069 | p | For a 208 MLD Capacity of waterwork |
| Ultraviolet lamp {GLO}\| market for \| Cut-off, U | 1 | p | 9 UV lamps for disinfection |
| Ultrafiltration module {GLO}\| market for \| Cut-off, U | 1 | p | UF: Pentair XIGA - 64 $m^2$ – 20 modules, each with 22 membranes |
| Nanofiltration module {GLO}\| market for \| Cut-off, U | 1 | p | NF: HFW1000 - 40 $m^2$ – 44 units, each with 120 modules |
| Activated carbon, granular {RER}\| treatment of spent activated carbon, granular from hard coal, reactivation \| Cut-off, U | 1.995 | ton | Added burden from reactivation (GAC per day) |
| | | | |
| **Emissions to water** | | | |
| Water, SE | 70437.28 | $m^3$ | Back to lake |
| | | | |
| **Waste to treatment** | | | |
| Raw sewage sludge {CH}\| drying, sewage sludge \| Cut-off, U | 6.744 | ton | To construction site |
| | | | |

**Table 18:** LCA inventory data for entry in SimaPro for Alternative 8 using ALG and PIX-111 with 208 MLD average capacity.

| | | | Comments |
|---|---|---|---|
| **Products** | | | |
| **A8 Chemical consumption (ALG)** | 1.32E-8 | p | To convert it to the functional unit. = (1p/ (208,000 * 365) |
| **Materials/assemblies** | | | |
| Sodium hypochlorite, without water, in 15% solution state {RER}\| sodium hypochlorite production, product in 15% solution state \| Cut-off, U | 81.92 | ton | Backwash Chemicals for UF/NF |
| Sodium hydroxide, without water, in 50% solution state {RER}\| chlor-alkali electrolysis, diaphragm cell \| Cut-off, U | 77.43 | ton | |
| Hydrochloric acid, without water, in 30% solution state {RER}\| hydrochloric acid production, from the reaction of hydrogen with chlorine \| Cut-off, U | 109.33 | ton | |
| Aluminium sulfate, powder {RER}\| production \| Cut-off, U | 1827.10 | ton | Chemicals upstream |
| Sulfuric acid {RER}\| production \| Cut-off, U | 458.72 | ton | |
| Soda ash, light, crystalline, heptahydrate {RER}\| soda production, solvay process \| Cut-off, U | 3306.30 | ton | Soda taken for all dosages |
| Activated carbon, granular {RER}\| activated carbon production, granular from hard coal \| Cut-off, U | 584.79 | ton | GAC for filtration |
| Ozone, liquid {RER}\| production \| Cut-off, U | 308.30 | ton | $O_3$ for Ozonation |
| Sodium hypochlorite, without water, in 15% solution state {RER}\| sodium hypochlorite production, product in 15% solution state \| Cut-off, U | 15.18 | ton | Chemicals downstream |
| Ammonium sulfate, as N {RER}\| ammonium sulfate production \| Cut-off, U | 37.96 | ton | |
| Polyacrylamide {GLO}\| production \| Cut-off, U | 3.48 | ton | Polymer for sludge |
| | | | |
| **Products** | | | |
| **A8 Energy consumption (ALG)** | 1.32E-8 | p | To convert it to the functional unit. = (1p/ (208,000 * 365) |
| | | | |
| **Materials/assemblies** | | | |
| Distribution | 28000.00 | p | Pumping through pipes for consumers (kWh) |
| Total (excluding distribution) | 40663.07 | p | Electricity consumption in WTP by all the unit processes (kWh) |
| **Products** | | | |
| **A8 Transportation (ALG)** | 1.32E-8 | p | To convert it to the functional unit. = (1p/ (208,000 * 365) |
| | | | |
| **Processes** | | | |
| Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Cut-off, U | 8417988.81 | tkm | Heavy transport for Chemicals |
| Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}\| market for transport, freight, lorry 3.5-7.5 metric ton, EURO6 \| Cut-off, U | 437268.05 | tkm | Light transport for Chemicals |
| Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Cut-off, U | 15761.41 | tkm | Heavy transport for Sludge |

| | | | |
|---|---|---|---|
| **Products** | | | |
| **A8 Chemical consumption (PIX-111)** | 1.32E-8 | p | To convert it to the functional unit. = (1p/ (208,000 * 365) |
| | | | |
| **Materials/assemblies** | | | |
| Sodium hypochlorite, without water, in 15% solution state {RER}\| sodium hypochlorite production, product in 15% solution state \| Cut-off, U | 81.92 | ton | Backwash Chemicals for UF/NF |
| Sodium hydroxide, without water, in 50% solution state {RER}\| chlor-alkali electrolysis, diaphragm cell \| Cut-off, U | 77.43 | ton | |
| Hydrochloric acid, without water, in 30% solution state {RER}\| hydrochloric acid production, from the reaction of hydrogen with chlorine \| Cut-off, U | 109.33 | ton | |
| Iron (III) chloride, without water, in 40% solution state {CH}\| iron (III) chloride production, product in 40% solution state \| Cut-off, U | 1446.13 | ton | Chemicals upstream |
| Sulfuric acid {RER}\| production \| Cut-off, U | 1904.85 | ton | |
| Soda ash, light, crystalline, heptahydrate {RER}\| soda production, solvay process \| Cut-off, U | 7994.80 | ton | Soda taken for all dosages |
| Activated carbon, granular {RER}\| activated carbon production, granular from hard coal \| Cut-off, U | 584.79 | ton | GAC for filtration |
| Ozone, liquid {RER}\| production \| Cut-off, U | 308.30 | ton | $O_3$ for Ozonation |
| Sodium hypochlorite, without water, in 15% solution state {RER}\| sodium hypochlorite production, product in 15% solution state \| Cut-off, U | 15.18 | ton | Chemicals downstream |
| Ammonium sulfate, as N {RER}\| ammonium sulfate production \| Cut-off, U | 37.96 | ton | |
| Polyacrylamide {GLO}\| production \| Cut-off, U | 3.48 | ton | Polymer for sludge |

| | | | |
|---|---|---|---|
| **Products** | | | |
| **A8 Energy consumption (PIX-111)** | 1.32E-8 | p | To convert it to the functional unit. = (1p/ (208,000 * 365) |
| | | | |
| **Materials/assemblies** | | | |
| Distribution | 28000.00 | p | Pumping through pipes for consumers (kWh) |
| Total (excluding distribution) | 40663.07 | p | Electricity consumption in WTP by all the unit processes (kWh) |

| | | | |
|---|---|---|---|
| **Products** | | | |
| **A8 Transportation (PIX-111)** | 1.32E-8 | p | To convert it to the functional unit. = (1p/ (208,000 * 365) |
| | | | |
| **Processes** | | | |
| Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Cut-off, U | 15115253.42 | tkm | Heavy transport for Chemicals |
| Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}\| market for transport, freight, lorry 3.5-7.5 metric ton, EURO6 \| Cut-off, U | 437268.05 | tkm | Light transport for Chemicals |
| Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Cut-off, U | 15761.41 | tkm | Heavy transport for Sludge |

| | | | |
|---|---|---|---|
| **Products** | | | |
| **WTP Other inputs - A8** | 1 | p | 1p of 208,000 ton will fit the functional unit |
| Drinking water (208MLD) | 208000 | ton | Produced drinking water (Converted to Mass) |
| | | | |
| **Avoided products** | | | |
| Activated carbon, granular {RER}\| activated carbon production, granular from hard coal \| Cut-off, U | 1.6022 | ton | To negate the burden from production (GAC per day) |
| | | | |
| **Resources** | | | |
| Water, lake, SE | 215162.67 | $m^3$ | Raw water intake |
| | | | |
| **Materials/fuels** | | | |
| Water works, capacity $1.1E^{10}$ l/year {Europe without Switzerland} \| water works construction, capacity $1.1E^{10}$ l/year, conventional treatment \| Cut-off, U | 0.0069 | p | For a 208 MLD Capacity of waterwork |
| Ultraviolet lamp {GLO}\| market for \| Cut-off, U | 1 | p | 9 UV lamps for disinfection |
| Ultrafiltration module {GLO}\| market for \| Cut-off, U | 2 | p | UF: Pentair XIGA - 64 $m^2$<br>UF1: 7 units with 44 modules<br>UF2: 7 units with 44 modules |
| Nanofiltration module {GLO}\| market for \| Cut-off, U | 0 | p | NF: HFW1000 - 40 $m^2$<br>(NO NF in this alternative) |
| Activated carbon, granular {RER}\| treatment of spent activated carbon, granular from hard coal, reactivation \| Cut-off, U | 1.6022 | ton | Added burden from reactivation (GAC per day) |
| | | | |
| **Emissions to water** | | | |
| Water, SE | 7127.63 | $m^3$ | Back to lake |
| | | | |
| **Waste to treatment** | | | |
| Raw sewage sludge {CH}\| drying, sewage sludge \| Cut-off, U | 0.782 | ton | To construction site |
| | | | |

**Table 19:** LCA inventory data for entry in SimaPro for Alternative 9 with 208 MLD average capacity.

| | | | Comments |
|---|---|---|---|
| **Products** | | | |
| **A9 Chemical consumption** | 1.32E-8 | p | To convert it to the functional unit. = (1p/(208,000 * 365) |
| | | | |
| **Materials/assemblies** | | | |
| Sodium hypochlorite, without water, in 15% solution state {RER}\| sodium hypochlorite production, product in 15% solution state \| Cut-off, U | 47.43 | ton | Backwash Chemicals for UF/NF |
| Sodium hydroxide, without water, in 50% solution state {RER}\| chlor-alkali electrolysis, diaphragm cell \| Cut-off, U | 18.05 | ton | |
| Hydrochloric acid, without water, in 30% solution state {RER}\| hydrochloric acid production, from the reaction of hydrogen with chlorine \| Cut-off, U | 0.36 | ton | |
| Sulfuric acid {RER}\| production \| Cut-off, U | 4.49 | ton | |
| Activated carbon, granular {RER}\| activated carbon production, granular from hard coal \| Cut-off, U | 692.45 | ton | GAC for filtration |
| Ozone, liquid {RER}\| production \| Cut-off, U | 308.30 | ton | $O_3$ for Ozonation |
| Soda ash, light, crystalline, heptahydrate {RER}\| soda production, solvay process \| Cut-off, U | 3782.82 | ton | Soda taken for all dosages |
| Sodium hypochlorite, without water, in 15% solution state {RER}\| sodium hypochlorite production, product in 15% solution state \| Cut-off, U | 15.18 | ton | Chemicals downstream |
| Ammonium sulfate, as N {RER}\| ammonium sulfate production \| Cut-off, U | 7.59 | ton | |
| Polyacrylamide {GLO}\| production \| Cut-off, U | 6.38 | ton | Polymer for sludge |
| | | | |
| **Products** | | | |
| **A9 Energy consumption** | 1.32E-8 | p | To convert it to the functional unit. = (1p/(208,000 * 365) |
| | | | |
| **Materials/assemblies** | | | |
| Distribution | 28000.00 | p | Pumping through pipes for consumers (kWh) |
| Total (excluding distribution) | 59820.10 | p | Electricity consumption in WTP by all the unit processes (kWh) |
| | | | |
| **Products** | | | |
| **A9 Transportation** | 1.32E-8 | p | To convert it to the functional unit. = (1p/(208,000 * 365) |
| | | | |
| **Processes** | | | |
| Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Cut-off, U | 6663352.16 | tkm | Heavy transport for Chemicals |
| Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}\| market for transport, freight, lorry 3.5-7.5 metric ton, EURO6 \| Cut-off, U | 127518.92 | tkm | Light transport for Chemicals |
| Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Cut-off, U | 28886.37 | tkm | Heavy transport for Sludge |

| | | | |
|---|---|---|---|
| **Products** | | | |
| **WTP Other inputs - A9** | 1 | p | 1p of 208,000 ton will fit the functional unit |
| Drinking water (208MLD) | 208000 | ton | Produced drinking water (Converted to mass) |
| | | | |
| **Avoided products** | | | |
| Activated carbon, granular {RER}\| activated carbon production, granular from hard coal \| Cut-off, U | 1.897 | ton | To negate the burden from production (GAC per day) |
| | | | |
| **Resources** | | | |
| Water, lake, SE | 265061.44 | $m^3$ | Raw water intake |
| | | | |
| **Materials/fuels** | | | |
| Water works, capacity $1.1E^{10}$ l/year {Europe without Switzerland} \| water works construction, capacity $1.1E^{10}$ l/year, conventional treatment \| Cut-off, U | 0.0069 | p | For a 208 MLD Capacity of waterwork |
| Ultraviolet lamp {GLO}\| market for \| Cut-off, U | 1 | p | 9 UV lamps for disinfection |
| Ultrafiltration module {GLO}\| market for \| Cut-off, U | 1 | p | UF: Pentair XIGA - 64 $m^2$ – 7 units with 44 modules |
| Nanofiltration module {GLO}\| market for \| Cut-off, U | 1 | p | NF: HFW1000 - 40 $m^2$ – 88 units with 120 modules |
| Activated carbon, granular {RER}\| treatment of spent activated carbon, granular from hard coal, reactivation \| Cut-off, U | 1.897 | ton | Added burden from reactivation (GAC per day) |
| | | | |
| **Emissions to water** | | | |
| Water, SE | 56997.24 | $m^3$ | Back to Lake |
| | | | |
| **Waste to treatment** | | | |
| Raw sewage sludge {CH}\| drying, sewage sludge \| Cut-off, U | 1.4337 | ton | To construction site |
| | | | |

**Table 20:** LCA inventory data for entry in SimaPro for Alternative 0 using ALG with 160 MLD average capacity.

| | | | Comments |
|---|---|---|---|
| **Products** | | | |
| **A0 Chemical consumption (ALG)** | 1.71E-8 | p | To convert it to the functional unit. = (1p/ (160,000 * 365) |
| **Materials/assemblies** | | | |
| Aluminium sulfate, powder {RER}\| production \| Cut-off, U | 2765.69 | ton | Chemicals upstream |
| Activated silica {GLO}\| production \| Cut-off, U | 145.76 | ton | |
| Activated carbon, granular {RER}\| activated carbon production, granular from hard coal \| Cut-off, U | 432.72 | ton | GAC for filtration |
| Quicklime, milled, loose {CH} production \| Cut-off, U | 1006.47 | ton | Chemicals downstream |
| Sodium hypochlorite, without water, in 15% solution state {RER}\| sodium hypochlorite production, product in 15% solution state \| Cut-off, U | 94.92 | ton | |
| Ammonium sulfate, as N {RER}\| ammonium sulfate production \| Cut-off, U | 13.56 | ton | |
| Polyacrylamide {GLO}\| production \| Cut-off, U | 1.24 | ton | Polymer for sludge |
| | | | |
| **Products** | | | |
| **A0 Energy consumption** | 1.71E-8 | p | To convert it to the functional unit. = (1p/ (160,000 * 365) |
| **Materials/assemblies** | | | |
| Distribution | 28000 | p | Pumping through pipes for consumers (kWh) |
| Total (excluding distribution) | 7179.70 | p | Electricity consumption in WTP by all the unit processes (kWh) |
| | | | |
| **Products** | | | |
| **A0 Transportation** | 1.71E-8 | p | To convert it to the functional unit. = (1p/ (160,000 * 365) |
| **Processes** | | | |
| Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Cut-off, U | 4943660.92 | tkm | Heavy transport for Chemicals |
| Transport, freight, lorry 3.5-7.5 metric ton, euro6 {RER}\| market for transport, freight, lorry 3.5-7.5 metric ton, EURO6 \| Cut-off, U | 253586.58 | tkm | Light transport for Chemicals |
| Transport, freight, lorry >32 metric ton, euro6 {RER}\| market for transport, freight, lorry >32 metric ton, EURO6 \| Cut-off, U | 5599.84 | tkm | Heavy transport for Sludge |

| | | | |
|---|---|---|---|
| **Products** | | | |
| **WTP Other Inputs – A0** | 1 | p | 1p of 160,000 ton will fit the functional unit |
| Drinking water (160MLD) | 160000 | ton | Produced drinking water (Converted to Mass) |
| | | | |
| **Avoided products** | | | |
| Activated carbon, granular {RER}\| activated carbon production, granular from hard coal \| Cut-off, U | 1.1855 | ton | To negate the burden from production (GAC per day) |
| | | | |
| **Resources** | | | |
| Water, lake, SE | 174104.85 | $m^3$ | Raw water intake |
| | | | |
| **Materials/fuels** | | | |
| Water works, capacity $1.1E^{10}$ l/year {Europe without Switzerland} \| water works construction, capacity $1.1E^{10}$ l/year, conventional treatment \| Cut-off, U | 0.0053 | p | For a 160 MLD Capacity of waterwork |
| Ultraviolet lamp {GLO}\| market for \| Cut-off, U | 1 | p | 9 UV lamps for disinfection |
| Activated carbon, granular {RER}\| treatment of spent activated carbon, granular from hard coal, reactivation \| Cut-off, U | 1.1855 | ton | Added burden from reactivation (GAC per day) |
| | | | |
| | | | |
| **Emissions to water** | | | |
| Water, SE | 4820.13 | $m^3$ | Back to lake |
| | | | |
| | | | |
| **Waste to treatment** | | | |
| Raw sewage sludge {CH}\| drying, sewage sludge \| Cut-off, U | 1.54 | ton | To construction site |
| | | | |

# Appendix 5: Other Models from SimaPro

## A5.1: Stand-alone assessment

### A5.1.1: Chemical consumption

**Alternative 7 with ALG**

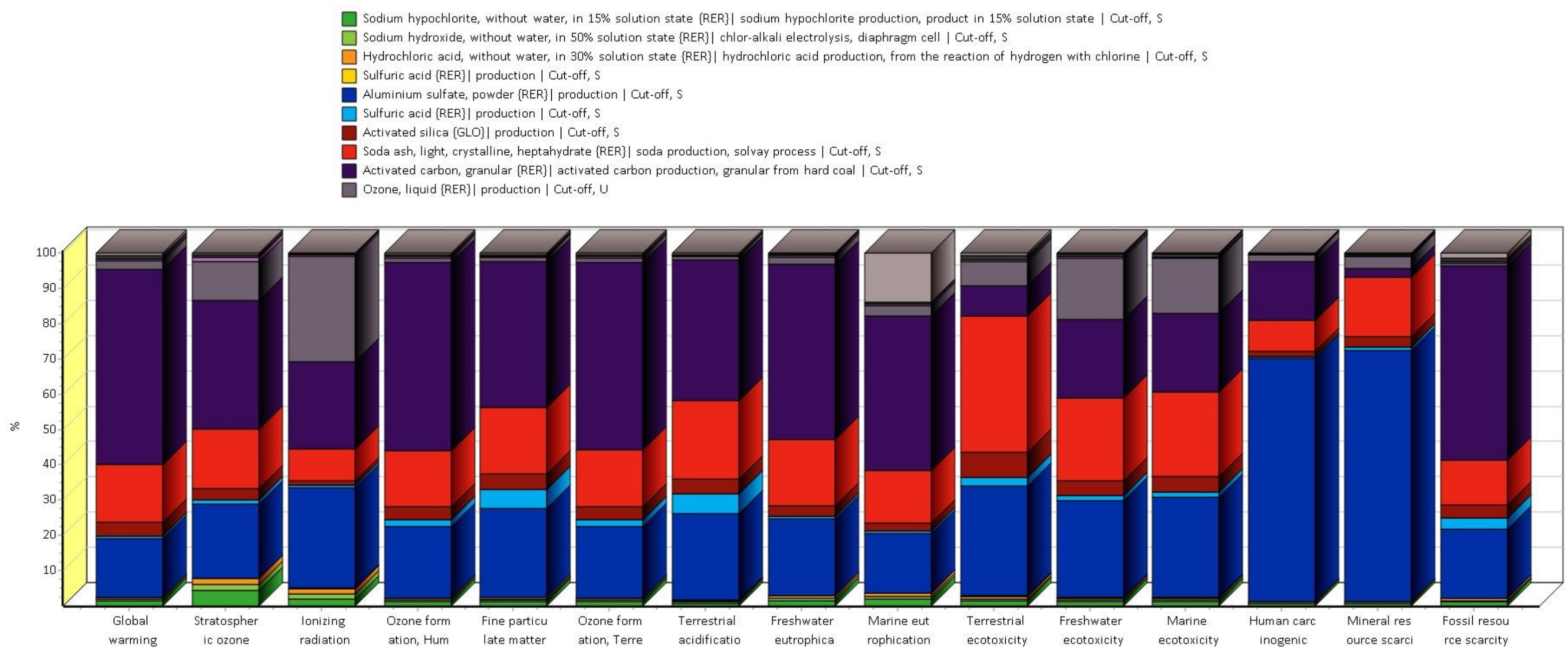



**Figure 34:** Characterized results of the environmental impacts from chemical consumption in Alternative 7 using ALG as main coagulant.

## Alternative 8 with ALG

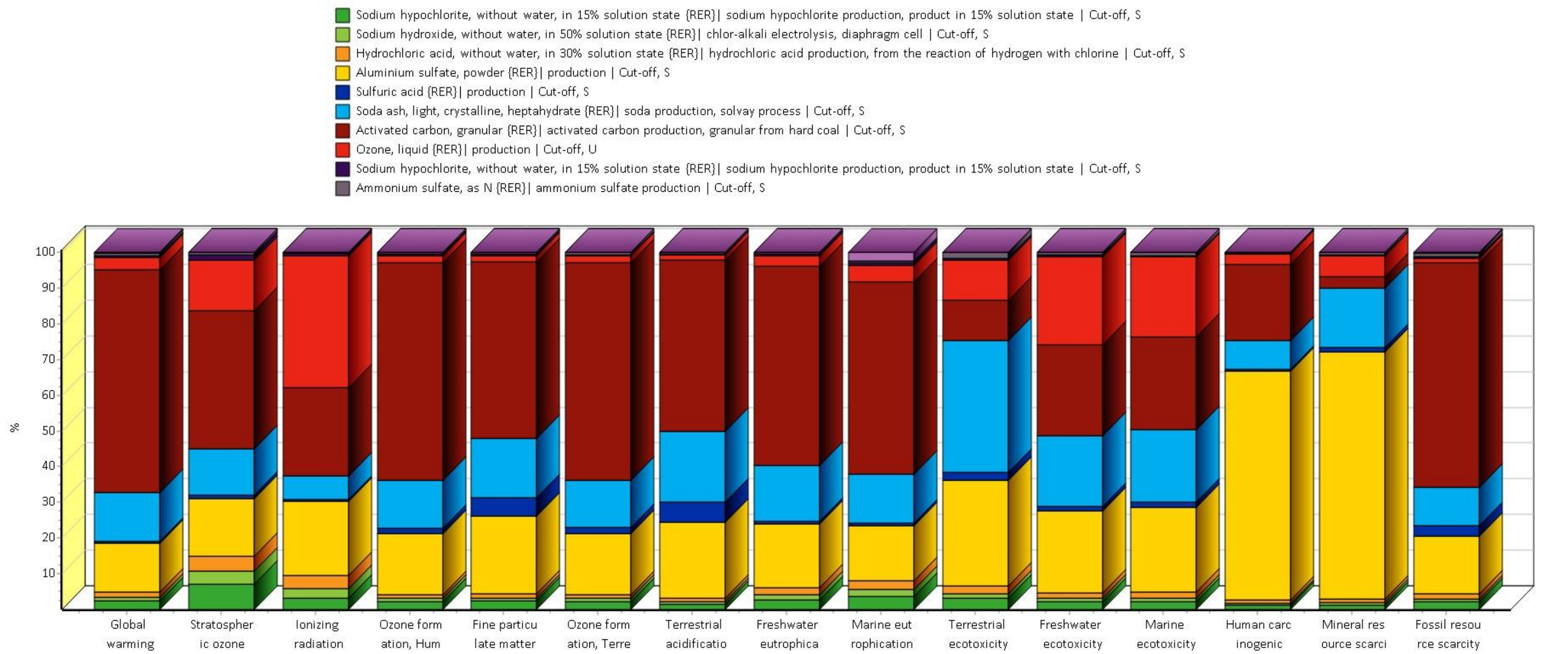



**Figure 35:** Characterized results of the environmental impacts from chemical consumption in Alternative 8 using ALG as main coagulant.

**Alternative 9**

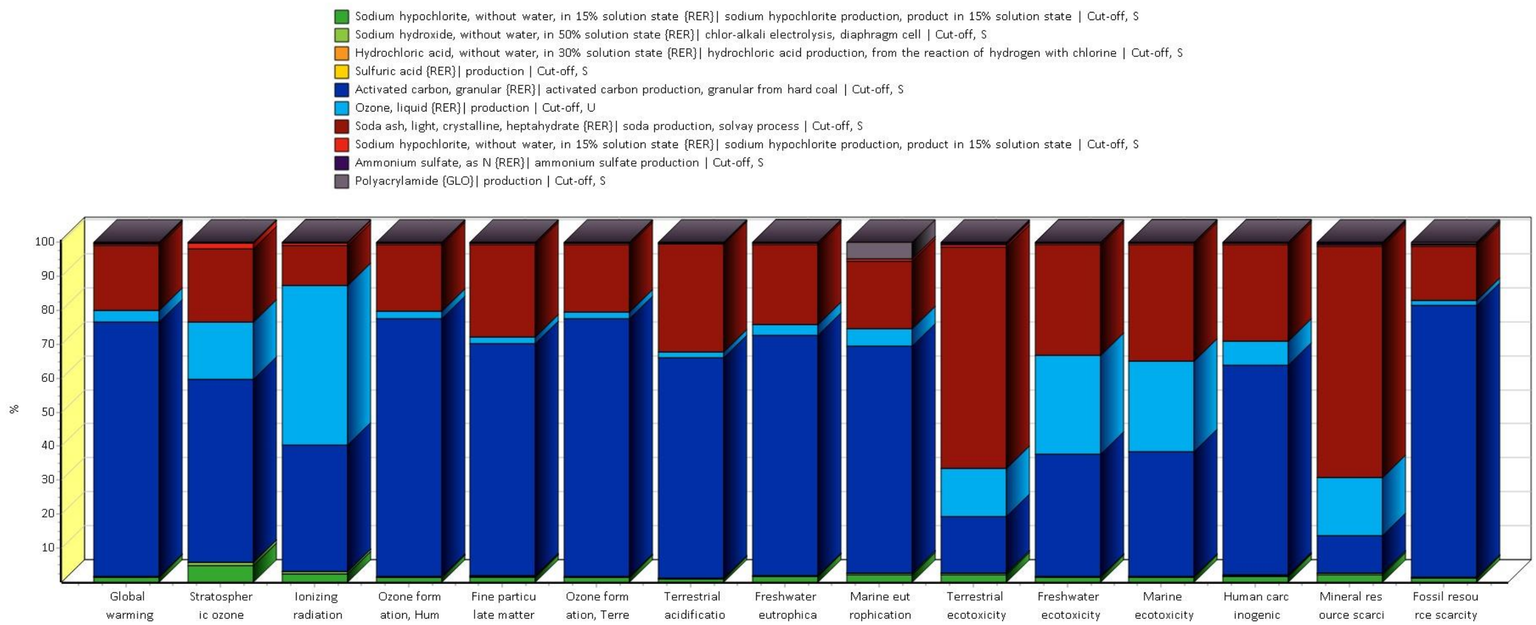



**Figure 36:** Characterized results of the environmental impacts from chemical consumption in Alternative 9.

**Alternative 0 with ALG**

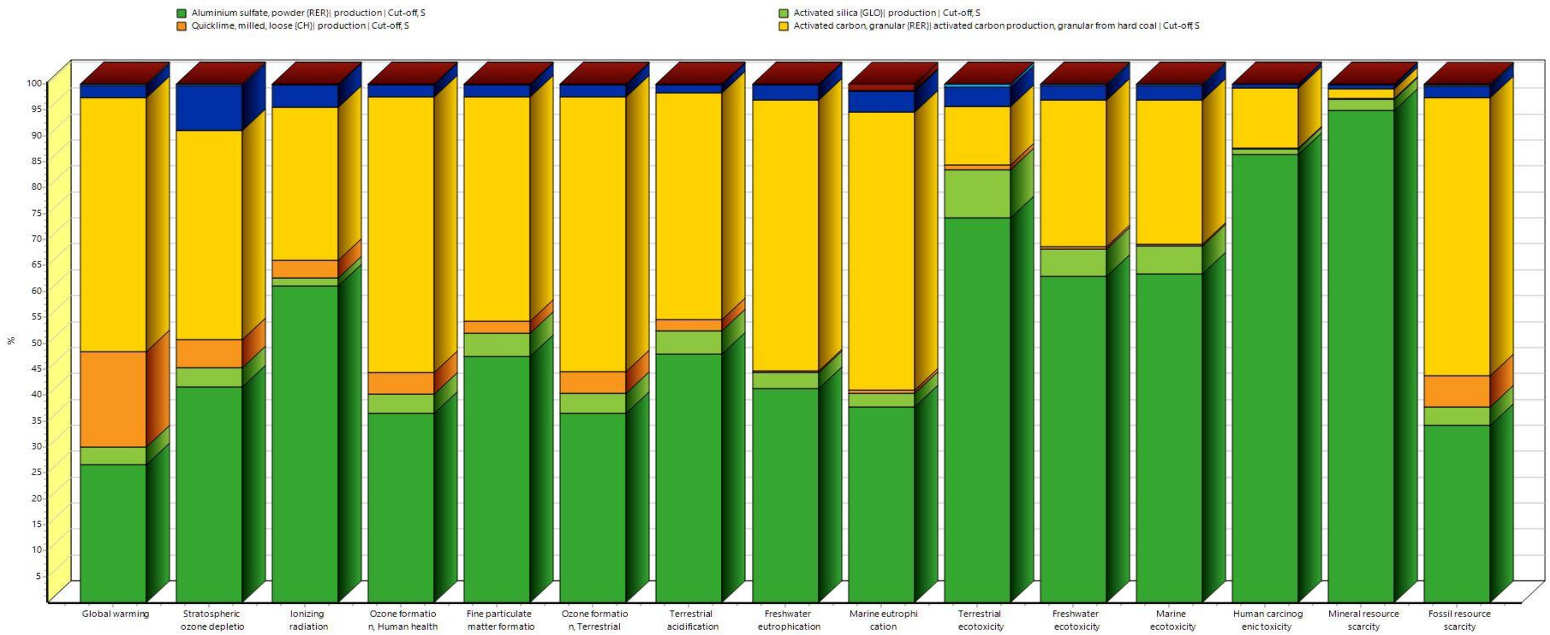



**Figure 37:** Characterized results of the environmental impacts from chemical consumption in Alternative 0 using ALG as main coagulant.

## A5.1.2: Energy consumption

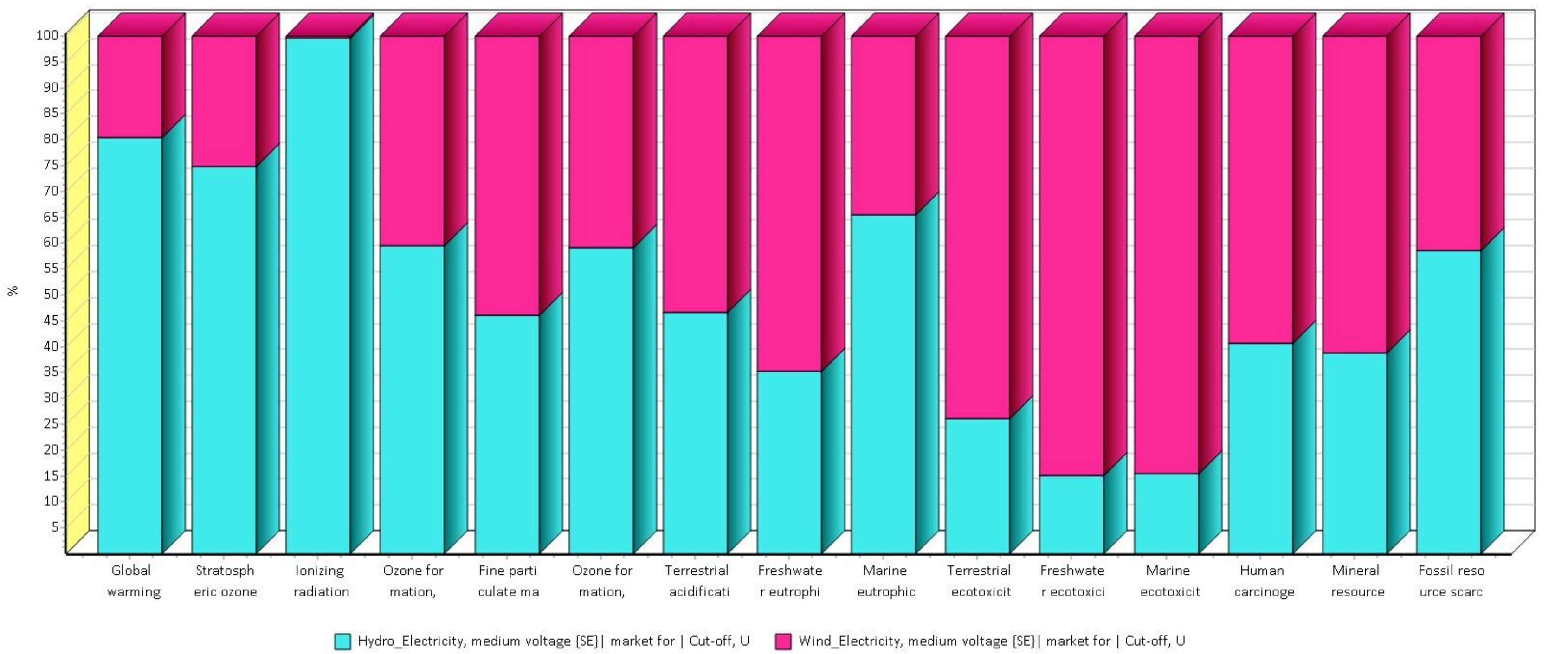



**Figure 38:** Characterized results of the environmental impacts from energy consumption for all the main alternatives.

## A5.1.3: Transportation

The results with orange color are representative of the environmental emissions from sludge transported to the construction site for disposal using *heavy trucks*.

**Alternative 7**

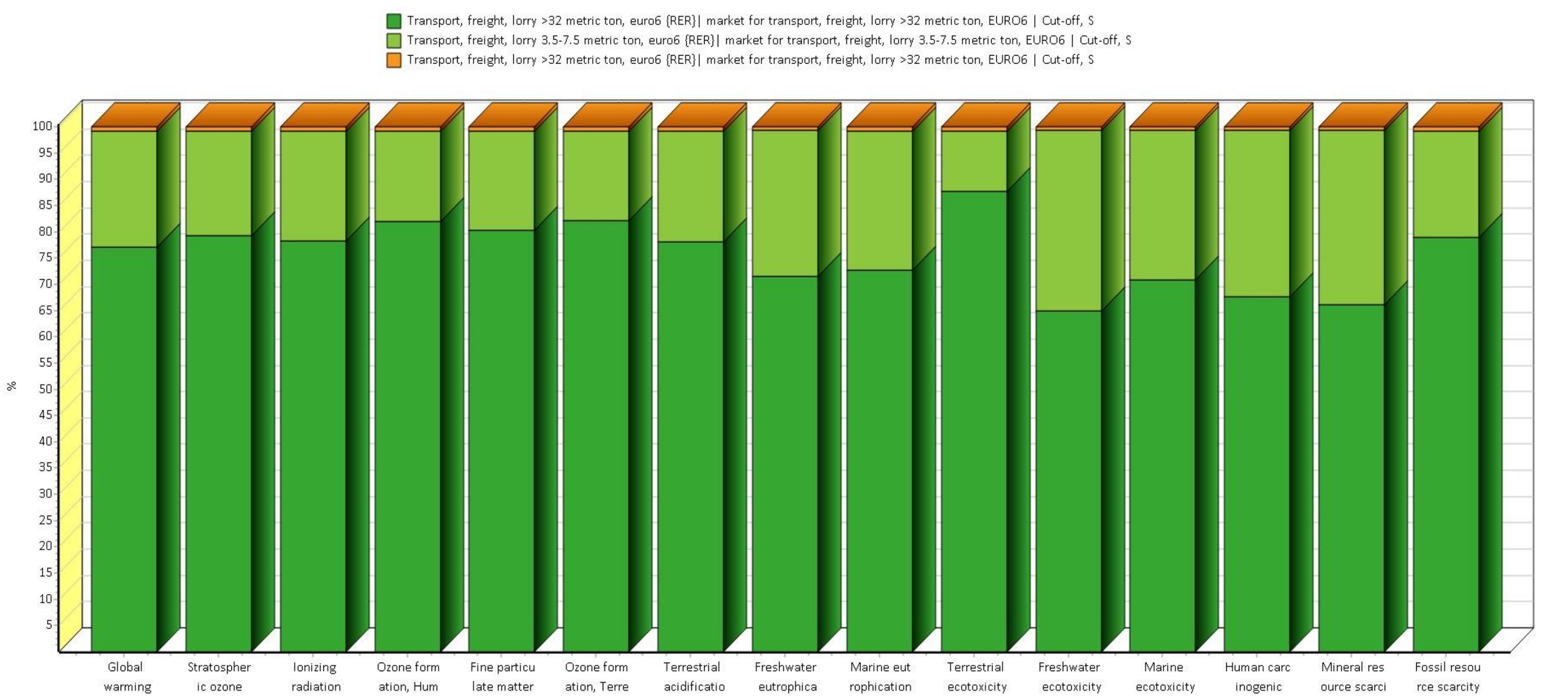



**Figure 39:** Characterized results of the environmental impacts from transportation in Alternative 7 using *heavy* and *light trucks.*

**Alternative 8**

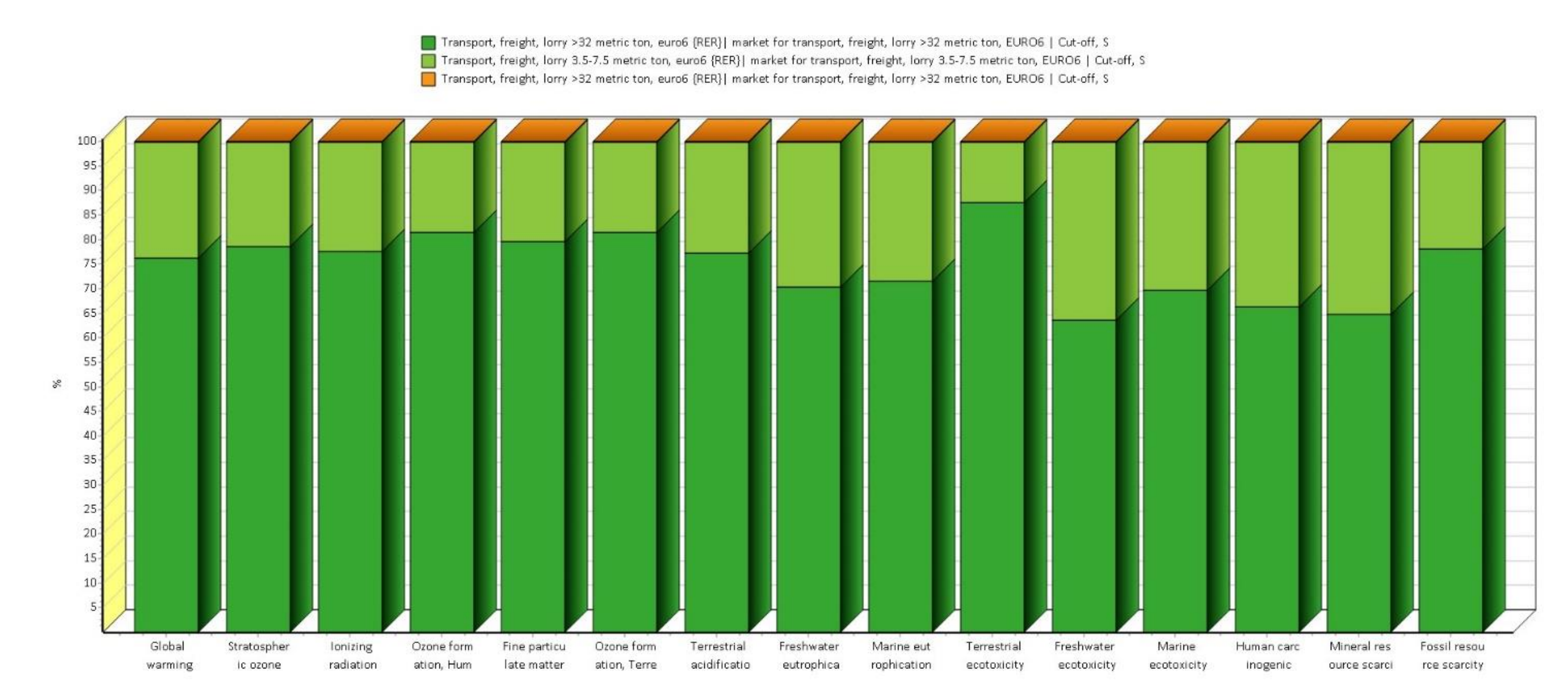



**Figure 40:** Characterized results of the environmental impacts from transportation in Alternative 8 using *heavy* and *light trucks*.

**Alternative 9**

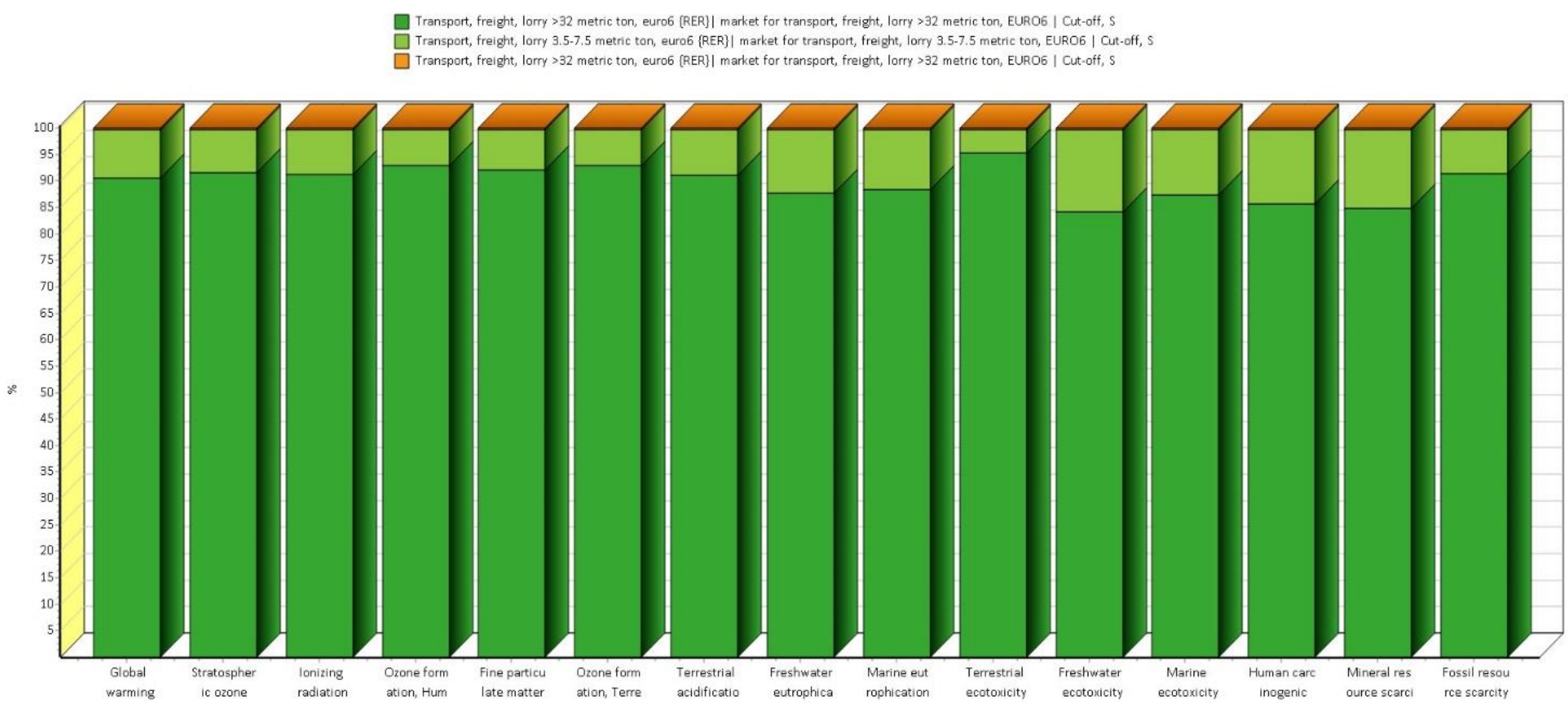



**Figure 41:** Characterized results of the environmental impacts from transportation in Alternative 9 using *heavy* and *light trucks.*

**Alternative 0**

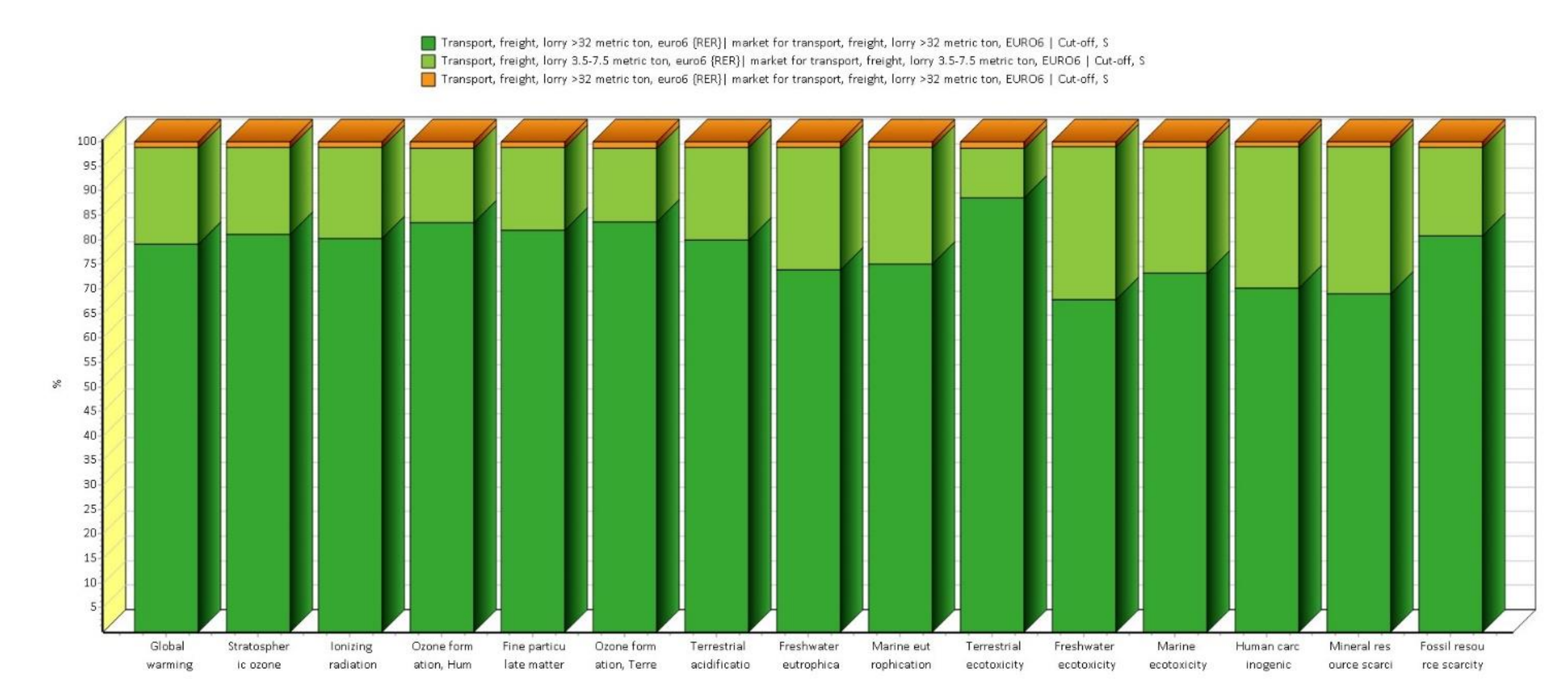



**Figure 42:** Characterized results of the environmental impacts from transportation in Alternative 0 using *heavy* and *light trucks.*

## A5.2: Comparative assessment

## A5.2.1: Chemical Consumption

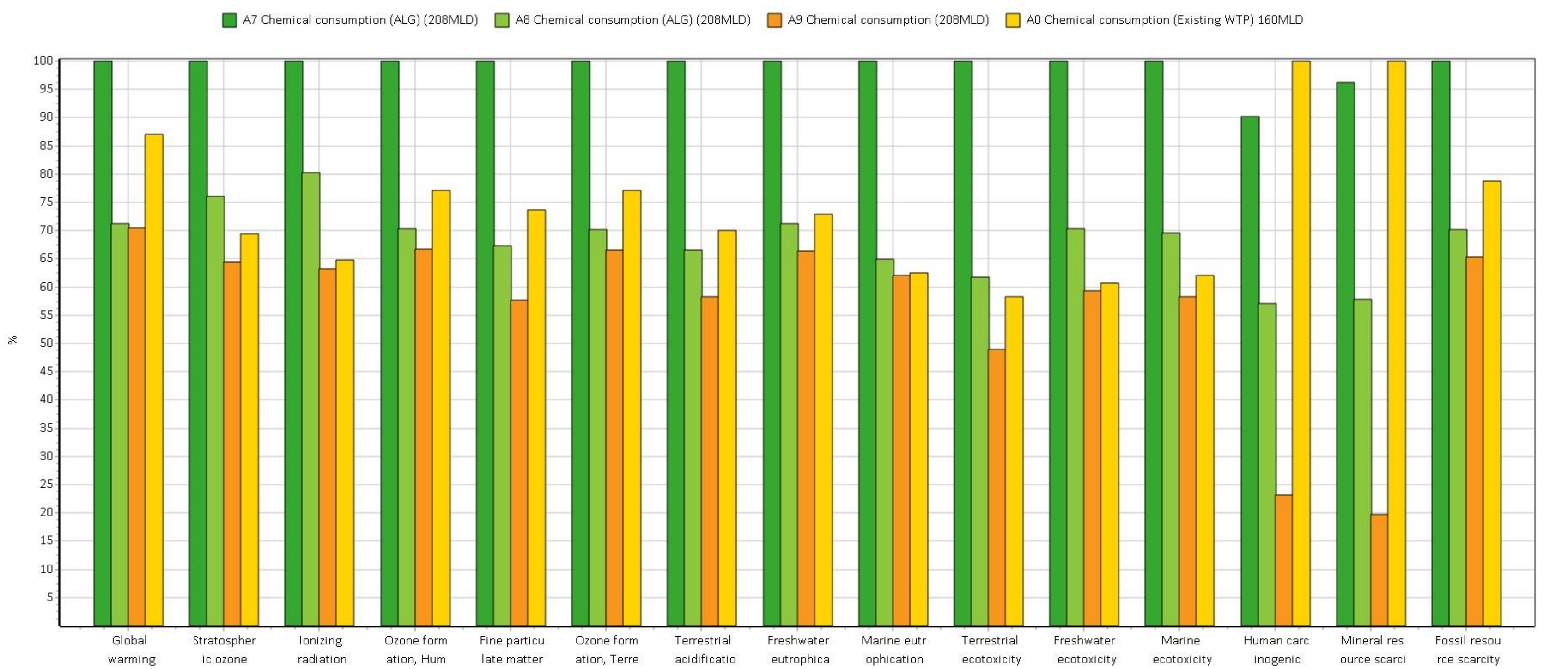



**Figure 43:** Characterized results of the environmental impacts from the comparative assessment of the chemical consumption in Alternative 7, Alternative 8, Alternative 9 and Alternative 0.

In terms of chemical consumption (See ***Figure 43*** above), Alternative 7 contributes to most of the impact categories except in human carcinogenic toxicity and mineral resource scarcity where Alternative 0 has the highest contribution. This is due to the higher consumption of ALG in Alternative 0. Contribution to the impact category mineral resource scarcity indicates that there is depletion in significant mineral resources from nature like aluminium, iron, cobalt, zinc etc. ALG consumption correlates to the depletion of aluminium from the earth's mineral resource and hence Alternative 0 is attributed with it for the highest contribution to its depletion. Alternative 9 has the lowest contribution across all the indicators due to the lowest chemical consumption. Alternative 9 has no pretreatment/ chemical precipitation, upstream of the treatment process as opposed to the other alternatives.

Contribution to the impact category human carcinogenic toxicity is due to the increase in emission of cancer inducing toxins to nature. This specific impact category is significant in the process solutions due to the highest contribution of the emission Chromium (VI) element in water and air. WHO (2003) reported that humans exposed to Chromium (VI) compounds will have respiratory carcinogenicity. Exposure to a mixture of various Chromium (VI) compounds will result in a high risk to humans. This element is emitted to nature from various processes, but the highest contribution is from the production and consumption of ALG in the process solutions. Alternative 8 follows with a 30% reduction in contribution to the all the impact categories from chemical consumption compared to Alternative 7. Alternative 9 has the lowest human carcinogenicity and mineral depletion compared to the other alternatives. It has an approximate 80% reduction in impact contribution from the mentioned impact categories compared with Alternative 0 with the highest impacts for the same.

Other impact categories like global warming, fine particulate matter formation, eutrophication in marine and freshwater, fossil resource scarcity and others have the highest contribution in Alternative 7 due to the preparation and consumption of reactivated carbon which results in the emission of Carbon dioxide, fossil. This is due to the usage of fossil resource hard coal, for the preparation of the activated carbon. Coal is one of the fossil fuels which contributes to a high kg $CO_2$ eq., due to a high carbon content (Forest research, 2019). Coal used for GAC filters contributes to the majority of the $CO_2$ emissions across all the alternatives.

## A5.2.2: Energy Consumption

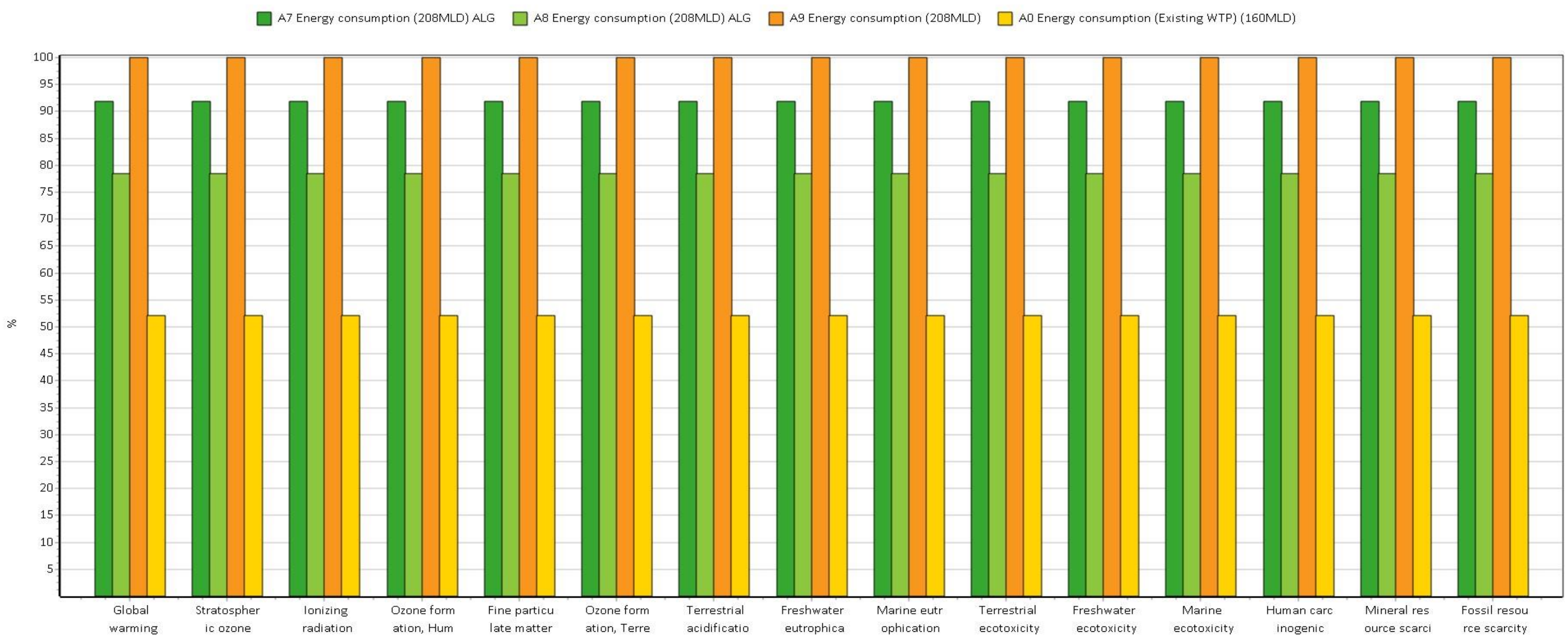



**Figure 44:** Characterized results of the environmental impacts from the comparative assessment of the Energy consumption in Alternative 7, Alternative 8, Alternative 9 and Alternative 0.

In terms of energy consumption (See ***Figure 44*** above), Alternative 9 has the majority of contributions from all considered impact indicators due to the energy intensive Nanofiltration process in the WTP. Alternative 7 also utilizes the NF process but for only a 50% of the specific flow intake in that process. The other 50% of the specific water flow goes to UF which has lower energy consumption (0.05 kWh/$m^3$ (Pentair, 2019)) compared to NF (0.3 kWh/$m^3$ (Pentair, 2019)). Hence, Alternative 7 follows Alternative 9 as the second biggest contributor to all the impact indicators due to the total energy consumption in the process solution. Alternative 7 is 9% lower than Alternative 9 in terms of energy consumption followed by Alternative 8 which is 22% lower than Alternative 9 and 14% lower than Alternative 7. Alternative 8 has just an UF process as opposed to Alternative 7 with both SF and UF contributing to more energy consumption. Alternative 0 has nearly a 50% reduced energy consumption compared to Alternative 9. It has a 40% lower energy consumption than Alternative 7 and a 26% lower energy consumption than Alternative 8. The highest energy consumption in the WTP is from hydropower generation (67%) and the lowest is from wind power (33%), both purchased from Vattenfall.

Across most of the impact indicators, the hydropower generation from a pumped storage scores the highest followed by the hydropower generation from reservoir and wind power generated from an onshore turbine. Both wind power and hydropower cause harmful impacts due to the change in biodiversity around their landscapes (Bergström, 2020). Hydropower plants do not cause emissions of particulates, radioactivity or any chemical compounds that can potentially harm human health (Flood, 2014) but the related environmental impacts in this study are due to addition of the infrastructure, energy and the water required for the hydropower plant to function. Hydropower from a pumped storage which needs energy to pump the water from a lower reservoir to a higher reservoir also contributes highly to the impacts due to the inclusion of two different reservoirs instead of just one which is the case for hydropower from the reservoir. The selected hydropower sources have the potential to negatively affect the neighboring waterways and the environment surrounding the waterway. (Karlberg, 2015). The neighbouring water can disappear or be consumed by the power plant which can endanger the biodiversity depending on it to survive. When the consumption of electricity is higher from the specific hydropower source, the water flow through the turbine is higher resulting in more water consumption and negative impacts to those waters (Karlberg, 2015).

## A5.2.3: Transportation

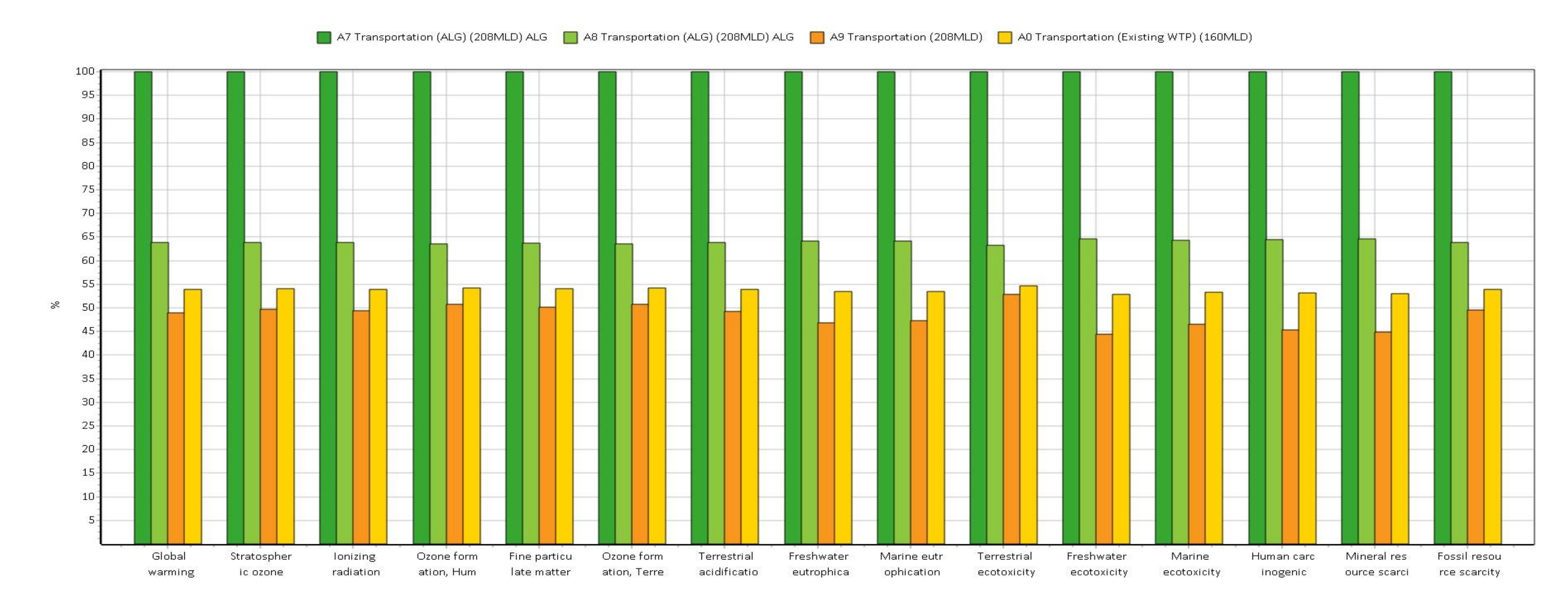



**Figure 45:** Characterized results of the environmental impacts from the comparative assessment of the Transportation in Alternative 7, Alternative 8, Alternative 9 and Alternative 0.

In terms of transportation (See ***Figure 45*** above), Alternative 7 has the majority of contributions from all the considered impact indicators due to the transportation of more amounts of the required chemicals compared to all other alternatives. There is also the transportation of the sludge which is higher in Alternative 7 as opposed to the other alternatives. The sludge is higher in Alternative 7 because of the additional effluents from sand filters which is sent to sludge treatment. This is not the case in Alternative 0 where the effluents from sand filters are backwashed and sent back to the lake instead of treatment. The chemicals used upstream are a lot more in quantity and number for Alternative 7 compared to Alternative 8, 9 and 0. The chemicals included are the main coagulant, auxiliary coagulant, soda, sulphuric acid and other backwash chemicals for both UF, NF processes. Even though Alternative 0 has a higher ALG consumption, there is no consumption of soda, sulphuric acid and backwash chemical usages. Hence Alternative 0 is analyzed to have contributions from all the impact categories in a much smaller percentage (46% lower) compared with Alternative 7. Out of all the alternatives, Alternative 9 has the lowest chemical consumption as stated before and hence lower transportation requirements. Alternative 9 has a 50% lower contribution from all the impact categories compared to Alternative 7. Alternative 7 is followed by Alternative 8 with a 36% reduced contribution compared to it.

### A5.2.4: Normalized Result of all the alternatives

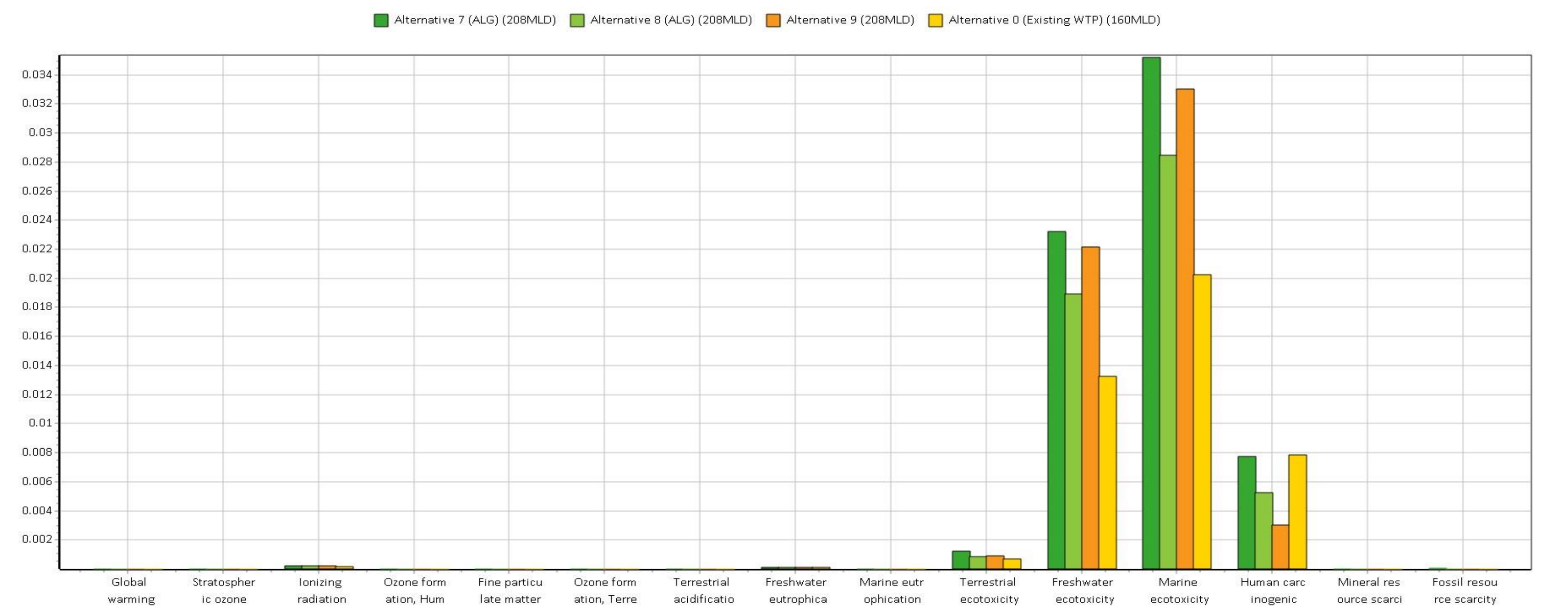



**Figure 46:** Normalized results of the environmental impacts from the comparative assessment of the Alternative 7, Alternative 8, Alternative 9 with 208 MLD as plant capacity vs Alternative 0 with 160 MLD as plant capacity.

The normalized results from each aspect indicates the immediate impact for the reference region from each impact category.

From an overall perspective of the modelled normalized results for all the alternatives (See ***Figure 46*** above), it was inferred that all the alternatives contribute majorly to marine ecotoxicity followed by freshwater ecotoxicity, human carcinogenic toxicity, terrestrial ecotoxicity and then a minor contribution to all the other impact categories. For marine and freshwater ecotoxicity, the major contribution is from Alternative 7, followed by Alternative 9, Alternative 8 and Alternatively 0, respectively. For human carcinogenic toxicity, the major contribution is from Alternative 0, followed closely by Alternative 7 as the second dominant alternative and then trailing behind are Alternative 8 and 9, respectively.

## A5.3: Other Models from Sensitivity assessment

## Sensitivity Analysis 1: Coagulant Change

### Standalone Assessment: Alternative 7 with PIX-111

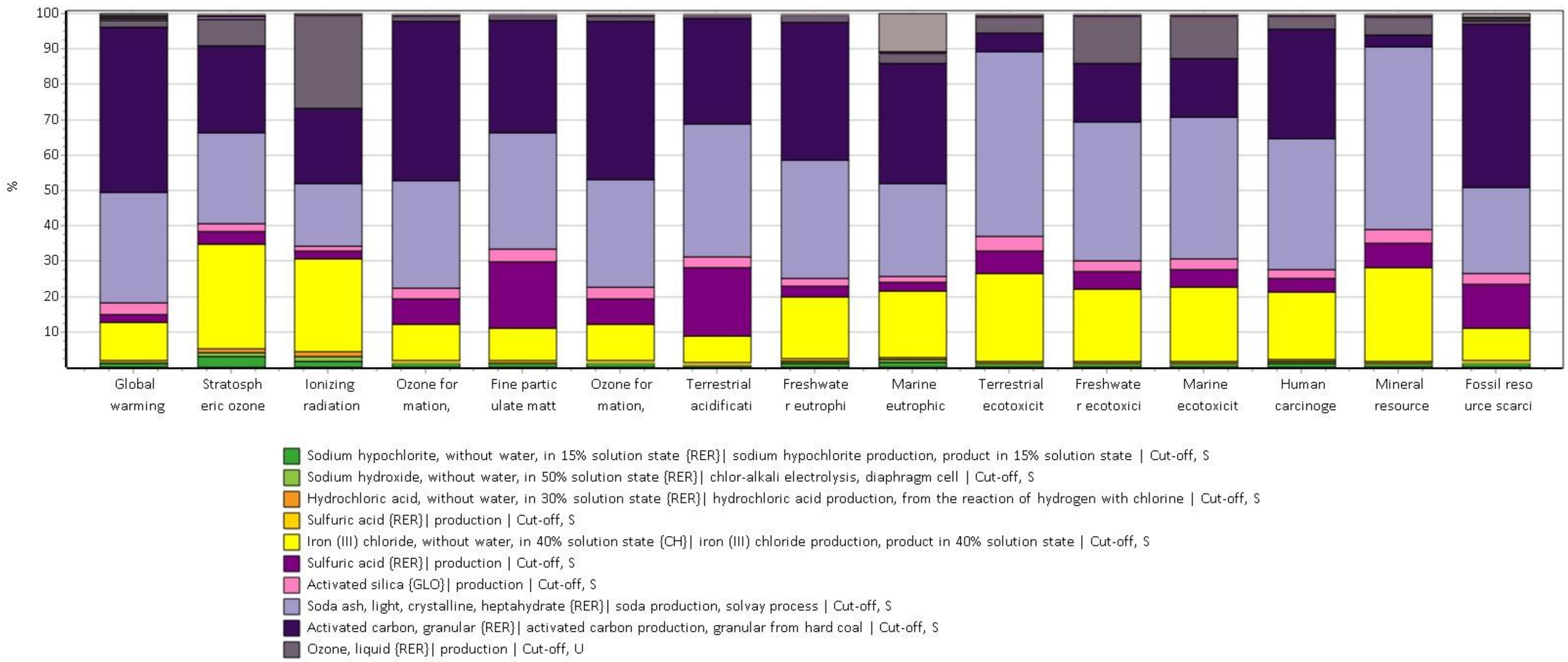



**Figure 47:** Characterized results of the environmental impacts from chemical consumption in sensitive alternative 7 using PIX-111 as main coagulant.

**Alternative 8 with PIX-111**

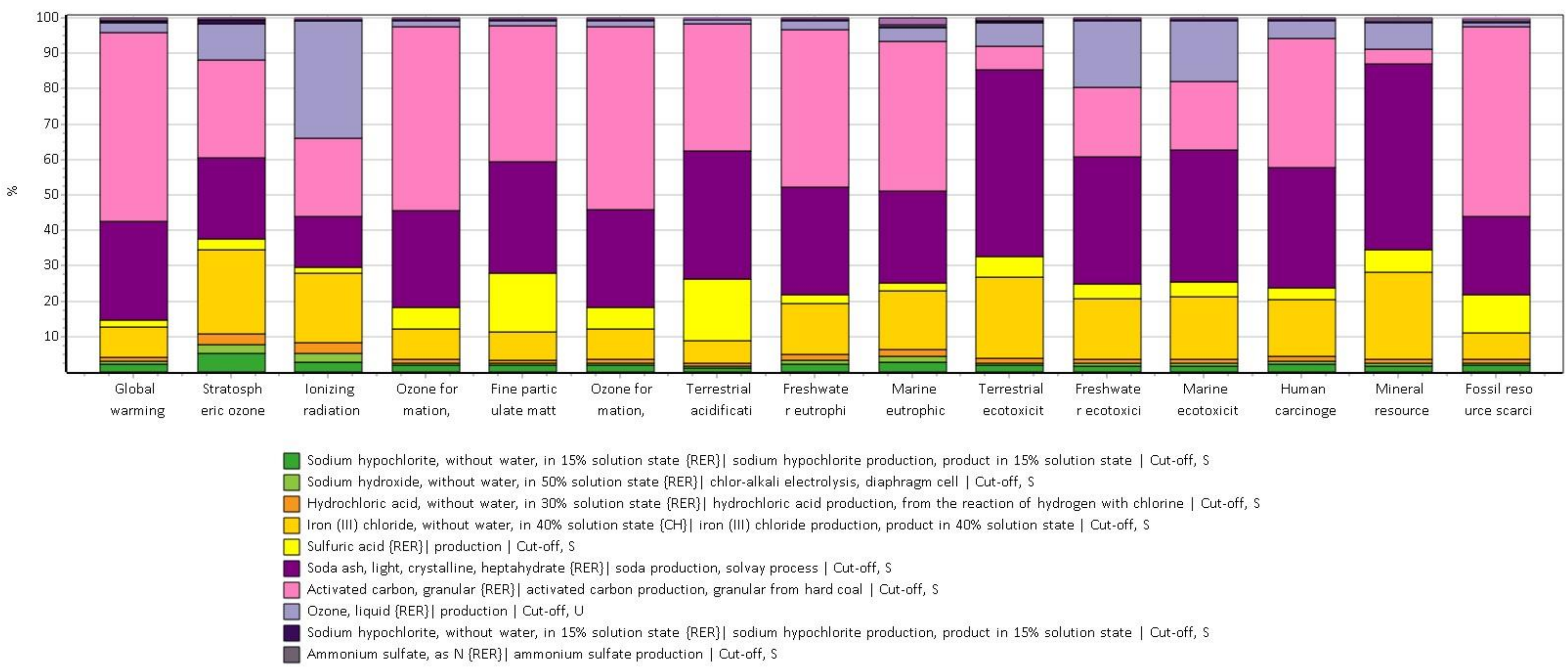



**Figure 48:** Characterized results of the environmental impacts from chemical consumption in sensitive alternative 8 using PIX-111 as main coagulant.

## A5.4: Alternate Sensitivity Analysis : Soda vs Lime

### Comparative assessment: 1 ton of Soda vs 1 ton of Lime

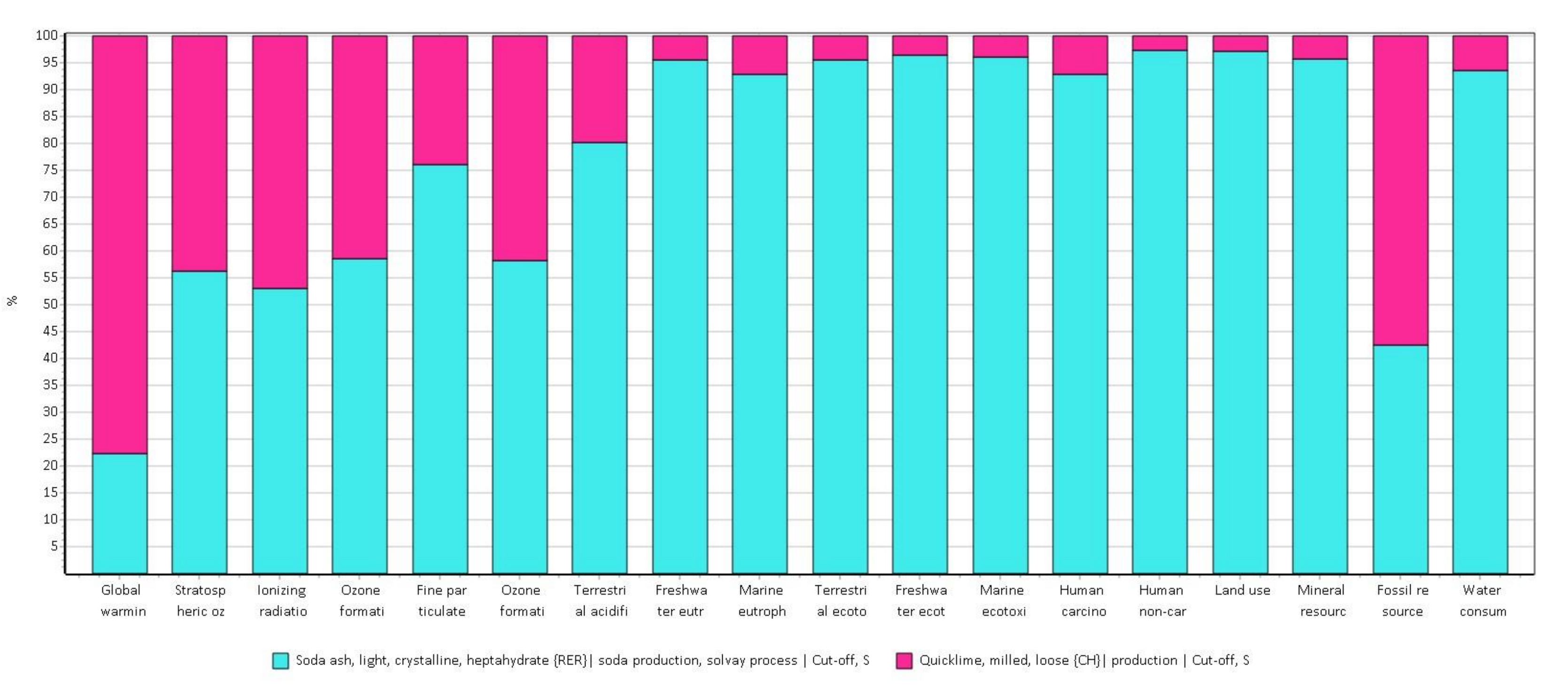



**Figure 49:** Characterized results of the environmental impacts from Comparative assessment of 1 ton of Soda preparation vs 1 ton of Lime preparation with all the 18 impact indicators.

The above assessment was done to aid Norrvatten to assess the impacts from the chemicals used/proposed for optimizing pH in the alternatives. Lime is currently used in the WTP and soda is suggested by Ramboll to be used as an alternative to be used for the future alternatives. (Reasons are stated in Chapter 3.6.1 in page **21**) One ton of Quicklime production is compared against producing one ton of soda to assess the associated environmental impacts from all the 18 impact categories.

From the modelled results, it was observed that production of Quicklime majorly contributed to global warming potential (77%) and a fossil resource scarcity (57.5%), while Soda had major contributions (< 90%) from all the ecotoxicity & eutrophication indicators. The absolute emission values for this analysis are attached in **Table *21*** below.

**Table 21:** Emissions from the production of 1 ton of Soda vs 1 ton of Lime

| Impact category | Unit | Total | Soda | Quicklime |
|---|---|---|---|---|
| Global warming | kg CO2 eq | 1.45E+03 | 3.23E+02 | 1.12E+03 |
| Stratospheric ozone depletion | kg CFC11 eq | 2.18E-04 | 1.22E-04 | 9.56E-05 |
| Ionizing radiation | kBq Co-60 eq | 4.48E+01 | 2.38E+01 | 2.10E+01 |
| Ozone formation, Human health | kg NOx eq | 1.43E+00 | 8.39E-01 | 5.94E-01 |
| Fine particulate matter formation | kg PM2.5 eq | 1.19E+00 | 9.05E-01 | 2.86E-01 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 1.46E+00 | 8.51E-01 | 6.11E-01 |
| Terrestrial acidification | kg SO2 eq | 4.21E+00 | 3.38E+00 | 8.35E-01 |
| Freshwater eutrophication | kg P eq | 2.58E-01 | 2.46E-01 | 1.15E-02 |
| Marine eutrophication | kg N eq | 1.51E-02 | 1.40E-02 | 1.09E-03 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 2.78E+03 | 2.66E+03 | 1.24E+02 |
| Freshwater ecotoxicity | kg 1,4-DCB | 2.59E+01 | 2.49E+01 | 9.44E-01 |
| Marine ecotoxicity | kg 1,4-DCB | 3.71E+01 | 3.56E+01 | 1.44E+00 |
| Human carcinogenic toxicity | kg 1,4-DCB | 2.38E+01 | 2.21E+01 | 1.71E+00 |
| Human non-carcinogenic toxicity | kg 1,4-DCB | 8.53E+02 | 8.30E+02 | 2.34E+01 |
| Land use | m2a crop eq | 3.82E+01 | 3.71E+01 | 1.10E+00 |
| Mineral resource scarcity | kg Cu eq | 3.13E+00 | 2.99E+00 | 1.37E-01 |
| Fossil resource scarcity | kg oil eq | 1.76E+02 | 7.48E+01 | 1.01E+02 |
| Water consumption | m3 | 1.80E+01 | 1.68E+01 | 1.15E+00 |

## A5.5 Alternate Sensitivity Analysis:

**Comparative assessment: Hydropower from reservoir 67% and Wind power from offshore wind turbine 33% (Green mix) vs Swedish grid mix**

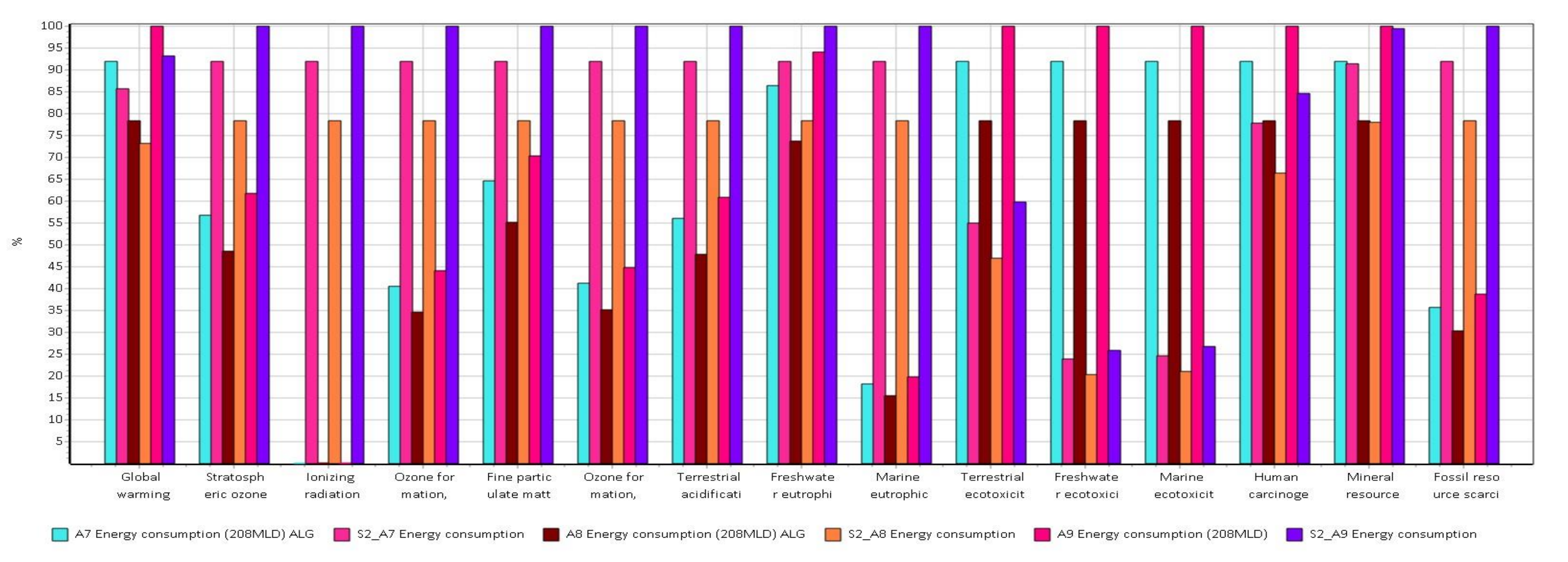



**Figure 50:** Characterized results of an alternate sensitivity analysis for comparisons between main alternatives 7, 8 and 9 using hydropower (67%) and wind power (33%) as the main energy mix vs the sensitive alternatives 7, 8 and 9 using the Swedish electricity mix.

As there were no literature reference for the actual hydropower source whence the required energy is extracted, the initial assumption for the green mix was made for the main analysis by including three different sources prevalent in Europe. The above assessment was done to limit the uncertainty of involving energy consumption in the WTP from the hydropower source having flow by water and pumped storage which in reality may not be utilized by Vattenfall from whom it was purchased from.

From the conducted assessment it was found that the change of energy sources in green mix had a big influence in the impact indicator Ionizing radiation. As the energy required to run the pumped storage taken from the Swedish grid mix was removed there were no indication of any radiation decay potential. Proportion of mineral resource scarcity impact contribution from the newly modified green mix and the Swedish grid mix were identified to be quite similar in terms of their emission potential than the previous assessment. Global warming and the other impact indicators for the newly modified green mix were identified to be mostly similar to the earlier obtained results with the initial assumption on the energy sources. The absolute emission values for this analysis are attached in ***Table 22*** below.

***Table 22:*** *Emissions from energy consumption in 7 and 8 utilizing a Modified Green energy mix vs Sensitive Alternatives 7 and 8 utilizing Swedish grid mix.*

| Impact category | Unit | A7 Energy consumption (Green energy mix) | SA7 Energy consumption (Swedish grid mix) | A8 Energy consumption (Green energy mix) | SA8 Energy consumption (Swedish grid mix) | A9 Energy consumption (Green energy mix) | SA9 Energy consumption (Swedish grid mix) |
|---|---|---|---|---|---|---|---|
| Global warming | kg $CO_2$ eq | 5.15E-02 | 4.81E-02 | 4.40E-02 | 4.10E-02 | 5.61E-02 | 5.23E-02 |
| Stratospheric ozone depletion | kg CFC11 eq | 6.60E-08 | 1.07E-07 | 5.64E-08 | 9.12E-08 | 7.18E-08 | 1.16E-07 |
| Ionizing radiation | kBq Co-60 eq | 7.70E-04 | 3.29E-01 | 6.57E-04 | 2.81E-01 | 8.37E-04 | 3.58E-01 |
| Ozone formation, Human health | kg NOx eq | 4.57E-05 | 1.04E-04 | 3.90E-05 | 8.85E-05 | 4.98E-05 | 1.13E-04 |
| Fine particulate matter formation | kg PM2.5 eq | 4.33E-05 | 6.16E-05 | 3.69E-05 | 5.25E-05 | 4.71E-05 | 6.70E-05 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 4.73E-05 | 1.06E-04 | 4.04E-05 | 9.00E-05 | 5.14E-05 | 1.15E-04 |
| Terrestrial acidification | kg $SO_2$ eq | 9.84E-05 | 1.61E-04 | 8.40E-05 | 1.38E-04 | 1.07E-04 | 1.76E-04 |
| Freshwater eutrophication | kg P eq | 2.13E-05 | 2.27E-05 | 1.82E-05 | 1.93E-05 | 2.32E-05 | 2.47E-05 |
| Marine eutrophication | kg N eq | 1.34E-06 | 6.75E-06 | 1.14E-06 | 5.76E-06 | 1.46E-06 | 7.35E-06 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 4.23E-01 | 2.53E-01 | 3.61E-01 | 2.16E-01 | 4.60E-01 | 2.75E-01 |
| Freshwater ecotoxicity | kg 1,4-DCB | 2.14E-02 | 5.56E-03 | 1.83E-02 | 4.75E-03 | 2.33E-02 | 6.05E-03 |
| Marine ecotoxicity | kg 1,4-DCB | 2.64E-02 | 7.08E-03 | 2.25E-02 | 6.04E-03 | 2.87E-02 | 7.70E-03 |
| Human carcinogenic toxicity | kg 1,4-DCB | 4.12E-03 | 3.49E-03 | 3.51E-03 | 2.98E-03 | 4.48E-03 | 3.79E-03 |
| Mineral resource scarcity | kg Cu eq | 4.86E-04 | 4.83E-04 | 4.14E-04 | 4.12E-04 | 5.28E-04 | 5.25E-04 |
| Fossil resource scarcity | kg oil eq | 3.16E-03 | 8.16E-03 | 2.70E-03 | 6.96E-03 | 3.44E-03 | 8.87E-03 |

# Appendix 6: Other data from Norrvatten

## Previous Researched Alternatives

**Table 23:** Previous investigated alternatives N1, N2 and N3 from Norrvatten.

| Step | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Alt. | Sieving + emergency chemical barrier | µ-biological barrier | NOM-removal / µ-biological barrier | Particle removal | (NOM-removal) / µ-biological barrier | Chemical barrier / taste and odor / µ-biological barrier | µ-biological barrier | µ-biological barrier | Post treatment |
| N1 | Micro-screen & PAC | SIX process | Precipitation (ALG/PIX-111) / sedimentation | - | UF | BAC ($O_3$ + GAC) | - | UV | Soda & $NH_2Cl$ |
| N2 | Micro-screen & PAC | - | Precipitation (ALG/PIX-111) / sedimentation | SF | - | GAC | UF | UV | Soda & $N.H_2Cl$ |
| N3 | Micro-screen & PAC | - | Precipitation (ALG/PIX-111) / sedimentation | - | UF | BAC ($O_3$ + GAC) | - | UV | Soda & $NH_2Cl$ |

## Proposed Future Alternatives

| Process design | Sieving + emergency chemical barrier | NOM-removal/ µ-biological barrier | Particle removal | (NOM-removal)/ µ-biological barrier | Chemical barrier /taste and odor /µ-biological barrier | µ-biological barrier | Post treatm. |
|---|---|---|---|---|---|---|---|
| 1 | Microsieve (PAC) | SIX | dF/UF (PAX-18) | | $O_3$ + BAC (+ GAC) | UV | Monochloramine |
| 2 | | Coagulation (ALG/PIX-111) / lamella/Sedimentation | SF | - | GAC | UV, UF | Monochloramine |
| 3 | | Coagulation (ALG/PIX-111) / lamella/Sedimentation | SF | - | GAC | UF, UV | Monochloramine |
| 4 | | Coagulation (ALG/PIX-111) / lamella/Sedimentation | SF | UF | $O_3$ + BAC (+ GAC) | UV | Monochloramine |
| 5 | | Coagulation (ALG/PIX-111) / lamella/Sedimentation | UF | | $O_3$ + BAC (+ GAC) | UV | Monochloramine |
| 6 | | Coagulation (ALG/PIX-111) / lamella/Sedimentation | MGF | | GAC | UV | Monochloramine |
| 7 | | Coagulation (ALG/PIX-111) / lamella/Sedimentation | SF | NF / UF | $O_3$ + BAC (+ GAC) | UV | Monochloramine |
| 8 | | dF/UF (ALG/PIX-111) | | - | $O_3$ + BAC (+ GAC) | UV | Monochloramine |
| 9 | | NF | | - | $O_3$ + BAC (+ GAC) | UV | Monochloramine |

**Figure 51:** Table representing the various alternatives considered by Norrvatten for the future expansion of the WTP.

All nine different alternatives are included in the figure. Only Alternative 7, 8 and 9 are taken for this study. Dark green color-coded unit process indicates the existing facility and light green color-coded unit process indicates the new facility. MGF = Membrane gravity filter; dF/UF = Chemical precipitation in ultrafiltration; PAX -18 = Poly-aluminium chloride.

## Water loss percentages for the selected Unit processes

**Table 24:** Assumed/estimated water losses for the unit process at Q avg in 2050.

| Process step | Water loss (%) | Reference |
|---|---|---|
| Backwash with Micro-screen | 1% | (Lindgren, 2020) |
| Sludge from lamellar sedimentation | 0.38% | (Lindgren, 2020) |
| Backwash from Sand filter | 5.4% | (Lindgren, 2020) |
| Backwash from the chosen UF filter | 5.6% for Alternative 7 & 5.5% and Alternative 8 | (Pentair, 2019) * |
| Backwash from the chosen NF filter | 7% for Alternative 7 & 8% for Alternative 9 | (Pentair, 2019) * |
| Backwash from GAK/BAK | 1.5% | (Lindgren, 2020) |
| Backwash from secondary UF to sludge | 15% | (Forsberg, 2019) |

*Selected type of UF and NF with the specific water losses for Alternative 7, Alternative 8 and Alternative 9 are based on the different scenarios mentioned in Pentair report (2019). Scenario 1 with UF and NF is selected for UF in Alternative 7 and NF in Alternative 7, respectively. Scenario 2 with UF and NF is selected for UF in Alternative 8 and Alternative 9, respectively. This is done with an assumption judging by the similarity of the specific scenario to the specific alternative in the study (See **Figure 52** below). The water losses regarding the biological barriers and other information will be explained in the following paragraphs.

## Other Information for the selected microbiological Barriers

### Nanofiltration

The selected NF units for implementing in the NF process for the alternatives are HFW1000 and HFW1000B. The NF units require a backwash to counteract the fouling at regular intervals of 36 to 48 hours (SVU, 2015 as cited in Karlsson, 2020) from CEB chemicals: NaOCl, NaOH & $H_2SO_4$. The NF unit HFW1000 from *scenario 1* of earlier conducted pilot trials is selected for the NF process in Alternative 7, and it has an initial water recovery of 75% and an overall water recovery of 68% (Pentair, 2019). This results in an initial concentrate loss of 25% and a final backwash water loss of 7%. This specific unit has a reported TOC removal rate of ≤ 1 mg/l (Pentair, 2019). The NF unit HFW1000B from *scenario 2* of the pilot trials is selected for the NF process in Alternative 9, and it has an initial recovery of 83% and an overall water recovery of 75%. This results in an initial concentrate loss of 17% and a final backwash water loss of 8%. This specific unit has a reported TOC removal rate of ≤ 3 mg/l (Pentair, 2019). The TOC rate for both the units are subject to change with incorporation of other chemical and biological barriers preceding it. According to Pentair (2019) report, there are a total of 44 membrane units for HFW1000 and a total of 88 membrane units for HFW1000B. Each of these NF units have 120 membranes within and they share the same energy consumption of 0.3 kWh/m$^3$ of permeate flow (Pentair, 2019). See **Figure 56** for more reference.

### Ultrafiltration

The selected UF units are both X-FLOW XIGA units which requires a backwash from CEB chemicals: NaOCl, NaOH & HCl at regular intervals. The UF unit XIGA from *scenario 1* is selected for Alternative 7, and it has an overall water recovery of 94.4% which results in a backwash water loss of 5.6%. The UF unit XIGA from scenario 2 is selected for Alternative 8, and it has an overall water recovery of 94.5%, which results in a backwash water loss of 5.5%. According to Pentair (2019) report, there are a total of 20 membrane units for the UF process in Alternative 7. In Alternative 8, the UF unit for the filtration direct filtration process has a total of 7 membrane units. Each of these UF units have 22 membranes within and they both share the same energy consumption of 0.05 kWh/m$^3$ of permeate flow (Pentair, 2019). The secondary UF in both Alternative 8 and 9 near the sludge tank is assumed to be the UF unit from *scenario 2*. See **Figure 56** for more reference.

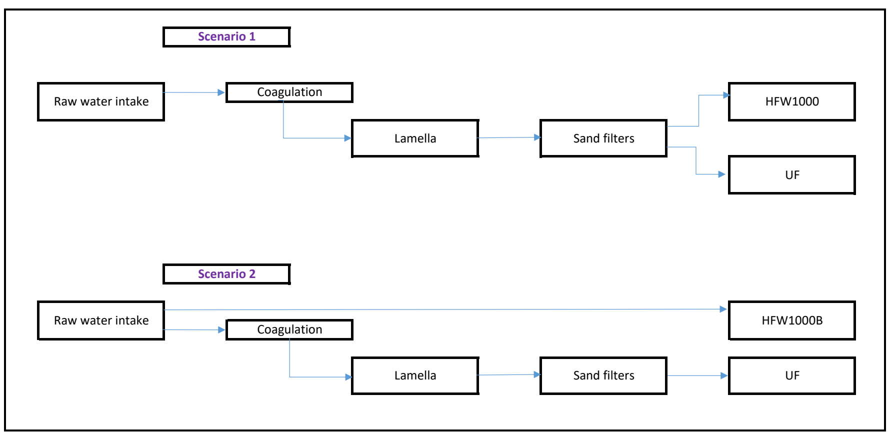



**Figure 52:** The two different scenarios from the earlier conducted pilot trials (Pentair, 2019).

**Table 25:** The flow of sludge in the sludge chamber as depicted from the previous alternative N2 for an average day (Forsberg, 2019).

| ***Sludge Calculation*** | **Sludge Separation Chamber** | | | | | |
|---|---|---|---|---|---|---|
| | **For mean flow** | **Unit** | **To lamella Thickener** | **To Mälaren** | **To Centrifuge** | **To Sludge handling** |
| Alternative **(N2)** | Total dry solid | % | 0.0433% | 0.10% | 2.233% | 18% |
| | Total Solid flow | tons/day | 6.80 | 0.14 | 6.66 | 6.662138 |
| | Flow | m3/day | 15700* | 15401.65 | 298.35 | 37.01 |

*The specific flow of the total water losses from the unit processes to the initial buffer tank in the sludge chamber.

A sludge content of 0.0433% is removed from the buffer tank and sent to the lamella thickener where polymer is added for thickening. A sludge content of 2.233% is removed from the sludge concentration and sent to a second buffer tank. From this outgoing sludge concentration, a separated waterflow of 0.10% flows back to Lake Mälaren. From the buffer tank, after the addition of polymer, a concentrated sludge content of 2.233% flows to the centrifuge for dewatering. A final dry sludge content of 18% is removed after dewatering and sent for disposal. The remaining content is sent back to the initial buffer tank for a continuous sludge treatment.

For this study, the alternatives utilizing ALG and PIX-111 are assumed to have the same sludge properties.

**Table 26:** The provided data from internal documents regarding the chemical consumption for the previous alternatives N1, N2 & N3. Values are converted from gram/m$^3$ to ton/m$^3$.

| Inputs | | N1 | N2 | N3 | Unit |
|---|---|---|---|---|---|
| | | For an inflow of | | | |
| | | 224000 | 236000 | 222000 | m3/day |
| | | For an outflow of | | | |
| | | 280000 | | | m3/day |
| Aluminium Sulphate (ALG) | | | 0.0000254 | 0.0000235 | t/m3 |
| Iron Chloride (PIX-111) (40%) | | | 0.0000205 | 0.0000186 | t/m3 |
| Sulfuric acid for ALG (96%) | | | 0.0000059 | 0.0000059 | t/m3 |
| Sulfuric acid for PIX-111 (96%) | | | 0.0000264 | 0.0000245 | t/m3 |
| Soda ash for ALG | | 0.0000391 | 0.0000450 | 0.0000421 | t/m3 |
| Soda ash for PIX-111 | | | 0.0001018 | 0.0001018 | t/m3 |
| Activated Silica for ALG | | | 0.0000021 | 0.0000020 | t/m3 |
| Activated Silica for PIX-111 | | | 0.0000021 | 0.0000020 | t/m3 |
| Granular Activated Carbon (GAC) | | 612 | 680 | 612 | t/y |
| Ozone liquid | | 0.000004 | 0.000004 | 0.000004 | t/m3 |
| Hypochlorite (15%) | | 0.0000002 | 0.0000002 | 0.0000002 | t/m3 |
| Ammonium sulfate (13%) | | 0.0000001 | 0.0000006 | 0.0000005 | t/m3 |

(Sources: Forsberg (2019), Lindgren (2019), (2020))

**Table 27:** The provided data from the internal document regarding GAC/BAC (Lindgren, 2020).

| Granular Activated Carbon Requirement | | |
|---|---|---|
| | | |
| Number of filters (BAC) | 36 | Pcs |
| Number of filters (GAC) | 30 | Pcs |
| Area of the filter | 50 | m2/filter |
| Filter load for BAC | 7.3 | m3/m2/h |
| Filter load for GAC | 9.5 | m3/m2/h |
| Annual Coal consumption for BAC | 612 | tons/year |
| Annual Coal consumption for GAC | 680 | tons/year |

**Table 28:** The provided data from the internal document regarding the chemical requirement for CEB (Pentair, 2019).

| Inputs | UF | From Pentair report | | | Unit |
|---|---|---|---|---|---|
| | | **A7** | **A8** | **A9** | |
| | | **For an incoming flow of** | | | |
| | | ***Scenario 1*** | ***Scenario 2*** | **NO UF** | Pentair report alternatives |
| | | 198000 | 76000 | | m3/day |
| | | **For a permeate flow of** | | | |
| | | ***Scenario 1*** | ***Scenario 2*** | **NO UF** | Pentair report alternatives |
| | | 187000 | 72000 | | m3/day |
| | | **The required Chemicals** | | | From Pentair report |
| Hydrochloric acid (25%) **UF** | | 98400 | 37500 | | litre/year |
| Sulphuric acid (37%) **NF** | | - | - | | litre/year |
| Sodium hydroxide (25%) **UF & NF** | | 113600 | 43300 | | litre/year |
| Sodium hypochlorite (12.5%) **UF & NF** | | 93100 | 31300 | | litre/year |

| Inputs | NF | From Pentair report | | | Unit |
|---|---|---|---|---|---|
| | | **A7** | **A8** | **A9** | |
| | | **For an incoming flow of** | | | |
| | | ***Scenario 1*** | **NO NF** | ***Scenario 2*** | Pentair report alternatives |
| | | 136500 | | 208000 | m3/day |
| | | **For a permeate flow of** | | | |
| | | ***Scenario 1*** | **NO NF** | ***Scenario 2*** | Pentair report alternatives |
| | | 93000 | | 208000 | m3/day |
| | | **The required Chemicals** | | | From Pentair report |
| Hydrochloric acid (25%) **UF** | | - | | - | litre/year |
| Sulphuric acid (37%) **NF** | | 4700 | | 10040 | litre/year |
| Sodium hydroxide (25%) **UF & NF** | | 11900 | | 28830 | litre/year |
| Sodium hypochlorite (12.5%) **UF & NF** | | 17260 | | 51760 | litre/year |

The mentioned percentages of CEB chemicals are the initially given data from internal documents. Calculations were done to convert them to the required percentages for datasets in SimaPro. Calculation reference is given in **Table 32**.

**Table 29:** Data provided from internal document for Alternative 0 based on the yearly report 2019.

| ***Input*** | **Alternative 0** | **Unit** |
|---|---|---|
| *Inflow of raw water* | 54311508 | $m^3/y$ |
| *Outflow of drinking water* | 51480394 | $m^3/y$ |
| *Aluminium Sulphate* | 2387.574 | t/y |
| *Activated Silica* | 125.832 | t/y |
| *Monochloramine* | 29.268 | t/y |
| *Lime* | 936.013 | t/y |
| *Amount of sludge produced* | 3984.65 | t/y |
| *Amount of polymer used* | 8.743 | t/y |
| *Total consumed energy* | 21984626 | kWh/y |
| *Energy for UV* | 555087 | kWh/y |

Other inputs like GAC are calculated using the given data from previous alternatives N1, N2 & N3. Calculation reference is provided in **Table 32**.

**Table 30:** The total energy consumption from each main aspect in Alternatives 7, 8, 9 (208 MLD) & 0 (160 MLD).

| Treatment process | Content | Alternative 7 (GWh/y) | Alternative 8 (GWh/y) | Alternative 9 (GWh/y) | Alternative 0 (GWh/y) |
|---|---|---|---|---|---|
| *Backflush pumps for UF* | Intermediate Reservoir 1 | - | 0.3 | - | - |
| *Aerators/blowers for UF* | | - | 0.3 | - | - |
| *Backflush pumps for SF* | | 0.3 | - | - | 0.3 |
| *Aerators/blowers for SF* | | 0.3 | - | - | 0.3 |
| *Backflush pumps for NF* | | - | - | 0.3* | - |
| *Aerators/blowers for NF* | | - | - | 0.3* | - |
| ***Total intermediate reservoir 1*** | | **0.6** | **0.6** | **0.6** | **0.6** |
| *Backflush pumps BAC/GAC* | Intermediate Reservoir 2 | 0.08 | 0.3 | 0.3 | 0.3 |
| *Aerators/blowers for BAC/GAC* | | 0.08 | 0.3 | 0.3 | 0.3 |
| *Backflush pumps for UF* | | 0.08 | - | - | - |
| *Aerators/blowers for UF* | | 0.08 | - | - | - |
| *Backflush pumps for NF* | | 0.08 | - | - | - |
| *Aerators/blowers for NF* | | 0.08 | - | - | - |
| ***Total intermediate reservoir 2*** | | **0.48** | **0.6** | **0.6** | **0.6** |
| *Backflush pumps for Secondary UF* | Intermediate Reservoir 3 | - | 0.3 | 0.3 | - |
| *Aerators/blowers for Secondary UF* | | - | 0.3 | 0.3 | - |
| *Backflush pumps for UF* | | - | - | - | - |
| *Aerators/blowers for UF* | | - | - | - | - |
| ***Total intermediate reservoir 3*** | | **-** | **0.6** | **0.6** | **-** |
| *Coagulant (ALG/PIX-111)* | Chemical Dosage Upstream | 0.15 | 0.15 | - | - |
| *Sulphuric Acid* | | 0.05 | 0.05 | - | - |
| *Soda* | | 0.05 | 0.05 | - | - |
| *Activated Silica* | | 0.05 | - | - | - |
| *Other Equipments* | | 0.15 | 0.15 | - | - |
| ***Total Chemical Dosage upstream*** | | **0.45** | **0.4** | **-** | **-** |
| *Monochloramine* | Chemical Dosage downstream | 0.08 | 0.08 | 0.08 | - |
| *Soda* | | 0.16 | 0.16 | 0.16 | - |
| *Hypochlorite* | | 0.08 | 0.08 | 0.08 | - |
| *Ammonium Sulphate* | | 0.08 | 0.08 | 0.08 | - |
| ***Total Chemical Dosage downstream*** | | **0.4** | **0.4** | **0.4** | **-** |
| *Micro-Screen* | Unit processes in the WTP | 0.1 | 0.1 | 0.1 | 0.1 |
| *Raw water pumps* | | 1.8 | 1.8 | 1.8 | 1.8 |
| *Lamellar separation* | | 0.4 | - | - | 0.4 |
| *Sand filters* | | 0.4 | - | - | 0.4 |
| *Ozonation* | | 1.5 | 1.5 | 1.5 | - |
| *GAC/BAC filtration* | | 0.0 | 0.0 | 0.0 | 0.0 |
| *General Electricity* | | 0.1 | 0.1 | 0.1 | 0.1 |
| *Sludge treatment* | | 1.7 | 1.7 | 2.0 | 1.7 |
| *Distribution pumps* | | 28.0 | 28.0 | 28.0 | 28.0 |
| *UF* | | 2.24 | 0.6 | - | |
| *Secondary UF* | | - | 0.19 | 0.6 | |
| *NF* | | 13.44 | - | 22.35 | |
| *UV* | | 0.819 | 0.819 | 0.819 | 0.629 |
| ***Total Unit Processes in the WTP*** | | **50.499** | **34.809** | **56.669** | **33.129** |
| ***TOTAL*** | All | **52.429** | **37.409** | **58.869** | **34.329** |

Data assumed from previous alternatives N1, N2 & N3. Data reference: (Forslund, personal communication, 2020); (calculations using data from (Pentair, 2019))
*NF values are assumed to be similar as UF and SF from the previous alternatives.

# Appendix 7: Calculations

This appendix provides the used formulas and adopted calculation procedure for the performed water balance calculations and other related inventory data calculations. Approximations are made in some cases.

**Table 31:** Calculation reference for the performed water balance calculations for the LCA Inventory data.

| CALCULATING THE WATER BALANCE AND OTHER REQUIREMENTS IN THE ALTERNATIVES |
| --- |
| **From the given data:** Final plant capacity & Water loses within, the specific water requirement at each unit process can be calculated with few formulae. |
| **Specific waterflow in a preceding unit step ($m^3/d$)** = **[** Outflow in the succeeding unit process ($m^3/d$) **] / [** 100% – water loss percentage from the previous unit process **]** |
| **Specific water loss in a unit process ($m^3/d$)** = **[** Specific flow in the unit process ($m^3/d$) **] x [** Water loss percentage for unit process **]** |
| **In case of Alternative 7 with 50% water to UF and 50% of water to NF**<br>*Assume the two flows ($m^3/d$) are split from 'A' basin and flowing towards 'B' basin.<br>**Specific UF flow ($m^3/d$)** = **[** Specific flow in 'B' ($m^3/d$) **] / [** Overall water recovery in UF (%) **+** Overall water recovery in NF (%) **]**<br>**Specific NF flow ($m^3/d$)** = **[** Specific flow in 'B' ($m^3/d$) **] / [** Overall water recovery in UF (%) **+** Overall water recovery in NF (%) **]**<br>*(See **Figure 56** below for reference) |
| **Each input of chemical, energy, transportation consumption per part in SimaPro (p)** = **[** Specific quantity of the respective consumption **] / [** Quantity of average water produced per day in the WTP ($m^3/d$) **x** 365 (conversion to year) **]** |

**Table 32:** Calculation reference for the required inputs in LCA Inventory data.

| FORMULAE USED FOR CALCULATING THE INVENTORY DATA |
|---|
| Chemicals for CEB |
| **Formula**: Density = Mass / Volume;<br>**Given data**: Volume of the chemical solution in a specific 'X' weight percentage.<br><br>**Mass of the specific CEB chemical (t/y)** = **[** Specific volume of the chemical solution (X%) (l/y) **] x [** Specific density of the chemical solution (X%) (g/ml) **] x [** Conversion of gram to ton and liter to milliliter (1000/10^6) **]**<br><br>**CEB chemical dose for UF/NF (t/y)** = **[** Mass of the specific CEB chemical (t/y) **x** Specific water inflow from concerned unit process in the respective alternative ($m^3/d$) **] / [** *Incoming flow from the specific selected scenario **]**<br><br>***See Table 28** for reference on the inflow from scenario |
| Energy consumption |
| **Energy consumption (MWh/y)** = **[** Given energy consumption (GWh/y) **] x [** 1000 (Conversion of GWh/y to MWh/y) **]**<br><br>**Energy needed for the unit process UF, NF & UV (MWh/y)** = **[** Permeate flow from the unit process ($m^3/d$) **] x [** Given specific electricity consumption ($kWh/m^3$) **] x [** 365/1000 (Conversion of day to year and kWh/y to MWh/y) **]** |
| Chemical consumption |
| **Specific chemical dose (t/y)** = **[** Specific water inflow in the unit process in the respective Alternative ($m^3/d$) **] x [** Given specific chemical dose ($t/m^3$) **] x [** 365 (Conversion of day to year) **]** |
| Transport utilization |
| **Specific transport use (tkm/y)** = **[** Round trip distance (km) **] x [** Specific amount of chemical (t/y) **]** |

## Granular Activated Carbon consumption

*a **Filter load for GAC/BAC ($m^3/d$)** = **[** Number of GAC/BAC filters (pcs) **x** Area of the filter ($m^2$/filter) **x** Filter load for BAC/GAC ($m^3/m^2/h$) **x** 24 (hour to day conversion) **]**

**Total needed Activated Carbons (t/y)** = **[** *b Maximum water inflow load for the specific alternative ($m^3/d$) **x** Annual coal consumption for BAC/GAC (t/y) **] / [** Filter load for BAC/GAC ($m^3$/day) **]**

*a (See **Table 27** for inputs)

*b **Maximum inflow load ($m^3/d$)** = Maximum raw water intake from the lake Mälaren

(In this study we have utilized only the average water capacity)

(See **Figure 53** below for Maximum inflow load inputs)

## Polymer consumption

***Given data:** Total amount of sludge produced (3984.65 t/y) & the total amount of polymer consumed per year (8.74 t/y)

**Formula:** Density = Mass / Volume

Density of Sludge = 1 ton/$m^3$

**Volume of sludge ($m^3/y$)** = **[** Mass of sludge produced (t/y) **/** Density of sludge ($t/m^3$) **]**

**Polymer ($t/m^3$) = [** Amount of polymer produced per year (t/y) **/** Volume of sludge ($m^3/y$) **]**

**Table 29** for reference for the given data from the yearly report 2019.

| Inflow required for Granular Activated Carbon calc. |
|---|
| Max inflow as filter load for A7 |
| 375225.98 |
| Max inflow as filter load for A8 |
| 301340.15 |
| Max inflow as filter load for A9 |
| 356813.48 |

| Inflow required for Granular Activated Carbon calc. |
|---|
| Max inflow as filter load for A7 |
| 321622.27 |
| Max inflow as filter load for A8 |
| 258291.56 |
| Max inflow as filter load for A9 |
| 305840.13 |

| Inflow required for Granular Activated Carbon calc. |
|---|
| Max inflow as filter load for A0 |
| 217631.07 |

**Figure 53:** Calculated Maximum inflow for the respective future alternatives (for a maximum of 280 MLD plant capacity (left), 240 MLD plant capacity (center), 200 MLD plant capacity (Right)).

| | Sludge Calculation | | | | | |
|---|---|---|---|---|---|---|
| | For Mean flow | Unit | From Lamella Seperator | To Mälaren | To Centrifuge | To Sludge handling |
| Reference (N2) | TS | % | 0.0433% | 0.10% | 2.233% | 18% |
| | TS flow | tonnes/day | 6.80 | 0.14 | 6.66 | 6.662138 |
| | Flow | m3/day | 15700 | 15401.65 | 298.35 | 37.01 |
| A7 | TS | % | 0.0433% | 0.10% | 2.233% | 18% |
| | TS flow | tonnes/day | 6.88 | 0.14 | 6.74 | 6.74 |
| | Flow | m3/day | 15893.39 | 15591.37 | 302.02 | 37.47 |
| A8 | TS | % | 0.0433% | 0.10% | 2.233% | 18% |
| | TS flow | tonnes/day | 0.80 | 0.02 | 0.78 | 0.78 |
| | Flow | m3/day | 1843.53 | 1808.49 | 35.03 | 4.35 |
| A9 | TS | % | 0.0433% | 0.10% | 2.233% | 18% |
| | TS flow | tonnes/day | 1.46 | 0.03 | 1.43 | 1.43 |
| | Flow | m3/day | 3378.68 | 3314.47 | 64.21 | 7.97 |

| Backwash to Sludge tank | | Unit |
|---|---|---|
| Lamella | 1048.62 | m3/day |
| Sand filter | 14844.78 | m3/day |
| 15893.39 | | m3/day |

| Backwash to Sludge tank | | Unit |
|---|---|---|
| UF BW | 12290.17 | m3/day |
| Outflow from UF | 10446.65 | m3/day |
| 1843.53 | | m3/day |

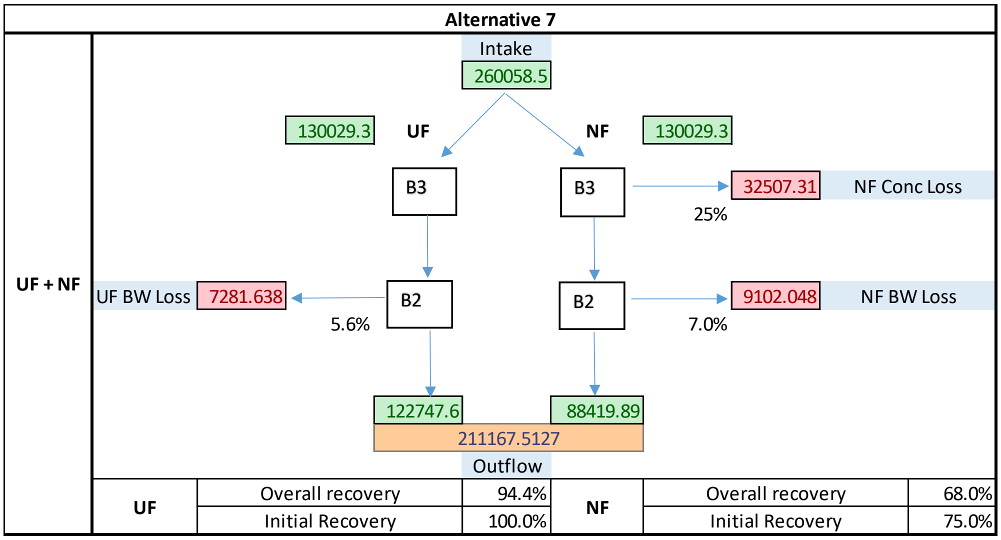
| Backwash to Sludge tank | | Unit |
|---|---|---|
| NF BW | 22524.53 | m3/day |
| Outflow from UF | 19145.85 | m3/day |
| 3378.68 | | m3/day |

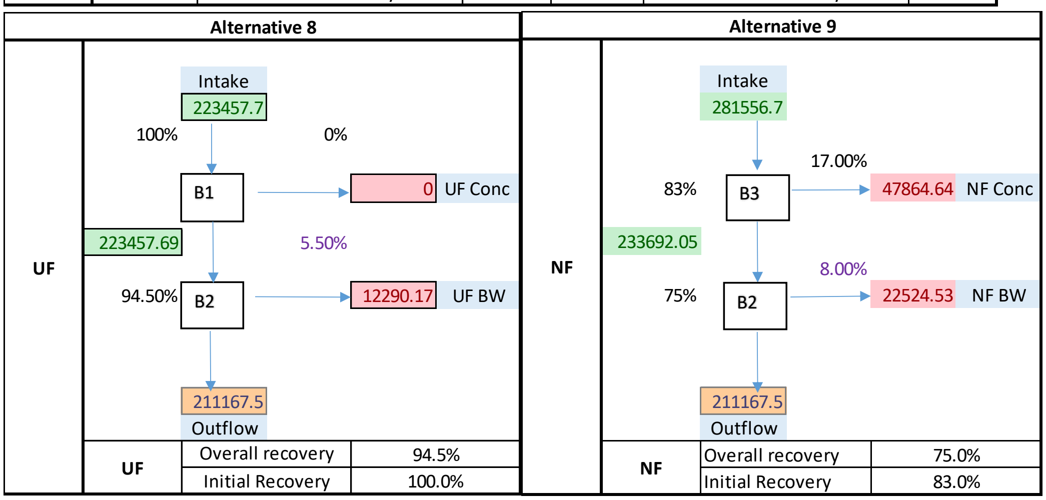
**Figure 54:** Calculated Sludge quantities at each unit step in the sludge separation tank for future alternatives 7, 8, & 9 (208 MLD).

| | Sludge Calculation | | | | | |
|---|---|---|---|---|---|---|
| | For Mean flow | Unit | From Lamella Seperator | To Mälaren | To Centrifuge | To Sludge handling |
| A0 | TS | % | 0.0433% | 0.10% | 2.233% | 18% |
| | TS flow | tonnes/day | 0.28 | 0.01 | 0.28 | 0.28 |
| | Flow | m3/day | 654.982 | 642.54 | 12.45 | 1.54 |

| Backwash to Sludge tank | | Unit |
|---|---|---|
| Lamella | 654.98 | m3/day |
| Sand filter | - | m3/day |
| 654.98 | | m3/day |
| Outflow from Sandfilter is sent back to lake | | |

**Figure 55:** Calculated Sludge quantities at each unit step in the sludge separation tank for the existing WTP (Alternative 0) (160 MLD).



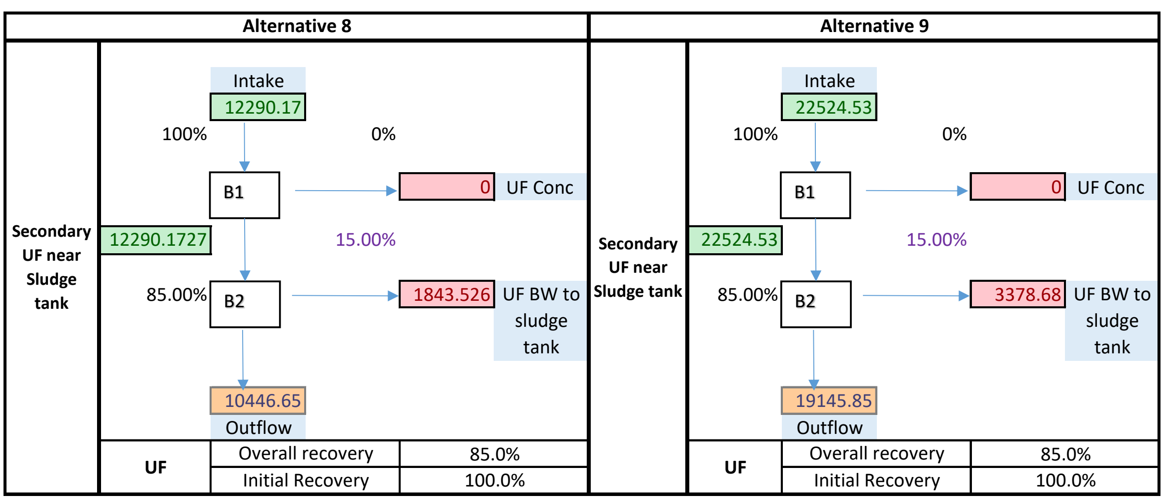




**Figure 56:** The calculated water and concentrate losses in the NF and UF units in Alternatives 7, 8 and 9 (208 MLD). This calculation is based on the water recovery percentages in Pentair report (2019).

**Table 33:** Calculation reference for the WTP other inputs in the LCA Inventory data.

| Calculation of WTP other inputs |
| --- |
| **Water treatment plant Infrastructure:** The given information for the WTP infrastructure in the selected dataset from Ecoinvent database is for a conventional waterwork with a capacity of $1.1E^{10}$ liter per year and a lifetime of 60 years.<br><br>**Specific part for infrastructure inclusion (p)** = **[** Quantity of average water produced per day in the WTP ($m^3/d$) **x** 365 (day to year conversion) **] / [** $1.1E^{10}$ (l/y) **]** |
| |
| **Ultraviolet lamp (p) =** 1p of UV lamp infrastructure with 9 individual units in all the alternatives. |
| |
| **Ultrafiltration unit (p)** = 1p of UF units, where there are 20 module units with 22 membranes included within as the hollow fibers, selected for Alternative 7.<br><br>1p of UF units, where there are 7 module units with 22 membranes included within as the hollow fibers, selected for *Alternative 8.<br><br>1p of secondary UF units, where there are 7 module units with 22 membranes included within as the hollow fibers, selected for *Alternatives 8 and 9.<br><br>*(1+1=2p for Alternative 8) |
| |
| **Nanofiltration unit (p)** = 1p of NF units, where there are 44 module units with 120 membranes included within as the hollow fibers, selected for Alternative 7.<br><br>1p of NF units, where there are 88 module units with 120 membranes included within as the hollow fibers, selected for Alternative 9. |
| |
| **GAC reactivation (t/d)** = **[** Quantity of GAC (t/y) **/** 365 (Conversion of year to day) **]**<br><br>**Avoided Burden of GAC (t/d)** = **[** Quantity of GAC (t/y) **/** 365 (Conversion of year to day) **]** |
| |
| **Raw sewage sludge (t/d)** = **[** Quantity of sludge (t/y) **/** 365 (Conversion of year to day) **]** |
| |
| **Produced drinking water (t/d) = [** Volume of average water produced per day in the WTP ($m^3/d$) **x** Density of water ($t/m^3$) **]** |

# Appendix 8: Emission data from results

The absolute values of the various emissions resulting from the environmental impacts related to the specific alternative and its key aspects are provided in the following pages.

**Table 34:** Emissions from chemical consumption in Alternative 7 (ALG) (208 MLD of average plant capacity).

| Impact category | Unit | Total | NaOCl for CEB | NaOH for CEB | HCl for CEB | $H_2SO_4$ for CEB | ALG | $H_2SO_4$ | Activated silica | Soda | GAC | $O_3$ | NaOCl | $(NH_4)_2SO_4$ | Polymer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 1.41E-01 | 1.99E-03 | 6.23E-04 | 7.79E-04 | 5.24E-05 | 2.37E-02 | 8.83E-04 | 5.50E-03 | 2.31E-02 | 7.85E-02 | 3.33E-03 | 5.45E-04 | 1.42E-03 | 1.13E-03 |
| Stratospheric ozone depletion | kg CFC11 eq | 5.19E-08 | 2.26E-09 | 9.08E-10 | 9.12E-10 | 3.76E-11 | 1.08E-08 | 6.34E-10 | 1.76E-09 | 8.74E-09 | 1.89E-08 | 5.68E-09 | 6.19E-10 | 4.41E-10 | 2.09E-10 |
| Ionizing radiation | kBq Co-60 eq | 1.88E-02 | 3.84E-04 | 2.54E-04 | 3.01E-04 | 6.43E-06 | 5.36E-03 | 1.08E-04 | 2.40E-04 | 1.70E-03 | 4.65E-03 | 5.58E-03 | 1.05E-04 | 6.10E-05 | 2.94E-05 |
| Ozone formation, Human health | kg NOx eq | 3.77E-04 | 4.79E-06 | 1.38E-06 | 1.71E-06 | 4.15E-07 | 7.65E-05 | 6.99E-06 | 1.44E-05 | 5.99E-05 | 2.01E-04 | 4.96E-06 | 1.31E-06 | 2.07E-06 | 1.73E-06 |
| Fine particulate matter formation | kg PM2.5 eq | 3.43E-04 | 4.31E-06 | 1.20E-06 | 1.48E-06 | 1.11E-06 | 8.64E-05 | 1.87E-05 | 1.53E-05 | 6.46E-05 | 1.42E-04 | 4.17E-06 | 1.18E-06 | 1.56E-06 | 1.46E-06 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 3.82E-04 | 4.85E-06 | 1.40E-06 | 1.73E-06 | 4.25E-07 | 7.75E-05 | 7.16E-06 | 1.47E-05 | 6.07E-05 | 2.03E-04 | 5.09E-06 | 1.33E-06 | 2.15E-06 | 1.82E-06 |
| Terrestrial acidification | kg SO2 eq | 1.08E-03 | 8.71E-06 | 3.26E-06 | 4.03E-06 | 3.73E-06 | 2.61E-04 | 6.27E-05 | 4.39E-05 | 2.41E-04 | 4.28E-04 | 9.87E-06 | 2.39E-06 | 4.03E-06 | 4.87E-06 |
| Freshwater eutrophication | kg P eq | 9.35E-05 | 1.39E-06 | 6.05E-07 | 7.60E-07 | 4.48E-08 | 2.03E-05 | 7.55E-07 | 2.78E-06 | 1.76E-05 | 4.62E-05 | 1.97E-06 | 3.82E-07 | 5.11E-07 | 2.02E-07 |
| Marine eutrophication | kg N eq | 6.70E-06 | 1.23E-07 | 5.50E-08 | 6.32E-08 | 2.80E-09 | 1.14E-06 | 4.72E-08 | 1.45E-07 | 1.00E-06 | 2.92E-06 | 2.09E-07 | 3.38E-08 | 2.87E-08 | 9.33E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 4.93E-01 | 7.70E-03 | 2.22E-03 | 3.78E-03 | 6.71E-04 | 1.54E-01 | 1.13E-02 | 3.57E-02 | 1.90E-01 | 4.23E-02 | 3.43E-02 | 2.11E-03 | 6.60E-03 | 3.04E-03 |
| Freshwater ecotoxicity | kg 1,4-DCB | 7.64E-03 | 9.14E-05 | 3.34E-05 | 4.84E-05 | 6.62E-06 | 2.11E-03 | 1.11E-04 | 3.21E-04 | 1.78E-03 | 1.71E-03 | 1.33E-03 | 2.50E-05 | 6.25E-05 | 1.94E-05 |
| Marine ecotoxicity | kg 1,4-DCB | 1.06E-02 | 1.28E-04 | 4.64E-05 | 6.77E-05 | 9.46E-06 | 3.01E-03 | 1.59E-04 | 4.63E-04 | 2.54E-03 | 2.38E-03 | 1.65E-03 | 3.51E-05 | 9.09E-05 | 2.84E-05 |
| Human carcinogenic toxicity | kg 1,4-DCB | 1.80E-02 | 1.11E-04 | 4.17E-05 | 5.51E-05 | 4.92E-06 | 1.24E-02 | 8.29E-05 | 2.58E-04 | 1.58E-03 | 3.00E-03 | 3.29E-04 | 3.04E-05 | 5.28E-05 | 2.39E-05 |
| Mineral resource scarcity | kg Cu eq | 1.27E-03 | 7.95E-06 | 2.55E-06 | 4.25E-06 | 8.51E-07 | 9.00E-04 | 1.43E-05 | 3.68E-05 | 2.13E-04 | 3.04E-05 | 4.41E-05 | 2.18E-06 | 8.00E-06 | 2.21E-06 |
| Fossil resource scarcity | kg oil eq | 4.20E-02 | 5.08E-04 | 1.58E-04 | 2.20E-04 | 8.28E-05 | 8.14E-03 | 1.39E-03 | 1.57E-03 | 5.34E-03 | 2.31E-02 | 3.66E-04 | 1.39E-04 | 4.71E-04 | 5.73E-04 |

**Table 35:** Emissions from chemical consumption in Alternative 8 (ALG) (208 MLD of average plant capacity).

| Impact category | Unit | Total | NaOCl for CEB | NaOH for CEB | HCl for CEB | ALG | $H_2SO_4$ | Soda | GAC | $O_3$ | NaOCl | $(NH_4)_2SO_4$ | Polymer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 1.01E-01 | 2.49E-03 | 9.74E-04 | 1.40E-03 | 1.39E-02 | 5.59E-04 | 1.37E-02 | 6.30E-02 | 3.33E-03 | 4.47E-04 | 9.70E-04 | 1.31E-04 |
| Stratospheric ozone depletion | kg CFC11 eq | 3.95E-08 | 2.83E-09 | 1.42E-09 | 1.64E-09 | 6.33E-09 | 4.01E-10 | 5.18E-09 | 1.52E-08 | 5.68E-09 | 5.08E-10 | 3.02E-10 | 2.42E-11 |
| Ionizing radiation | kBq Co-60 eq | 1.51E-02 | 4.80E-04 | 3.98E-04 | 5.42E-04 | 3.14E-03 | 6.86E-05 | 1.01E-03 | 3.73E-03 | 5.58E-03 | 8.63E-05 | 4.17E-05 | 3.41E-06 |
| Ozone formation, Human health | kg NOx eq | 2.65E-04 | 6.00E-06 | 2.16E-06 | 3.08E-06 | 4.48E-05 | 4.43E-06 | 3.55E-05 | 1.61E-04 | 4.96E-06 | 1.08E-06 | 1.41E-06 | 2.01E-07 |
| Fine particulate matter formation | kg PM2.5 eq | 2.31E-04 | 5.39E-06 | 1.87E-06 | 2.66E-06 | 5.06E-05 | 1.18E-05 | 3.83E-05 | 1.14E-04 | 4.17E-06 | 9.68E-07 | 1.06E-06 | 1.70E-07 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 2.68E-04 | 6.07E-06 | 2.18E-06 | 3.12E-06 | 4.54E-05 | 4.54E-06 | 3.60E-05 | 1.63E-04 | 5.09E-06 | 1.09E-06 | 1.47E-06 | 2.11E-07 |
| Terrestrial acidification | kg SO2 eq | 7.18E-04 | 1.09E-05 | 5.09E-06 | 7.25E-06 | 1.53E-04 | 3.97E-05 | 1.43E-04 | 3.44E-04 | 9.87E-06 | 1.96E-06 | 2.76E-06 | 5.64E-07 |
| Freshwater eutrophication | kg P eq | 6.66E-05 | 1.75E-06 | 9.46E-07 | 1.37E-06 | 1.19E-05 | 4.78E-07 | 1.04E-05 | 3.71E-05 | 1.97E-06 | 3.14E-07 | 3.50E-07 | 2.34E-08 |
| Marine eutrophication | kg N eq | 4.35E-06 | 1.54E-07 | 8.60E-08 | 1.14E-07 | 6.68E-07 | 2.99E-08 | 5.94E-07 | 2.34E-06 | 2.09E-07 | 2.77E-08 | 1.96E-08 | 1.08E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 3.05E-01 | 9.63E-03 | 3.46E-03 | 6.81E-03 | 9.00E-02 | 7.16E-03 | 1.13E-01 | 3.40E-02 | 3.43E-02 | 1.73E-03 | 4.51E-03 | 3.53E-04 |
| Freshwater ecotoxicity | kg 1,4-DCB | 5.38E-03 | 1.14E-04 | 5.22E-05 | 8.71E-05 | 1.23E-03 | 7.06E-05 | 1.05E-03 | 1.37E-03 | 1.33E-03 | 2.05E-05 | 4.27E-05 | 2.25E-06 |
| Marine ecotoxicity | kg 1,4-DCB | 7.38E-03 | 1.60E-04 | 7.25E-05 | 1.22E-04 | 1.76E-03 | 1.01E-04 | 1.51E-03 | 1.91E-03 | 1.65E-03 | 2.88E-05 | 6.21E-05 | 3.29E-06 |
| Human carcinogenic toxicity | kg 1,4-DCB | 1.14E-02 | 1.39E-04 | 6.52E-05 | 9.91E-05 | 7.29E-03 | 5.25E-05 | 9.36E-04 | 2.41E-03 | 3.29E-04 | 2.50E-05 | 3.61E-05 | 2.78E-06 |
| Mineral resource scarcity | kg Cu eq | 7.60E-04 | 9.95E-06 | 3.99E-06 | 7.65E-06 | 5.27E-04 | 9.08E-06 | 1.26E-04 | 2.44E-05 | 4.41E-05 | 1.79E-06 | 5.47E-06 | 2.57E-07 |
| Fossil resource scarcity | kg oil eq | 2.95E-02 | 6.35E-04 | 2.47E-04 | 3.97E-04 | 4.77E-03 | 8.83E-04 | 3.16E-03 | 1.85E-02 | 3.66E-04 | 1.14E-04 | 3.22E-04 | 6.64E-05 |

**Table 36:** Emissions from chemical consumption in Alternative 9 (208MLD of average plant capacity).

| Impact category | Unit | Total | NaOCl for CEB | NaOH for CEB | HCl for CEB | $H_2SO_4$ for CEB | GAC | $O_3$ | Soda | NaOCl | $(NH_4)_2SO_4$ | Polymer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Global warming | kg $CO_2$ eq | 9.96E-02 | 1.44E-03 | 2.27E-04 | 4.62E-06 | 5.65E-06 | 7.46E-02 | 3.33E-03 | 1.91E-02 | 4.61E-04 | 2.00E-04 | 2.40E-04 |
| Stratospheric ozone depletion | kg CFC11 eq | 3.35E-08 | 1.64E-09 | 3.31E-10 | 5.41E-12 | 4.05E-12 | 1.80E-08 | 5.68E-09 | 7.24E-09 | 5.24E-10 | 6.22E-11 | 4.43E-11 |
| Ionizing radiation | kBq Co-60 eq | 1.19E-02 | 2.78E-04 | 9.27E-05 | 1.78E-06 | 6.92E-07 | 4.42E-03 | 5.58E-03 | 1.40E-03 | 8.90E-05 | 8.61E-06 | 6.25E-06 |
| Ozone formation, Human health | kg NOx eq | 2.52E-04 | 3.47E-06 | 5.03E-07 | 1.01E-08 | 4.47E-08 | 1.91E-04 | 4.96E-06 | 4.96E-05 | 1.11E-06 | 2.92E-07 | 3.68E-07 |
| Fine particulate matter formation | kg PM2.5 eq | 1.98E-04 | 3.12E-06 | 4.36E-07 | 8.76E-09 | 1.20E-07 | 1.35E-04 | 4.17E-06 | 5.35E-05 | 9.98E-07 | 2.20E-07 | 3.11E-07 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 2.54E-04 | 3.51E-06 | 5.08E-07 | 1.03E-08 | 4.58E-08 | 1.93E-04 | 5.09E-06 | 5.03E-05 | 1.12E-06 | 3.04E-07 | 3.86E-07 |
| Terrestrial acidification | kg $SO_2$ eq | 6.28E-04 | 6.31E-06 | 1.19E-06 | 2.39E-08 | 4.01E-07 | 4.07E-04 | 9.87E-06 | 2.00E-04 | 2.02E-06 | 5.69E-07 | 1.03E-06 |
| Freshwater eutrophication | kg P eq | 6.22E-05 | 1.01E-06 | 2.21E-07 | 4.51E-09 | 4.83E-09 | 4.40E-05 | 1.97E-06 | 1.46E-05 | 3.23E-07 | 7.22E-08 | 4.29E-08 |
| Marine eutrophication | kg N eq | 4.15E-06 | 8.94E-08 | 2.01E-08 | 3.75E-10 | 3.02E-10 | 2.77E-06 | 2.09E-07 | 8.30E-07 | 2.86E-08 | 4.05E-09 | 1.98E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 2.42E-01 | 5.58E-03 | 8.08E-04 | 2.24E-05 | 7.23E-05 | 4.02E-02 | 3.43E-02 | 1.57E-01 | 1.78E-03 | 9.31E-04 | 6.47E-04 |
| Freshwater ecotoxicity | kg 1,4-DCB | 4.54E-03 | 6.62E-05 | 1.22E-05 | 2.87E-07 | 7.13E-07 | 1.63E-03 | 1.33E-03 | 1.47E-03 | 2.12E-05 | 8.82E-06 | 4.12E-06 |
| Marine ecotoxicity | kg 1,4-DCB | 6.18E-03 | 9.29E-05 | 1.69E-05 | 4.01E-07 | 1.02E-06 | 2.26E-03 | 1.65E-03 | 2.11E-03 | 2.97E-05 | 1.28E-05 | 6.04E-06 |
| Human carcinogenic toxicity | kg 1,4-DCB | 4.63E-03 | 8.04E-05 | 1.52E-05 | 3.26E-07 | 5.31E-07 | 2.86E-03 | 3.29E-04 | 1.31E-03 | 2.57E-05 | 7.45E-06 | 5.09E-06 |
| Mineral resource scarcity | kg Cu eq | 2.60E-04 | 5.76E-06 | 9.31E-07 | 2.52E-08 | 9.17E-08 | 2.89E-05 | 4.41E-05 | 1.77E-04 | 1.84E-06 | 1.13E-06 | 4.71E-07 |
| Fossil resource scarcity | kg oil eq | 2.75E-02 | 3.68E-04 | 5.76E-05 | 1.31E-06 | 8.92E-06 | 2.20E-02 | 3.66E-04 | 4.42E-03 | 1.18E-04 | 6.65E-05 | 1.22E-04 |

**Table 37:** Emissions from chemical consumption in Alternative 0 (Existing WTP) (160MLD of average plant capacity).

| Impact category | Unit | Total | ALG | Activated silica | Quicklime | GAC | NaOCl | $(NH_4)_2 SO_4$ | Polymer |
|---|---|---|---|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 1.23E-01 | 3.28E-02 | 4.16E-03 | 2.26E-02 | 6.04E-02 | 2.76E-03 | 3.42E-04 | 6.04E-05 |
| Stratospheric ozone depletion | kg CFC11 eq | 3.60E-08 | 1.50E-08 | 1.33E-09 | 1.93E-09 | 1.45E-08 | 3.13E-09 | 1.06E-10 | 1.12E-11 |
| Ionizing radiation | kBq Co-60 eq | 1.22E-02 | 7.43E-03 | 1.81E-04 | 4.24E-04 | 3.58E-03 | 5.32E-04 | 1.47E-05 | 1.57E-06 |
| Ozone formation, Human health | kg NOx eq | 2.91E-04 | 1.06E-04 | 1.09E-05 | 1.20E-05 | 1.55E-04 | 6.64E-06 | 4.98E-07 | 9.27E-08 |
| Fine particulate matter formation | kg PM2.5 eq | 2.53E-04 | 1.20E-04 | 1.15E-05 | 5.75E-06 | 1.09E-04 | 5.97E-06 | 3.75E-07 | 7.83E-08 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 2.94E-04 | 1.08E-04 | 1.11E-05 | 1.23E-05 | 1.56E-04 | 6.72E-06 | 5.18E-07 | 9.73E-08 |
| Terrestrial acidification | kg SO2 eq | 7.55E-04 | 3.62E-04 | 3.32E-05 | 1.68E-05 | 3.30E-04 | 1.21E-05 | 9.71E-07 | 2.61E-07 |
| Freshwater eutrophication | kg P eq | 6.82E-05 | 2.82E-05 | 2.10E-06 | 2.31E-07 | 3.56E-05 | 1.93E-06 | 1.23E-07 | 1.08E-08 |
| Marine eutrophication | kg N eq | 4.19E-06 | 1.58E-06 | 1.10E-07 | 2.20E-08 | 2.25E-06 | 1.71E-07 | 6.92E-09 | 4.99E-08 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 2.88E-01 | 2.13E-01 | 2.70E-02 | 2.50E-03 | 3.26E-02 | 1.07E-02 | 1.59E-03 | 1.63E-04 |
| Freshwater ecotoxicity | kg 1,4-DCB | 4.64E-03 | 2.92E-03 | 2.43E-04 | 1.90E-05 | 1.32E-03 | 1.27E-04 | 1.51E-05 | 1.04E-06 |
| Marine ecotoxicity | kg 1,4-DCB | 6.59E-03 | 4.18E-03 | 3.50E-04 | 2.89E-05 | 1.83E-03 | 1.78E-04 | 2.19E-05 | 1.52E-06 |
| Human carcinogenic toxicity | kg 1,4-DCB | 2.00E-02 | 1.73E-02 | 1.95E-04 | 3.45E-05 | 2.31E-03 | 1.54E-04 | 1.27E-05 | 1.28E-06 |
| Mineral resource scarcity | kg Cu eq | 1.32E-03 | 1.25E-03 | 2.78E-05 | 2.75E-06 | 2.34E-05 | 1.10E-05 | 1.93E-06 | 1.18E-07 |
| Fossil resource scarcity | kg oil eq | 3.31E-02 | 1.13E-02 | 1.19E-03 | 2.04E-03 | 1.78E-02 | 7.03E-04 | 1.13E-04 | 3.07E-05 |

**Table 38:** Emissions from chemical consumption in Alternative 7 (PIX-111) (208 MLD average plant capacity).

| Impact category | Unit | Total | NaOCl for CEB | NaOH for CEB | HCl for CEB | $H_2SO_4$ for CEB | PIX-111 | $H_2SO_4$ | Activated silica | Soda | GAC | $O_3$ | NaOCl | $(NH_4)_2SO_4$ | Polymer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Global warming | kg $CO_2$ eq | 1.68E-01 | 1.99E-03 | 6.23E-04 | 7.79E-04 | 5.24E-05 | 1.78E-02 | 3.95E-03 | 5.50E-03 | 5.22E-02 | 7.85E-02 | 3.33E-03 | 5.45E-04 | 1.42E-03 | 1.13E-03 |
| Stratospheric ozone depletion | kg CFC11 eq | 7.69E-08 | 2.26E-09 | 9.08E-10 | 9.12E-10 | 3.76E-11 | 2.26E-08 | 2.84E-09 | 1.76E-09 | 1.98E-08 | 1.89E-08 | 5.68E-09 | 6.19E-10 | 4.41E-10 | 2.09E-10 |
| Ionizing radiation | kBq Co-60 eq | 2.16E-02 | 3.84E-04 | 2.54E-04 | 3.01E-04 | 6.43E-06 | 5.71E-03 | 4.84E-04 | 2.40E-04 | 3.84E-03 | 4.65E-03 | 5.58E-03 | 1.05E-04 | 6.10E-05 | 2.94E-05 |
| Ozone formation, Human health | kg NOx eq | 4.47E-04 | 4.79E-06 | 1.38E-06 | 1.71E-06 | 4.15E-07 | 4.65E-05 | 3.13E-05 | 1.44E-05 | 1.35E-04 | 2.01E-04 | 4.96E-06 | 1.31E-06 | 2.07E-06 | 1.73E-06 |
| Fine particulate matter formation | kg PM2.5 eq | 4.45E-04 | 4.31E-06 | 1.20E-06 | 1.48E-06 | 1.11E-06 | 4.14E-05 | 8.37E-05 | 1.53E-05 | 1.46E-04 | 1.42E-04 | 4.17E-06 | 1.18E-06 | 1.56E-06 | 1.46E-06 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 4.53E-04 | 4.85E-06 | 1.40E-06 | 1.73E-06 | 4.25E-07 | 4.72E-05 | 3.20E-05 | 1.47E-05 | 1.37E-04 | 2.03E-04 | 5.09E-06 | 1.33E-06 | 2.15E-06 | 1.82E-06 |
| Terrestrial acidification | kg $SO_2$ eq | 1.45E-03 | 8.71E-06 | 3.26E-06 | 4.03E-06 | 3.73E-06 | 1.06E-04 | 2.81E-04 | 4.39E-05 | 5.45E-04 | 4.28E-04 | 9.87E-06 | 2.39E-06 | 4.03E-06 | 4.87E-06 |
| Freshwater eutrophication | kg P eq | 1.19E-04 | 1.39E-06 | 6.05E-07 | 7.60E-07 | 4.48E-08 | 2.09E-05 | 3.38E-06 | 2.78E-06 | 3.98E-05 | 4.62E-05 | 1.97E-06 | 3.82E-07 | 5.11E-07 | 2.02E-07 |
| Marine eutrophication | kg N eq | 8.59E-06 | 1.23E-07 | 5.50E-08 | 6.32E-08 | 2.80E-09 | 1.60E-06 | 2.11E-07 | 1.45E-07 | 2.27E-06 | 2.92E-06 | 2.09E-07 | 3.38E-08 | 2.87E-08 | 9.32E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 8.23E-01 | 7.70E-03 | 2.22E-03 | 3.78E-03 | 6.71E-04 | 2.05E-01 | 5.06E-02 | 3.57E-02 | 4.30E-01 | 4.23E-02 | 3.43E-02 | 2.11E-03 | 6.60E-03 | 3.04E-03 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1.03E-02 | 9.14E-05 | 3.34E-05 | 4.84E-05 | 6.62E-06 | 2.10E-03 | 4.99E-04 | 3.21E-04 | 4.02E-03 | 1.71E-03 | 1.33E-03 | 2.50E-05 | 6.25E-05 | 1.94E-05 |
| Marine ecotoxicity | kg 1,4-DCB | 1.43E-02 | 1.28E-04 | 4.64E-05 | 6.77E-05 | 9.46E-06 | 2.98E-03 | 7.12E-04 | 4.63E-04 | 5.75E-03 | 2.38E-03 | 1.65E-03 | 3.51E-05 | 9.09E-05 | 2.84E-05 |
| Human carcinogenic toxicity | kg 1,4-DCB | 9.71E-03 | 1.11E-04 | 4.17E-05 | 5.51E-05 | 4.92E-06 | 1.85E-03 | 3.71E-04 | 2.58E-04 | 3.57E-03 | 3.00E-03 | 3.29E-04 | 3.04E-05 | 5.28E-05 | 2.39E-05 |
| Mineral resource scarcity | kg Cu eq | 9.33E-04 | 7.95E-06 | 2.55E-06 | 4.25E-06 | 8.51E-07 | 2.47E-04 | 6.41E-05 | 3.68E-05 | 4.83E-04 | 3.04E-05 | 4.41E-05 | 2.18E-06 | 8.00E-06 | 2.21E-06 |
| Fossil resource scarcity | kg oil eq | 5.00E-02 | 5.08E-04 | 1.58E-04 | 2.20E-04 | 8.28E-05 | 4.50E-03 | 6.24E-03 | 1.57E-03 | 1.21E-02 | 2.31E-02 | 3.66E-04 | 1.39E-04 | 4.71E-04 | 5.73E-04 |

**Table 39:** Emissions from chemical consumption in Alternative 8 (PIX-111) (208 MLD average plant capacity).

| Impact category | Unit | Total | NaOCl for CEB | NaOH for CEB | HCl for CEB | ALG | $H_2SO_4$ | Soda | GAC | $O_3$ | NaOCl | $(NH_4)_2SO_4$ | Polymer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 1.18E-01 | 2.49E-03 | 9.74E-04 | 1.40E-03 | 1.02E-02 | 2.32E-03 | 3.31E-02 | 6.30E-02 | 3.33E-03 | 4.47E-04 | 9.70E-04 | 1.31E-04 |
| Stratospheric ozone depletion | kg CFC11 eq | 5.48E-08 | 2.83E-09 | 1.42E-09 | 1.64E-09 | 1.30E-08 | 1.67E-09 | 1.25E-08 | 1.52E-08 | 5.68E-09 | 5.08E-10 | 3.02E-10 | 2.42E-11 |
| Ionizing radiation | kBq Co-60 eq | 1.69E-02 | 4.80E-04 | 3.98E-04 | 5.42E-04 | 3.28E-03 | 2.85E-04 | 2.43E-03 | 3.73E-03 | 5.58E-03 | 8.63E-05 | 4.17E-05 | 3.41E-06 |
| Ozone formation, Human health | kg NOx eq | 3.11E-04 | 6.00E-06 | 2.16E-06 | 3.08E-06 | 2.67E-05 | 1.84E-05 | 8.58E-05 | 1.61E-04 | 4.96E-06 | 1.08E-06 | 1.41E-06 | 2.01E-07 |
| Fine particulate matter formation | kg PM2.5 eq | 2.96E-04 | 5.39E-06 | 1.87E-06 | 2.66E-06 | 2.38E-05 | 4.92E-05 | 9.26E-05 | 1.14E-04 | 4.17E-06 | 9.68E-07 | 1.06E-06 | 1.70E-07 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 3.15E-04 | 6.07E-06 | 2.18E-06 | 3.12E-06 | 2.71E-05 | 1.88E-05 | 8.70E-05 | 1.63E-04 | 5.09E-06 | 1.09E-06 | 1.47E-06 | 2.11E-07 |
| Terrestrial acidification | kg SO2 eq | 9.54E-04 | 1.09E-05 | 5.09E-06 | 7.25E-06 | 6.12E-05 | 1.65E-04 | 3.45E-04 | 3.44E-04 | 9.87E-06 | 1.96E-06 | 2.76E-06 | 5.64E-07 |
| Freshwater eutrophication | kg P eq | 8.31E-05 | 1.75E-06 | 9.46E-07 | 1.37E-06 | 1.20E-05 | 1.99E-06 | 2.52E-05 | 3.71E-05 | 1.97E-06 | 3.14E-07 | 3.50E-07 | 2.34E-08 |
| Marine eutrophication | kg N eq | 5.54E-06 | 1.54E-07 | 8.60E-08 | 1.14E-07 | 9.21E-07 | 1.24E-07 | 1.44E-06 | 2.34E-06 | 2.09E-07 | 2.77E-08 | 1.96E-08 | 1.08E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 5.14E-01 | 9.63E-03 | 3.46E-03 | 6.81E-03 | 1.18E-01 | 2.97E-02 | 2.72E-01 | 3.40E-02 | 3.43E-02 | 1.73E-03 | 4.51E-03 | 3.53E-04 |
| Freshwater ecotoxicity | kg 1,4-DCB | 7.07E-03 | 1.14E-04 | 5.22E-05 | 8.71E-05 | 1.21E-03 | 2.93E-04 | 2.55E-03 | 1.37E-03 | 1.33E-03 | 2.05E-05 | 4.27E-05 | 2.25E-06 |
| Marine ecotoxicity | kg 1,4-DCB | 9.79E-03 | 1.60E-04 | 7.25E-05 | 1.22E-04 | 1.71E-03 | 4.19E-04 | 3.65E-03 | 1.91E-03 | 1.65E-03 | 2.88E-05 | 6.21E-05 | 3.29E-06 |
| Human carcinogenic toxicity | kg 1,4-DCB | 6.66E-03 | 1.39E-04 | 6.52E-05 | 9.91E-05 | 1.07E-03 | 2.18E-04 | 2.26E-03 | 2.41E-03 | 3.29E-04 | 2.50E-05 | 3.61E-05 | 2.78E-06 |
| Mineral resource scarcity | kg Cu eq | 5.83E-04 | 9.95E-06 | 3.99E-06 | 7.65E-06 | 1.42E-04 | 3.77E-05 | 3.06E-04 | 2.44E-05 | 4.41E-05 | 1.79E-06 | 5.47E-06 | 2.57E-07 |
| Fossil resource scarcity | kg oil eq | 3.46E-02 | 6.35E-04 | 2.47E-04 | 3.97E-04 | 2.59E-03 | 3.67E-03 | 7.65E-03 | 1.85E-02 | 3.66E-04 | 1.14E-04 | 3.22E-04 | 6.64E-05 |

**Table 40:** Emissions from energy consumption excluding distribution in Alternative 0 (Existing WTP) (160MLD of average plant capacity).

| Impact category | Unit | Total | Hydro Electricity | Wind Electricity |
|---|---|---|---|---|
| Global warming | kg $CO_2$ eq | 6.28E-03 | 5.05E-03 | 1.24E-03 |
| Stratospheric ozone depletion | kg CFC11 eq | 1.12E-08 | 8.38E-09 | 2.81E-09 |
| Ionizing radiation | kBq Co-60 eq | 1.12E-02 | 1.11E-02 | 4.65E-05 |
| Ozone formation, Human health | kg NOx eq | 8.65E-06 | 5.15E-06 | 3.50E-06 |
| Fine particulate matter formation | kg PM2.5 eq | 6.91E-06 | 3.18E-06 | 3.73E-06 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 8.89E-06 | 5.26E-06 | 3.64E-06 |
| Terrestrial acidification | kg $SO_2$ eq | 1.63E-05 | 7.60E-06 | 8.67E-06 |
| Freshwater eutrophication | kg P eq | 3.11E-06 | 1.09E-06 | 2.02E-06 |
| Marine eutrophication | kg N eq | 3.75E-07 | 2.46E-07 | 1.30E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 5.44E-02 | 1.42E-02 | 4.02E-02 |
| Freshwater ecotoxicity | kg 1,4-DCB | 2.54E-03 | 3.83E-04 | 2.16E-03 |
| Marine ecotoxicity | kg 1,4-DCB | 3.13E-03 | 4.83E-04 | 2.65E-03 |
| Human carcinogenic toxicity | kg 1,4-DCB | 5.66E-04 | 2.30E-04 | 3.36E-04 |
| Mineral resource scarcity | kg Cu eq | 7.03E-05 | 2.73E-05 | 4.30E-05 |
| Fossil resource scarcity | kg oil eq | 6.33E-04 | 3.71E-04 | 2.62E-04 |

**Table 41:** Emissions from energy consumption excluding distribution in Alternative 7 (208 MLD of average plant capacity).

| Impact category | Unit | Total | Hydro Electricity | Wind Electricity |
|---|---|---|---|---|
| Global warming | kg CO2 eq | 3.53E-02 | 2.84E-02 | 6.94E-03 |
| Stratospheric ozone depletion | kg CFC11 eq | 6.28E-08 | 4.71E-08 | 1.58E-08 |
| Ionizing radiation | kBq Co-60 eq | 6.27E-02 | 6.25E-02 | 2.61E-04 |
| Ozone formation, Human health | kg NOx eq | 4.86E-05 | 2.90E-05 | 1.97E-05 |
| Fine particulate matter formation | kg PM2.5 eq | 3.88E-05 | 1.78E-05 | 2.10E-05 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 5.00E-05 | 2.95E-05 | 2.04E-05 |
| Terrestrial acidification | kg SO2 eq | 9.14E-05 | 4.27E-05 | 4.87E-05 |
| Freshwater eutrophication | kg P eq | 1.75E-05 | 6.14E-06 | 1.13E-05 |
| Marine eutrophication | kg N eq | 2.11E-06 | 1.38E-06 | 7.28E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 3.06E-01 | 8.00E-02 | 2.26E-01 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1.43E-02 | 2.15E-03 | 1.21E-02 |
| Marine ecotoxicity | kg 1,4-DCB | 1.76E-02 | 2.71E-03 | 1.49E-02 |
| Human carcinogenic toxicity | kg 1,4-DCB | 3.18E-03 | 1.29E-03 | 1.89E-03 |
| Mineral resource scarcity | kg Cu eq | 3.95E-04 | 1.54E-04 | 2.41E-04 |
| Fossil resource scarcity | kg oil eq | 3.55E-03 | 2.08E-03 | 1.47E-03 |

**Table 42:** Emissions from energy consumption excluding distribution in Alternative 8 (208 MLD of average plant capacity).

| Impact category | Unit | Total | Hydro Electricity | Wind Electricity |
|---|---|---|---|---|
| Global warming | kg $CO_2$ eq | 2.74E-02 | 2.20E-02 | 5.39E-03 |
| Stratospheric ozone depletion | kg CFC11 eq | 4.87E-08 | 3.65E-08 | 1.22E-08 |
| Ionizing radiation | kBq Co-60 eq | 4.87E-02 | 4.85E-02 | 2.03E-04 |
| Ozone formation, Human health | kg NOx eq | 3.77E-05 | 2.25E-05 | 1.52E-05 |
| Fine particulate matter formation | kg PM2.5 eq | 3.01E-05 | 1.38E-05 | 1.63E-05 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 3.88E-05 | 2.29E-05 | 1.58E-05 |
| Terrestrial acidification | kg $SO_2$ eq | 7.09E-05 | 3.31E-05 | 3.78E-05 |
| Freshwater eutrophication | kg P eq | 1.35E-05 | 4.77E-06 | 8.78E-06 |
| Marine eutrophication | kg N eq | 1.64E-06 | 1.07E-06 | 5.64E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 2.37E-01 | 6.21E-02 | 1.75E-01 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1.11E-02 | 1.67E-03 | 9.39E-03 |
| Marine ecotoxicity | kg 1,4-DCB | 1.37E-02 | 2.11E-03 | 1.15E-02 |
| Human carcinogenic toxicity | kg 1,4-DCB | 2.47E-03 | 1.00E-03 | 1.46E-03 |
| Mineral resource scarcity | kg Cu eq | 3.06E-04 | 1.19E-04 | 1.87E-04 |
| Fossil resource scarcity | kg oil eq | 2.76E-03 | 1.62E-03 | 1.14E-03 |

**Table 43:** Emissions from energy consumption excluding distribution in Alternative 9 (208 MLD of average plant capacity).

| Impact category | Unit | Total | Hydro Electricity | Wind Electricity |
|---|---|---|---|---|
| Global warming | kg CO2 eq | 4.00E-02 | 3.22E-02 | 7.88E-03 |
| Stratospheric ozone depletion | kg CFC11 eq | 7.13E-08 | 5.34E-08 | 1.79E-08 |
| Ionizing radiation | kBq Co-60 eq | 7.12E-02 | 7.09E-02 | 2.97E-04 |
| Ozone formation, Human health | kg NOx eq | 5.52E-05 | 3.29E-05 | 2.23E-05 |
| Fine particulate matter formation | kg PM2.5 eq | 4.40E-05 | 2.02E-05 | 2.38E-05 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 5.67E-05 | 3.35E-05 | 2.32E-05 |
| Terrestrial acidification | kg SO2 eq | 1.04E-04 | 4.85E-05 | 5.53E-05 |
| Freshwater eutrophication | kg P eq | 1.98E-05 | 6.97E-06 | 1.28E-05 |
| Marine eutrophication | kg N eq | 2.39E-06 | 1.57E-06 | 8.26E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 3.47E-01 | 9.08E-02 | 2.56E-01 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1.62E-02 | 2.44E-03 | 1.37E-02 |
| Marine ecotoxicity | kg 1,4-DCB | 2.00E-02 | 3.08E-03 | 1.69E-02 |
| Human carcinogenic toxicity | kg 1,4-DCB | 3.61E-03 | 1.46E-03 | 2.14E-03 |
| Mineral resource scarcity | kg Cu eq | 4.48E-04 | 1.74E-04 | 2.74E-04 |
| Fossil resource scarcity | kg oil eq | 4.03E-03 | 2.36E-03 | 1.67E-03 |

**Table 44:** Emissions from energy consumption for the common water distribution in Alternative 7, 8 and 9 (208 MLD of average plant capacity).

| Impact category | Unit | Total | Hydro Electricity | Wind Electricity |
|---|---|---|---|---|
| Global warming | kg $CO_2$ eq | 1.88E-02 | 1.51E-02 | 3.71E-03 |
| Stratospheric ozone depletion | kg CFC11 eq | 3.36E-08 | 2.51E-08 | 8.43E-09 |
| Ionizing radiation | kBq Co-60 eq | 3.35E-02 | 3.34E-02 | 1.40E-04 |
| Ozone formation, Human health | kg NOx eq | 2.60E-05 | 1.55E-05 | 1.05E-05 |
| Fine particulate matter formation | kg PM2.5 eq | 2.07E-05 | 9.53E-06 | 1.12E-05 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 2.67E-05 | 1.58E-05 | 1.09E-05 |
| Terrestrial acidification | kg $SO_2$ eq | 4.88E-05 | 2.28E-05 | 2.60E-05 |
| Freshwater eutrophication | kg P eq | 9.33E-06 | 3.28E-06 | 6.05E-06 |
| Marine eutrophication | kg N eq | 1.13E-06 | 7.37E-07 | 3.89E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 1.63E-01 | 4.27E-02 | 1.21E-01 |
| Freshwater ecotoxicity | kg 1,4-DCB | 7.61E-03 | 1.15E-03 | 6.47E-03 |
| Marine ecotoxicity | kg 1,4-DCB | 9.40E-03 | 1.45E-03 | 7.95E-03 |
| Human carcinogenic toxicity | kg 1,4-DCB | 1.70E-03 | 6.89E-04 | 1.01E-03 |
| Mineral resource scarcity | kg Cu eq | 2.11E-04 | 8.20E-05 | 1.29E-04 |
| Fossil resource scarcity | kg oil eq | 1.90E-03 | 1.11E-03 | 7.86E-04 |

**Table 45:** Emissions from energy consumption for the water distribution in Alternative 0 (Existing WTP) (160 MLD of average plant capacity).

| Impact category | Unit | Total | Hydro Electricity | Wind Electricity |
|---|---|---|---|---|
| Global warming | kg CO2 eq | 2.45E-02 | 1.97E-02 | 4.81E-03 |
| Stratospheric ozone depletion | kg CFC11 eq | 4.36E-08 | 3.26E-08 | 1.09E-08 |
| Ionizing radiation | kBq Co-60 eq | 4.35E-02 | 4.33E-02 | 1.81E-04 |
| Ozone formation, Human health | kg NOx eq | 3.37E-05 | 2.01E-05 | 1.36E-05 |
| Fine particulate matter formation | kg PM2.5 eq | 2.69E-05 | 1.24E-05 | 1.45E-05 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 3.46E-05 | 2.05E-05 | 1.42E-05 |
| Terrestrial acidification | kg SO2 eq | 6.34E-05 | 2.96E-05 | 3.38E-05 |
| Freshwater eutrophication | kg P eq | 1.21E-05 | 4.26E-06 | 7.85E-06 |
| Marine eutrophication | kg N eq | 1.46E-06 | 9.57E-07 | 5.04E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 2.12E-01 | 5.55E-02 | 1.57E-01 |
| Freshwater ecotoxicity | kg 1,4-DCB | 9.88E-03 | 1.49E-03 | 8.39E-03 |
| Marine ecotoxicity | kg 1,4-DCB | 1.22E-02 | 1.88E-03 | 1.03E-02 |
| Human carcinogenic toxicity | kg 1,4-DCB | 2.20E-03 | 8.95E-04 | 1.31E-03 |
| Mineral resource scarcity | kg Cu eq | 2.74E-04 | 1.07E-04 | 1.67E-04 |
| Fossil resource scarcity | kg oil eq | 2.46E-03 | 1.44E-03 | 1.02E-03 |

**Table 46:** Emissions from transportation in Alternative 0 (Existing WTP) (160 MLD of average plant capacity).

| Impact category | Unit | Total | Heavy truck Transport, freight, lorry >32 metric ton, EURO-6 (For Chemicals) | Light Truck Transport, freight, lorry 3.5-7.5 metric ton, EURO-6 (For Chemicals) | Heavy truck Transport, freight, lorry >32 metric ton, EURO-6 (For Sludge) |
|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 1.04E-02 | 8.21E-03 | 2.05E-03 | 1.26E-04 |
| Stratospheric ozone depletion | kg CFC11 eq | 7.22E-09 | 5.86E-09 | 1.27E-09 | 8.96E-11 |
| Ionizing radiation | kBq Co-60 eq | 2.26E-04 | 1.81E-04 | 4.19E-05 | 2.77E-06 |
| Ozone formation, Human health | kg NOx eq | 1.86E-05 | 1.56E-05 | 2.83E-06 | 2.38E-07 |
| Fine particulate matter formation | kg PM2.5 eq | 1.09E-05 | 8.93E-06 | 1.82E-06 | 1.37E-07 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 1.98E-05 | 1.65E-05 | 2.99E-06 | 2.53E-07 |
| Terrestrial acidification | kg SO2 eq | 2.17E-05 | 1.73E-05 | 4.07E-06 | 2.66E-07 |
| Freshwater eutrophication | kg P eq | 9.14E-07 | 6.76E-07 | 2.28E-07 | 1.03E-08 |
| Marine eutrophication | kg N eq | 7.02E-08 | 5.26E-08 | 1.68E-08 | 8.06E-10 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 1.74E-01 | 1.54E-01 | 1.75E-02 | 2.36E-03 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1.56E-04 | 1.05E-04 | 4.86E-05 | 1.61E-06 |
| Marine ecotoxicity | kg 1,4-DCB | 2.95E-04 | 2.16E-04 | 7.57E-05 | 3.31E-06 |
| Human carcinogenic toxicity | kg 1,4-DCB | 2.20E-04 | 1.54E-04 | 6.30E-05 | 2.36E-06 |
| Mineral resource scarcity | kg Cu eq | 2.03E-05 | 1.40E-05 | 6.10E-06 | 2.14E-07 |
| Fossil resource scarcity | kg oil eq | 3.85E-03 | 3.11E-03 | 6.94E-04 | 4.76E-05 |

**Table 47:** Emissions from transportation in Alternative 7 (208 MLD of average plant capacity).

| Impact category | Unit | Total | Heavy truck Transport, freight, lorry >32 metric ton, EURO-6 (For Chemicals) | Light Truck Transport, freight, lorry 3.5-7.5 metric ton, EURO-6 (For Chemicals) | Heavy truck Transport, freight, lorry >32 metric ton, EURO-6 (For Sludge) |
|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 1.93E-02 | 1.49E-02 | 4.27E-03 | 1.55E-04 |
| Stratospheric ozone depletion | kg CFC11 eq | 1.34E-08 | 1.06E-08 | 2.65E-09 | 1.11E-10 |
| Ionizing radiation | kBq Co-60 eq | 4.18E-04 | 3.28E-04 | 8.73E-05 | 3.42E-06 |
| Ozone formation, Human health | kg NOx eq | 3.43E-05 | 2.82E-05 | 5.88E-06 | 2.94E-07 |
| Fine particulate matter formation | kg PM2.5 eq | 2.01E-05 | 1.62E-05 | 3.79E-06 | 1.69E-07 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 3.65E-05 | 2.99E-05 | 6.22E-06 | 3.13E-07 |
| Terrestrial acidification | kg SO2 eq | 4.02E-05 | 3.14E-05 | 8.47E-06 | 3.28E-07 |
| Freshwater eutrophication | kg P eq | 1.71E-06 | 1.22E-06 | 4.74E-07 | 1.28E-08 |
| Marine eutrophication | kg N eq | 1.31E-07 | 9.53E-08 | 3.49E-08 | 9.96E-10 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 3.19E-01 | 2.79E-01 | 3.64E-02 | 2.92E-03 |
| Freshwater ecotoxicity | kg 1,4-DCB | 2.94E-04 | 1.91E-04 | 1.01E-04 | 1.99E-06 |
| Marine ecotoxicity | kg 1,4-DCB | 5.53E-04 | 3.91E-04 | 1.57E-04 | 4.09E-06 |
| Human carcinogenic toxicity | kg 1,4-DCB | 4.13E-04 | 2.79E-04 | 1.31E-04 | 2.92E-06 |
| Mineral resource scarcity | kg Cu eq | 3.83E-05 | 2.53E-05 | 1.27E-05 | 2.65E-07 |
| Fossil resource scarcity | kg oil eq | 7.13E-03 | 5.63E-03 | 1.44E-03 | 5.88E-05 |

**Table 48:** Emissions from transportation in Alternative 8 (208 MLD of average plant capacity).

| Impact category | Unit | Total | Heavy truck Transport, freight, lorry >32 metric ton, EURO-6 (For Chemicals) | Light Truck Transport, freight, lorry 3.5-7.5 metric ton, EURO-6 (For Chemicals) | Heavy truck Transport, freight, lorry >32 metric ton, EURO-6 (For Sludge) |
|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 1.23E-02 | 9.39E-03 | 2.92E-03 | 1.80E-05 |
| Stratospheric ozone depletion | kg CFC11 eq | 8.53E-09 | 6.70E-09 | 1.81E-09 | 1.29E-11 |
| Ionizing radiation | kBq Co-60 eq | 2.67E-04 | 2.07E-04 | 5.96E-05 | 3.97E-07 |
| Ozone formation, Human health | kg NOx eq | 2.19E-05 | 1.78E-05 | 4.02E-06 | 3.41E-08 |
| Fine particulate matter formation | kg PM2.5 eq | 1.28E-05 | 1.02E-05 | 2.59E-06 | 1.96E-08 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 2.32E-05 | 1.89E-05 | 4.25E-06 | 3.63E-08 |
| Terrestrial acidification | kg SO2 eq | 2.57E-05 | 1.98E-05 | 5.79E-06 | 3.81E-08 |
| Freshwater eutrophication | kg P eq | 1.10E-06 | 7.73E-07 | 3.24E-07 | 1.48E-09 |
| Marine eutrophication | kg N eq | 8.42E-08 | 6.02E-08 | 2.38E-08 | 1.16E-10 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 2.02E-01 | 1.77E-01 | 2.49E-02 | 3.39E-04 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1.90E-04 | 1.21E-04 | 6.91E-05 | 2.31E-07 |
| Marine ecotoxicity | kg 1,4-DCB | 3.55E-04 | 2.47E-04 | 1.08E-04 | 4.74E-07 |
| Human carcinogenic toxicity | kg 1,4-DCB | 2.66E-04 | 1.76E-04 | 8.96E-05 | 3.39E-07 |
| Mineral resource scarcity | kg Cu eq | 2.47E-05 | 1.60E-05 | 8.67E-06 | 3.07E-08 |
| Fossil resource scarcity | kg oil eq | 4.55E-03 | 3.56E-03 | 9.87E-04 | 6.82E-06 |

**Table 49:** Emissions from transportation in Alternative 9 (208 MLD of average plant capacity).

| Impact category | Unit | Total | Heavy truck Transport, freight, lorry >32 metric ton, EURO-6 (For Chemicals) | Light Truck Transport, freight, lorry 3.5-7.5 metric ton, EURO-6 (For Chemicals) | Heavy truck Transport, freight, lorry >32 metric ton, EURO-6 (For Sludge) |
|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 9.43E-03 | 8.54E-03 | 8.59E-04 | 3.30E-05 |
| Stratospheric ozone depletion | kg CFC11 eq | 6.65E-09 | 6.09E-09 | 5.33E-10 | 2.36E-11 |
| Ionizing radiation | kBq Co-60 eq | 2.07E-04 | 1.88E-04 | 1.75E-05 | 7.28E-07 |
| Ozone formation, Human health | kg NOx eq | 1.74E-05 | 1.62E-05 | 1.18E-06 | 6.26E-08 |
| Fine particulate matter formation | kg PM2.5 eq | 1.01E-05 | 9.28E-06 | 7.62E-07 | 3.59E-08 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 1.85E-05 | 1.72E-05 | 1.25E-06 | 6.65E-08 |
| Terrestrial acidification | kg SO2 eq | 1.98E-05 | 1.80E-05 | 1.70E-06 | 6.98E-08 |
| Freshwater eutrophication | kg P eq | 8.01E-07 | 7.03E-07 | 9.54E-08 | 2.72E-09 |
| Marine eutrophication | kg N eq | 6.20E-08 | 5.48E-08 | 7.01E-09 | 2.12E-10 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 1.68E-01 | 1.61E-01 | 7.33E-03 | 6.21E-04 |
| Freshwater ecotoxicity | kg 1,4-DCB | 1.30E-04 | 1.10E-04 | 2.03E-05 | 4.24E-07 |
| Marine ecotoxicity | kg 1,4-DCB | 2.57E-04 | 2.25E-04 | 3.16E-05 | 8.69E-07 |
| Human carcinogenic toxicity | kg 1,4-DCB | 1.87E-04 | 1.60E-04 | 2.64E-05 | 6.20E-07 |
| Mineral resource scarcity | kg Cu eq | 1.72E-05 | 1.45E-05 | 2.55E-06 | 5.63E-08 |
| Fossil resource scarcity | kg oil eq | 3.54E-03 | 3.23E-03 | 2.90E-04 | 1.25E-05 |

**Table 50:** Emissions from other WTP inputs in Alternative 7 (208 MLD of average plant capacity).

| Impact category | Unit | Total | Water work Infrastructure | Ultraviolet lamp | Ultrafiltration modules | Nanofiltration modules | Reactivation of GAC | Avoided Burden from production of GAC | Raw sewage sludge |
|---|---|---|---|---|---|---|---|---|---|
| Global warming | kg CO2 eq | -0.06586 | 3.78E-03 | 4.61E-06 | 1.81E-05 | 8.31E-06 | 8.42E-03 | -7.83E-02 | 2.04E-04 |
| Stratospheric ozone depletion | kg CFC11 eq | -1.42E-08 | 1.81E-09 | 1.17E-12 | 6.87E-12 | 3.15E-12 | 2.57E-09 | -1.88E-08 | 2.39E-10 |
| Ionizing radiation | kBq Co-60 eq | -0.00315 | 1.05E-04 | 1.24E-07 | 1.22E-06 | 5.58E-07 | 1.36E-03 | -4.64E-03 | 2.39E-05 |
| Ozone formation, Human health | kg NOx eq | -0.00017 | 1.05E-05 | 1.02E-08 | 2.42E-08 | 1.11E-08 | 1.53E-05 | -2.01E-04 | 3.33E-07 |
| Fine particulate matter formation | kg PM2.5 eq | -0.00012 | 6.65E-06 | 1.30E-08 | 2.29E-08 | 1.05E-08 | 1.13E-05 | -1.42E-04 | 1.01E-07 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | -0.00018 | 1.10E-05 | 1.04E-08 | 2.50E-08 | 1.14E-08 | 1.55E-05 | -2.02E-04 | 3.42E-07 |
| Terrestrial acidification | kg SO2 eq | -0.00038 | 1.24E-05 | 1.68E-08 | 4.48E-08 | 2.05E-08 | 3.39E-05 | -4.27E-04 | 3.40E-07 |
| Freshwater eutrophication | kg P eq | -4.15E-05 | 1.94E-06 | 1.32E-09 | 5.03E-09 | 2.31E-09 | 2.69E-06 | -4.61E-05 | 4.69E-08 |
| Marine eutrophication | kg N eq | -2.42E-06 | 1.24E-07 | 9.88E-11 | 1.09E-09 | 4.99E-10 | 1.89E-07 | -2.91E-06 | 1.79E-07 |
| Terrestrial ecotoxicity | kg 1,4-DCB | -0.01003 | 2.35E-02 | 3.48E-04 | 2.49E-05 | 1.14E-05 | 7.96E-03 | -4.22E-02 | 2.95E-04 |
| Freshwater ecotoxicity | kg 1,4-DCB | -0.00131 | 2.74E-04 | 1.88E-07 | 4.07E-07 | 1.87E-07 | 1.18E-04 | -1.71E-03 | 2.79E-06 |
| Marine ecotoxicity | kg 1,4-DCB | -0.00181 | 3.87E-04 | 3.04E-07 | 5.69E-07 | 2.61E-07 | 1.67E-04 | -2.37E-03 | 4.08E-06 |
| Human carcinogenic toxicity | kg 1,4-DCB | -0.00187 | 9.51E-04 | 5.12E-07 | 5.17E-07 | 2.37E-07 | 1.75E-04 | -3.00E-03 | 4.73E-06 |
| Mineral resource scarcity | kg Cu eq | 6.80E-05 | 9.35E-05 | 3.40E-08 | 2.22E-08 | 1.02E-08 | 4.49E-06 | -3.03E-05 | 3.10E-07 |
| Fossil resource scarcity | kg oil eq | -0.02035 | 7.96E-04 | 1.33E-06 | 4.10E-06 | 1.88E-06 | 1.82E-03 | -2.30E-02 | 6.62E-05 |

**Table 51:** Emissions from other WTP inputs in Alternative 8 (208 MLD of average plant capacity).

| Impact category | Unit | Total | Water work Infrastructure | Ultraviolet lamp | Ultrafiltration modules | Reactivation of GAC | Avoided Burden from production of GAC | Raw sewage sludge |
|---|---|---|---|---|---|---|---|---|
| Global warming | kg $CO_2$ eq | -5.23E-02 | 3.78E-03 | 4.61E-06 | 3.63E-05 | 6.76E-03 | -6.29E-02 | 2.36E-05 |
| Stratospheric ozone depletion | kg CFC11 eq | -1.12E-08 | 1.81E-09 | 1.17E-12 | 1.37E-11 | 2.07E-09 | -1.51E-08 | 2.77E-11 |
| Ionizing radiation | kBq Co-60 eq | -2.53E-03 | 1.05E-04 | 1.24E-07 | 2.43E-06 | 1.09E-03 | -3.73E-03 | 2.77E-06 |
| Ozone formation, Human health | kg NOx eq | -1.38E-04 | 1.05E-05 | 1.02E-08 | 4.84E-08 | 1.23E-05 | -1.61E-04 | 3.86E-08 |
| Fine particulate matter formation | kg PM2.5 eq | -9.80E-05 | 6.65E-06 | 1.30E-08 | 4.58E-08 | 9.09E-06 | -1.14E-04 | 1.17E-08 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | -1.39E-04 | 1.10E-05 | 1.04E-08 | 4.99E-08 | 1.24E-05 | -1.63E-04 | 3.96E-08 |
| Terrestrial acidification | kg $SO_2$ eq | -3.03E-04 | 1.24E-05 | 1.68E-08 | 8.97E-08 | 2.72E-05 | -3.43E-04 | 3.94E-08 |
| Freshwater eutrophication | kg P eq | -3.29E-05 | 1.94E-06 | 1.32E-09 | 1.01E-08 | 2.16E-06 | -3.71E-05 | 5.44E-09 |
| Marine eutrophication | kg N eq | -2.04E-06 | 1.24E-07 | 9.88E-11 | 2.18E-09 | 1.51E-07 | -2.34E-06 | 2.08E-08 |
| Terrestrial ecotoxicity | kg 1,4-DCB | -3.54E-03 | 2.35E-02 | 3.48E-04 | 4.98E-05 | 6.39E-03 | -3.39E-02 | 3.42E-05 |
| Freshwater ecotoxicity | kg 1,4-DCB | -1.00E-03 | 2.74E-04 | 1.88E-07 | 8.14E-07 | 9.45E-05 | -1.37E-03 | 3.23E-07 |
| Marine ecotoxicity | kg 1,4-DCB | -1.38E-03 | 3.87E-04 | 3.04E-07 | 1.14E-06 | 1.34E-04 | -1.90E-03 | 4.73E-07 |
| Human carcinogenic toxicity | kg 1,4-DCB | -1.31E-03 | 9.51E-04 | 5.12E-07 | 1.03E-06 | 1.41E-04 | -2.41E-03 | 5.49E-07 |
| Mineral resource scarcity | kg Cu eq | 7.29E-05 | 9.35E-05 | 3.40E-08 | 4.45E-08 | 3.61E-06 | -2.43E-05 | 3.60E-08 |
| Fossil resource scarcity | kg oil eq | -1.62E-02 | 7.96E-04 | 1.33E-06 | 8.19E-06 | 1.46E-03 | -1.85E-02 | 7.68E-06 |

**Table 52:** Emissions from other WTP inputs in Alternative 9 (208 MLD of average plant capacity).

| Impact category | Unit | Total | Water work Infrastructure | Ultraviolet lamp | Ultrafiltration modules | Nanofiltration modules | Reactivation of GAC | Avoided Burden from production of GAC | Raw sewage sludge |
|---|---|---|---|---|---|---|---|---|---|
| Global warming | kg $CO_2$ eq | -6.26E-02 | 3.78E-03 | 4.61E-06 | 3.63E-05 | 8.31E-06 | 8.01E-03 | -7.45E-02 | 4.33E-05 |
| Stratospheric ozone depletion | kg CFC11 eq | -1.36E-08 | 1.81E-09 | 1.17E-12 | 1.37E-11 | 3.15E-12 | 2.45E-09 | -1.79E-08 | 5.08E-11 |
| Ionizing radiation | kBq Co-60 eq | -3.01E-03 | 1.05E-04 | 1.24E-07 | 2.43E-06 | 5.58E-07 | 1.29E-03 | -4.41E-03 | 5.08E-06 |
| Ozone formation, Human health | kg NOx eq | -1.66E-04 | 1.05E-05 | 1.02E-08 | 4.84E-08 | 1.11E-08 | 1.46E-05 | -1.91E-04 | 7.07E-08 |
| Fine particulate matter formation | kg PM2.5 eq | -1.17E-04 | 6.65E-06 | 1.30E-08 | 4.58E-08 | 1.05E-08 | 1.08E-05 | -1.35E-04 | 2.15E-08 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | -1.67E-04 | 1.10E-05 | 1.04E-08 | 4.99E-08 | 1.14E-08 | 1.47E-05 | -1.92E-04 | 7.27E-08 |
| Terrestrial acidification | kg $SO_2$ eq | -3.61E-04 | 1.24E-05 | 1.68E-08 | 8.97E-08 | 2.05E-08 | 3.23E-05 | -4.06E-04 | 7.22E-08 |
| Freshwater eutrophication | kg P eq | -3.94E-05 | 1.94E-06 | 1.32E-09 | 1.01E-08 | 2.31E-09 | 2.56E-06 | -4.39E-05 | 9.98E-09 |
| Marine eutrophication | kg N eq | -2.42E-06 | 1.24E-07 | 9.88E-11 | 2.18E-09 | 4.99E-10 | 1.79E-07 | -2.77E-06 | 3.81E-08 |
| Terrestrial ecotoxicity | kg 1,4-DCB | -8.56E-03 | 2.35E-02 | 3.48E-04 | 4.98E-05 | 1.14E-05 | 7.57E-03 | -4.01E-02 | 6.28E-05 |
| Freshwater ecotoxicity | kg 1,4-DCB | -1.23E-03 | 2.74E-04 | 1.88E-07 | 8.14E-07 | 1.87E-07 | 1.12E-04 | -1.62E-03 | 5.93E-07 |
| Marine ecotoxicity | kg 1,4-DCB | -1.71E-03 | 3.87E-04 | 3.04E-07 | 1.14E-06 | 2.61E-07 | 1.58E-04 | -2.26E-03 | 8.67E-07 |
| Human carcinogenic toxicity | kg 1,4-DCB | -1.73E-03 | 9.51E-04 | 5.12E-07 | 1.03E-06 | 2.37E-07 | 1.67E-04 | -2.85E-03 | 1.01E-06 |
| Mineral resource scarcity | kg Cu eq | 6.91E-05 | 9.35E-05 | 3.40E-08 | 4.45E-08 | 1.02E-08 | 4.27E-06 | -2.88E-05 | 6.60E-08 |
| Fossil resource scarcity | kg oil eq | -1.94E-02 | 7.96E-04 | 1.33E-06 | 8.19E-06 | 1.88E-06 | 1.73E-03 | -2.19E-02 | 1.41E-05 |

**Table 53:** Emissions from other WTP inputs in Alternative 0 (Existing WTP) (160 MLD of average plant capacity).

| Impact category | Unit | Total | Water work Infrastructure | Ultraviolet lamp | Reactivation of GAC | Avoided Burden from production of GAC | Raw sewage sludge |
|---|---|---|---|---|---|---|---|
| Global warming | kg $CO_2$ eq | -0.05013 | 3.78E-03 | 5.99E-06 | 6.51E-03 | -6.05E-02 | 6.05E-05 |
| Stratospheric ozone depletion | kg CFC11 eq | -1.07E-08 | 1.81E-09 | 1.52E-12 | 1.99E-09 | -1.46E-08 | 7.09E-11 |
| Ionizing radiation | kBq Co-60 eq | -0.00242 | 1.05E-04 | 1.61E-07 | 1.05E-03 | -3.58E-03 | 7.09E-06 |
| Ozone formation, Human health | kg NOx eq | -0.00013 | 1.05E-05 | 1.33E-08 | 1.18E-05 | -1.55E-04 | 9.87E-08 |
| Fine particulate matter formation | kg PM2.5 eq | -9.40E-05 | 6.65E-06 | 1.69E-08 | 8.74E-06 | -1.09E-04 | 3.00E-08 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | -0.00013 | 1.10E-05 | 1.35E-08 | 1.20E-05 | -1.56E-04 | 1.01E-07 |
| Terrestrial acidification | kg $SO_2$ eq | -0.00029 | 1.24E-05 | 2.19E-08 | 2.62E-05 | -3.30E-04 | 1.01E-07 |
| Freshwater eutrophication | kg P eq | -3.16E-05 | 1.94E-06 | 1.72E-09 | 2.08E-06 | -3.56E-05 | 1.39E-08 |
| Marine eutrophication | kg N eq | -1.93E-06 | 1.24E-07 | 1.28E-10 | 1.46E-07 | -2.25E-06 | 5.31E-08 |
| Terrestrial ecotoxicity | kg 1,4-DCB | -0.00238 | 2.35E-02 | 4.52E-04 | 6.15E-03 | -3.26E-02 | 8.76E-05 |
| Freshwater ecotoxicity | kg 1,4-DCB | -0.00095 | 2.74E-04 | 2.45E-07 | 9.09E-05 | -1.32E-03 | 8.28E-07 |
| Marine ecotoxicity | kg 1,4-DCB | -0.00132 | 3.87E-04 | 3.95E-07 | 1.29E-04 | -1.83E-03 | 1.21E-06 |
| Human carcinogenic toxicity | kg 1,4-DCB | -0.00123 | 9.51E-04 | 6.66E-07 | 1.35E-04 | -2.32E-03 | 1.40E-06 |
| Mineral resource scarcity | kg Cu eq | 7.37E-05 | 9.35E-05 | 4.42E-08 | 3.47E-06 | -2.34E-05 | 9.21E-08 |
| Fossil resource scarcity | kg oil eq | -0.01557 | 7.96E-04 | 1.74E-06 | 1.41E-03 | -1.78E-02 | 1.97E-05 |

**Table 54:** Emissions from energy consumption in 7 and 8 utilizing Green energy mix vs Sensitive Alternatives 7 and 8 utilizing Swedish grid mix.

| Impact category | Unit | A7 Energy consumption (Green energy mix) | SA7 Energy consumption (Swedish grid mix) | A8 Energy consumption (Green energy mix) | SA8 Energy consumption (Swedish grid mix) | A9 Energy consumption (Green energy mix) | SA9 Energy consumption (Swedish grid mix) |
|---|---|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 5.42E-02 | 4.81E-02 | 4.63E-02 | 4.10E-02 | 5.90E-02 | 5.23E-02 |
| Stratospheric ozone depletion | kg CFC11 eq | 9.66E-08 | 1.07E-07 | 8.24E-08 | 9.12E-08 | 1.05E-07 | 1.16E-07 |
| Ionizing radiation | kBq Co-60 eq | 9.64E-02 | 3.29E-01 | 8.23E-02 | 2.81E-01 | 1.05E-01 | 3.58E-01 |
| Ozone formation, Human health | kg NOx eq | 7.47E-05 | 1.04E-04 | 6.38E-05 | 8.85E-05 | 8.13E-05 | 1.13E-04 |
| Fine particulate matter formation | kg PM2.5 eq | 5.96E-05 | 6.16E-05 | 5.09E-05 | 5.25E-05 | 6.49E-05 | 6.70E-05 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 7.68E-05 | 1.06E-04 | 6.55E-05 | 9.00E-05 | 8.35E-05 | 1.15E-04 |
| Terrestrial acidification | kg SO2 eq | 1.41E-04 | 1.61E-04 | 1.20E-04 | 1.38E-04 | 1.53E-04 | 1.76E-04 |
| Freshwater eutrophication | kg P eq | 2.68E-05 | 2.27E-05 | 2.29E-05 | 1.93E-05 | 2.92E-05 | 2.47E-05 |
| Marine eutrophication | kg N eq | 3.24E-06 | 6.75E-06 | 2.76E-06 | 5.76E-06 | 3.52E-06 | 7.35E-06 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 4.70E-01 | 2.53E-01 | 4.01E-01 | 2.16E-01 | 5.11E-01 | 2.75E-01 |
| Freshwater ecotoxicity | kg 1,4-DCB | 2.19E-02 | 5.56E-03 | 1.87E-02 | 4.75E-03 | 2.38E-02 | 6.05E-03 |
| Marine ecotoxicity | kg 1,4-DCB | 2.71E-02 | 7.08E-03 | 2.31E-02 | 6.04E-03 | 2.94E-02 | 7.70E-03 |
| Human carcinogenic toxicity | kg 1,4-DCB | 4.88E-03 | 3.49E-03 | 4.17E-03 | 2.98E-03 | 5.31E-03 | 3.79E-03 |
| Mineral resource scarcity | kg Cu eq | 6.07E-04 | 4.83E-04 | 5.18E-04 | 4.12E-04 | 6.60E-04 | 5.25E-04 |
| Fossil resource scarcity | kg oil eq | 5.46E-03 | 8.16E-03 | 4.66E-03 | 6.96E-03 | 5.94E-03 | 8.87E-03 |

**Table 55:** Emissions from chemical consumption in 7 and 8 utilizing ALG vs Sensitive Alternatives 7 and 8 utilizing PIX-111.

| Impact category | Unit | A7 Chemical consumption (ALG) | SA7 Chemical consumption (PIX-111) | A8 Chemical consumption (ALG) | SA8 Chemical consumption (PIX-111) |
|---|---|---|---|---|---|
| Global warming | kg CO2 eq | 1.41E-01 | 1.68E-01 | 1.01E-01 | 1.18E-01 |
| Stratospheric ozone depletion | kg CFC11 eq | 5.19E-08 | 7.69E-08 | 3.95E-08 | 5.48E-08 |
| Ionizing radiation | kBq Co-60 eq | 1.88E-02 | 2.16E-02 | 1.51E-02 | 1.69E-02 |
| Ozone formation, Human health | kg NOx eq | 3.77E-04 | 4.47E-04 | 2.65E-04 | 3.11E-04 |
| Fine particulate matter formation | kg PM2.5 eq | 3.43E-04 | 4.45E-04 | 2.31E-04 | 2.96E-04 |
| Ozone formation, Terrestrial ecosystems | kg NOx eq | 3.82E-04 | 4.53E-04 | 2.68E-04 | 3.15E-04 |
| Terrestrial acidification | kg SO2 eq | 1.08E-03 | 1.45E-03 | 7.18E-04 | 9.54E-04 |
| Freshwater eutrophication | kg P eq | 9.35E-05 | 1.19E-04 | 6.66E-05 | 8.31E-05 |
| Marine eutrophication | kg N eq | 6.70E-06 | 8.59E-06 | 4.35E-06 | 5.54E-06 |
| Terrestrial ecotoxicity | kg 1,4-DCB | 4.93E-01 | 8.23E-01 | 3.05E-01 | 5.14E-01 |
| Freshwater ecotoxicity | kg 1,4-DCB | 7.64E-03 | 1.03E-02 | 5.38E-03 | 7.07E-03 |
| Marine ecotoxicity | kg 1,4-DCB | 1.06E-02 | 1.43E-02 | 7.38E-03 | 9.79E-03 |
| Human carcinogenic toxicity | kg 1,4-DCB | 1.80E-02 | 9.71E-03 | 1.14E-02 | 6.66E-03 |
| Mineral resource scarcity | kg Cu eq | 1.27E-03 | 9.33E-04 | 7.60E-04 | 5.83E-04 |
| Fossil resource scarcity | kg oil eq | 4.20E-02 | 5.00E-02 | 2.95E-02 | 3.46E-02 |

# Appendix 9: List of Figures & Tables

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