Disc filter facility at Gryaab [photograph, by Emelie Asplund, 2021].

A Comparative Life Cycle Assessment of Advanced Processes for the Removal of Pharmaceutical Residues in Wastewater

A Detailed Analysis Based on a Pre-study by Gryaab at Rya Wastewater Treatment Plant

Master's thesis in Industrial Ecology

Sara Andersson
Maria Karlsson

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se
Report No. E2022:015

REPORT NO. E2022:015

A Comparative Life Cycle Assessment of Advanced Processes for the Removal of Pharmaceutical Residues in Wastewater

A Detailed Analysis Based on a Pre-study by Gryaab at Rya Wastewater Treatment Plant

Sara Andersson
Maria Karlsson

Department of Technology Management and Economics
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022

A Comparative Life Cycle Assessment of Advanced Processes for the Removal of Pharmaceutical Residues in Wastewater
A Detailed Analysis Based on a Pre-study by Gryaab at Rya Wastewater Treatment Plant
Sara Andersson
Maria Karlsson

Report No. E2022:015
Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: +46 (0)31-772 1000

Cover:
The disc filter facility at Gryaab and basins for wastewater treatment.

Gothenburg, Sweden 2022

A Comparative Life Cycle Assessment of Advanced Processes for the Removal of Pharmaceutical Residues in Wastewater.
A Detailed Analysis Based on a Pre-study by Gryaab at Rya Wastewater Treatment Plant

SARA ANDERSSON
MARIA KARLSSON

Department of Technology Management and Economics
Chalmers University of Technology

Abstract

There are no requirements for wastewater treatment plants to treat pharmaceutical residues today. However, the Swedish Environmental Protection Agency has distributed grants to investigate solutions for improving the aquatic environment. Gryaab received grants in 2019 to examine processes for the removal of pharmaceutical residues. A pre-study including a multicriteria-analysis was conducted where three processes were investigated: ozonation, Pulverized Activated Carbon (PAC), and Granular Activated Carbon (GAC). The result showed the importance of further studies on the processes' environmental impact, leading to this life cycle assessment (LCA) study.

This LCA study analysed the processes from five midpoint impact categories: global warming potential, fossil depletion, energy use, eutrophication potential, and acidification potential. The aim was to provide Gryaab with useful data regarding which of the three processes is the environmentally preferable choice and regarding the major environmental impacts of each advanced process. Furthermore, several sensitivity analyses were made to depict what parts of the advanced processes are most crucial for the total environmental impact.

This study included two functional units to enable comparisons with both the pre-study and with other LCA studies. They were: the treatment of Gryaab's wastewater for the removal of pharmaceutical residues for one year; and the treatment of one m^3 of wastewater to this end. The calculations in this LCA were made in the software GaBi 9.2.1 Education, where the three processes and the existing sludge treatment were modelled separately. All flows were added in GaBi per m^3 of wastewater and then scaled up for the yearly functional unit.

According to the results, ozonation with wind power and the GAC process with renewable GAC, wind power, the largest possible bed volumes, and a regeneration plant at Rya wastewater treatment plant were considered the two most preferable alternatives in terms of environmental impact. Ozonation contributed the most to the midpoint impact category energy use. The PAC process contributed the most to global warming and acidification, while global warming was most significant for the GAC process. The value of using renewable alternatives where it is possible was thus strengthened. However, the environmental benefit of advanced wastewater treatment in comparison to its environmental burden must be further analysed to conclude if an implementation is environmentally advantageous.

Keywords: Gryaab, Rya WWTP, Advanced wastewater treatment, Life Cycle Assessment, Ozonation, PAC, GAC

Acknowledgements

It has been a pleasure to perform our master's thesis at Gryaab and evaluate the area of advanced wastewater treatment processes. Besides, it has been exciting to develop the results in the pre-study, conducted by Gryaab, and compare them with the results from this LCA study.

We would like to thank our supervisor Maria Neth, industrial PhD student at Gryaab, for making it possible for us to write this master's thesis at Gryaab, and for introducing us to valuable contact persons. Moreover, we would also like to thank our examiner Gregory Peters for being a part of our master's thesis and for his help likewise guidance throughout this project. Lastly, we would like to thank everyone at Gryaab for their generosity and valuable competence in wastewater treatment.

Sara Andersson, Maria Karlsson, Gothenburg, June, 2022

Content

1. Introduction 2
2. Background 3
   2.1. Pharmaceutical Residues 3
   2.2. Gryaab 4
   2.3. Life Cycle Assessment 5
   2.4. Processes for the Reduction of Pharmaceutical Residues 6
      2.4.1. Ozonation 6
      2.4.2. Activated Carbon Adsorption 7
         2.4.2.1. PAC Process 8
         2.4.2.2. GAC Process 8
3. Literature Study 10
   3.1. Previous Studies 10
   3.2. Previous LCA-Studies 12
   3.3. Implemented Advanced WWT Processes and Pilot Studies 13
   3.4. The Flows Entering WWTPs 14
4. Goal and Scope 15
   4.1. Goal of the Study 15
   4.2. Functional Units 15
   4.3. System Boundaries 16
   4.4. Flowchart 17
      4.4.1. Ozonation 17
      4.4.2. PAC Process 18
      4.4.3. GAC Process 19
   4.5. Midpoint Impact Categories 20
   4.6. Actors 21
   4.7. Data Quality Requirements 22
5. Method 23
   5.1. Delimitations 23
   5.2. Conduct of Study 23
6. Life Cycle Inventory Analysis 25
   6.1. System Description 25
      6.1.1. System Description of the Ozonation Process 25
      6.1.2. System Description of the PAC Process 26
      6.1.3. System Description of the GAC Process 30

6.1.4. System Description of the Existing Sludge Treatment 34
6.2. Emissions and Energy Use 35
7. Results and Interpretation 37
7.1. Total Environmental Impact of All Including Processes 37
7.1.1. Treatment of a Yearly Flow of Wastewater 37
7.1.2. Treatment of 1 m^3 of Wastewater 39
7.2. Ozonation with Sensitivity Analysis 40
7.3. PAC Process with Sensitivity Analyses 45
7.4. GAC Process with Sensitivity Analyses 50
8. Discussion 56
8.1. Which of the Three Advanced Processes is the Environmentally Preferable Choice? 56
8.1.1. Treatment of a Yearly Flow of Wastewater 56
8.1.2. Treatment of 1 m^3 of Wastewater 59
8.2. What are the Major Environmental Impacts Considering the Selected Midpoint Impact Categories, of Each Advanced Process? 60
8.3. What Parts of the Advanced Processes are Most Crucial for the Total Environmental Impact? 62
8.3.1. Ozonation 62
8.3.2. PAC Process 62
8.3.3. GAC Process 62
8.4. Impact on Actors 63
8.5. The Recipient of Rya WWTP 64
8.6. Ethical Aspects 65
8.7. Source of Errors and Improvements 66
9. Conclusions and Recommendations 68
10. References 69
Appendix 1 – LCIA Methods i
Appendix 2 – Concentrations of Pharmaceutical Residues in Effluent Treated Wastewater from the Existing WWTP ii
Appendix 3 – Chosen Flows in GaBi iii
Appendix 4 – Inventory Data xii
Appendix 5 – Example of Calculations xli
Appendix 6 – GaBi Modelling xlii
Appendix 7 – Results xlvi

List of Abbreviations

AP	Acidification Potential [g SO_2-eq.]
BOD	Biochemical Oxygen Demand
DOC	Dissolved Organic Carbon
EP	Eutrophication Potential [g PO_4^{3-}-eq.]
GAC	Granular Activated Carbon
GWP	Global Warming Potential [kg CO_2-eq.]
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Analysis
PAC	Pulverized Activated Carbon
PNEC	Predicted No-Effect Concentration
SEPA	Swedish Environmental Protection Agency
WWT	Wastewater Treatment
WWTP	Wastewater Treatment Plant

1. Introduction

In Sweden, over 1000 different active substances are used in approximately 7600 pharmaceuticals. The possible effects of the residues on organisms and plants are uncertain, leading to many unanswered questions regarding the spreading of pharmaceutical residues in the outgoing water and sludge from wastewater treatment plants (WWTPs) (Naturvårdsverket, n.d.a). In general, Swedish WWTPs are not designed to treat pharmaceutical residues. The removal of pharmaceutical residues is therefore often incomplete. However, pharmaceutical residues in wastewater have become an issue of increasing concern (Hoff, 2020), and the Swedish Environmental Protection Agency (SEPA) states the need to introduce advanced treatment of pharmaceutical residues in wastewater (Naturvårdsverket, 2017). American Institute of Chemical Engineers (AIChE, n.d) defines advanced wastewater treatment (WWT) as "any process which reduces the level of impurities in a wastewater below that attainable through conventional secondary or biological treatment".

Several of Sweden's environmental goals are affected by the potential effects of pharmaceutical residues in the environment. Therefore, SEPA (2021) has established an intermediate target to minimize pharmaceutical residues in the environment. The implementation of advanced WWT processes is among the measures that can contribute to achieving the goals. Moreover, regulations and other measures for minimizing potential environmental burdens should be in place in Sweden, in the EU, or internationally by the latest 2030. Research and experimental studies are important for achieving the intermediate target and the goal by 2030 (Naturvårdsverket, 2021).

At the request of the Swedish government, SEPA was commissioned to distribute grants to implement measures aimed at improving the aquatic environment (Hoff, 2020). Gryaab, the company that owns and operates the Rya WWTP, received grants to investigate processes for the removal of pharmaceutical residues in wastewater in the year 2019. Therefore, Gryaab conducted a pre-study that included a sustainability analysis in terms of a multicriteria-analysis, where all dimensions of sustainability were present, i.e., ecological, social, and economic. The results showed the importance of further studies concerning the environmental impact of the three advanced analysed processes: ozonation, Pulverized Activated Carbon (PAC), and Granular Activated Carbon (GAC) (Ernst et al., 2020).

A detailed study regarding a potential implementation of a process for the removal of pharmaceutical residues is thereby of high concern for Gryaab. This study, therefore, includes a Life Cycle Assessment (LCA), to compare and evaluate the environmental burden of each advanced process. For this study, the same assumptions and data are used to the largest degree as possible as for the pre-study, to make the two analyses comparable. However, as a first part, a literature study is made to gain knowledge on previously made LCAs on the topic. In the end, the results of the study are expected to serve as a basis for decision-makers at Gryaab on which of the three processes is the environmentally preferable choice, and if an implementation at Rya WWTP is necessary.

2. Background

This section presents a description of pharmaceutical residues and the background to the problem of spreading them. The company Gryaab is introduced as well as the existing wastewater treatment at Rya WWTP. Furthermore, the procedure of doing an LCA followed by the investigated processes is described.

2.1. Pharmaceutical Residues

In general, WWTPs are designed for the removal of oxygen-consuming substances as well as nitrogen and phosphorus (Westling, 2021a). The technical solutions at WWTPs can vary to a high degree, but all WWTPs include a chemical-, mechanical-, and biological treatment in different steps (Svenskt Vatten, 2016). However, as mentioned in Section 1, the WWTPs are not designed to reduce pharmaceutical residues or other micropollutants, which to a relatively large extent pass through the WWTP (Westling, 2021a).

Pharmaceutical residues are chemically stable and can, therefore, accumulate in the environment. In Sweden, current measurements have so far demonstrated low concentrations of pharmaceutical residues in nature (Naturvårdsverket, n.d.a). However, low concentrations of residues can affect nature and organisms since the substances can bioaccumulate and accumulate in the food chain. It has been reported that pharmaceutical residues can cause optically observable adverse effects in organisms (Björlenius, 2018). Though, SEPA points out a lack of knowledge concerning the potential effects of several substances on nature, humans and organisms via soil and water in the environment (Naturvårdsverket, n.d.a).

Oxazepam, an anti-anxiety drug, has been shown to alter the behaviour and feeding rate of wild European perch, which can result in ecological and evolutionary consequences (Björlenius, 2018). The substance is also included in the list of SEPA which contains substances considered important to analyse in wastewater (Naturvårdsverket, n.d.b). Diclofenac, a common analgesic, is another substance included in the list of SEPA that has shown effects on organisms (Björlenius, 2018; Naturvårdsverket, n.d.b). Moreover, Baresel et al., (2017) convey that antibiotics are of particular concern since antibiotic residues in the environment can be linked to increased antibiotic resistance.

The effects in nature of pharmaceutical residues from WWTPs depend on the sensitivity of the recipient, the concentration of pharmaceutical residues, the dilution factor, and the turnover in the recipient (Lüdtke, 2019). The receiver of raw or purified wastewater is called the recipient, for instance, watercourses, a lake, or the sea (Avloppsguiden, n.d.). A low dilution factor and a low turnover mean a greater risk of reaching harmful concentrations in the recipient (Lüdtke, 2019). When the recipient is the sea, this results in a higher dilution factor and turnover, which entails larger dispersion of pharmaceutical residues. Similarly, a small lake recipient offers less dilution and turnover which can lead to a greater risk of reaching harmful concentrations in the recipient (Čelić et al., 2019). These aspects make the analysis considering the removal of pharmaceutical residues from wastewater more difficult, since it can be problematic to measure the persistent substances in the effluent treated wastewater from the WWTP.

Another risk regarding pharmaceutical residues is the tendency for bioaccumulation in animals. Martínez Bueno et al., (2014) analysed residues of venlafaxine and found trace levels of it in marine mussels. Additionally, Álvarez-Muñoz et al., (2015) studied the occurrence of pharmaceutical residues in macroalgae, bivalves, and fish from different coastal areas in Europe. The result showed the presence of pharmaceutical compounds in varying amounts in each analysed organism. This means a risk of pharmaceutical residues being introduced into the human food chain.

2.2. Gryaab

Gryaab is located in Gothenburg, Sweden, and the company is responsible for the WWT from seven different municipalities in the nearby region: Ale, Gothenburg, Härryda, Kungälv, Lerum, Mölndal, and Partille. As mentioned in Section 1, the company owns and operates Rya WWTP and based on data from 2018, the inflow to the plant was on average 13 990 m^3/h (3.9 m^3/s) (Ernst et al., 2020). Moreover, due to a rather small available area at Gryaab, the retention time at Rya WWTP is relatively low. The effluent treated wastewater is released into the estuary of Göta Älv and part of the energy and nutrients are returned into the cycle as biogas or sludge (Gryaab, n.d.d). Moreover, the discharge point of effluent treated wastewater in Göta Älv is close to the ocean Kattegatt. Göta Älv is, therefore, the primary recipient and Kattegatt the secondary recipient at Rya WWTP. Since the effluent treated wastewater is released close to the ocean Kattegatt, the dilution factor is probably high leading to quick spreading of eventual residues.

Gryaab meets today's emission requirements of nitrogen and phosphorus, and the company is certified according to the International Organisation for Standardization (ISO) standard 14 001. Still, it continuously works on how to improve and meet future demands for WWT, Gryaab is expanding (Gryaab, n.d.a). The expansion started in 2020 with the planning of what new treatment processes to evaluate further, and the expansion is planned to be finished in 2036 (Gryaab, n.d.b). Figure 1 presents the existing WWT process without any removal of pharmaceutical residues, which is divided into three main types of treatment: mechanical, chemical, and biological.

The mechanical step is the first part of the WWT process, and it consists of a coarse bar screen where larger waste material is being separated, a sand trap where heavy solid particles are separated followed by a fine bar screen. The mechanical step also includes the primary settling (PS) where solid particles are separated as sludge. Furthermore, in the chemical step, different chemicals are used to remove phosphorous. For instance, iron sulphate reacts with phosphorous forming a precipitate that sediments to sludge. The sludge can then be used for producing biogas and used as fertilizer on agricultural land (Gryaab, n.d.a). The amount of sludge used as fertilizer on agricultural land meets the requirements of Revaq, which is a certification system ensuring sludge of good quality (Ernst et al., 2020). The chemical step is present in the activated sludge (AS) basins where iron sulphate is dosed to the wastewater.

In the biological treatment steps, bacteria and microorganisms are used to decompose organic material and to release nitrogen into the air instead of into the water (Gryaab, n.d.a). The biological step consists of AS basins with a following secondary settling (SS), nitrifying trickling filters (TF), and nitrifying and denitrifying Moving Bed Biological Reactor (MBBR)-

basins. Aeration is present in the nitrifying MBBR to enable oxidation in the chemical step. The TF work as a process for recirculation back to AS since all water must pass the nitrifying MBBR. However, the nitrifying MBBR has a limiting maximum flow of 4.5 m^3/s, which explains the reason for the recirculation through the TF. The recycling loop from the SS to AS is present since sludge is the working material in AS. Though, due to a continuous inflow of sludge, not everything can be saved. Therefore, some sludge is returned to the PS where it is passed on to the sludge treatment to be used as biogas or on agricultural land. Lastly, some sludge is also recycled from the disc filter (DF), back to the PS for the same reason.

During large influent of wastewater to Rya WWTP, the Direct Precipitation (DP) is used, where the influent is divided into two separate flows. One flow continues to PS, and thereby to the complete purification, whilst the other flow continues to DP. A more efficient precipitating chemical and polymer is added to the wastewater in DP, whereafter the effluent wastewater is released into the primary recipient.

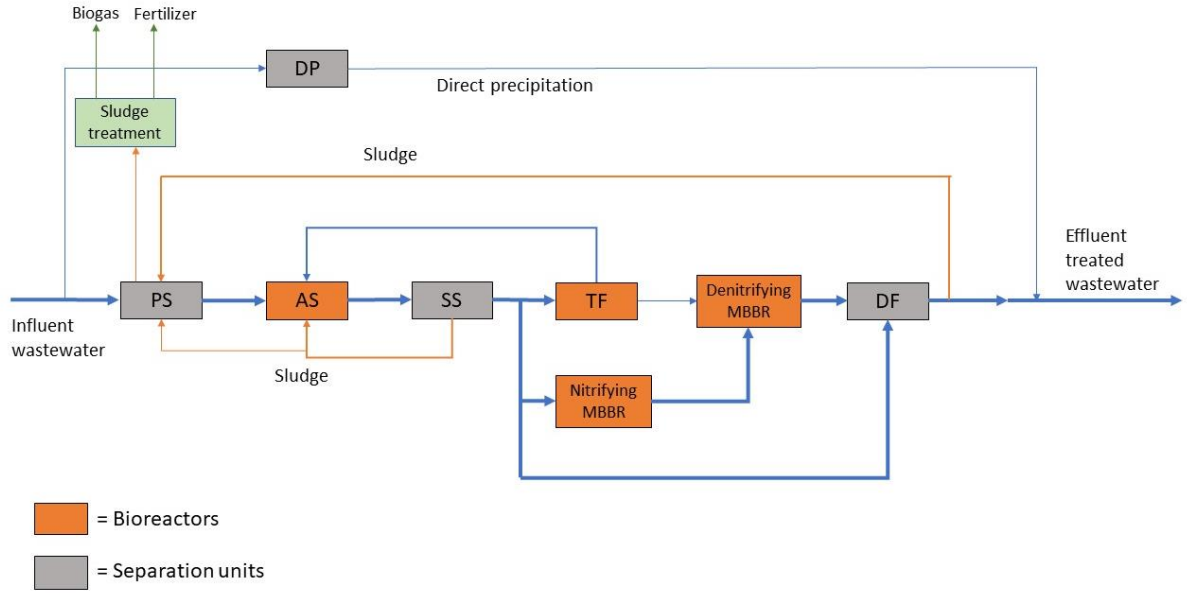


Figure 1. The existing WWT at Rya WWTP without any process for the removal of pharmaceutical residues. Abbreviations: PS=Primary Settling, AS=Activated Sludge, SS=Secondary Settling, TF=Nitrifying Trickling Filter, DF=Disc Filter, DP=Direct Precipitation

2.3. Life Cycle Assessment

LCA is a tool that calculates and describes a product or a process's environmental performance. The analysis can focus on the whole life cycle, i.e., from "cradle", where raw materials are extracted, to "grave", the waste management, or only on specific parts in the life cycle. ISO 14 044 is the provided standard that obtains specific requirements and guidelines to follow when doing an LCA. The procedure starts with defining the goal and scope of the study. Here, questions like "why", "who", and "what" are answered, and the purpose of the study is described. To continue, the scope is defined by deciding on a functional unit, a reference flow, system boundaries, and impact categories. Midpoint impact categories and endpoint impact categories can be selected, where the latter is an aggregation of different midpoint impact categories. Affected actors are also presented and an initial flowchart for the product or process is created.

The next step is the inventory analysis where all data are collected, and the initial flowchart is developed. With all data gathered, calculations are made over the life cycle in relation to the functional unit. The continuing step in the LCA procedure is the impact assessment where emissions first are classified according to which of the chosen impact category they contribute to. A categorization is then made which calculates each emission's impact in the specific category with the help of characterization factors. The final step in the LCA is the interpretation where the results from the impact assessment are analysed and compared. An overview of the LCA framework is presented in Figure 2. As can be seen, it is an iterative process and hence the reverse arrows, making it possible to do changes as the study progresses.

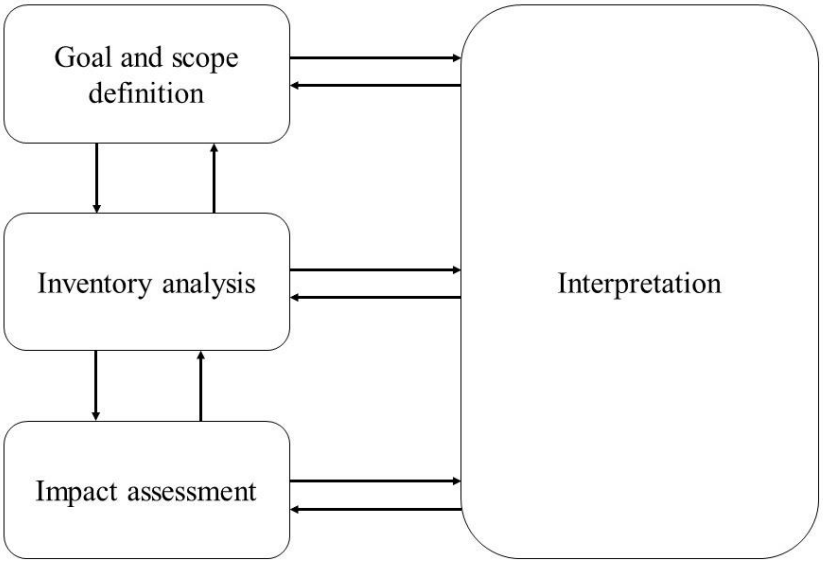


Figure 2. An overview of the LCA framework.

2.4. Processes for the Reduction of Pharmaceutical Residues

Efficiency, energy demand, and costs are three examples of factors that can be significantly different among processes for the reduction of pharmaceutical residues. In comparison to the existing WWTPs, advanced WWT processes can result in up to ten times higher energy use (Finnson, 2019). Therefore, it is of importance to weigh treatment efforts against additional environmental burdens caused by the advanced WWT processes.

Moreover, there is a lack of studies concerning environmental impacts, in terms of LCAs, of advanced WWT processes. Therefore, there is a need for further LCA studies to investigate unknown environmental effects caused by energy- and material consumption for advanced WWT processes (Li et al., 2019).

The following sections describe the three investigated advanced WWT processes and the suggested implementation at Rya WWTP.

2.4.1. Ozonation

Ozonation is an oxidizing method (Wahlberg et al., n.d.), where ozone is mixed into the wastewater. Ozone gas can be used to destroy organic molecules, such as pharmaceutical residues, and the design enables a high reaction rate (Tekniska verken, n.d). In the process, ozone reacts with organic molecules and generates new smaller molecules from the parent

substance. A disadvantage with the ozonation process is that the process is resource-intense regarding electricity use (Ernst et al., 2020). Another disadvantage of ozonation is the risk for the production of by-products and transformation products, which occurs in the presence of non-organic molecules in the wastewater (Clerc et al., 2021). The formation of bromate from bromide, which is present in varying degrees in wastewater, is especially problematic since bromate is carcinogenic. The potential formation of bromate from bromide at Rya WWTP was evaluated in the pre-study, which presented concentrations of bromate below reporting limits. Therefore, bromate formation was not considered a reason to exclude ozonation as a potential technical solution for reducing pharmaceutical residues at Rya WWTP (Ernst et al., 2020).

Moreover, ozonation requires that ozone must be produced locally since it is not a stable compound. Therefore, the production of ozone for the ozonation must take place on-site at Rya WWTP (Ernst et al., 2020). In general, power consumption to produce ozone is proportional to the mass of ozone generated (Baresel et al., 2020). Oxygen will be produced at the site as well, in a Vacuum Pressure Swing Adsorption (VPSA) facility, and used in the production of ozone. Production of oxygen at the site does not require any external chemicals, which is beneficial (Ernst et al., 2020).

2.4.2. Activated Carbon Adsorption

Activated carbon adsorption is a commonly used method for removing, inter alia, organic compounds in WWTPs (Bui et al., 2016). The origin of the carbon can be from both fossil- and renewable resources. Carbon has a large surface area per unit weight, which entails high adsorption (Ernst et al., 2020). An advantage of activated carbon is that no by-products are produced that may be harmful to organisms or humans (Baresel et al., 2015). The adsorption occurs either by charges, by the formation of covalent bonds between hydrocarbons in the aqueous solution and hydrocarbons from the surface, or by physical adsorption by Van der Waals forces (Ernst et al., 2020). Moreover, the adsorption is proportional to temperature and pressure ("Kolrester från industrier", n.d.).

Hydrochars, a compound of carbon and hydrogen, generally have low surface areas but the properties can be improved by a chemical- or physical activation process. In these processes, activated carbon is generated from a carbon source and the porosity is increased, specific surface functionalities can be created, or the pore size of materials adjusted. Chemical activation requires a chemical reagent, such as KOH, $ZnCl_2$, NaOH and H_3PO_4, to impregnate the material. Thermal treatment in an inert atmosphere is then followed to generate activated carbon. Moreover, physical activation means that the material is heated to a high temperature of 700-900 degrees Celsius in the presence of a controlled amount of air, steam, or CO_2. Bituminous coal, charcoal, coconut shell and lignite are generally activated by physical activation. On the other hand, wood and peat are generally activated with phosphoric acid via chemical activation. In comparison to physical activation, chemical activation entails better control of the material porosity through variations in chemical reagents and/or reagent concentrations. However, industrial production prefers physical activation due to the lack of chemical reagents and its technical viability (Niinipuu, 2019).

There are two types of processes for activated carbon adsorption, the PAC process and the GAC process, which are further described in Section 2.4.2.1 and Section 2.4.2.2.

2.4.2.1. PAC Process

In water purification with PAC, pulverized activated carbon is used as an adsorbent. Large organic molecules and charged molecules can be separated in the process since they adsorb to the carbon surface (Ernst et al., 2020). For PAC, the adsorption process is controlled by contact time (Bui et al., 2016). In the pre-study at Rya WWTP, the result showed a high variation in the degree of adsorption in the interval of 30 minutes to six hours. However, adsorption could be observed in the interval of six hours to 24 hours (Ernst et al., 2020). Disadvantages of this process are a large consumption of carbon, the potential usage of fossil-based carbon, and that PAC cannot be recycled (Bailey, 2020). PAC is classified as a dust-explosive substance, and it is therefore important to handle it carefully. On the other hand, an advantage of using PAC and to applicate it directly to an already existing MBBR is that it reduces the need for new areas and basins. It also makes it possible to handle the activated carbon separately which means that most of the sludge from the WWTP can continue to be returned to agricultural land (Ernst et al., 2020).

There are multiple ways to integrate the PAC process into an existing WWTP. The dosing of PAC can, for instance, take place in the influent, the biological treatment, or in the secondary effluent. The different alternatives have varied benefits and drawbacks, generating diverse results. For instance, depending on the process design, the sludge can be contaminated which leads to that the sludge cannot be used on agricultural land (Krahnstöver, 2018). However, there are no facilities to use as a reference for the intended design of the PAC process at Rya WWTP, which complicates the investigation.

2.4.2.2. GAC Process

In the process of GAC, a filter with granular activated carbon is used as an adsorbent (Ernst et al., 2020). GAC has a high adsorption capacity and efficiently adsorbs and removes various organic contaminants (Xing et al., 2020), and the adsorption process is controlled by the empty bed contact time (EBCT) (Bui et al., 2016). In the pre-study, 20 minutes was decided as the contact time (Ernst et al., 2020), even though the recommended time varied from 12-14 minutes (Baresel et al., 2015) to 20-40 minutes (Mulder et al., 2015). Similar to PAC, the disadvantages of the GAC process are the consumption of carbon and the potential usage of fossil-based carbon. However, GAC can be regenerated through a thermal process which means that the adsorbed micropollutants decompose, and the activated carbon can be reused. This procedure is done approximately 12 times in a ten-year period, but a negative aspect is that the regeneration currently is managed in Belgium (Ernst et al., 2020).

A frequently used concept considering GAC is bed volumes, which implies how much wastewater can flow through the filter before it stops adsorbing the micropollutants, i.e., the adsorption capacity. Often, it is referred to as “spent carbon”, meaning that the activated carbon is saturated and thus has an insufficient adsorption capacity left for the intended application (Bailey, 2020). Based on the water content of suspended substances and dissolved organic carbon (DOC), the bed volume was defined as 20 000 in the pre-study (Ernst et al., 2020).

A challenge with the GAC process at Rya WWTP is the required area for the GAC process in comparison to the available area. The most realistic place to build the GAC process is in the Rya forest, which includes areas that are nature reserves. The proposed part to place the GAC

facility is not classified as a nature reserve, but Gryaab must ensure that they are allowed to build on that specific area (Ernst et al., 2020).

An advantage of the GAC process is its capability to reduce the amount of organic material in the wastewater. Biochemical oxygen demand (BOD) is a measure of the organic material that is biodegradable. In biological WWT, bacteria can degrade soluble BOD in wastewater. The bacteria require oxygen for the degradation, leading to a lower concentration of oxygen in the wastewater. However, the bacteria cannot degrade BOD in particulate form which can lead to that particulate BOD being released to the recipient where it eventually will degrade, resulting in a lower concentration of oxygen in the recipient. This is an issue since an oxygen-poor environment can result in the death of ecosystems. Therefore, it is of importance to reduce the release of BOD into the recipient (Neth at Gryaab, 2022).

3. Literature Study

A literature study was performed to gain deeper knowledge within the field of wastewater treatment and to increase the relevance likewise credibility of the report. The results and discussions in this study become more relevant by comparing them to previous studies and results, since it indicates if the result from this study differs significantly or follows the same path as previous studies. A literature study also reveals the degree of research in the area, which is important for further development in the research field.

Moreover, a literature study was also conducted to collect data not available in the pre-study. The data was gathered from internal sources at Gryaab, independent sources, and sources specific to Gryaab, such as chemical suppliers. The following data was collected:

- Facility specific data at Gryaab (Operating data Gryaab, 2020; Reports from Sweco to Gryaab, 2020)
- Alternative country for activation of active carbon (Zhulincarbon, n.d.)
- Distance with a ship from China to Sweden (Aho Vanhatapio & Wensing, 2021)
- Distance with a ship from China to Belgium (Ports.com, n.d.)
- Origin of hard coal and coconut shells (DESOTEC through Seiler, 2022)
- Polymer and polymerization (Supplier of polymer, 2022)

The following sections summarize results from previous environmental studies and LCA studies, where differences likewise similarities in the results and assumptions are described. Locations of full-scale implementations and pilot studies of advanced WWT processes are also presented.

3.1. Previous Studies

Research within the field of current WWT processes shows that out of 62 identified pharmaceutical residues, around 25 percent are removed completely. This means that 75 percent of the 62 identified substances remain when the wastewater leaves the WWTP (Hörsing et al., 2014). In recent years, more studies have been made in the investigated area of processes for the removal of pharmaceutical residues at WWTPs. Baresel et al. (2020) claim that there are many aspects to take into consideration before deciding on which process to focus on, such as specific conditions and limitations at the WWTP. Besides, it can differ what type of micropollutants enter the plant, which also matters in the decision. Moreover, the study also points out that it is important to carefully consider where to place the advanced WWT in the existing system since it can affect the entire WWTP.

Advanced WWT processes can also be combined in the system. An investigation of a pilot study in Tierp WWTP showed that the ozonation removed pharmaceutical residues completely, but had a large energy consumption (Tierps Energi & Miljö AB [TEMAB], 2020). By combining the ozonation with a following GAC process, the study demonstrated a lower energy consumption for the ozonation. Moreover, a combination of the two processes also resulted in the most effective reduction of pharmaceutical residues, since potential by-products and transformation products from the ozonation were removed by the GAC process. The investigation also revealed potential seasonal variations in levels of pharmaceutical residues.

The variations are important to be aware of and to consider in future facilities, to achieve the highest possible efficiency. In the final report of investigations in Simrishamn at WWTP Stengården, the combination of ozonation and a GAC process were likewise presented as working more effective than only the process of GAC (Baresel et al., 2020). The evaluation from WWTP Stengården showed that the combination of microfiltration, ozonation, and a GAC process, in comparison to only the GAC process, significantly reduced 20 out of 21 investigated pharmaceuticals. This result was obtained at an ozone dose of four mg/l. The evaluation in Simrishamn did not investigate the ozonation process separately, but only in a combination.

The use of ozonation upstream from the GAC-filter increases the biological activity in the GAC-filter via the addition of dissolved oxygen gas (Baresel et al., 2020). Furthermore, the combination of ozonation results in a longer lifetime of the filters in GAC. Longer durability of the filter is beneficial due to the large operational cost of filter change. It is also environmentally preferable with longer durability of the filters (TEMAB, 2020).

At Swedish WWTPs, sludge is treated to make it useful in agriculture (Baresel et al., 2017). By using sludge as a fertilizer, natural recycling of nutrients occurs. At the same time, the sludge contains minerals and organic material that are beneficial for the soil quality and the mull structure. Baresel et al. (2017) describe that the majority of existing WWTPs do not include any removal of pharmaceutical residues, meaning that these enter the agricultural land along with the sludge. The authors present that approximately 25 percent of the pharmaceutical residues are removed from the wastewater, either by degradation or by transferring to the sludge. Moreover, around 50 percent of the pharmaceutical residues cannot be removed by WWTPs without an advanced process. Therefore, approximately 50 percent of the pharmaceutical residues follow the effluent treated wastewater to the recipient.

There have been discussions regarding the treatment of sludge, where one suggestion was to forbid the spreading of sludge on agricultural land to reduce the dispersion of pharmaceutical residues (Walldén, 2020). The author presents a second suggestion: to only allow the spreading of sludge on cropping land, meaning agricultural land where crops must be harvested and the vegetation renewed (Länsstyrelsen Jämtlands län, 2014). This second suggestion makes it possible to recycle nutrients from the sludge that otherwise are lost during combustion when phosphorous is recycled from ashes (Walldén, 2020). The article presents the importance of reusing nutrients and resources from the wastewater, making the second alternative favourable from a circular point of view. Therefore, it is vital to develop the treatment of wastewater, enabling continuing use of sludge on agricultural land.

A disadvantage of advanced WWT processes, such as the PAC process, is that they will increase the contaminant levels in the sludge. This means that such processes are difficult to consider as realistic in Sweden. However, Baresel et al., (2017) claim that alternative methods for sludge treatment before spreading could open for the use of advanced WWT processes that may adversely affect the sludge. The report describes that sludge conditioning and thermal treatment, including physical or chemical treatment with for instance varying temperature and pressure, are possible alternative methods.

3.2. Previous LCA-Studies

There are several previously made LCA studies on processes for the removal of pharmaceutical residues at WWTPs (Azapagic &Tarpani, 2018; Rahman et al., 2018). Pesqueira et al. (2020) reviewed 18 LCA studies on processes for the treatment of micropollutants and discovered that many of them concern ozonation and the GAC process, while studies on the PAC process are less frequent. One important aspect of those studies is the importance of considering resources and energy consumed when implementing these processes in the existing WWT, and thus the added environmental burden. Not all studies found an environmental benefit with implementing the processes in the existing WWT, but it is vital to have in mind the lack of information on how the pharmaceutical residues impact living organisms (Pesqueira et al., 2020).

A typical functional unit is a certain volume of wastewater to be treated or a certain percentage of removal of pharmaceutical residues from the wastewater. Different LCA studies can only be compared if they address an object that shares the same function. Also, system boundaries are similar for many studies, including energy and resources needed and the emissions. The treated effluent is also a common flow to include within the system boundary. However, varying among the studies is the size of the LCA, for instance, if the construction phase and end-of-life are included (Pesqueira et al., 2020). The investigated impact categories vary, but common is that most studies consider rather many impact categories. Frequently investigated are, for instance, Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Ozone Depletion Potential (ODP) at steady state, ecotoxicity, and human health (Rahman et al., 2018; Arena et al., 2016), where the normal time horizon for global warming potential is 100 years (Muñoz et al., 2009).

Pesqueira et al. (2020) showed that the GAC process performed environmentally better than ozonation. In addition, the authors claim that the choice of energy is most essential when considering the processes' environmental burden, followed by chemical use. Furthermore, the result also concludes that processes for the removal of pharmaceutical residues have a high energy demand, where ozonation has two to four times higher demand than the GAC process and the PAC process. Also, the ozone dosage is a critical aspect of the electrical demand for ozonation (Mousel et al., 2017). Therefore, an environmentally beneficial energy favours ozonation. In addition, ozonation in combination with other processes is concluded as being one of the most efficient processes when studying the reduction of pharmaceutical residues (Pesqueira et al., 2020). Considering the GAC process, the result showed that the use of reactivated GAC saves energy in comparison to the use of virgin GAC or PAC (Mousel et al., 2017).

Li et al., (2019) studied 126 pharmaceuticals and personal care products by doing an LCA of three advanced WWT processes. The authors lacked studies focusing on and including the environmental impact caused by organic micropollutants. Since long-term exposure to the micropollutants can cause potential hazards to both the aquatic environment and human health, it seemed vital to include micropollutants in an LCA. Also, the lack of characterization factors for pharmaceutical residues and personal care increased the importance of including them in a study to develop available data. By including these 126 pharmaceutical and personal care products in the Life Cycle Inventory (LCI), a significant increase in the ecotoxicity impact was

noticed. The result showed that it is necessary to include the effects of micropollutants in LCA studies of advanced WWT processes, since the outcome can differ compared to an LCA that only considers the impact of the processes for the removal of micropollutants.

3.3. Implemented Advanced WWT Processes and Pilot Studies

Advanced WWT processes have been implemented in some countries, inter alia in Switzerland, Sweden, Denmark, and Germany. Switzerland has been at the forefront of research concerning advanced WWT processes (Westling, 2021a), and was the first country to introduce a legislation for the expansion of WWTPs (Cimbritz & Mattsson, 2018). The legislation was introduced in 2016 and included an expansion of 100 out of 700 WWTPs within 25 years, to reduce micropollutants, and protect sensitive plants and organisms as well as drinking water sources (Westling, 2021a). Processes using activated carbon, especially the PAC process, and ozonation are considered the most suitable process in Switzerland for the reduction of pharmaceutical residues (Edefell et al., 2019).

In Sweden, Knivsta municipality was the first municipality to introduce a full-scale advanced WWT process. The plant consists of an ozonation process and was commissioned in 2015 (Eskebaek, 2016). Moreover, in 2014, a pilot study in Linköping demonstrated a significant reduction of pharmaceutical residues by the implementation of the advanced WWT process ozonation. The pilot study resulted in an expansion to a full-scale ozonation plant at Nykvarnsverket WWTP in Linköping and was inaugurated by the minister of environment in Sweden in 2017 (Sehlén et al., 2020).

Moreover, in 2020 Tierp municipality became the third municipality in Sweden to have a full-scale advanced WWT process. The system consists of ozonation as the main process for removal of pharmaceutical residues, supplemented with a GAC-filter downstream- and sand filters upstream from the ozonation. The advanced WWT process in Tierp entails a reduction of pharmaceutical residues of 90 percent (TEMAB, 2020).

In addition to the full-scale advanced WWT processes in Sweden, several pilot plants have been introduced. Between 2019-2022, governmental grants distributed by SEPA have resulted in 36 studies in different Swedish municipalities. They all investigated measures aimed at improving the aquatic environment (Westling, 2021b).

In 2020, a pilot plant using activated carbon in Degerberga, in Kristianstad municipality, was ready to bring into operation. Preliminary results indicated a high degree of reduction of pharmaceutical residues (Kristianstads kommun, 2020). A pilot plant in Kalmarsundsverket, in Kalmar, is another project that has demonstrated good results in the reduction of pharmaceutical residues. This pilot study investigated the effects of an implementation of an ultrafilter and a subsequent filter of GAC (Edefell et al., 2019).

Several pilot studies for advanced WWT processes are also present in Denmark (Karlstads Kommun, 2020). The country has likewise one full-scale plant for the reduction of pharmaceutical residues in hospital wastewater (“New standard”, 2015). Furthermore, a report from Karlstad municipality (Karlstad Kommun, 2020) presents that Germany is another country with implemented advanced WWT processes. Karlstad Kommun (2020) describes that the implementation was initiated early and already in 2015, 17 plants were present. Germany has

continued the development and has today 22 WWTPs with advanced WWT processes implemented for the reduction of pharmaceutical residues. The PAC process is popular in the country and is used in 13 plants, whereas the GAC process is used in five plants, and ozonation in four plants.

3.4. The Flows Entering WWTPs

Wastewater is a collective name for water that in some way has been affected by society, but the origin and area of use differ. The influent wastewater to WWTPs can be divided into, inter alia, sewage water, stormwater, infiltration and inflow (I/I), and industrial water. Water from households, such as water for showering, flushing the toilet, and washing, can be classified as sewage water. Stormwater consists of rain, snow, and meltwater. In urban areas, stormwater flows down into street wells and is discharged in own pipes to the nearest watercourse or collected in combined wastewater systems. In a combined system, stormwater and sewage water are linked to the same pipes to the WWTP. Furthermore, water used in manufacturing and industry is classified as industrial water. The field of application and the content of this water varies greatly. Moreover, I/I is a collective name for the water entering a WWTP in addition to sewage water. I/I consists of, for instance, stormwater, seawater, and drinking water that leaks into the sewage water tunnels. Depending on the sewer system, large amounts of I/I can come to the WWTP during heavy rainfalls and high sea levels, which is the case in Gothenburg (Gryaab, n.d.e).

The influent wastewater to Rya WWTP consists of 40 percent sewage water and 60 percent I/I. Beyond sewage water from households, Rya WWTP also receives sewage water from schools, hospitals, companies, and industries. However, this sewage water is only accepted if it does not contain other substances or more pollutants than the sewage water from households. Moreover, Gryaab strives to reduce the amount of infiltration and inflow since it dilutes the sewage water and complicates the purification (Gryaab, n.d.e).

Climate change is an aspect which may influence the WWTPs. A higher frequency of heavy rainfall events can result in more untreated wastewater directly to the recipient, since the WWTP has an inlet capacity limit. Another consequence of heavy rainfalls is the leaching of nutrients and humus, which implies higher demands on the treatment of wastewater. Furthermore, climate change may lead to a new spreading of microorganisms and, in turn, new health risks. Today's WWTPs are not built to take care of viruses and parasites. Measures where all these risks are in mind are therefore of importance, where infrastructure planning is an essential aspect. One possible measure is to separate and redirect the stormwater during heavy rainfalls, to minimize the risk of damage (Klimatanpassning.se, 2020).

4. Goal and Scope

This section covers the goal and scope of the study, including why the study is relevant, the aim of the study, a description of the two functional units, system boundaries and a flowchart of each advanced WWT process. It also introduces the chosen impact categories and why these are relevant. Additionally, relevant actors and data quality requirements are presented.

4.1. Goal of the Study

There are no current legal requirements for the removal of pharmaceutical residues in Sweden. However, as described in Section 1, regulations, and other measures for minimizing potential environmental burdens should be in place in Sweden, in the EU, or internationally by the latest 2030 (Naturvårdsverket, 2021). Moreover, processes for the removal of pharmaceutical residues are acknowledged as resource-intensive (Li et al., 2019). It is therefore of importance to investigate the implementation and potential environmental burden of advanced WWT processes. This study evaluates the environmental impact of three potential advanced WWT processes at Rya WWTP. The study aims to investigate the most environmentally preferable choice of the three processes: ozonation, PAC, and GAC, for the removal of pharmaceutical residues in wastewater. Also, possible improvements of the processes and a comparison to previous LCA studies are investigated. The analysed design of each process is equal to the one defined in the pre-study (Ernst et al., 2020). The expectation is to provide useful data for Gryaab regarding a possible implementation of an advanced WWT process at Rya WWTP.

This study should answer to the following research questions:

1. *Based on an LCA study, which of the three advanced WWT processes is the environmentally preferable choice?*
2. *What are the major environmental impacts considering the selected midpoint impact categories, of each advanced WWT process?*
3. *What parts of the advanced WWT processes are most crucial for the total environmental impact?*

4.2. Functional Units

This study includes two functional units that are based on the function of the system, which is to treat wastewater to reduce its content of pharmaceutical residues. The first functional unit is to treat the influent wastewater at Rya WWTP for the removal of pharmaceutical residues for one year. This functional unit provides a result showing the environmental impact with the specific conditions at Rya WWTP of the investigated processes in this study. The second functional unit is to treat one m^3 of wastewater for the removal of pharmaceutical residues. As described in Section 3.2, this is a common functional unit in previous LCA studies and enables a comparison of this result to other LCA studies. Moreover, this functional unit also entails that the results from this study can be compared to other WWTPs with a different yearly flow. Furthermore, the reference flow for both functional units is the effluent from the SS process. To compare the environmental impact of each process, the reference flow is based on a common point for each advanced WWT process. An indication, which is marked in red, presents where the reference flow is placed in Figure 3.

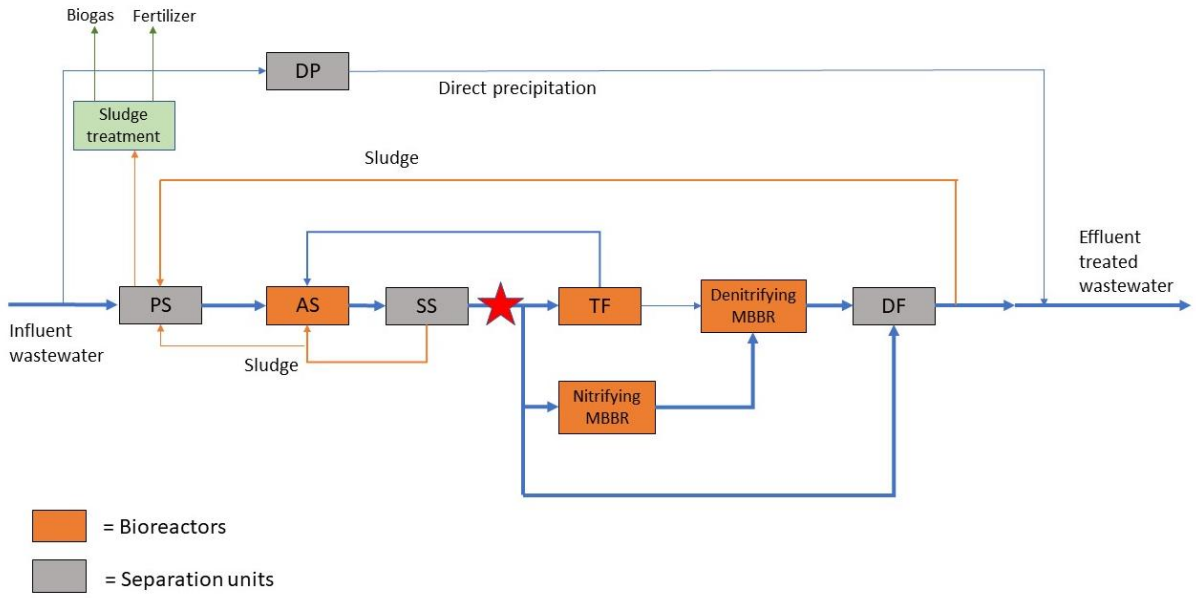


Figure 3. The existing WWT at Rya WWTP including an indication in red of where the reference flow is placed. Abbreviations: PS=Primary Settling, AS=Activated Sludge, SS=Secondary Settling, TF=Nitrifying Trickling Filter, DF=Disc Filter, DP=Direct Precipitation

4.3. System Boundaries

This LCA evaluates the operational phase of the three different processes, and the system boundary is therefore gate-to-gate. The system boundary for each process is illustrated in Section 4.4. As mentioned in Section 4.2, the function of the system is to treat wastewater for the removal of pharmaceutical residues, which means that the material used for achieving the function is within the system boundary, i.e., ozone, PAC, and GAC. Since the process is active all the time, it is assumed that material is added continuously. Therefore, the production of the materials, as well as the regeneration of GAC, are included within the system boundary. The analysis is a comparative attributional LCA, focusing on establishing the environmental impact of each advanced process.

A simplified illustration of the system boundary is presented in Figure 4. The three processes for the reduction of pharmaceutical residues are within the system boundaries with consideration to transportation, chemicals, energy, electricity, heat production, and emissions. The existing WWT process is not included within the system boundary. However, the existing sludge treatment is within the system boundary. Pharmaceutical residues still left in the effluent treated wastewater leaving the WWTP are not considered in the study, and hence not its eventual impact on the aquatic environment. Eventual impacts on the recipient are not considered since the concentration of pharmaceutical residues in the effluent treated wastewater is low, and thereby difficult to measure. Moreover, the content of pharmaceutical residues in the influent wastewater cannot be affected. Further explanations of assumptions and limitations within the study are presented in Section 5.1.

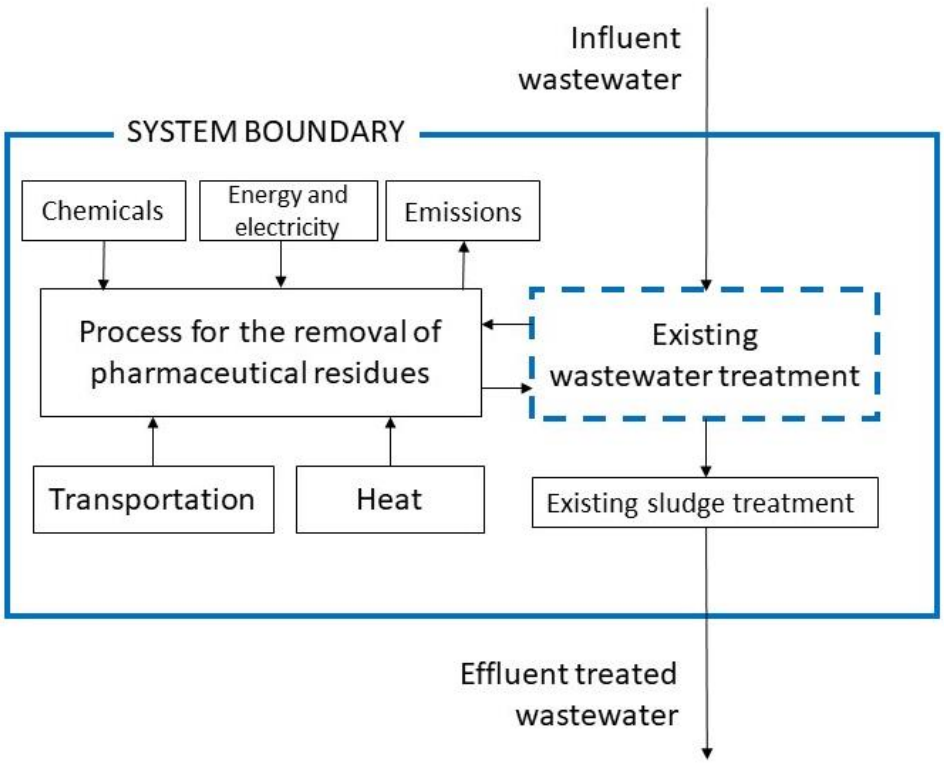


Figure 4. A simplified illustration of the system boundary including the existing WWT with dashed lines.

As mentioned in Section 2.2, Rya WWTP is located in Gothenburg, but the geographical boundaries are expanded to also include locations where transportations and production of chemicals occur. Furthermore, local effects in the recipient are taken into consideration where the potential environmental benefit is compared to the environmental burden of the advanced WWT processes. Moreover, the expected time horizon for the LCI analysis is set to 15 years based on the depreciation period for the processes. Also, it is believed that the decision will have an impact during the whole depreciation period since the outcome of this LCA can serve as a basis for decision-makers at Gryaab on which of the three advanced WWT processes to potentially implement. No allocation is made in the calculations, though it may be present in background systems in GaBi, for instance, energy and chemical supplies.

4.4. Flowchart

The following section presents the studied flowchart for the processes ozonation, PAC, and GAC, respectively.

4.4.1. Ozonation

To utilize the benefit that the nitrifying MBBR and the denitrifying MBBR potentially could have an effect on the degradation of by-products and transformation products from the ozonation, the ozonation process is intended to be placed in-between the SS and the nitrifying MBBR. The investigated process design for a possible implementation of ozonation can be seen in Figure 5. The intended position entails a large concentration of oxygen in the outflow from the ozonation, which can be used in the nitrifying MBBR and reduces the need for aeration. However, there are also drawbacks with the intended position of the ozonation process, and with the process in general. For instance, the content of suspended material in the influent wastewater to the ozonation is usually rather high, which may result in ozone being consumed

for non-pharmaceutical residues. There is also a risk that a high content of suspended material can cause disturbances in the cooling process if the facility is to be cooled with wastewater (Ernst et al., 2020). The system boundary refers to the studied part, i.e., the ozonation, while the existing system is included to indicate where in the existing WWT the ozonation process is expected to be placed. General inflows and outflows are presented, but a more detailed presentation can be seen in Section 6.

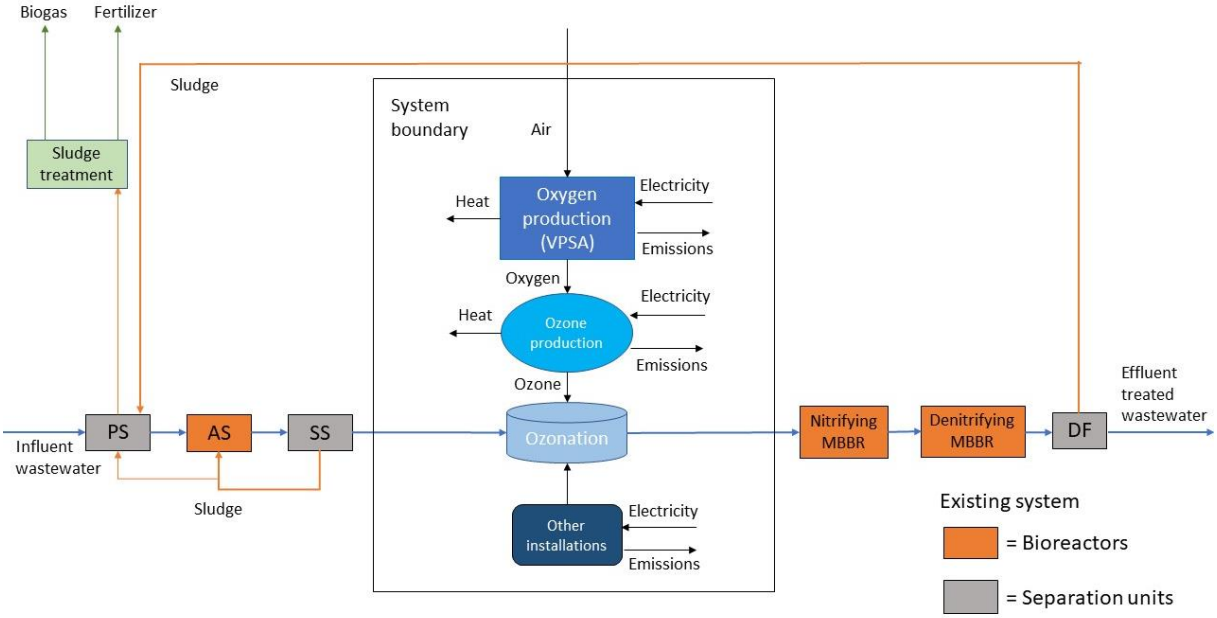


Figure 5. Flowchart presenting the intended position of the ozonation process. The system boundary refers to the studied part, i.e., the ozonation, while the existing system is included to indicate where in the existing wastewater treatment the ozonation is expected to be placed. General inflows and outflows are presented. Abbreviations: PS=Primary Settling, AS=Activated Sludge, SS=Secondary Settling, DF=Disc Filter

4.4.2. PAC Process

As presented in Figure 6, the intended position of the PAC process means that PAC is dosed to the nitrifying MBBR to maximize the hydraulic retention time. Also, it is here the adsorption of the pharmaceutical residues occurs. Another possible design would be to dose PAC to the AS, but it was considered an inferior alternative since it would have contaminated all sludge, and thus no sludge could have been used as fertilizer for agricultural land. For the chosen design of the PAC process, the PAC sludge is separated from the wastewater through DF and the sludge is handled individually. In the end, sludge containing activated carbon is incinerated. This means a lower amount of sludge that can be used as fertilizer for agricultural land or biogas production in comparison to the ozonation and the GAC process. On the other hand, the heat emitted from incineration can possibly be used as district heating.

A precipitating polymer called polyacrylamide is used twice with the PAC alternative and the polymer is produced from the two monomers acrylic acid and acrylonitrile (Supplier of polymer, 2022). The system boundary refers to the studied part, i.e., the PAC process and the new sludge treatment, while the existing system is included to indicate where in the existing system the PAC process and the new sludge treatment would be placed. General inflows and outflows are presented, but a more detailed presentation can be seen in Section 6.

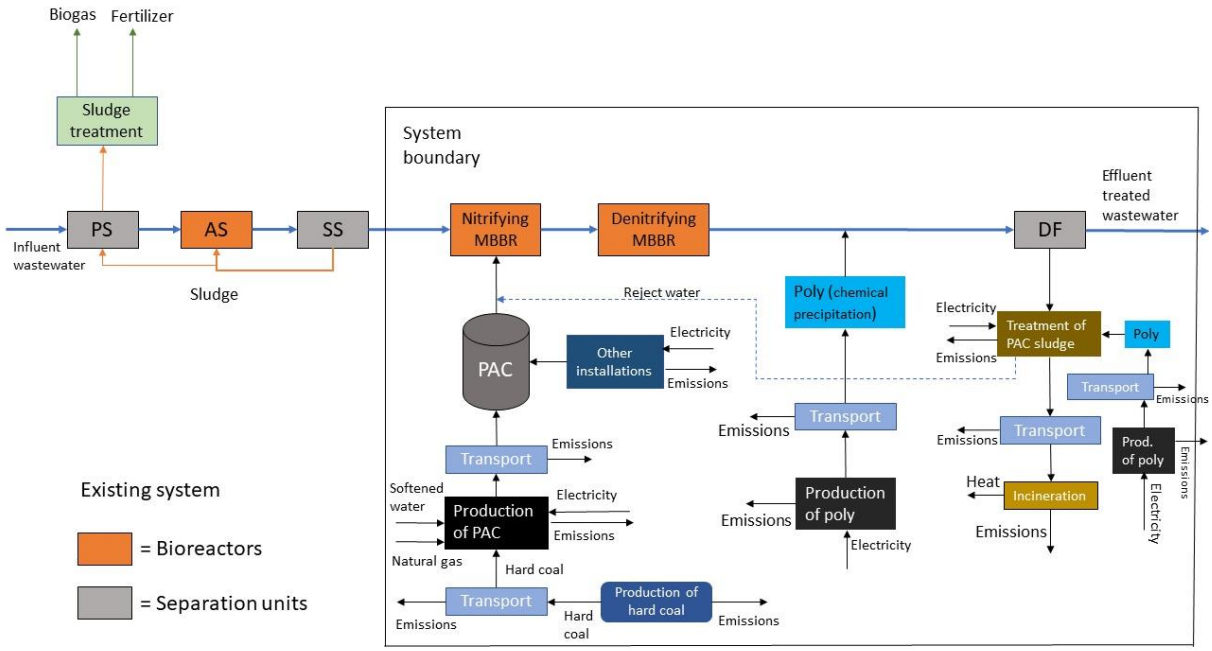


Figure 6. Flowchart presenting the intended position of the PAC process. The system boundary refers to the studied part, i.e., the PAC process and treatment of the sludge, while the existing system is included to indicate where in the existing wastewater treatment the PAC process and treatment of the sludge are expected to be placed. General inflows and outflows are presented. Abbreviations: PS=Primary Settling, AS=Activated Sludge, SS=Secondary Settling, DF=Disc Filter

4.4.3. GAC Process

The intended position of the GAC process is presented in Figure 7. The filtration through GAC occurs in concrete basins where the wastewater flows with gravitation by downstream filtration. The filters are back-washed every other day with effluent treated wastewater. The used wastewater is pumped back to the inflow of the WWTP, according to Figure 7. When the GAC-filter has lost its potential for adsorption, it is transported to Belgium for regeneration. During the regeneration, some GAC is lost and therefore approximately 10 percent of the annual consumption is virgin GAC. Regenerated GAC corresponds to 80 percent of the purchase price for virgin GAC. The system boundary refers to the studied part, i.e., the GAC process and the regeneration, while the existing system is included to indicate where in the existing WWT the GAC process is expected to be placed. General inflows and outflows are presented, but a more detailed presentation can be seen in Section 6.

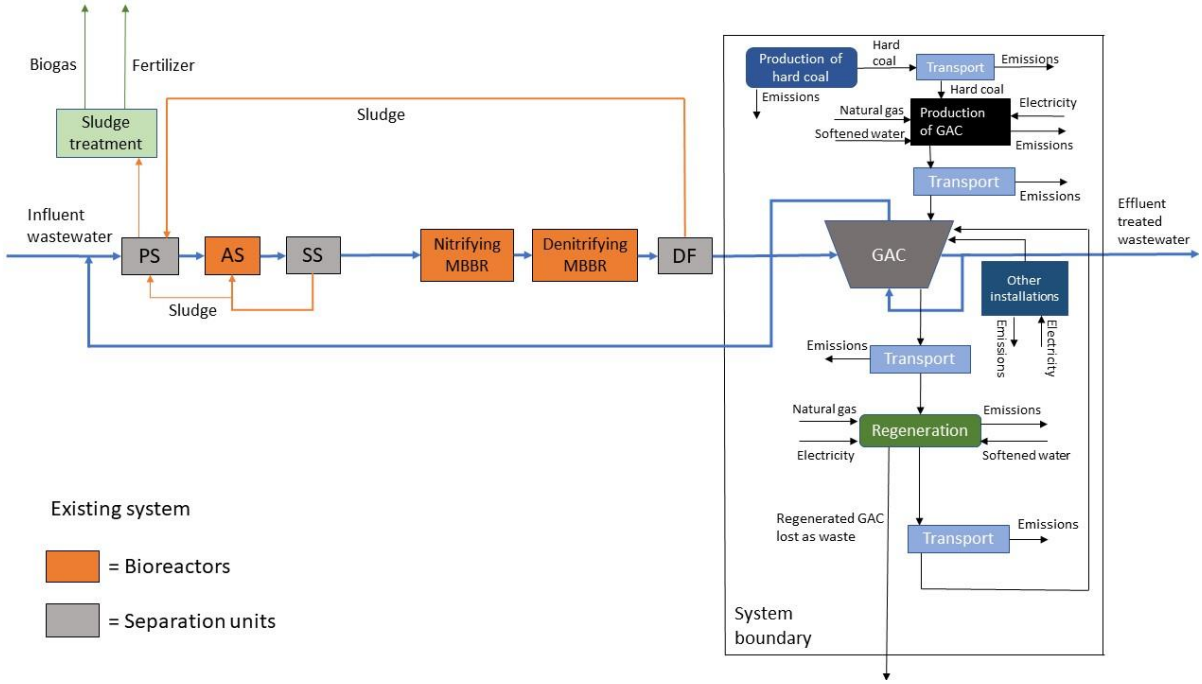


Figure 7. Flowchart presenting the intended position of the GAC process. The system boundary refers to the studied part, i.e., the GAC process and the regeneration, while the existing system is included to indicate where in the existing wastewater treatment the GAC process is expected to be placed. General inflows and outflows are presented. Abbreviations: PS=Primary Settling, AS=Activated Sludge, SS=Secondary Settling, DF=Disc Filter

4.5. Midpoint Impact Categories

This study aggregates emissions from the inventory results into characterisation results. The study aims to provide a more detailed result of the environmental impact, in comparison to the pre-study. Therefore, the degree of aggregation is chosen to include midpoint impact categories, where each midpoint result shows the impact of various environmental aspects, such as global warming. The study addresses the following midpoint impact categories: *Global Warming Potential (GWP)* for 100 years [kg CO_2-eq.], *Fossil depletion* [kg oil-eq.], *Total use of non-renewable primary energy resources (PENRT)* [MJ], *Total use of renewable primary energy resources (PERT)* [MJ], *Eutrophication Potential (EP)* [kg PO_4^{3-}-eq.], and *Acidification Potential (AP)* [kg SO_2-eq.]. *GWP*, *EP*, *AP*, and *fossil depletion* were selected based on the emissions from the operation phase of the three different studied processes. Also, emissions from the production of oxygen, ozone, and activated carbon, as well as from transports, were considered when choosing the impact categories. Moreover, as mentioned in Section 3.2, contribution to global warming, eutrophication, and acidification is often evaluated in similar LCA studies.

As mentioned in Section 2.4.1, the ozonation process is an electricity demanding process. Therefore, a midpoint impact category presenting the total energy use is of interest to include in this LCA analysis. It is also of interest to include a midpoint impact category depicting the renewable- and non-renewable use of energy, since a large use of renewable energy also affects the environment. Although the energy is renewable, a large use results in a lower total supply of renewable energy which should cover many areas. Therefore, it is of importance to use resources efficiently whether they are of a renewable origin or not. The two midpoint impact

categories, PERT and PNERT, were assessed to cover this aspect and thus selected in this LCA analysis.

Table 1 presents the six selected midpoint impact categories and a description of each category. A description of which substances contribute to which midpoint impact category is presented in Section 6.2, in Table 9.

Table 1. The selected midpoint impact categories and a description of each category.

Midpoint impact categories	
Name	Description
Global warming	A measure of the total amount of greenhouse gases, which affect the radiation in the atmosphere. Emissions of greenhouse gases contribute to the heating of the earth and thus climate change.
Fossil depletion	A measure of the extraction of fossil resources from the geosphere, which contains energy.
Total use of non-renewable primary energy resources	The total use of non-renewable energy, including for instance electricity and fuels.
Total use of renewable primary energy resources	The total use of renewable energy, including for instance electricity and fuels.
Eutrophication	Eutrophication is the enrichment of nutrients in soils or watercourses. The enrichment can lead to the vigorous growth of organisms, such as algae, which in turn can result in a lack of oxygen in watercourses. Moreover, the enrichment of nutrients in soils can disturb the balance in the ecosystems.
Acidification	Acidification is the change in H^+-balance caused by an acid solution, which acidifies land and water. The acid solution is formed when emitted oxides react with water drops in the air.

4.6. Actors

The study includes aspects that are of high importance for Gryaab and, as mentioned in Section 4.1, aims to provide useful data to the company. Gryaab is therefore the commissioner, i.e., the main actor of this study. The authors of this LCA are the analysts and perform additional calculations and data collection not provided in the pre-study, whilst the project group of the pre-study are the main data collectors. As described in Section 1, regulations, and other measures for minimizing potential environmental burdens should be in place in Sweden, in the EU, or internationally by the latest 2030. Therefore, the Swedish government and SEPA can also be seen as actors in this study. Furthermore, this study contributes to the research field of reducing pharmaceutical residues in wastewater. Other WWTPs are, therefore, actors in this study since it is of their interest to follow the development of processes for the reduction of pharmaceutical residues. Moreover, citizens being environmentally conscious can also be considered actors in this study.

4.7. Data Quality Requirements

The quality of an LCA study depends on the included data. This study, therefore, includes literature that is reviewed, scientific, and up to date. Calculations for the LCA are done in the software GaBi 9.2.1 Education. GaBi guarantees that their data is up to date and reliable (Sphera, n.d.a), which also increases the reliability of the study. Recent data and data from full-scale plants in operation are highlighted and considered more consistent with the current development within the field of advanced WWT processes. However, site-specific data from Gryaab and data from the pre-study is prioritised to facilitate a comparison of the results in the pre-study, and since the main geographical boundary is set to the Rya WWTP. In addition, more profound data is provided from consulting reports that were performed for the pre-study. Though, the pre-study and the consulting reports lack detailed data for, inter alia, the polymer used in the sludge treatment and in the PAC process. As mentioned in Section 3, data for polymer production and emissions during usage is therefore provided from a supplier of polymer. Some activities occur in other areas and countries, such as Sävenäs in Sweden and Belgium. Resource flows in other areas than Rya WWTP, such as electricity and the production of activated carbon, are therefore included within the system boundary.

5. Method

The following section presents delimitations and assumptions made in the study, followed by a description of how the study was conducted.

5.1. Delimitations

The influent wastewater was assumed to contain a certain amount of pharmaceutical residues and that all three advanced processes have the same effect on the reduction of pharmaceutical residues. The concentration of pharmaceutical residues in the effluent wastewater from the existing WWT at Rya WWTP is presented in Table B.1 in Appendix 2. An additional removal of pharmaceutical residues entailed by advanced WWT processes was estimated to be 80-90 percent, in accordance with recommendations of Naturvårdsverket for substances of high concern (n.d.c). Therefore, the focus of this thesis was on the processes' environmental impact, and thus not on possible ecotoxicological effects in nature caused by pharmaceutical residues. Also, the LCA only compared the three investigated processes and not the existing WWT. In comparison to the pre-study, this LCA study primarily evaluated the operational phase, i.e. gate to gate. The analysis was mainly based on data from the pre-study conducted by Gryaab and secondly on literature studies, and thus no laboratory work was made.

The influent wastewater flowrate to the PAC process and ozonation is limited by the capacity of the nitrifying- and denitrifying MBBR. Therefore, the maximum influent flowrate was defined as 4.5 m^3/s for all three processes (Ernst et al., 2020). Moreover, due to the lack of recipe specific data, a ratio of 50 percent acrylic acid and 50 percent acrylonitrile was assumed for polyacrylamide production in this study.

A general limitation of LCA is that it does not consider all environmental impacts, for example, biodiversity and the effects in various ecosystems. Also, even though the effects of emissions can differ depending on geographical position, LCA only summarizes the total impact. Therefore, local effects could not be investigated quantitatively. However, as described in Section 4.3, qualitatively reasoning concerning local effects was performed, where the potential environmental benefit was compared to the environmental burden of the advanced WWT processes.

5.2. Conduct of Study

The initial step of the study was the literature study, where databases such as ScienceDirect and SpringerLink were used to find relevant literature and previous studies. Examples of initial search words were *pharmaceutical residues in WWTPs, technologies for pharmaceutical residues in WWTPs, LCA wastewater treatment processes, ozonation in WWTPs, GAC in WWTPs, PAC in WWTPs, LCA ozonation WWTP, LCA GAC WWTP, LCA PAC WWTP, effects of pharmaceuticals residues from wastewater in recipients.* The literature was reviewed to find relevant and scientific sources.

In the following step, an initial flowchart was constructed for each of the three advanced WWT processes based on the description in the pre-study. The flowcharts were then developed to the final versions, which can be seen in Section 4.4. The software GaBi 9.2.1 Education was used for modelling the processes. A plan was created for each of the three processes in GaBi, where the existing sludge treatment was in a separate plan in the software. When all plans, including

activities, were created and all flows specified, the flows were expressed per the functional unit. To express the flows per functional unit, the scaling factor in GaBi was set to one and then fixed for the activities *ozonation and other installations*, the *addition of PAC to nitrifying MBBR and other installations*, the *GAC process and other installations*, and the *primary settling*. All flows were first specified per m^3 and then scaled up to the yearly flow of influent wastewater for the removal of pharmaceutical residues (128 666 880 m^3), which corresponds to 80 percent of the influent wastewater to Rya WWTP. The yearly flow was calculated based on an average influent of 4.08 m^3/s which was assumed in the pre-study. Moreover, all added activities were renamed to the associated processes to distinguish them from each other. The size of all flows added in GaBi are presented in Tables D.1, D.3, D.5, D.7, D.8, D.9, and D.10 in Appendix 4, and the corresponding yearly flows are presented in Section 6.

When all activities and flows were added in GaBi, the result of the impact on each midpoint impact category was transferred to Excel. CML2001 (updated 2016), EN 15804 + A1 (updated 2013), and ReCiPe (updated 2016) were selected to cover the chosen midpoint impact categories. The Life Cycle Inventory Analysis (LCIA) methods were selected based on which categories they covered and their relevance in time. Information about the three different LCIA methods is presented in Table A.1 in Appendix 1. Characterisation factors from CML2001 were selected for *GWP*, *EP* and *AP*, while factors for *PERT*, and *PNERT* were selected from EN 15804 + A1. Factors for *Fossil depletion* were selected from ReCiPe. Figures presenting the total environmental impact of each process for all studied midpoint impact categories were created. Also, figures presenting detailed information of the environmental impact of all activities within each process were made. Moreover, the result from the midpoint impact categories *PERT*, and *PNERT* are presented as a sum and named *Energy use.* Since the numbers for *PERT* and *PNERT* come in MJ, it was converted to kWh to make the comparison with the pre-study easier. The conversion was made by multiplying the value in MJ with 0.2778. Due to the large electricity consumption for the ozonation process, electricity was separated from energy use and presented separately.

Furthermore, several sensitivity analyses were performed for a deeper understanding of how the results depend on different choices within the systems. For each process, a hot spot analysis was also conducted to visualize the most crucial parts considering the total environmental impact. Since some sensitivity analyses accounted for credited heat, its effect on the result was subtracted from the associated activity's environmental impact. In this way, the total environmental impact of each activity was achieved and presented in each figure.

6. Life Cycle Inventory Analysis

The following section presents a system description of each advanced WWT process and the existing sludge treatment, including data for inflows and outflows. It also covers a presentation of emissions contributing to each midpoint impact category.

6.1. System Description

A system description of each advanced WWT process is presented in the following section. To make the calculations easier to follow, the flows were named by a letter for each process as presented in Figure 8-10.

6.1.1. System Description of the Ozonation Process

The flowchart for the ozonation process including flows named by letters is presented in Figure 8. For the ozonation process, air is used to produce oxygen and as mentioned in Section 2.4.1, the reaction occurs in a VPSA oxygen generator. The process requires electricity, and heat is generated as a by-product. In ozone production, three oxygen molecules react to produce two ozone molecules. Similar to oxygen production, ozone production consumes energy with heat generated as a by-product. There are also other installations present at different stages in the process, for instance, pumps and ventilation. These activities require energy, but they are handled as one activity called other installations.

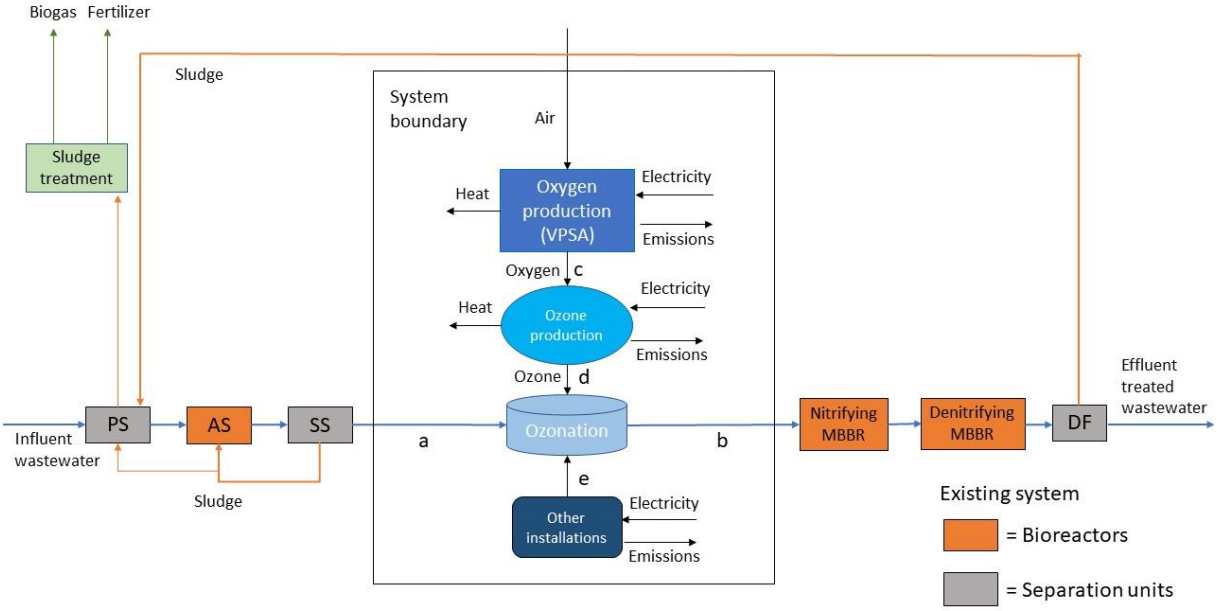


Figure 8. The flowchart for ozonation including letters as names for the flows.

Table C.1 in Appendix 3 presents the chosen flows and activities in GaBi for each activity within the system boundary for the ozonation process. As described in Section 2.4.1, all activities within the system boundary for the ozonation process occur in Sweden. Flows of electricity were therefore added as *SE: electricity, production mix Sweden*. Moreover, the produced heat from the oxygen- and the ozone production was added as a negative inflow to each activity and then linked to *EU-28 Heat ts*. GaBi interprets the negative inflow as a produced heat, which is credited to the activity. To calculate the environmental burden of the activity other installations, the electricity demand was added as an inflow to the ozonation

process. This was possible since the ozonation process itself does not require any electricity, and the flow of other installations was then not mixed up with the flows of the ozonation process.

Furthermore, a sensitivity analysis was performed for the ozonation process by using wind power instead of Swedish electricity mix. *Electricity from wind power [System-dependent]* then linked to the activity *SE: Electricity from wind power ts*. Figures for all midpoint impact categories were created visualizing the total environmental impact for each activity within the ozonation process: *Electricity of other installations, Electricity of oxygen production*, and *Electricity of ozone production*. Values for the sensitivity analysis are presented in Table D.2 in Appendix 4.

Table 2 presents the inflows and outflows for all activities included within the system boundary for the ozonation process, i.e., oxygen production, ozone production, ozonation, and other installations. As can be seen in Table 2, ozone production stands out for being a very energy-intense activity. However, also oxygen production and other installations have a large energy consumption.

Table 2. The inflows and outflows upscaled to one year for all activities within the system boundary for the ozonation process, i.e., oxygen production, ozone production, ozonation, and other installations.

Flow / Activity		Electricity (kWh/year)	Oxygen (kg/year)	Ozone (kg/year)	Heat (kWh/year)	Wastewater (m^3/year)
Oxygen production (VPSA)	Inflow	7 750 000[A]	-	-		-
	Outflow	-	12 807 120[A]	-	1 076 000[B]	-
Ozone production	Inflow	10 940 000[A]	12 807 120[A]	-	-	-
	Outflow	-	-	1 287 720[A]	10 354 000[B]	-
Ozonation	Inflow	-	-	1 287 720[A]	-	128 666 880[C]
	Outflow	-	-	-	-	128 666 880[C]
Other installations	Inflow	3 510 000[A]	-	-	-	-
	Outflow	-	-	-	-	-

References: A: (Ozonation report from Sweco to Gryaab, 2020), B: (Neth at Gryaab, 2022), C: (Gryaab, 2020)

6.1.2. System Description of the PAC Process

The flowchart for the PAC process including flows named by letters is presented in Figure 9. Hard coal is used to produce virgin PAC, which is manufactured in China and then transported to Belgium by ship as presented in flow *b* and *c*. The production of virgin PAC occurs in an industrial furnace and the procedure consumes natural gas, electricity, and softened water which in turn generates emissions. PAC is stocked and purchased from Belgium. Therefore, the activated carbon is transported from Belgium to Rya WWTP according to flow *d* and *e*. At Rya WWTP, PAC is applied to the nitrifying MBBR and mixed with the wastewater in flow *a*.

The activity other installations is also included in the PAC process, consisting of for instance pumps. To simplify, other installations is added to the step where PAC is dosed to the nitrifying MBBR according to flow *f* in Figure 9. Furthermore, a flocculant polymer called polyacrylamide is applied to the PAC treated wastewater in flow *g*. This polymer is produced

in Italy, and the production requires electricity. Thereafter, the polymer is transported to Rya WWTP according to flow *h* and *i*. Sludge containing PAC is generated at the end of the process and treated separately in accordance with flow *k*. The treatment of PAC sludge consumes electricity and an additional amount of polyacrylamide that is transported to Rya WWTP in flow *l* and *m*. Thereafter, the treated sludge is transported to incineration as stated in flow *o* and *p*. In the incineration, a specified amount of heat is produced.

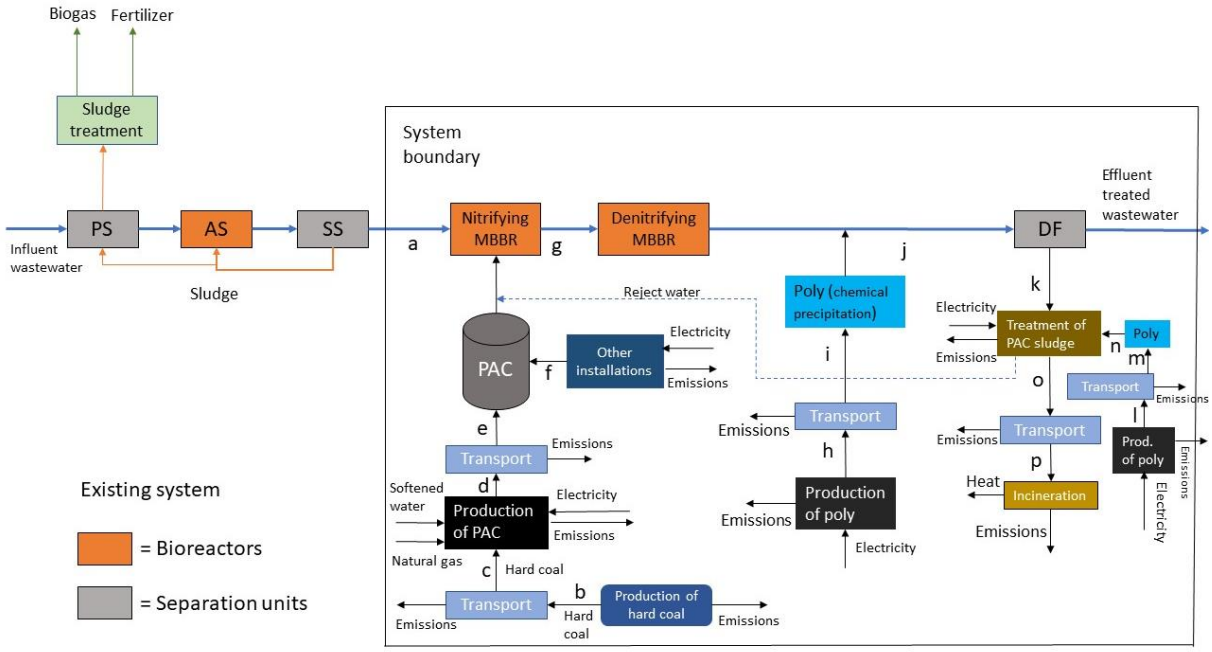


Figure 9. The flowchart for the PAC process including letters as names for the flows.

Table C.2 in Appendix 3 presents the chosen flows and activities in GaBi for each activity within the system boundary for the PAC process. For the activation of PAC, emissions were added manually to GaBi due to the lack of detailed data in GaBi. The emissions are presented in Table D.7 in Appendix 4. Furthermore, Table C.3 in Appendix 3 presents the change of flows and activities in GaBi for the sensitivity analyses of the PAC process, which are based on the primary flows and activities in Table C.2. Values for the sensitivity analyses are presented in Table D.4 in Appendix 4. For the PAC process, the following sensitivity analyses were performed: *Wind power*, *Activation in China*, *Activation in China with wind power*, *and Renewable PAC (coconut shells).*

Figures for all midpoint impact categories were created visualizing the total environmental impact of each activity within the PAC process. The activities were aggregated into four main activities: *Production of virgin PAC*, *Electricity of other installations*, *Polymer*, and *Treatment of PAC sludge*. The *Production of virgin PAC* includes production of hard coal in China, transportation to Belgium for activation of virgin PAC, and transportation of virgin PAC to Rya WWTP. *Electricity of other installations* includes the activity other installations. The main activity *Polymer* includes production and transportation of polymer for both the PAC process and treatment of PAC sludge. Lastly, the *Treatment of PAC sludge* includes treatment of PAC sludge, transportation of PAC sludge from Rya WWTP to Sävenäs, and incineration. The partitioning was partly based on the partitioning made in the pre-study and partly to get the best overview of each activity.

Table 3 presents the inflows and outflows for all activities included in the system boundary for the PAC process. As described above and in Section 4.4.2, sludge containing activated carbon is incinerated and corresponds to a yearly amount of 21 000 tonnes PAC sludge. Moreover, in comparison to the process of GAC, the process of PAC requires a large amount of virgin material and is thereby more energy-intensive. However, incineration of PAC sludge contributes to a large amount of heat which can be credited to energy use. As previously described in Section 5.1, a 50 percent ratio of each monomer, acrylic acid and acrylonitrile, is assumed in the production of the polymer polyacrylamide.

Table 3. The inflows and outflows upscaled to one year for all activities within the system boundary for the PAC process, i.e., production of hard coal, production (activation) of virgin PAC, addition of PAC to nitrifying MBBR, other installations, production of polymer for the PAC process, addition of polymer to the PAC process, production of polymer for the sludge treatment, treatment of PAC sludge, and incineration.

Activity \ Flow		Electricity industrial furnace (kWh/year)	Hard coal (kg/year)	Natural gas (kWh/year)	Activated carbon (virgin PAC) (kg/year)	Acrylic acid (kg/year)	Acrylo-nitrile (kg/year)	Polymer (kg/year)	Softened water (kg/year)	Heat (kWh/year)	Wastewater (m^3/year)	PAC sludge (tonnes/year)
Production of hard coal			5 799 000[D]		-	-	-	-		-	-	-
			5 799 000[D]		-	-	-	-		-	-	-
Production (activation) of virgin PAC	Inflow	3 556 720[D]	5 799 000[D]	7 141 932[D]	-	-	-	-	24 027 190[D]	-	-	-
	Outflow	-	-	-	1 933 000[C]	-	-	-	-	-	-	-
Addition of PAC to nitrifying MBBR	Inflow	-	-	-	1 933 000[C]	-	-	-	-	-	128 666 880[C]	-
	Outflow	-	-	-	1 933 000[C]	-	-	-	-	-	128 666 880[C]	-
Other installations	Inflow	1 000 000[C]	-	-		-	-	-	-	-		-
	Outflow	-	-	-		-	-	-	-	-		-

Production of polymer for the PAC process	Inflow	44 100[G]	-	-	-	73 500[G]	73 500[G]		-	-	-	-
	Outflow	-	-	-	-			147 000[C]	-	-	-	-
Addition of polymer to the PAC process	Inflow	-	-	-	1 933 000[C]			147 000[C]	-	-	128 666 880[C]	-
	Outflow	-	-	-	-	-	-	-	-	-	128 666 880[C]	21 000[C]
Production of polymer for sludge treatment	Inflow	60 165[G]	-	-	-	100 275[G]	100 275[G]	-	-	-	-	-
	Outflow	-	-	-	-			200 550[E]	-	-	-	-
Treatment of PAC sludge	Inflow	462 000[F]	-	-	-	-	-	200 550[E]	-		-	21 000[C]
	Outflow	-	-	-	-	-	-	-	-	-	-	21 000[C]
Incineration	Inflow	-	-	-	-	-	-	-	-	-	-	21 000[C]
	Outflow	-	-	-	-	-	-	-	-	5 444 444[C]	-	-

References: C: (Gryaab, 2020), D: (Contactica S.L & Emivasa, 2018), E: (Operating data Gryaab, chemicals and water, 2020), F: (Operating data Gryaab, energy, 2020), G: (Supplier of polymer, 2022)

In the pre-study, a truck with a payload of 40 tonnes that consumes 0.3 litre diesel/km was assumed in the calculations. Since GaBi contains limited options, a truck with a payload of 27 tonnes was chosen. Therefore, a re-calculation of the number of trips and the total distance was made to find the total diesel consumption. Also, the consumption of diesel/km is not specified in GaBi, but a calculation based on data from the pre-study and values in GaBi was made to find out the calculated fuel consumption in GaBi. Thereafter, a ratio with the assumed diesel consumption in the pre-study was obtained to calculate the driven distance in GaBi. By doing this, GaBi calculated for the same diesel consumption as in the pre-study. One example of how the fuel consumption was calculated is presented in Figure E.1 in Appendix 5. Table 4 presents the calculated number of trips and the distances based on calculations in GaBi for each transport within the PAC process.

Table 4. The calculated number of trips and the distances based on calculations in GaBi for each transport within the PAC process.

	Transport (b-c)[H] ship	Transport (d-e)[C] truck	Transport (h-i)[C] truck	Transport (l-m)[C] truck	Transport (o-p)[C] truck
Trips	1	72	6	8	778
Distance in GaBi (km)	22054	690	1104	1104	17

References: C: (Gryaab, 2020), H: (Ports.com, n.d.)

6.1.3. System Description of the GAC Process

The flowchart for the GAC process including flows named by letters is presented in Figure 10. As for the PAC process, the GAC process starts with the production of hard coal in China followed by a transport of hard coal from China to Belgium, as stated in flow *b* and *c*. Virgin GAC is thereby produced which stands for approximately 10 percent of the total consumption of GAC. The production occurs in an industrial furnace and electricity, natural gas, and softened water are consumed, and emissions are generated. The virgin GAC is transported to Rya WWTP from Belgium in accordance to flow *d* and *e*. In the GAC process, both virgin and regenerated GAC are added as inflows *e* and *k*. Furthermore, the influent wastewater from flow *a* passes the GAC-filters to then continue as effluent treated wastewater in flow l.

The activity other installations is included in the GAC process, consisting of for instance pumps. To simplify, other installations is added to the GAC process according to flow *f* in Figure 10. When the adsorption of the GAC-filters has reached its full potential, GAC is transported to Belgium for regeneration as stated in flow *g* and *h*. The regeneration consumes natural gas, electricity, and softened water. During the reactivation, approximately 10 percent of GAC is lost as waste which explains the need for virgin GAC. Regenerated GAC is transported back to Rya WWTP in flow *j* and *k*.

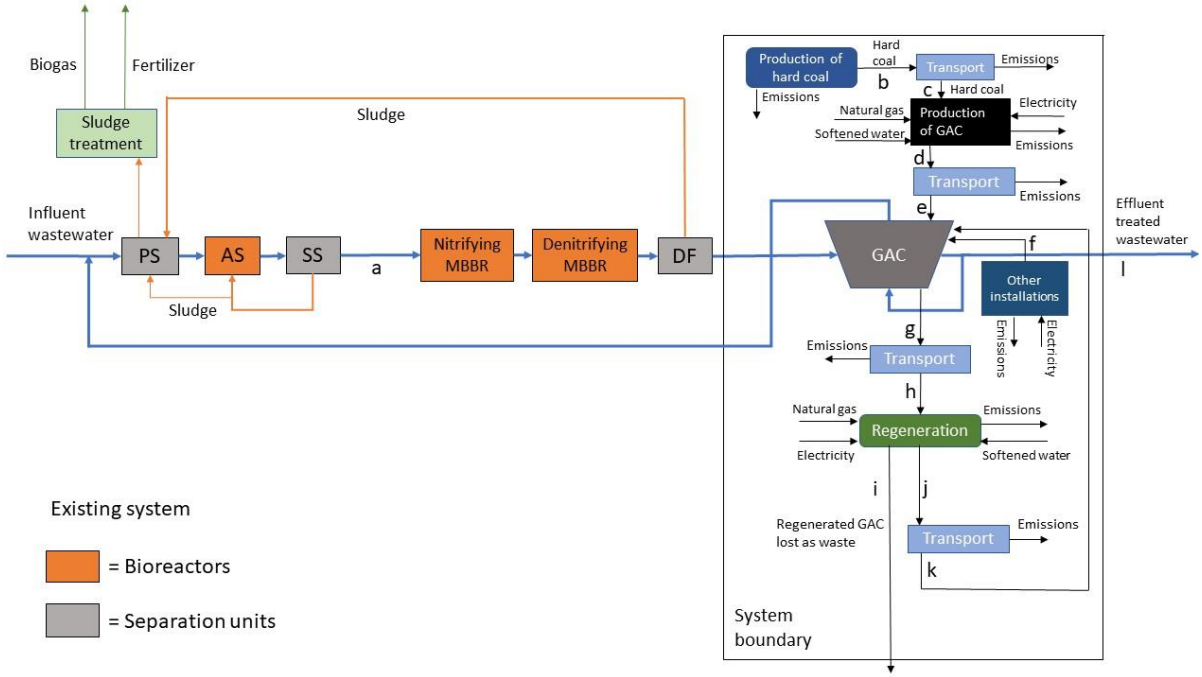


Figure 10. The flowchart for the GAC process including letters as names for the flows.

Table C.4 in Appendix 3 presents the chosen flows and activities in GaBi for each activity within the system boundary for the GAC process. For the activation and the regeneration of GAC, emissions were added manually to GaBi due to the lack of detailed data for the affected activity in GaBi. The emissions are presented in Table D.7 and Table D.8 in Appendix 4. Table C.5 in Appendix 3 presents the change of flows and activities in GaBi for the sensitivity analyses of the GAC process, which are based on the primary flows and activities in Table C.5. Values for the sensitivity analyses are presented in Table D.6 in Appendix 4. For the GAC process, the following sensitivity analyses were performed: *Wind power*, *Activation in China*, *Activation in China with wind power*, *Main case accounting for credited heat from regeneration*, *Regeneration plant at Rya WWTP*, *Credited heat from regeneration plant at Rya WWTP*, *Credited heat from regeneration plant at Rya WWTP with natural gas*, *Renewable GAC (coconut shells)*, *30 000 bed volumes*, and *10 000 bed volumes*.

For the three cases of *Regeneration plant at Rya WWT*, which are presented in Table C.5 in Appendix 3, the biogas or natural gas that is being used was replaced by diesel. The reason is that Rya WWTP produces biogas, which is supposed to be used as a fuel for the regeneration instead of natural gas that is used when regeneration takes place in Belgium, if Gryaab decides to implement a regeneration plant at Rya WWTP. Today, the produced biogas at Rya WWTP is upgraded and then used as a vehicle fuel, meaning that the amount of biogas for vehicle fuel will decrease in the mentioned cases of regeneration plant at Rya WWTP. Thus, more vehicles must be driven on diesel, which is the reason for the replacement of natural gas with diesel. Gryaab has already accounted for the credited emissions of producing biogas for the existing WWT. Therefore, the biogas was excluded from the calculations in this LCA study.

Figures for all midpoint impact categories were created visualizing the total environmental impact for each activity within the GAC process. The activities were aggregated into four main activities: *Production of virgin GAC*, *Electricity of other installations*, *Regeneration*, and

Transports regeneration. The *Production of virgin GAC* includes production of hard coal in China, transportation to Belgium for activation of virgin GAC, and transportation of virgin GAC to Rya WWTP. *Electricity of other installations* includes the activity other installations, and *Regeneration* only includes the regeneration. Lastly, *Transport regeneration* includes transportation of GAC to regeneration in Belgium and transportation of regenerated GAC back to Rya WWTP. The partitioning was partly based on the partitioning made in the pre-study and partly to get the best overview of each activity.

Table 5 presents the inflows and outflows for all activities included in the system boundary of the GAC process. As described above and in Section 4.4.3, approximately 10 percent of GAC is lost during regeneration, which corresponds to 322 000 kg/year. A large amount of GAC is thereby regenerated and corresponds to 2 878 000 kg/year, which reduces the need for virgin material. Wet GAC is transported for regeneration and the weight is thus higher than the weight of the dry GAC, after regeneration.

Table 5. The inflows and outflows upscaled to one year for all activities within the system boundary for the process of GAC, i.e., production of hard coal, production (activation) of virgin GAC, GAC process, other installations, and regeneration.

Flow / Activity		Electricity industrial furnace (kWh/year)	Hard coal (kg/year)	Virgin GAC (kg/year)	Activated carbon (kg/year)	Natural gas (kWh/year)	Softened water (kg/year)	Loss of GAC (kg/year)	Regenerated GAC (kg/year)	Wastewater (m^3/year)
Production of hard coal	Inflow		966 000[D]					-	-	-
	Outflow		966 000[D]					-	-	-
Production (activation) of virgin GAC	Inflow	592 480[D]	966 000[D]			1 189 706[D]	4 002 460[D]	-	-	-
	Outflow	-	-	322 000[C]		-	-	-	-	-
GAC process	Inflow	-	-	322 000[C]		-	-	-	2 878 000[I]	128 666 880[C]
	Outflow	-	-		5 800 000[C]	-	-	-	-	128 666 880[C]
Other installations	Inflow	3 000 000[C]	-	-	-	-	-	-	-	-
	Outflow	-	-	-	-	-	-	-	-	-
Regeneration	Inflow	1 755 580[D]	-	-	5 800 000[C]	3 941 576[D]	-	-		-
	Outflow	-	-	-	-	-	-	322 000[C]	2 878 000[I]	-

References: C: (Gryaab, 2020), D: (Contactica S.L & Emivasa, 2018), I: (Ernst et al., 2020)

Similar to the transports within the PAC process, calculations based on data from the pre-study and values in GaBi were made for each trip within the GAC process. Table 6 presents the calculated number of trips and the distances based on calculations in GaBi for each transport within the GAC process.

Table 6. The calculated number of trips and the distances based on calculations in GaBi for each transport within the GAC process.

	Transport (b-c)[H] ship	Transport (d-e)[C] truck	Transport (g-h)[C] truck	Transport (j-k)[C] truck
Trip	1	12	215	107
Distance in GaBi (km)	22054	690	690	690

References: C: (Gryaab, 2020), H: (Ports.com, n.d.)

6.1.4. System Description of the Existing Sludge Treatment

Table C.6 in Appendix 3 presents the chosen flows and activities in GaBi for each activity within the system boundary for the existing sludge treatment, which produces sludge that can be applied on agricultural land. All activities within the existing sludge treatment are the same for the three processes, but the amount of sludge for the PAC process differs. With the PAC process, part of the sludge is contaminated, meaning a lower amount of sludge to agriculture. A lower amount of sludge to the existing sludge treatment for the PAC process results in less produced biogas and less consumed electricity. Calculations for the loss of biogas production and the less consumed electricity are presented in Figure E.2 in Appendix 5. Values for how the existing sludge treatment would be for the ozonation and the GAC process are presented in Table D.9 in Appendix 4. Moreover, values for how the existing sludge treatment would be for the PAC process are presented in Table D.10 in Appendix 4.

Table 7 presents the inflows and outflows for all activities included in the system boundary for the existing sludge treatment of the processes ozonation, PAC, and GAC.

Table 7. The existing sludge treatment for the ozonation, the PAC process, and the GAC process, including the amount of sludge to agriculture as well as electricity and polymer consumed.

Activity		Flow	Sludge treatment ozonation	Sludge treatment PAC	Sludge treatment GAC
Primary settling	Inflow	Wastewater (m^3/year)	128 666 880[C]	128 666 880[C]	128 666 880[C]
	Outflow	Wastewater (m^3/year)	128 666 880[C]	128 666 880[C]	128 666 880[C]
		Sludge (tonnes/year)	40 000[C]	36 000[C]	40 000[C]
Polymer production	Inflow	Electricity (kWh/year)	114 600[G]	103 140[G]	114 600[G]
		Acrylonitrile (kg/year)	191 000[G]	171 900[G]	191 000[G]

		Acrylic acid (kg/year)	191 000[G]	171 900[G]	191 000[G]
	Outflow	Polyacrylamide (kg/year)	382 000[E]	343 800[E]	382 000[E]
Sludge treatment	Inflow	Sludge (tonnes/year)	40 000[C]	36 000[C]	40 000[C]
		Electricity (kWh/year)	2 340 000[F]	2 105 072[F]	2 340 000[F]
		Polyacrylamide (kg/year)	382 000[E]	343 800[E]	382 000[E]
	Outflow	Sludge to agriculture (tonnes/year)	40 000[C]	36 000[C]	40 000[C]

References: C: (Gryaab, 2020), E: (Operating data Gryaab, chemicals and water, 2020), F: (Operating data Gryaab, energy, 2020), G: (Supplier of polymer, 2022)

Since the existing sludge treatment consumes polymer, it means transports of polymer to Rya WWTP. The calculations for the transports are made in the same way as for the PAC- and GAC process. Table 8 presents the calculated number of trips and the distance based on calculations in GaBi for the transports required in each sludge treatment.

Table 8. The calculated number of trips and the distance based on calculations in GaBi for the transports required in each sludge treatment.

	Transport (sludge treatment ozonation)[C]	Transport (sludge treatment for the PAC process)[C]	Transport (sludge treatment for the GAC process)[C]
Trip	15	13	15
Distance in GaBi	1104	1104	1104

References: C: (Gryaab, 2020)

6.2. Emissions and Energy Use

Depending on the strength of a substance, it contributes with a different potential to a midpoint impact category. Generally, a midpoint impact category includes many substances which contribute with an effect of varying degrees. In Table 9, a selection of the contributing substances to global warming, acidification, eutrophication, and fossil depletion are presented.

Table 9. A selection of the contributing substances to each chosen midpoint impact category, i.e., GWP, AP, EP, and Fossil depletion.

GWP (kg CO_2-eq)	AP (kg SO_2-eq)	EP (kg PO_4-eq)	Fossil depletion (kg oil-eq)
CO_2	SO_2	PO_4^{3-}	Hard coal
CH_4	HCI	H_3PO_4	Crude oil
N_2O	HF	P	Fossil energy
CCl_4	NO_x	NO_x	Natural gas
SF_6	NH_3	NO_2	Fe
CF_4		NH_3	Al

The amount of MJ for the midpoint impact categories *PERT* and *PNERT* depends on the type of energy utilised, and its efficiency. The efficiency of a process is the ratio between utilised and supplied energy in a system (NE, n.d.), where a low efficiency means a large proportion of losses. Table 10 presents which type of energy contributes to *PERT* and *PNERT*, where the former is solely of renewable origin and the latter of non-renewable origin. Nuclear power results in radioactive waste and therefore impacts PNERT in GaBi.

Table 10. A selection of which type of energy that contributes to the midpoint impact categories PERT and PNERT.

PERT (MJ)	PNERT (MJ)
Wind power	Diesel
Hydro power	Natural gas
Solar power	Nuclear power

The efficiency of wind power is low, meaning that more mechanical energy needs to be transformed into electrical energy to acquire the required amount of electricity, in comparison to a process with greater efficiency. Similarly, it implies that hydro power with great efficiency requires a lower share of mechanical energy to be transformed into electrical energy to acquire the required amount of electricity. Therefore, the contribution to PERT is larger for wind power than for hydro power since wind power has lower efficiency.

7. Results and Interpretation

Section 7 presents the total environmental impact of ozonation, the PAC process, and the GAC process, based on the treatment of both a yearly flow of wastewater and 1 m^3 wastewater. Furthermore, sensitivity analyses for each process are presented separately to display crucial choices of activities and flows. More detailed results are presented in Tables G.1-G.21 in Appendix 7. The modelling in GaBi for the main case of each advanced WWT process and the existing sludge treatment are presented in Figures F.1-F.4 in Appendix 6.

7.1. Total Environmental Impact of All Including Processes

The following section presents the total environmental impact of all three processes included in the study, i.e., ozonation, PAC, and GAC. The two functional units are presented separately, and the processes are compared based on the five chosen impact categories.

7.1.1. Treatment of a Yearly Flow of Wastewater

Figure 11 presents the total environmental impact of the chosen midpoint impact categories for the treatment of a yearly flow of wastewater, including the ozonation process, the PAC process, and the GAC process. Electricity use is presented separately from energy use to show the impact of different types of electricity production, i.e., electricity mixes and wind power. The impact of the existing sludge treatment on Rya WWTP is included to depict how it would have been affected by the potential implementation of an advanced WWT process.

As can be seen in Figure 11, the PAC process contributes most to the different midpoint impact categories overall. The impact of the existing sludge treatment is a bit lower for the potential implementation of the PAC process than for the GAC process and the ozonation, due to lower inflows of resources, as presented in Table D.9 and Table D.10 in Appendix 4. However, the impact of the existing sludge treatment is very low in comparison to the impact of the three processes, meaning that the very small difference of impact from the existing sludge treatment for the PAC process is insignificant. Moreover, the impact of ozonation and the GAC process is similar in Fossil depletion and Energy use, while ozonation is the most preferable alternative based on GWP, EP, and AP. However, ozonation has the largest contribution to electricity use due to its high consumption, which is shown for both the renewable- and non-renewable alternative of electricity.

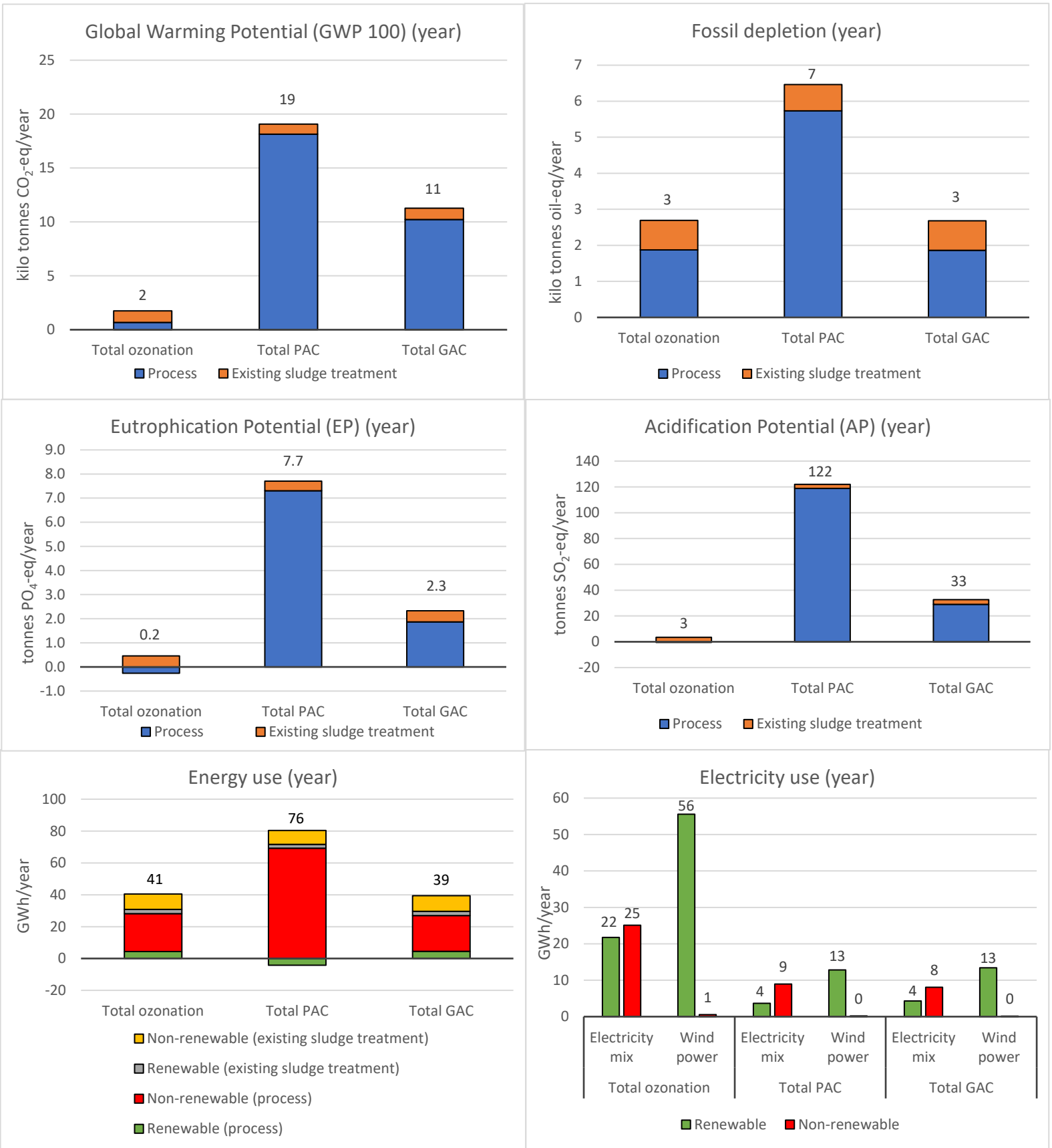


Figure 11. A comparison of the three studied processes; ozonation, the PAC process, and the GAC process, based on the five midpoint impact categories for treatment of a yearly flow of wastewater. Global Warming Potential is presented in kilo tonnes CO_2-eq/year, Fossil depletion is presented in kilo tonnes oil-eq/year, Eutrophication Potential is presented in tonnes PO_4-eq/year, Acidification Potential is presented in tonnes SO_2-eq/year, and Energy use is presented in GWh/year and includes both renewable and non-renewable energy, Electricity use is presented in GWh/year and compares the use of Swedish, Belgian, and Italian electricity mix with Swedish, Belgian, and Italian wind power for ozonation, the PAC process, and the GAC process, respectively.

7.1.2. Treatment of 1 m^3 of Wastewater

Figure 12 presents the total environmental impact of the chosen midpoint impact categories for the treatment of 1 m^3 of wastewater, including the ozonation process, the PAC process, and the GAC process. The values in Figure 12 are down-scaled numbers of the ones presented in Figure 11, and the results are therefore equal.

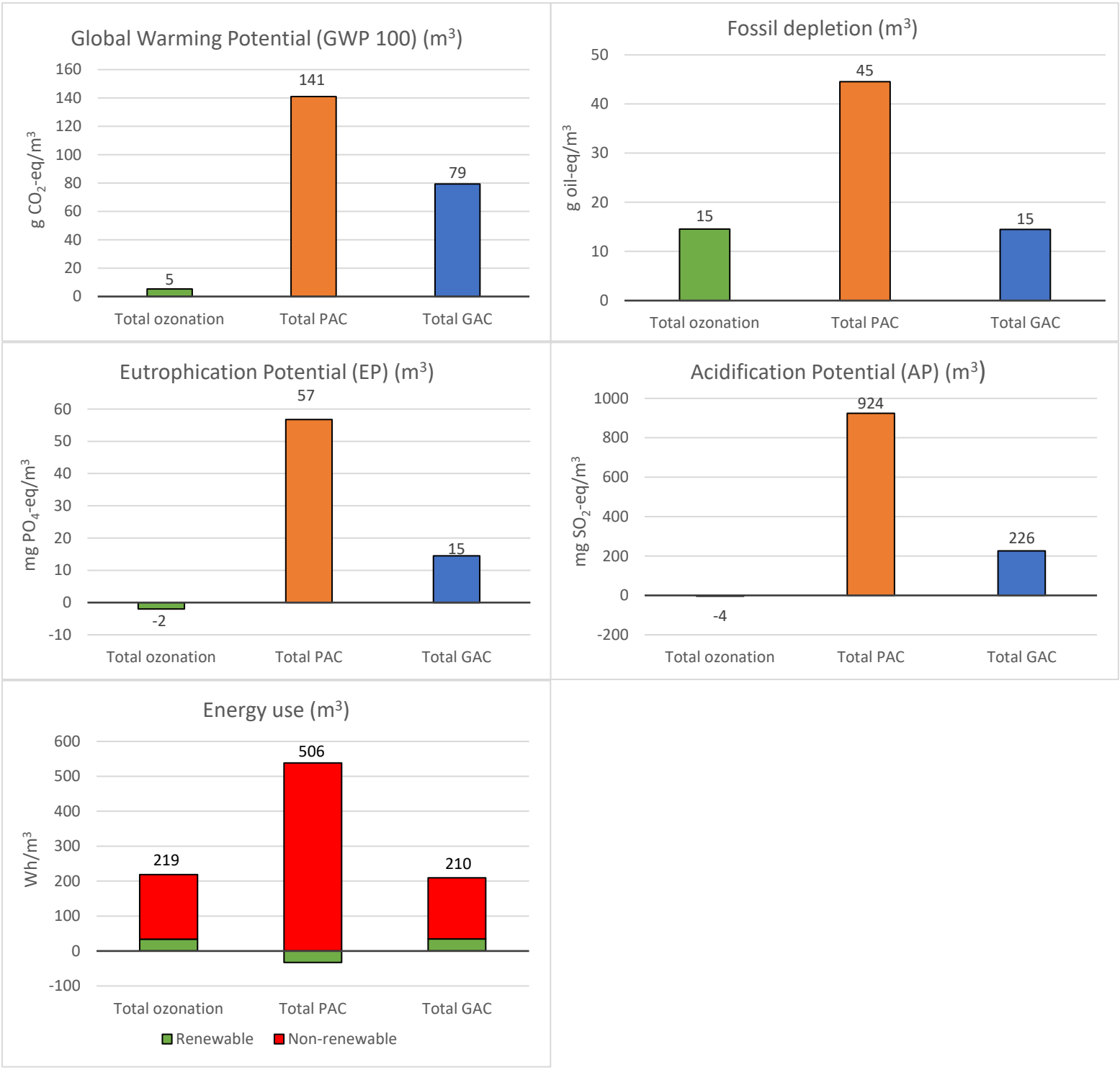


Figure 12. A comparison of the three studied processes; ozonation, the PAC process, and the GAC process, based on the five midpoint impact categories for treatment of 1 m^3 of wastewater. Global Warming Potential is presented in g CO_2-eq/m^3, Fossil depletion is presented in g oil-eq/m^3, Eutrophication Potential is presented in mg PO_4-eq/m^3, Acidification Potential is presented in mg SO_2-eq/m^3, and Energy use is presented in Wh/m^3 and includes both renewable and non-renewable energy.

7.2. Ozonation with Sensitivity Analysis

The following section presents the ozonation with the main case and one sensitivity analysis for all five midpoint impact categories. The main case includes Swedish electricity mix and the sensitivity analysis Swedish wind power. The effect of credited heat is included in Figures 13-17, as specified in Section 5.2. Therefore, this section presents detailed results for the environmental impact of the including activities within the ozonation: *Electricity of other installations*, *Electricity of oxygen production*, and *Electricity of ozone production*.

Figure 13 presents the yearly contribution to global warming in tonnes CO_2-eq for *Electricity of other installations*, *Electricity of oxygen production*, and *Electricity of ozone production* for the main case and the sensitivity analysis with wind power. For the main case, the yellow section representing the oxygen production, has the largest yearly contribution to global warming. Furthermore, the usage of wind power can reduce the impact on global warming for all three activities. There is no distinct difference between the impact of the oxygen production and other installations in either case and it is, therefore, difficult to determine which of the two activities contributes the most to global warming. Moreover, wind power results in negative CO_2-eq emissions which is caused by the "saved" amount of CO_2-eq that otherwise would have been emitted when producing residential heating from wood. Emissions related to residential heating systems from wood in GaBi are caused by activities, such as transportation and electricity. Therefore, it is not the combustion of wood that results in the emissions. Furthermore, Figure 13 conveys that the case with wind power leads to a much smaller yearly impact on global warming than the main case with Swedish electricity mix.

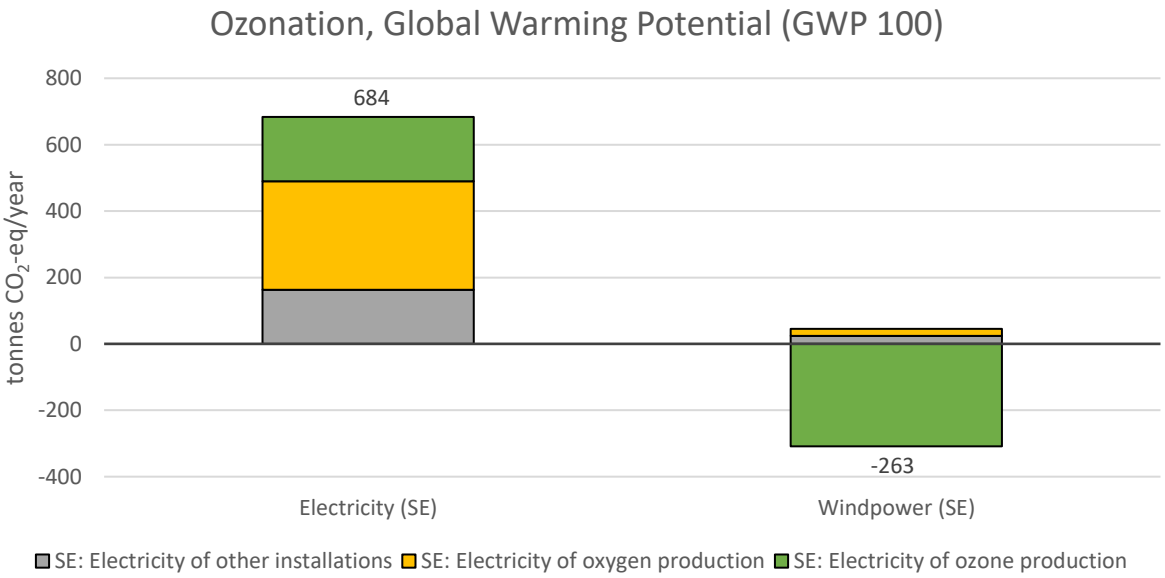


Figure 13. The yearly contribution in tonnes CO_2-eq to global warming from Electricity of other installations, Electricity of oxygen production, and Electricity of ozone production included in the ozonation process with the use of Swedish electricity mix or Swedish wind power.

Figure 14 presents the yearly contribution to fossil depletion in tonnes oil-eq for *Electricity of other installations*, *Electricity of oxygen production*, and *Electricity of ozone production* for the main case and the sensitivity analysis with wind power. Ozone production contributes the most to the yearly impact in the main case. Moreover, the usage of wind power results in a much less yearly impact on fossil depletion than the main case with Swedish electricity mix.

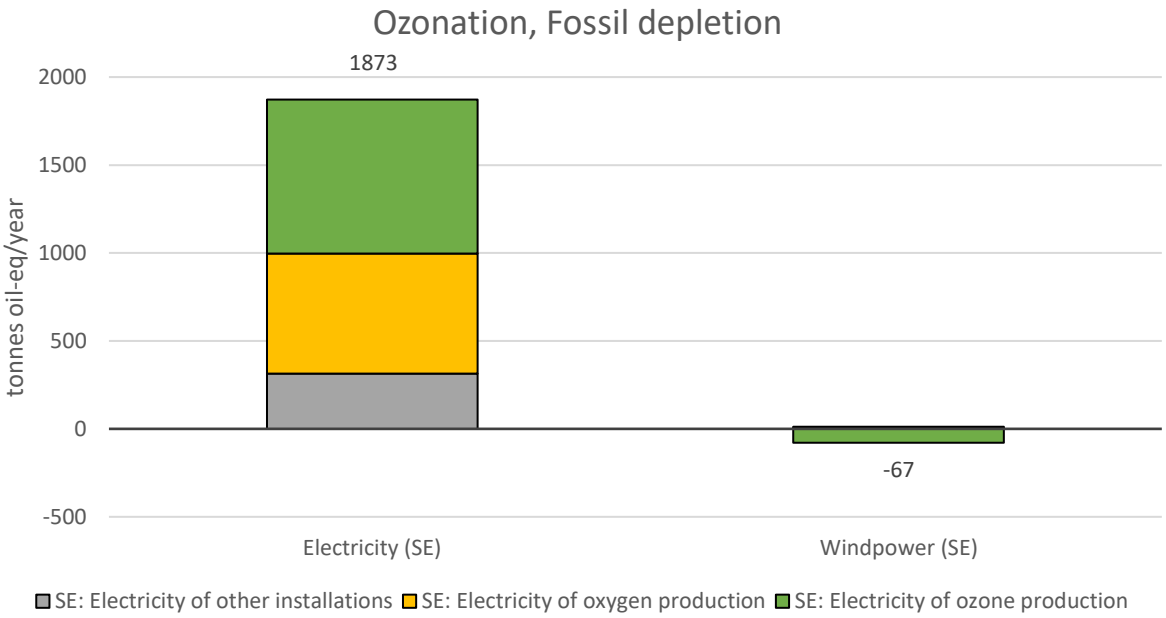


Figure 14. The yearly contribution in tonnes oil-eq to fossil depletion from Electricity of other installations, Electricity of oxygen production, and Electricity of ozone production included in the ozonation process with the use of Swedish electricity mix or with Swedish wind power.

Figure 15 presents the yearly contribution to energy use, including both renewable- and non-renewable energy, for *Electricity of other installations*, *Electricity of oxygen production*, and *Electricity of ozone production* in the ozonation. Oxygen production represents the largest contributor to energy use in both the main case and the case with wind power. Furthermore, there is no distinct difference in the yearly contribution of GWh for other installations in the main case and the case with wind power. Moreover, the usage of wind power results in a larger yearly impact on energy use than the main case. As described in Section 6.2, wind power has a low efficiency meaning that a larger amount of mechanical energy is required to produce the prerequisite amount of electricity in comparison to the main case.

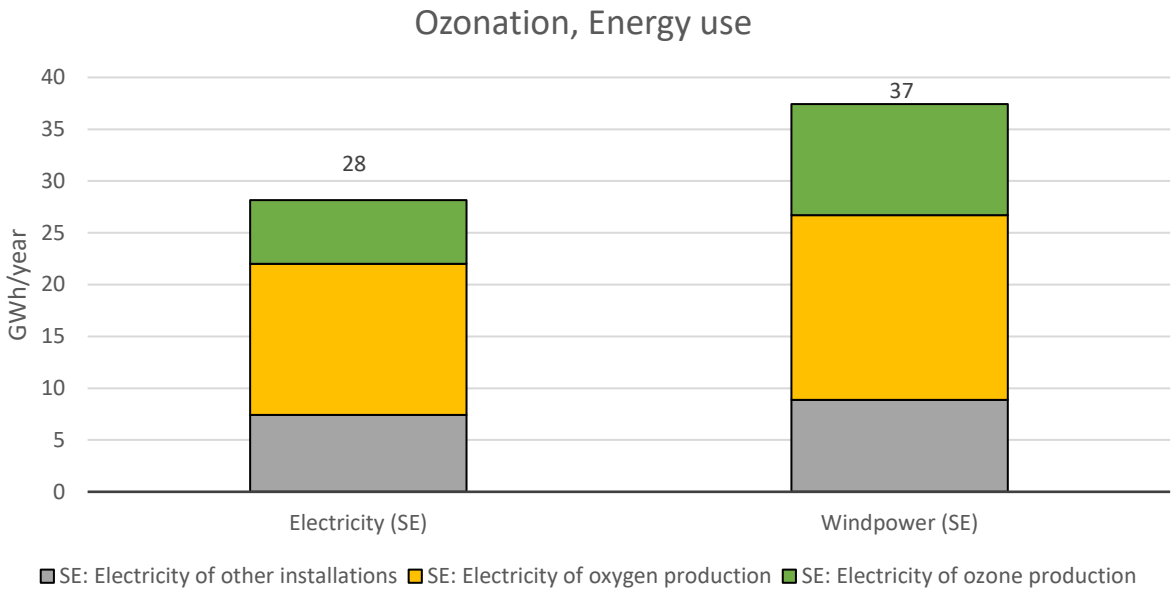


Figure 15. The yearly contribution in GWh to energy use from Electricity of other installations, Electricity of oxygen production, and Electricity of ozone production included in the ozonation process with the use of Swedish electricity mix or with Swedish wind power. The energy use includes both renewable- and non-renewable energy.

Figure 16 presents the yearly contribution to eutrophication in tonnes PO_4-eq for *Electricity of other installations*, *Electricity of oxygen production*, and *Electricity of ozone production* in the ozonation. For the main case, there is no distinct difference between the yearly contribution to eutrophication for other installations and oxygen production. In the case with wind power, the impact of all three activities is reduced. Moreover, wind power depicts a clearer difference in the yearly impact on eutrophication among the including activities. Both the main case and the sensitivity analysis result in a yearly total negative value of PO_4-eq, caused by the "saved" amount of PO_4-eq that otherwise would have been emitted when producing residential heat from wood. This demonstrates that both the main case and the case with wind power are advantageous in terms of effects on eutrophication.

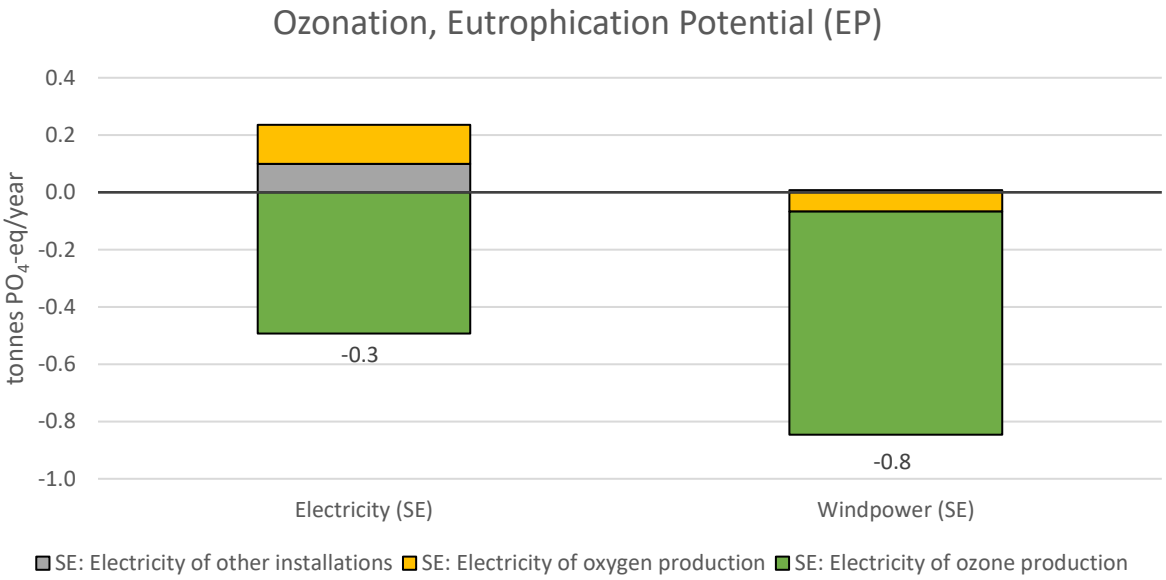


Figure 16. The yearly contribution in tonnes PO_4-eq to eutrophication from Electricity of other installations, Electricity of oxygen production, and Electricity of ozone production included in the ozonation process with the use of Swedish electricity mix or with Swedish wind power.

Figure 17 presents the yearly contribution to acidification in tonnes SO_2-eq for *Electricity of other installations*, *Electricity of oxygen production*, and *Electricity of ozone production in the ozonation.* The oxygen production has the largest impact on acidification in the main case and other installations in the case with wind power. Moreover, both the main case and the case with wind power results in a total yearly negative value of SO_2-eq caused by the "saved" amount of SO_2-eq that otherwise would have been emitted when producing residential heat from wood. Therefore, both the main case and the case with wind power are advantageous in terms of effects on acidification.

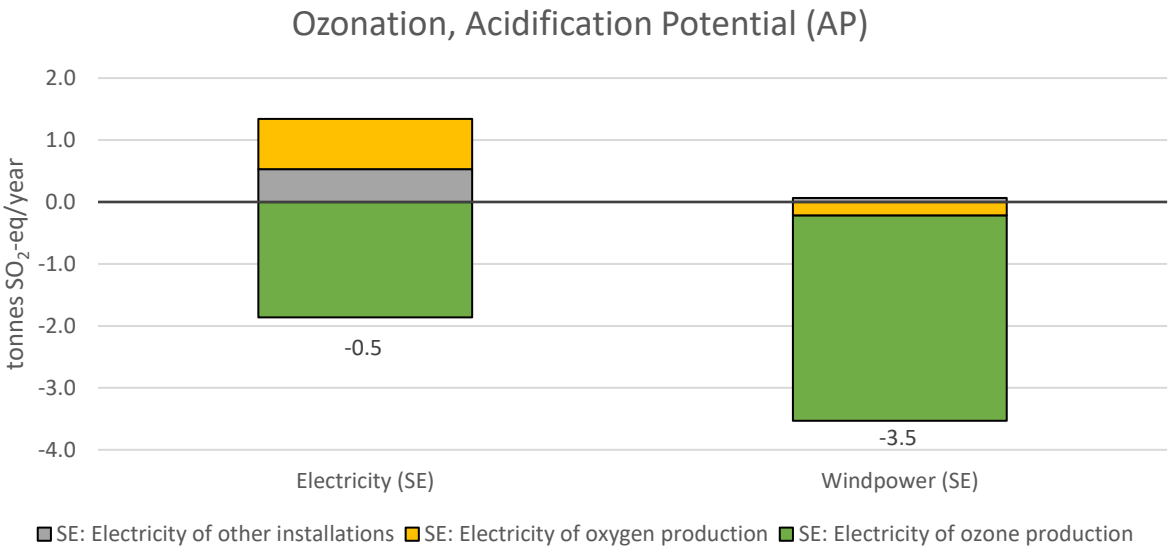


Figure 17. The yearly contribution in tonnes SO_2-eq to acidification from Electricity of other installations, Electricity of oxygen production, and Electricity of ozone production included in the ozonation process with the use of Swedish electricity mix and with Swedish wind power.

7.3. PAC Process with Sensitivity Analyses

The following section presents the PAC process with four sensitivity analyses for all five midpoint impact categories. The included activities within the PAC process have been aggregated into four major activities: *Production of virgin PAC*, *Electricity of other installations*, *Polymer*, and *Treatment of PAC sludge*. The main case with Swedish, Italian, and Belgian electricity mix is abbreviated as β. The four sensitivity analyses then present different changes based on the main case. Different electricity mixes are used, and they are abbreviated as followed; γ represents Swedish, Italian, and Belgian wind power, δ represents Chinese, Italian, and Swedish electricity mix, and η represents Chinese, Italian, and Swedish wind power. The four different sensitivity analyses are named as followed; Main case with γ; Activation in China with δ; Activation of in China with η; Renewable PAC (coconut shells) with δ. An extensive description of the sensitivity analyses is presented in Table C.3 in Appendix 3.

Figure 18 presents the yearly contribution to global warming in kilo tonnes CO_2-eq for the main PAC process and the four different sensitivity analyses. The production of virgin PAC has the largest environmental impact on global warming, while electricity of other installations and treatment of PAC sludge have a low yearly contribution to CO_2-eq. Moreover, the sensitivity analysis with coconut shells conveys that a renewable resource of activated carbon such as coconut shells has a great potential to reduce the contribution to global warming. Therefore, the case with coconut shells is most advantageous regarding the environmental impact of global warming. Furthermore, the environmental impact of the polymer is unchanged for all sensitivity analyses in comparison to the main case.

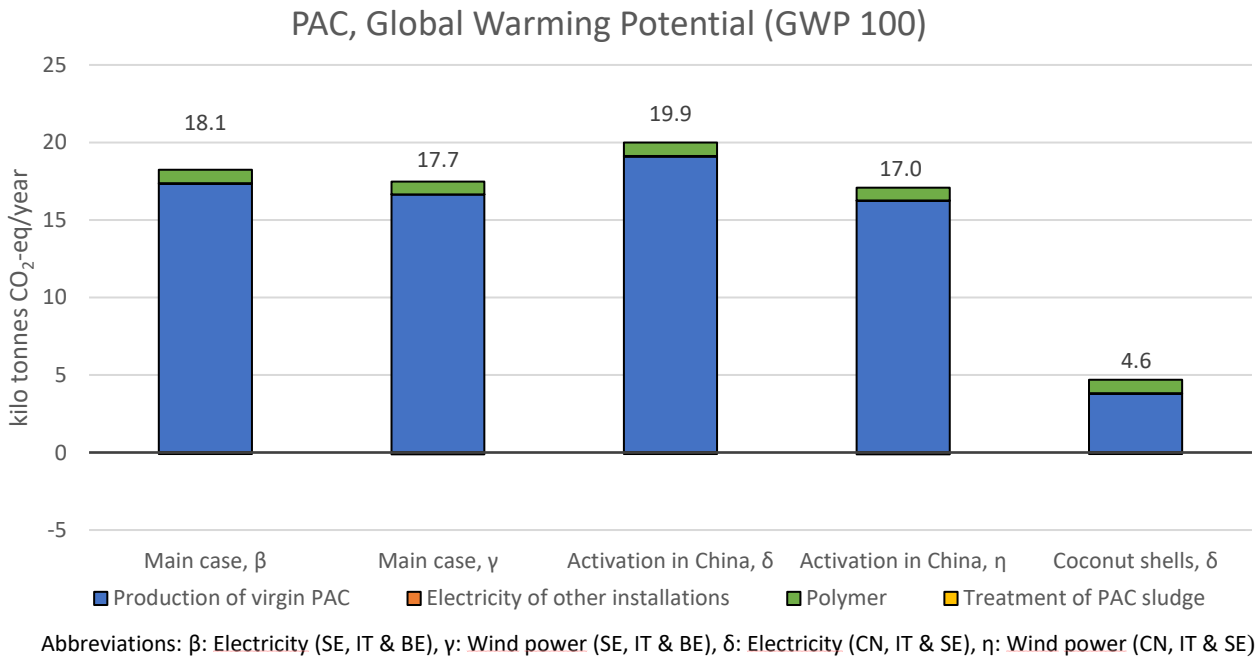
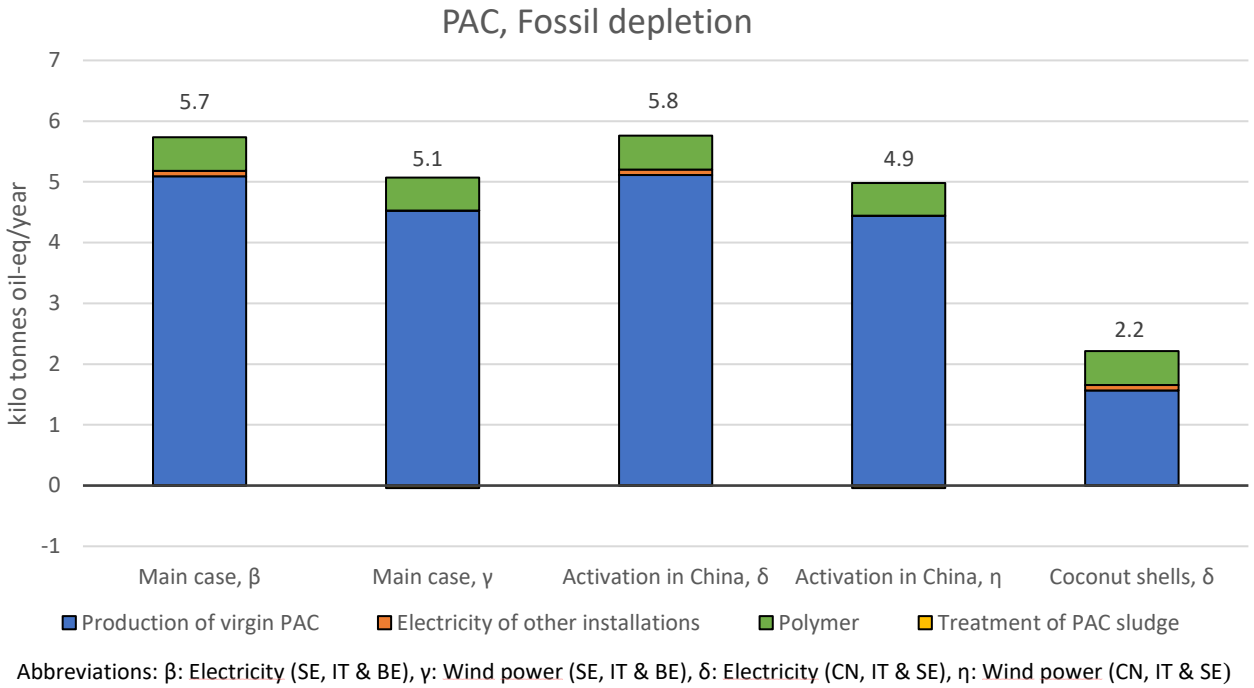


Figure 18. The yearly contribution in kilo tonnes CO_2-eq to global warming for the main PAC process and the four sensitivity analyses.

Figure 19 presents the yearly contribution to fossil depletion in kilo tonnes oil-eq for the main PAC process and the four different sensitivity analyses. As for global warming, the production of virgin PAC represents the largest environmental impact also for fossil depletion as demonstrated in Figure 19. The sensitivity analysis with coconut shells conveys that the usage of coconut shells for activated carbon has a great potential to reduce the contribution to fossil depletion.



Abbreviations: β: Electricity (SE, IT & BE), γ: Wind power (SE, IT & BE), δ: Electricity (CN, IT & SE), η: Wind power (CN, IT & SE)

Figure 19. The yearly contribution in kilo tonnes oil-eq to fossil depletion for the main PAC process and the four sensitivity analyses.

Figure 20 presents the yearly contribution to energy use in GWh for the main PAC process and the four different sensitivity analyses. The total pressure on energy use for the PAC process is similar for all cases except the case with coconut shells. Moreover, the production of virgin PAC contributes the most to energy use in the main case and all sensitivity analyses. As for global warming and fossil depletion, the use of coconut shells as activated carbon is the most preferable choice regarding pressure on energy use.

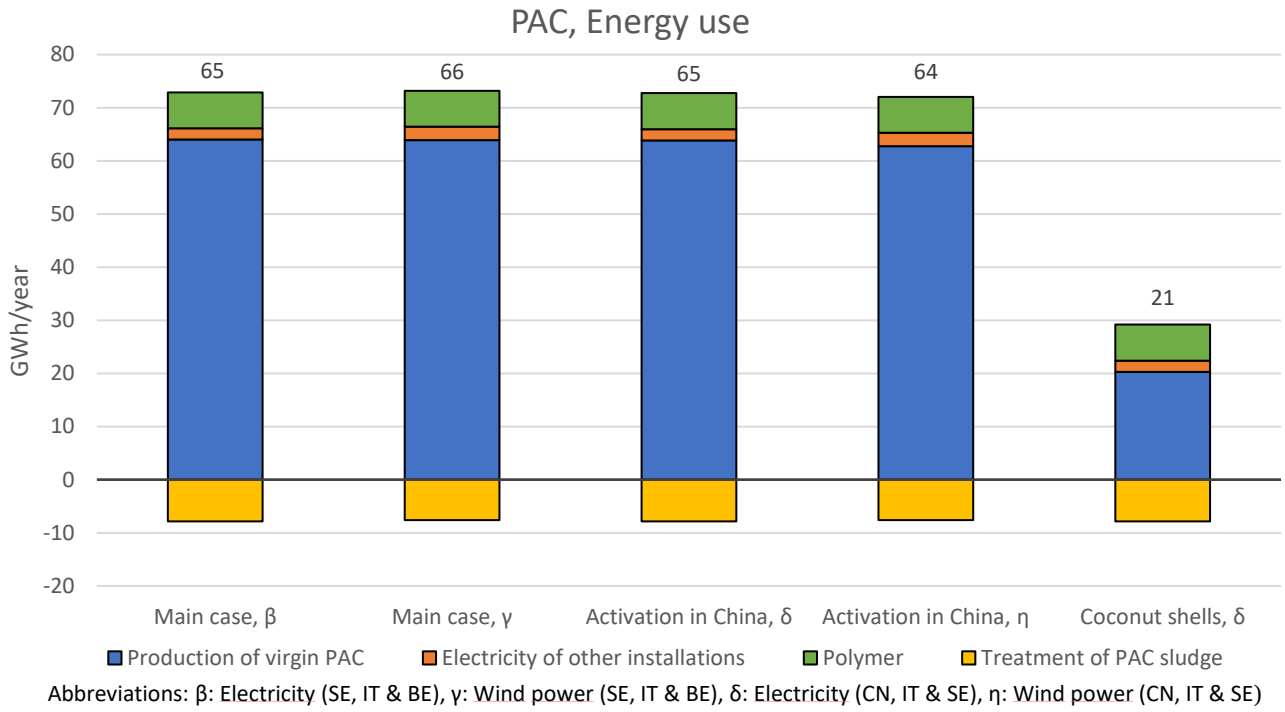


Figure 20. The yearly contribution in GWh to energy use for the main PAC process and the four sensitivity analyses.

Figure 21 presents the yearly contribution to eutrophication in tonnes PO_4-eq for the main PAC process and the four different sensitivity analyses. The production of virgin PAC has the largest environmental impact on eutrophication, while the treatment of PAC sludge in total has a negative contribution to eutrophication. Moreover, the use of coconut shells has the potential to reduce the environmental impact of eutrophication and is, therefore, the most advantageous option. However, all sensitivity analyses result in a decreased contribution to eutrophication in comparison to the main case.

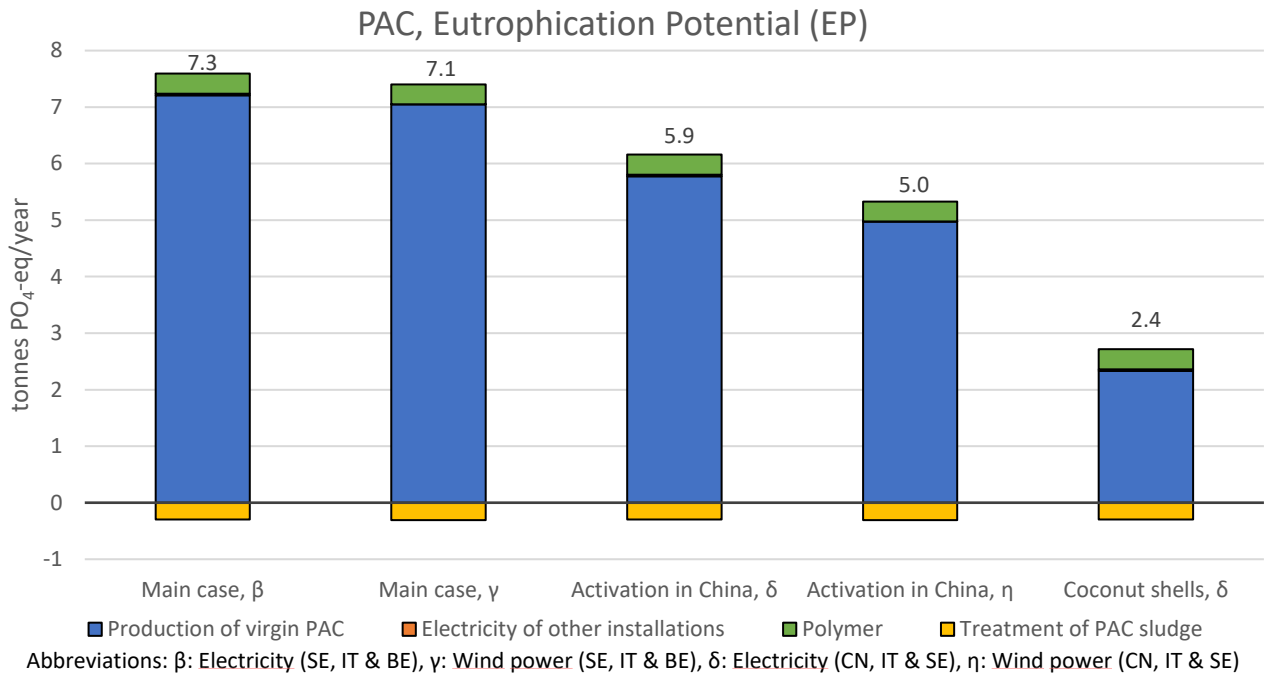


Figure 21. The yearly contribution in tonnes PO_4-eq to eutrophication for the main PAC process and the four sensitivity analyses.

Figure 22 presents the yearly contribution to acidification in tonnes SO_2-eq for the main PAC process and the four different sensitivity analyses. As for the four other midpoint impact categories, the production of virgin PAC is the major contributor to acidification as well. The electricity of other installations, polymer, and treatment of PAC sludge all have a low environmental impact on acidification in comparison to the production of virgin PAC. Moreover, the case with coconut shells has the lowest yearly contribution and is, therefore, the most advantageous option regarding the impact on acidification. However, all sensitivity analyses result in a decreased contribution to acidification in comparison to the main case.

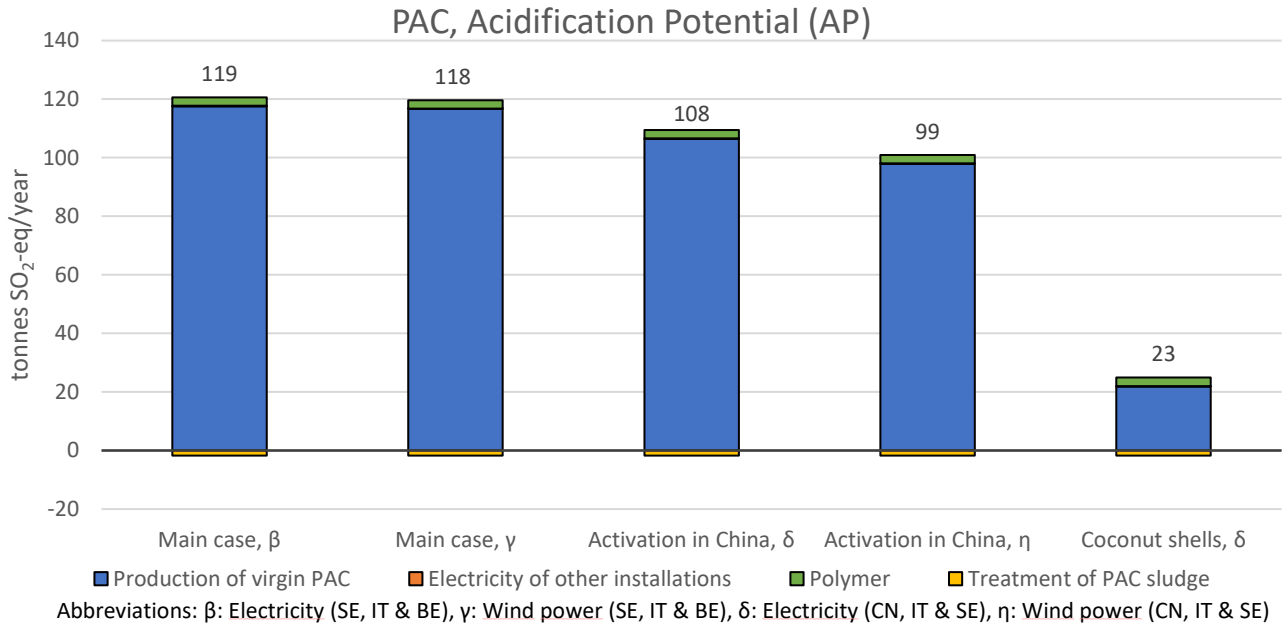


Figure 22. The yearly contribution in tonnes SO_2-eq to acidification for the main PAC process and the four sensitivity analyses.

7.4. GAC Process with Sensitivity Analyses

The following section presents the GAC process with sensitivity analyses for all five midpoint impact categories. The included activities within the GAC process have been aggregated into four major activities: *Production of virgin GAC, Electricity of other installations, Regeneration,* and *Transports regeneration*. The main case with Swedish and Belgian electricity mix is abbreviated as α. Furthermore, the ten sensitivity analyses present different changes based on the main case. Therefore, different electricity mixes are used, and are abbreviated as followed; μ is Swedish and Belgian wind power, ε is Chinese and Swedish electricity mix, and π is Chinese and Swedish wind power.

The ten different sensitivity analyses are named as followed; Main case with μ; Activation in China with ε; Activation of in China with π; Main case accounting for credited heat from regeneration, with α; Regeneration plant at Rya WWTP with α; Regeneration plant at Rya WWTP accounting for credited heat, with α; Regeneration plant with natural gas at Rya WWTP accounting for credited heat, with α; Renewable GAC (coconut shells) with ε; 30 000 bed volumes with α; 10 000 bed volumes with α. An extensive description of the sensitivity analyses is presented in Table C.5 in Appendix 3. The effect of credited heat is included in the three cases: main case accounting for credited heat from regeneration, regeneration plant at Rya WWTP accounting for credited heat, and regeneration plant with natural gas at Rya WWTP accounting for credited heat.

Figure 23 presents the yearly contribution to global warming in kilo tonnes CO_2-eq for the main GAC process and the ten different sensitivity analyses. The production of virgin GAC and regeneration are the two activities contributing the most to global warming for all ten cases. By varying the number of bed volumes and using a renewable resource in the production of virgin GAC, the largest alteration in global warming is achieved. However, the other sensitivity analyses do not indicate any large variations in their impact on global warming.

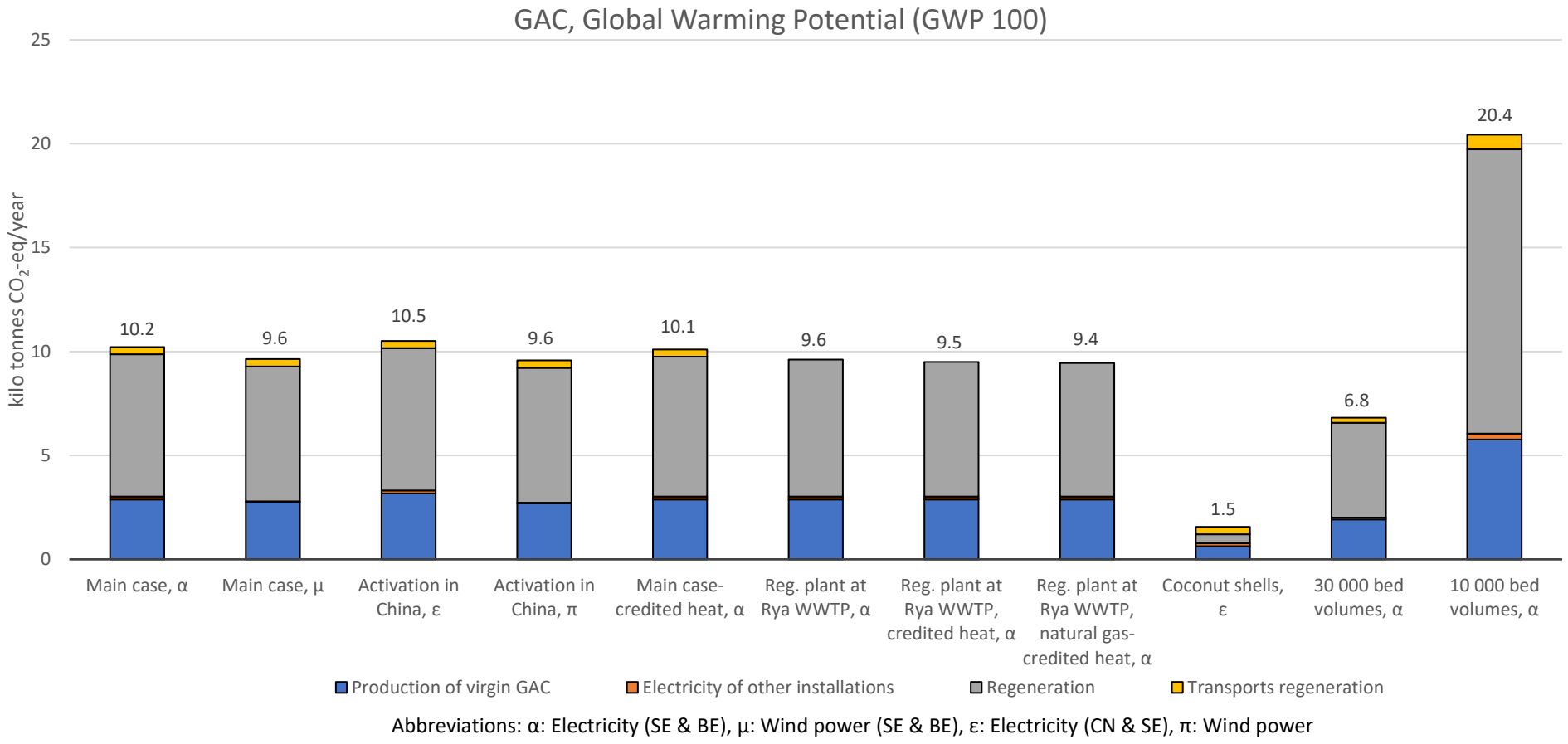


Figure 23. The yearly contribution in kilo tonnes CO_2-eq to global warming for the main GAC process and the ten sensitivity analyses.

Figure 24 presents the yearly contribution to fossil depletion in kilo tonnes oil-eq for the main case of the GAC process and the ten different sensitivity analyses. For fossil depletion, there is a larger variation between the eleven different cases (Figure 24) than the variation between the cases for global warming (Figure 23). The use of wind power as electricity means a lower dependence on fossil resources and thus a reduced contribution to fossil depletion. Another part of the process resulting in a decreased dependence on fossil fuels is the use of coconut shells as a renewable resource in the production of virgin GAC. Also, 30 000 bed volumes results in a lower impact on fossil depletion than the main case, and here all included activities within the process are affected.

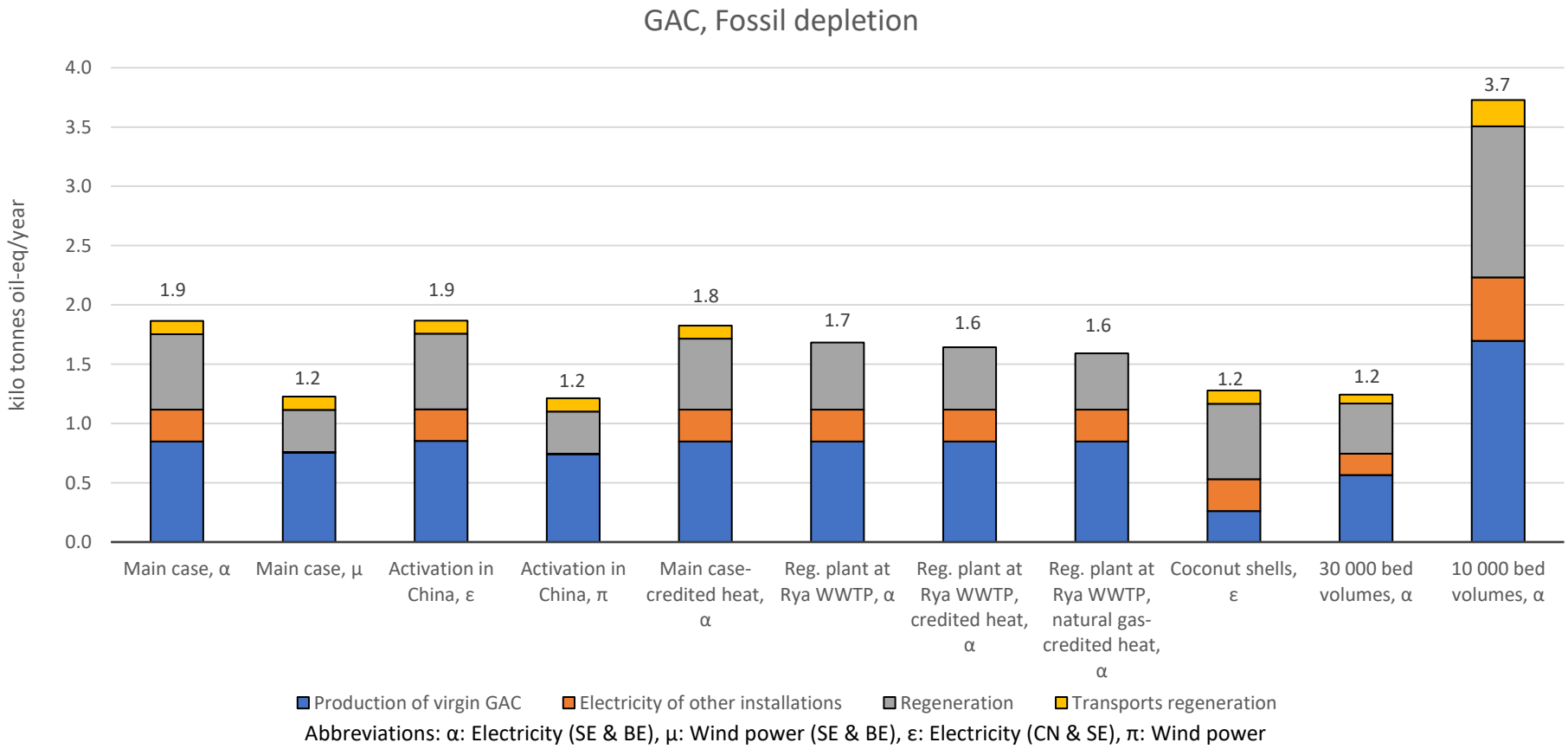


Figure 24. The yearly contribution in kilo tonnes oil-eq to fossil depletion for the main GAC process and the ten sensitivity analyses.

Figure 25 presents the yearly contribution to energy use in GWh for the main case of the GAC process and the ten different sensitivity analyses. In comparison to the main case, the three cases accounting for credited heat result in a lower pressure on energy use since the produced heat during regeneration can be utilised. A larger bed volume is beneficial as well as using a renewable resource for GAC instead of a fossil resource.

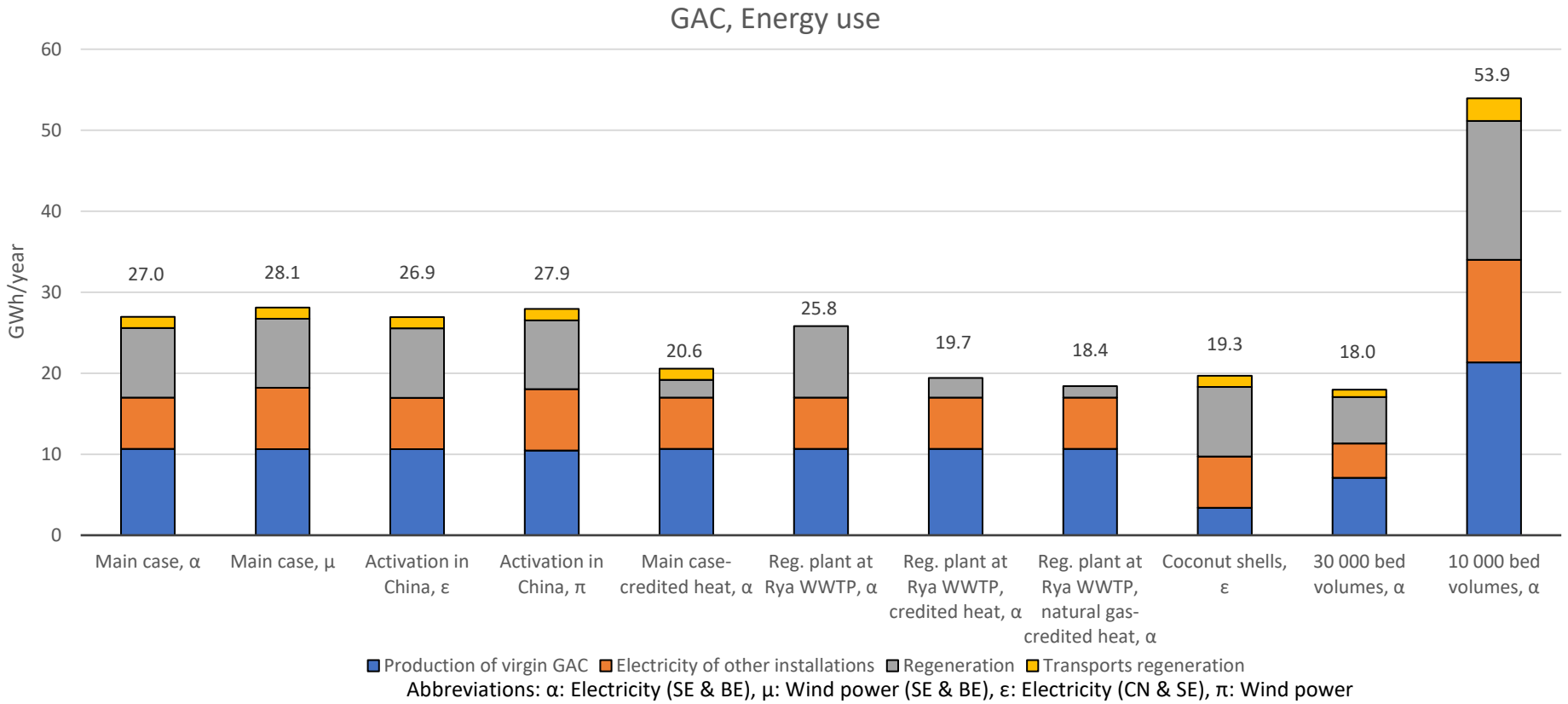


Figure 25. The yearly contribution in GWh to energy use for the main GAC process and the ten sensitivity analyses.

Figure 26 presents the yearly contribution to eutrophication in tonnes PO_4-eq for the main GAC process and the ten different sensitivity analyses. By studying the eutrophication for the eleven different cases, a variation in impact can be observed. Also in this case, the production of virgin GAC is the activity contributing the most overall. Transports regeneration is likewise an activity with a rather high impact on eutrophication, which is shown when fewer transports are needed for the cases of regeneration plant at Rya WWTP. No additional emissions are assumed for the activation and regeneration of coconut shells since it is classified as a renewable resource. Using coconut shells is, therefore, the most favourable alternative since it affects eutrophication less than the other alternatives.

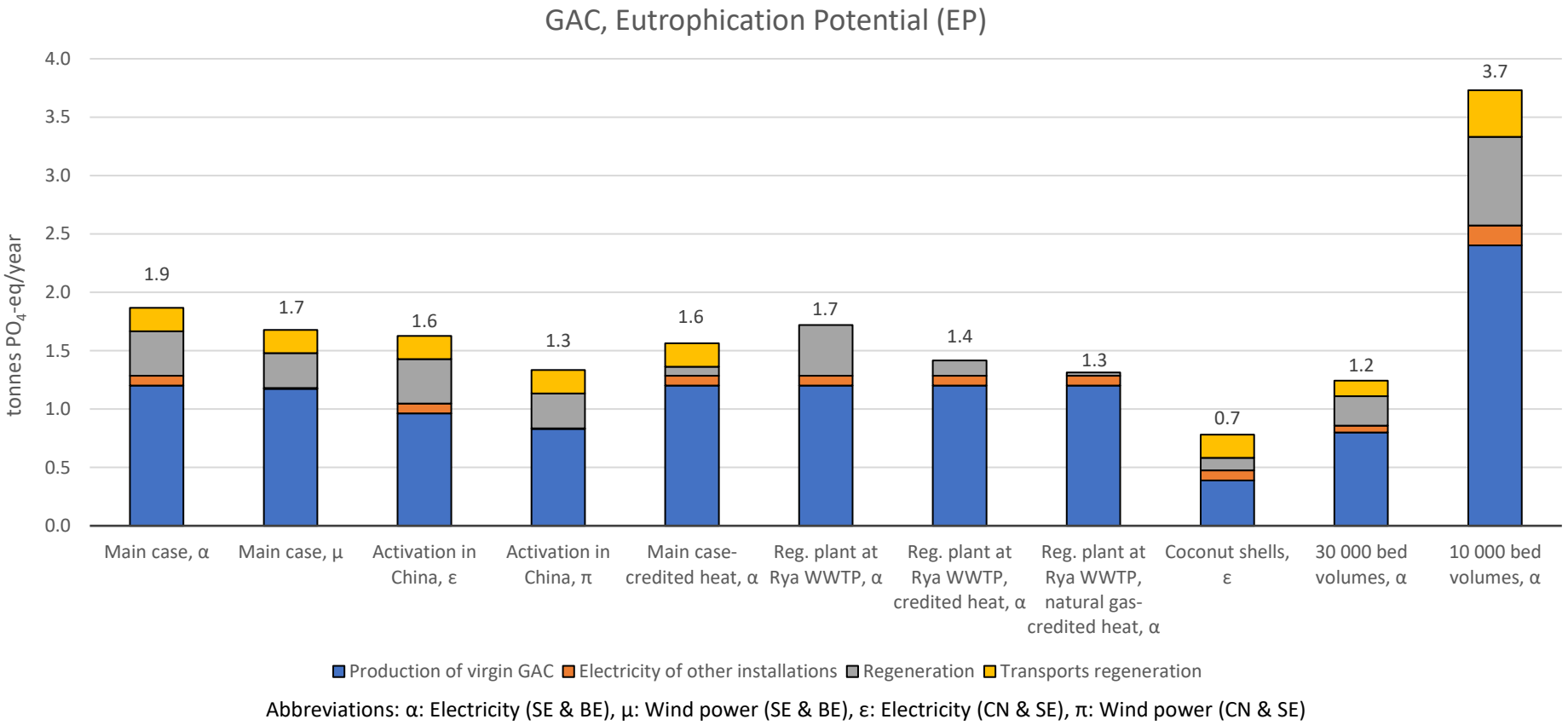


Figure 26. The yearly contribution in tonnes PO_4-eq to eutrophication for the main GAC process and the ten sensitivity analyses.

Figure 27 presents the yearly contribution to acidification in tonnes SO_2-eq for the main GAC process and the ten different sensitivity analyses. The production of virgin GAC and the regeneration are the two activities contributing the most to acidification. Most cases are rather similar in their impact except for coconut shells, 30 000 bed volumes, and 10 000 bed volumes. The use of coconut shells in the production of virgin GAC and 30 000 bed volumes has a lower impact on acidification than the other nine alternatives, while the case with 10 000 bed volumes results in a higher contribution to acidification.

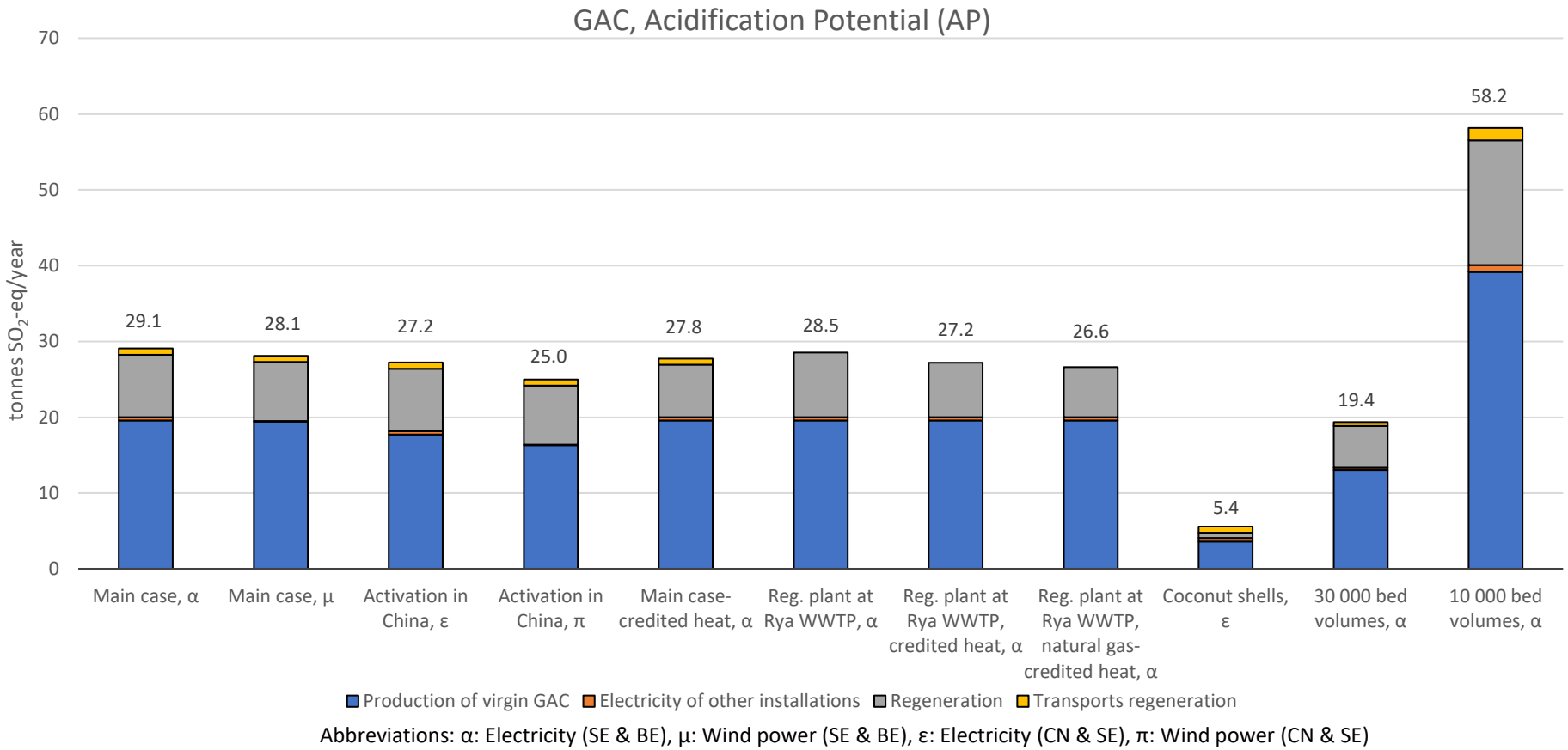


Figure 27. The yearly contribution in tonnes SO_2-eq to acidification for the main GAC process and the ten sensitivity analyses.

8. Discussion

Section 8 presents a comparison of the results in this study with the results from the pre-study. A reasoning of which of the three advanced WWT processes is the environmentally preferable choice is included. The results of this study are also compared to results from previous LCA studies. There is also a reasoning of the major environmental impacts for each of the three advanced WWT processes, and thus which of the five midpoint impact categories that is affected the most. Moreover, the most crucial parts of the total environmental impact of the three processes are also discussed.

Furthermore, potential impacts on actors are described based on the results. A discussion of the recipient of Rya WWTP is also presented, where questions regarding the environmental burden of advanced WWT processes are weighed towards the environmental benefit of removal of pharmaceutical residues. Moreover, ethical reasoning regarding the work environment and safety, and claims of the unexploited area in Rya forest, are presented. Lastly, the source of errors and improvements are discussed.

8.1. Which of the Three Advanced Processes is the Environmentally Preferable Choice?

The following section discusses which of the three advanced processes is the environmentally preferable choice. The reasoning involves the two functional units, separately.

8.1.1. Treatment of a Yearly Flow of Wastewater

As visualised in Figure 13, Figure 18, and Figure 23 the total contribution to global warming is 684 tonnes CO_2-eq/year for the ozonation, 18 142 tonnes CO_2-eq/year for the PAC process, and 10 216 tonnes CO_2-eq/year for the GAC process. These numbers can also be seen in Table 11, where the corresponding values from the pre-study are presented.

Table 11. A comparison of the total contribution to global warming in tonnes CO_2-eq/year for the results in the LCA study and the results from the pre-study.

	Ozonation	PAC process	GAC process
Total contribution to global warming, this study (tonnes CO_2-eq/year)	684	18 142	10 216
Total contribution to global warming excluding the contribution of materials for construction, pre-study (tonnes CO_2-eq/year)	186[C]	25 263[C]	8958[C]

Reference: C: (Gryaab, 2020)

The total contribution to global warming differs between this LCA study and the pre-study. The yearly amount of tonnes CO_2-eq for ozonation is considerably larger in this LCA study and a probable cause for this is the selected credited heat in GaBi. The credited in this study corresponds to 347 tonnes CO_2-eq, which is presented in Table G.1 in Appendix 7, and the credited heat in the pre-study amounted to 857 tonnes CO_2-eq. As mentioned in Section 6.1.1, this LCA study includes heat from residential heating systems from wood. This heat was considered most likely in Sweden in comparison to the other two alternatives GaBi offered:

heat from residential heating systems from natural gas and heat from residential heating systems incinerating light fuel oil (low sulphur content). Since the credited heat in the pre-study results in larger "saved" emissions in comparison to producing the heat in question, it is probably heat for which the production has a greater environmental burden than residential heating systems from wood. This aspect complicates the comparison of the results from this LCA study and the pre-study, but it also demonstrates the benefits of conducting a comprehensive analysis such as an LCA since the results are more detailed.

The result for the PAC process from this LCA study and the pre-study is in the same order of magnitude. The yearly contribution of CO_2-eq from this LCA study is though lower than the results from the pre-study, where it is the production of virgin PAC and the production of polymer that differ the most (Ernst et al., 2020). The impact from the production of virgin PAC is in this LCA study lower than the impact in the pre-study, while the impact from the polymer is larger in the LCA study in comparison to the pre-study. Possible explanations for the difference are, partly, the lack of detail in how the environmental burden was calculated in Contactica S.L & Emivasa (2018), where the pre-study retrieved data. Therefore, the comparison could not be identical. Also, the calculations of the polymer are in this LCA study based on data from a supplier of polymer, while the pre-study used data from Gryaab's carbon footprint tool (Gustavsson & Tumlin, 2013) to calculate the environmental impact of the polymer. Moreover, the ratio of the monomers in the used polymer, polyacrylamide, is unknown. Therefore, as described in Section 5.1, a ratio of 50 percent acrylic acid and 50 percent acrylonitrile was assumed in this study, even though acrylonitrile resulted in larger emissions. More detailed data could have led to more equivalent results as in the pre-study for the polymer.

The environmental impact of global warming from the GAC process is larger in this LCA study than in the pre-study. The impact of the electricity is, as for both the ozonation and the PAC process, like the pre-study and thus not the reason for the difference. However, similar to the PAC process, the environmental impact from the production of virgin GAC is lower in this LCA study compared to the pre-study. On the other hand, the impact of regeneration is larger in this LCA study, which can be explained by the use of different sources that differentiates. In this study, electricity, natural gas, and the manual emissions in Table D.5 and Table D.8 in Appendix 4 were added for the regeneration while only natural gas was accounted for in the pre-study. Also, the environmental burden from transport is larger in this study.

As depicted in Table 11, ozonation is the most advantageous process in terms of contribution to global warming. The values in Table 11 can also be linked to Gryaab's total contribution to global warming in the year 2019, which amounted to 13 000 tonnes CO_2-eq (Ernst et al., 2020). A comparison of Gryaab's total contribution to global warming reveals how beneficial a possible implementation of an ozonation process would be in comparison to a PAC- or a GAC process from a climate impact perspective only. However, in comparison to the pre-study, this LCA also entails midpoint impact results in terms of contribution to fossil depletion, energy use, eutrophication, and acidification. For a more detailed analysis, the contribution to these midpoint impact categories is important to consider when comparing the three advanced WWT processes.

Furthermore, ozonation is the most beneficial alternative considering eutrophication and acidification while the impact on fossil depletion and energy use is similar for ozonation and the GAC process, as presented in Figure 11. However, an important aspect is the large use of electricity for ozonation (Operating data Gryaab, energy, 2020). Rya WWTP consumes almost 41 GWh of electricity per year for the existing treatment of wastewater. The ozonation process consumes approximately 22 GWh of electricity per year, which can be seen in Table 2. An implementation of ozonation thus requires an increase of approximately 50 percent considering the consumption of electricity at Rya WWTP, regardless of the electricity origins from non-renewable- or renewable resources. Important to remember is, therefore, that even if the electricity is renewable, it consumes energy that could have been used for other purposes. As described in Section 6.2, wind power has low efficiency and results in large losses. Another renewable alternative, such as hydro power with higher efficiency, could potentially result in lower electricity use.

Moreover, Gryaab's current environmental permit allows for emissions of 40 tonnes phosphorus per year and 1000 tonnes nitrogen per year for the effluent treated wastewater (Gryaab, n.d.c). The characterization factor for phosphorus and nitrogen is 3.06 g PO_4-eq/g and 0.42 g PO_4-eq/g, respectively (Baumann & Tillmann, 2004). Therefore, conversion to EP results in 542 tonnes PO_4-eq/year in accordance with Equation 1:

$$(40 \cdot 10^6 \cdot 3.06 + 1000 \cdot 10^6 \cdot 0.42) \cdot 10^{-6} = 542 \qquad (1)$$

When comparing the permit with the emissions contribution to eutrophication for the processes, the emissions from all three processes are well below the permit. However, ozonation is the most preferable process, considering emissions contributing to eutrophication, given its almost non-existent influence as can be seen in Figure 11.

No emissions contributing to acidification are included in the environmental permit. As can be seen in Table G.20 and Table G.21 in Appendix 7, the largest contributors to AP are the production of activated carbon, regeneration, and transport by container ship. Both heavy oil and hard coal contain sulphur (Bruneau, n.d.), resulting in emissions of substances contributing to AP in Table 9. Therefore, using renewable fuels and coconut shells in the production of activated carbon reduces emissions contributing to AP. Moreover, the fact that the emissions associated with the production of activated carbon affect AP the most, can explain the low impact of acidification from the ozonation process.

Ozonation with wind power and the GAC process with coconut shells are thus the most environmental advantageous alternatives based on the contribution to the five midpoint impact categories. Two further beneficial aspects of the GAC process are the additional removal of BOD and no additional risks regarding work environment and safety, which are further described in Section 8.6. As mentioned in Section 2.2, the retention time at Rya WWTP is relatively low which can be one factor that BOD is released into the recipient since there is not enough time for all BOD to be hydrolysed and degraded by bacteria. Moreover, as described in Section 2.4.2.2, removal of BOD in the wastewater is important since it otherwise can cause eutrophication and an oxygen-poor environment. Due to the current issue of released BOD into the recipient, an implementation of the GAC processes would probably both reduce the amount

of BOD and pharmaceutical residues in the wastewater. Furthermore, more stringent regulations regarding the removal of BOD will arise in the future which also demonstrates the benefit of the GAC process. Additional aspects indicating the GAC process as more advantageous compared to ozonation is the risk for by-products likewise transformation products and the possible effects to humans and organisms. However, as also further described in Section 8.6, a disadvantage of the GAC process is the ethical aspects with claims of current unexploited areas in Rya forest.

8.1.2. Treatment of 1 m^3 of Wastewater

Similar as described by Pesqueira et al., (2020) in Section 3.2, this LCA study also indicates the importance of analysing the energy use of the processes. As discussed in Section 8.1.1, ozonation is the most beneficial process considering most midpoint impact categories. However, the process consumes a large amount of energy in terms of electricity. Even if the electricity is made of renewable resources, it is used energy that must be produced which could have been used for other purposes. Therefore, reflecting on the processes' environmental benefits compared to their environmental burden is vital. Pesqueira et al., (2020) also noted the lack of information on how pharmaceutical residues can impact living organisms, and that not all studies find a beneficial environmental impact with implementing advanced WWT processes. As described in Section 2.2, the effluent treated wastewater from Rya WWTP flows into the primary recipient Göta Älv, close to the ocean Kattegatt. The dilution is high, which also complicates the measuring of eventual impacts in the recipient. However, the potential environmental benefit compared to the possible environmental burden of implementing the advanced WWT processes is further described in Section 8.5.

Furthermore, also presented in Section 3.2 is that the GAC process overall performs environmentally better than the ozonation in several studies. It differs compared to this LCA study, where Figure 12 shows that the ozonation process in general performs environmentally better. Similar as described by Pesqueira et al., (2020), Section 7.2 displays the value of choosing renewable alternatives where it is possible. Mousel et al., (2017) mean that the ozone dosage is a critical aspect considering the electrical demand for ozonation, whereas Pesqueira et al., (2020) at the same time point out the benefits of using environmentally beneficial energy mixes in the ozonation process. The previously mentioned aspects in combination with combining the GAC process and ozonation in Section 3.1, entail a possible environmentally beneficial alternative. In this LCA study, 10 g ozone/m^3 wastewater is used, which can be compared with the ozone dosage of 4 g/m^3 at the WWTP Stengården. However, the available area at Rya WWTP is limited, and an eventual implementation of two processes for the reduction of pharmaceutical residues may therefore be difficult. Hence, further investigations concerning the question are vital.

Table 12 presents the contribution to GWP, EP, and AP of all process within the existing WWT at three different WWTPs. These values can be compared to the results from this LCA for ozonation, the PAC process, and the GAC process. The environmental burden of the advanced WWT processes investigated in this study can then be compared to the impact of existing WWTPs without any advanced WWT process. A perception of the order of magnitude regarding the environmental impact of advanced WWT processes can thus be obtained.

Table 12. The contribution to global warming, eutrophication, and acidification for the existing WWTP at Henriksdal WWTP, Käppala WWTP, and Kungsängen WWTP. Also, the contribution to the three different midpoint impact categories is presented for ozonation, the PAC process, and the GAC process for a possible implementation at Rya WWTP.

	Implementation at Rya WWTP	Henriksdal WWTP	Käppala WWTP	Kungsängen WWTP
Contribution to global warming (g CO_2-eq/m^3)	Ozonation: 5 PAC process: 141 GAC process: 79	115[H]	279[H]	118[H]
Contribution to eutrophication (mg PO_4-eq/m^3)	Ozonation: ~ 0 PAC process: 57 GAC process: 15	4560[H]	4580[H]	5720[H]
Contribution to acidification (mg SO_2-eq/m^3)	Ozonation: ~ 0 PAC process: 924 GAC process: 226	890[H]	647[H]	776[H]

References: H: (Arnell et al., 2016)

As can be seen in Table 12, the ozonation contributes to a low degree or not at all to the three different midpoint impact categories, in relation to the existing WWT at Henriksdal WWTP, Käppala WWTP, and Kungsängen WWTP. The GAC process contributes in a significant way to global warming and acidification, but only trivial to eutrophication. Furthermore, the contribution of the PAC process is high to global warming and acidification, where the impact might be larger than the total impact from the existing WWT at Henriksdal-, Käppala-, and Kungsängen WWTP. On the other hand, the contribution to eutrophication of the PAC process is low. As discussed in Section 8.1.1, there are possibilities to reduce the processes' environmental impact by choosing more environmentally beneficial alternatives. However, the alternatives for the PAC process do not affect the result in such a way to make it more advantageous to ozonation and the GAC process.

8.2. What are the Major Environmental Impacts Considering the Selected Midpoint Impact Categories, of Each Advanced Process?

The three advanced WWT processes contribute to various degrees to each of the five midpoint impact categories. The contribution within one process can also be very different for each of the midpoint impact categories, which demonstrates the importance of including several midpoint impact categories. However, this also complicates the analysis since the processes can be advantageous in some aspects but disadvantageous in other aspects.

As described in Section 8.1.1, the ozonation has a large contribution to energy use and consumes 22 GWh. The total use of electricity at Gryaab is 41 GWh/year (Operating data Gryaab, energy, 2020) and a potential implementation of an ozonation process at Rya WWTP would consequently increase the total energy use by approximately 50 percent, in relation to the current situation. Moreover, as depicted in Figure 16 and Figure 17, a possible implementation of an ozonation process would result in no contribution to eutrophication and acidification. As described in Section 8.1.1, the potential contribution to global warming for the ozonation process is low in comparison to Rya WWTP's current yearly contribution to CO_2-eq. Furthermore, the contribution to fossil depletion is large for the ozonation since Swedish

electricity mix includes a large share of nuclear power. Unfortunately, no reference value was found for fossil depletion and, therefore, no comparison to other studies could be made. Based on the discussion regarding the impact on each of the five midpoint impact categories, a possible implementation of an ozonation process at Rya WWTP contributes the most to energy use and fossil depletion.

Unlike the ozonation, the PAC- and GAC process has a large impact on global warming. As mentioned in Section 8.1.1, both the PAC- and GAC process exceeds Gryaab's total contribution to global warming in the year 2019. The yearly contribution to GWP, EP, and AP of the PAC- and GAC process can be compared to the results from the LCA study by Arnell et al. (2016) of the Henriksdal WWTP in Stockholm. The yearly influent wastewater to Henriksdal WWTP is 103 660 000 m^3/year and it contributes to 17 900 tonnes CO_2-eq/year, 706 tonnes PO_4-eq/year, and 138 tonnes SO_2-eq/year, which is presented in Table 13. The contribution to global warming of the PAC process is larger than the total contribution to global warming of Henrikdal WWTP, which demonstrates the great impact on global warming for the PAC process. As discussed in Section 8.1.1, neither the PAC process nor the GAC process is close to Gryaab's current environmental permit regarding emissions of phosphorus and nitrogen in effluent treated wastewater. Also, both the PAC- and the GAC process have a low impact on eutrophication in comparison to Henriksdal WWTP. The contribution of the PAC process to acidification is, however, similar to Henriksdal WWTP.

Table 13. The contribution to global warming, eutrophication, and acidification for the existing WWTP at Henriksdal. The contribution to the three different midpoint impact categories is also presented for the PAC process and the GAC process for an eventual implementation at Rya WWTP.

	Implementation at Rya WWTP	Henriksdal WWTP
Contribution to global warming (tonnes CO_2-eq/year)	PAC process: 19 100 GAC process: 11 300	17 900[H]
Contribution to eutrophication (tonnes PO_4-eq/year)	PAC process: 8 GAC process: 2	706[H]
Contribution to acidification (tonnes SO_2-eq/year)	PAC process: 122 GAC process: 32	138[H]

References: H: (Arnell et al., 2016)

Furthermore, the PAC process has a great impact on fossil depletion as presented in Figure 11, which depends on the large use of energy sources in the production of virgin PAC. Moreover, both the PAC- and the GAC process have a great impact on energy use. The electricity use of the PAC- and the GAC process is, however, low in comparison to the ozonation. Therefore, the large use of energy can be derived from the large consumption of natural gas and fossil fuels. Based on the discussion regarding the impact on each of the five midpoint impact categories, an eventual implementation of the PAC process would contribute the most to global warming and acidification. Moreover, an eventual implementation of the GAC process would contribute the most to global warming.

8.3. What Parts of the Advanced Processes are Most Crucial for the Total Environmental Impact?

The following section evaluates what parts of the advanced WWT processes are most crucial for the total environmental impact. The evaluation is based on which activities contribute the most to each midpoint impact category.

8.3.1. Ozonation

As mentioned in Section 7.2 and depicted in Figure 13, Figure 15, and Figure 17, oxygen production has the largest contribution to global warming, energy use, and acidification although ozone production is more energy-intensive which is depicted in Table G.19 in Appendix 7. The possible credited heat from the ozone production is though greater than for the oxygen production, which likewise is presented in Table G.19 in Appendix 7, and results in a larger overall impact of the oxygen production. Since oxygen production has the largest impact in three out of five midpoint impact categories, this activity is assigned to be the most crucial for the total environmental impact of the ozonation. The impact of the ozone production is, however, the activity most affected by the introduction of wind power.

8.3.2. PAC Process

The production of virgin PAC is the major contributor to each of the five midpoint impact categories, and consequently most crucial for the total environmental impact of the PAC process. As can be seen in Table G.2, G.5, G.14, G.17, and G.20 in Appendix 7, the extraction of hard coal, the consumption of natural gas likewise electricity, and the activation of PAC are major contributors to the production of virgin PAC. Therefore, a disadvantage of the PAC process is the need for virgin PAC, since it contributes to a large environmental impact. However, as described in Section 7.3, renewable activated carbon has the potential to largely reduce the environmental impact of the production of virgin PAC. Using coconut shells instead of hard coal to produce virgin PAC is, therefore, an important aspect to consider. The production of non-renewable activated carbon requires more energy-intense steps, such as coal mining, in comparison to the production of renewable activated carbon. On the other hand, due to the lack of detailed data in GaBi to produce activated carbon from coconut shells, the result for the energy use can be developed further to be more reliable. Several producers of activated carbon already produce PAC and GAC from coconut shells, for instance, DESOTEC (DESOTEC through Seiler, 2022) and Zhulincarbon (Zhulincarbon, n.d.). Moreover, the Research Institute of Sweden (RISE) is currently working on a project in which different methods to produce activated carbon from biocarbon are evaluated (RISE, 2021). Renewable alternatives instead of fossil resources are thus possible to find, which is beneficial for both the PAC process and the GAC process.

8.3.3. GAC Process

The production of virgin GAC and the regeneration of activated carbon are the major contributors within the GAC process, and thus most crucial for the total environmental impact of the GAC process. Therefore, it is important to evaluate which factors contribute to the production of virgin GAC and the regeneration if the GAC process is considered a further candidate at Rya WWTP. The amount of bed volumes is a factor with great impact on the total environmental impact of the GAC process. Figures 23-27 convey that a reduced amount of bed

volumes has a greater environmental burden. Therefore, it is advantageous with a large number of bed volumes, since it increases the lifetime of the GAC and reduces the need for regeneration. The amount of suspended material at Rya WWTP is relatively low, which enables a potentially larger bed volume (Neth at Gryaab, 2022). However, the specific number of bed volumes needs to be further evaluated.

The usage of renewable resources to produce virgin GAC is another factor with great impact on the total environmental burden. Coconut shells have the potential to reduce the contribution of the GAC process to all selected midpoint impact categories. However, as described in Section 8.3.3, the result depicting the energy use can be developed further to be more reliable. Furthermore, the GAC process is dependent on transport and natural gas in all cases. In this study, only fossil diesel mix and natural gas have been evaluated, but possible renewable alternatives in the future may lead to the GAC process as a more beneficial alternative. However, an important aspect is that even though the energy is renewable, the energy must be produced which always has an environmental impact, as indicated in Figure 25. By combining different sensitivity analyses, an even lower impact on the different midpoint impact categories can be reached. For instance, one advantageous combination is the one with coconut shells, 30 000 bed volumes, and wind power. Finding these crucial activities and their possible improvements is thus a way to develop the processes further.

8.4. Impact on Actors

The choice of implementing a process for the reduction of pharmaceutical residues in wastewater is not straightforward. There are several factors and perspectives to consider that both can help and complicate the choice to make. As mentioned in Section 4.6, several actors are affected when it comes to changes in a WWTP. The WWTP, in this case the Rya WWTP, is of course the main actor being affected. However, other WWTPs, both within and outside of Sweden, evaluating the same question, are also influenced by Gryaab's choice in the matter. Also, the inhabitants around Rya WWTP and the connected municipalities probably have an interest in the decision since it can result in changing costs and handling of water. An eventual side effect of implementing a process for the reduction of pharmaceutical residues is, for example, increased water- and sewer costs for the households (Neth at Gryaab, 2022). Furthermore, an advanced WWT process results in emissions and it is therefore of importance to further investigate its eventual impact on, for example, the air quality and ecotoxicity, from a broader perspective.

Moreover, mentioned in Section 4.6 and Section 1 is the upcoming regulations and other measures for minimizing potential environmental burdens from wastewater. This is a question currently discussed at the EU level. Therefore, Susanne Tumlin, development engineer at Gryaab and one of Sweden's representatives in sewer, environment, and circulation at the EU level, briefly explained the development work within the EU considering WWTPs (Tumlin, 2022). First, a WWTP is classified as an environmentally hazardous activity and a permission is therefore needed to conduct the activity. There are no terms or requirements on WWTPs to remove pharmaceutical residues from the wastewater, but Gryaab's current permission includes a condition to study how the recipient reacts to environmentally hazardous substances, for instance, pharmaceutical residues. However, measuring the recipient is not easy and it is,

therefore, difficult to conclude its current condition and how it responds to ensuing changes. Due to low concentrations, it is uncertain if it is possible to measure any effect and thus also difficult to conclude anything regarding the need of implementing an advanced process.

At the EU level, there are directives that all member countries must follow. Also, the EU have strategies and alignments that are up to each country to what extent they want to follow them. All countries follow a baseline that currently is in the progression to be updated. However, deciding on a baseline is not an easy task. The reason is varied developed WWTs throughout the EU countries but also differences in how much each country can afford to invest in WWT. Due to uncertainties, other solutions are also considered, for instance, changed rules in how doctors prescribe drugs to their patients. More clear and better markings on the products is another measure in the development work.

However, Sweden now performs voluntary development work on how to improve the WWT. The pre-study at Gryaab, funded by SEPA, is a part of this development work. Depending on the result of these projects, different actors can be affected. Still, Tumlin emphasizes the importance of mapping the recipients with the lowest dilution or the largest WWTPs in terms of treated wastewater. By finding these vital WWTPs, the implementation of processes for the reduction of pharmaceutical residues can be prioritised at those locations, or possibly even limited to them (Tumlin, 2022). In this way, advanced WWT processes are only implemented where needed.

Ozonation and the GAC process are the preferred alternatives based on the results of this study. However, the choice of which process to choose is not straightforward due to safety risks with ozonation that are more discussed in Section 8.6. One thing for sure is that the risks have an impact on actors, and further investigations in how to limit the risks are, therefore, essential.

8.5. The Recipient of Rya WWTP

As described in Section 2.1, the effects in nature of pharmaceutical residues depend on several factors such as the sensitivity of the recipient, the concentration of pharmaceutical residues, the dilution factor, and the turnover in the recipient. The characteristics of the recipient play a major role in terms of the required level of reduced pharmaceutical residues to minimise environmental risks (Baresel, n.d.). Therefore, there is no universal method nor universal process that is the most preferred choice for all WWTPs. Moreover, as mentioned in Section 4.1, processes for the removal of pharmaceutical residues are acknowledged as resource-intense. The potential environmental benefits of the removal of pharmaceutical residues against the possible environmental burden of the advanced WWT process must therefore be evaluated.

The primary recipient of Rya WWTP is large and has a high turnover, entailing larger dispersion of pharmaceutical residues, which is described in Section 2.2. Therefore, it is difficult to measure the current concentrations of pharmaceutical residues in the recipient, likewise a potential reduction of pharmaceutical residues entailed by the implementation of advanced WWT processes. The installation and operation of an advanced WWT process, with a large environmental impact, can potentially result in a greater environmental burden than an environmental benefit. Moreover, the pre-study conveys the importance of further analyses to

achieve a deeper comprehension and thereby perform a more righteous conclusion about the risk assessment of the recipient (Ernst et al., 2020).

As described in section 3.3, the implementation of an ozonation plant at Nykvarnsverket WWTP in Linköping resulted in a significant reduction of pharmaceutical residues in the effluent treated wastewater. For Nykvarnsverket WWTP, the discharge point of effluent treated wastewater is in the river Stångån (Gålfalk, 2020). In comparison to the recipient of Rya WWTP, Stångån is very small, has less turnover, and a lower dilution factor. Therefore, it is difficult to compare the effects of reduced pharmaceutical residues in Stångån and Göta Älv.

Furthermore, Ullared WWTP is another plant for which the need for increased treatment of wastewater has been investigated. The river Högvadsån is the recipient of Ullared WWTP and is classified as a Natura 2000 area (Baresel, n.d.). Natura 2000 is a network of valuable natural areas with species or habitats considered particularly worthy of protection from a European perspective (Naturvårdsverket, n.d.b). Högvadsån mostly flows into a gently hilly agricultural landscape, with several endangered and vulnerable biotopes and species. Moreover, high levels of pharmaceutical residues are judged to have negative consequences for the reproduction of salmon and trout. The need for increased treatment of wastewater at Ullared WWTP was therefore evaluated, but the report concluded that there was no need for an advanced WWT process at Ullared WWTP (Baresel, n.d.). The report highlighted the high dilution effect of wastewater in the river Högvadsåsen as the underlying factor behind the motivation.

Characteristics, such as flow conditions, of Högvadsåsen are similar to the ones of Göta Älv. Therefore, to some extent, the results from the study of Ullared WWTP can be linked to the question of whether an increased treatment of wastewater is preferable or not at Rya WWTP. However, the pre-study describes that the substances Citalopram, Diclofenac, Oxazepam, Ranitidine, Estradiol, and Estrone exceed the predicted no-effect concentration (PNEC) at a ten times dilution in the primary recipient (Ernst et al., 2020). Moreover, the pre-study also presents that Citalopram, Ranitidine, and Estrone exceed PNEC values at a 100 times dilution in the recipient, which demonstrates the importance of further analyses to enable righteous conclusions of the recipient's sensitivity. Therefore, it is difficult to compare the results of Ullared WWTP and Rya WWTP, since they in some aspects are comparable but in some they differ.

8.6. Ethical Aspects

Emissions in nature caused by humans always entail several ethical aspects. The discharge of pharmaceutical residues into water is an issue that raises many ethical questions. An important question is if humans have the right to emit pharmaceutical residues into rivers, lakes, and oceans? Moreover, the installation and operation of advanced WWT processes entail several ethical aspects, such as work environment and safety. As discussed in Section 8.4, the installation and operation of advanced WWT processes also involve a financial aspect, where a potential increase in water- and sewer costs for households is an ethical aspect. However, WWT is available for all people in the society independent of the income and the area of living.

Furthermore, as described in Section 2.4.2.2, the most suitable solution is to place the GAC process in the Rya forest. Although the proposed area is not classified as a nature reserve, it

results in claims on current unexploited nature. Moreover, previous proposals to build in the Rya forest have provoked strong reactions from the public (Ernst et al., 2020). This aspect is, therefore, important to include when evaluating the strengths and weaknesses of the GAC process.

Regarding work environment and safety, the GAC process is the most preferable since it does not lead to any new risks in relation to the existing WWT at Rya WWTP (Ernst et al., 2020). There are, therefore, both positive and negative ethical aspects concerning the implementation and operation of the GAC process. Ernst et al. (2020) also convey that, unlike the GAC process, the PAC process and ozonation raise several issues of concern regarding the work environment and safety. The PAC process causes dust and dirt, whilst the ozonation causes high-frequency sounds which means that people with pacemakers cannot enter that part of the plant. Furthermore, Ernst et al. (2020) depict the fire- and explosion risks with handling PAC since it is classified as a dust-explosive substance, likewise the fire risk and hazardous aspects of handling ozone. Moreover, the pre-study also mentions the risk of leakage of ozone from the ozonation process which can result in a contribution to the greenhouse effect.

As mentioned in Section 5.1, biodiversity is not well addressed in LCA. By only considering the LCA results when making a decision, several environmental aspects may be missed. A relevant question is therefore how the lack of these aspects can affect human influence on nature? Moreover, effects in nature are not always local which strengthens the value of investigating all possible alternatives and effects before deciding. Humans in other geographical areas can be influenced by the decision, even though they do not benefit from it. These aspects promote the fact of using more than one sustainability tool in studies, to reinforce the result with data from different perspectives.

8.7. Source of Errors and Improvements

This LCA study includes several sources of error, which to large extent depends on limitations and assumptions. GaBi offers a wide range of options but lacks detailed data regarding the production of polyacrylamide. Moreover, as described in Section 5.1, this LCA study also lacks recipe specific data on polyacrylamide production. The environmental impact of the production of polyacrylamide is therefore a source of error, which is described in Section 8.1.1. A variation in the recipe of acrylic acid and acrylonitrile is assumed to have a rather large impact on the result, since acrylonitrile results in larger emissions. The environmental impact of polyacrylamide production could be developed further by including more detailed data from companies. The result of the polymer production is dependent on the required amount of energy and monomers, likewise the production of heat. Therefore, the calculations related to the polymer production could be improved, and thus its environmental impact for the five midpoint impact categories. However, more specific data for the polymer production would probably still depict the PAC process as the least environmental preferable alternative.

As mentioned in Section 5, credited heat from oxygen production, ozone production, and sensitivity analyses was assumed to represent heat from residential systems from wood. As discussed in Section 8.1.1, the “saved” impact of the credited heating differs between the pre-study and this LCA study. Using another software package with a larger variation of data than GaBi, could enable a more conforming result in relation to the pre-study.

Moreover, the authors' lack of experience performing in-depth LCA analyses is another potential source of error. However, the LCA study has been guided by a supervisor and examiner with a great experience of the tool. This source of error is therefore assessed to have a rather low impact on the final results.

The study could be improved by verifying the data for the regeneration in relation to existing facilities. A longer timeframe of the study could have opened the possibility to find relevant facilities for regeneration in Belgium and evaluate if the data used in this LCA study could be considered adequate. Contact was made with a person at the organisation Svenskt Vatten asking for relevant facilities in Belgium, unfortunately without any response within the timeframe.

Including several countries for the production of coconut shells is another aspect that could have been taken into consideration. As mentioned in Section 6.1.2 and Section 6.1.3, the production of coconut shells was assumed to occur in China. However, other potential countries may exist, and it is therefore important to not stare blindly at China as a country of production. A relevant country closer to Sweden would result in fewer transports and thus a lower impact. Furthermore, alternative renewable resources in the production of activated carbon exist, such as wood, which could have been included in this study to evaluate the environmental impact of renewable resources further. Another improvement of the study would be to include hydropower as an alternative source of electricity since it has higher efficiency than wind power.

Furthermore, a possible improvement of the study would be to investigate a combination of advanced WWT processes for the reduction of pharmaceutical residues. As described in Section 3.1, a combined process can potentially be more resource-efficient and a combination of the energy-intensive ozonation and the GAC process would therefore be interesting to investigate at Rya WWTP. A combination of the two processes could enable a lower required amount of electricity for oxygen production and ozone production in the ozonation. If the ozonation process is placed first, it could result in a decreased consumption of activated carbon in the GAC process, resulting in a reduced required amount of virgin GAC. Thereby, less GAC needs to be regenerated which in turn could reduce the environmental burden.

Another improvement would be to expand this LCA study to also consider the existing WWT without any advanced WWT process and include a quantitative result of relevant pharmaceutical residues. As described in Section 3.2, the result of the LCA can be largely affected by including the effects of pharmaceutical residues in the analysis. A development of this LCA study could therefore be to include pharmaceuticals of concern and expand the study to also include the midpoint impact category ecotoxicity. However, this would require a measure of the current concentration of pharmaceutical residues in the effluent treated wastewater released to the recipient. As discussed in Section 8.5, this is difficult due to several aspects and would therefore require a lot of pre-work for the study.

9. Conclusions and Recommendations

The results of this LCA study conclude that the ozonation with wind power and the GAC process with renewable GAC, wind power, the largest possible bed volume, and a regeneration plant at Rya WWTP are the two environmentally preferred alternatives. The PAC process is not recommended as an option for a potential implementation of an advanced WWT process at Rya WWTP, due to the large environmental burden of the process. Oxygen production is the most crucial activity for the total environmental impact of the ozonation, favouring the use of wind power. For both the PAC- and the GAC process, the production of virgin activated carbon is the most crucial activity. Using a renewable resource in the production of PAC and GAC is advantageous, since it considerably reduces the impact of both processes. For the GAC process, regeneration is also crucial.

Ozonation has the lowest environmental impact based on the contribution to each midpoint impact category. However, the ozonation results in a large consumption of electricity which demonstrates the importance of using renewable energy at a potential implementation at Rya WWTP. Unlike the GAC process, a potential implementation of the ozonation at Rya WWTP also entails additional risks regarding the production of by-products and transformation products, likewise work environment and safety. Therefore, the earlier mentioned combination of the sensitivity analyses for the GAC process is considered an advantageous option for a potential implementation of an advanced WWT process at Rya WWTP.

The results of this LCA study depict the large environmental burden of implementing an advanced WWT process. The large environmental burden of the advanced processes in combination with the need for further analyses regarding the sensitivity of Göta Älv, concludes that further investigations evaluating the treatment efforts against the additional environmental burdens caused by the advanced WWT processes are essential.

This LCA study demonstrates the importance of a more detailed investigation than the multicriteria-analysis in the pre-study. Including several midpoint impact categories revealed the impact on fossil depletion, energy use, eutrophication, and acidification, which were not obtained in the pre-study. Ozonation contributed the most to the midpoint impact category energy use. The PAC process contributed the most to global warming and acidification, while global warming was most significant for the GAC process. Moreover, the inclusion of more detailed data resulted in a greater assessed environmental burden of the PAC process in this study in comparison to the pre-study. This LCA study has contributed to more extensive results considering the environmental impact of the three investigated processes, which is important for the potential selection of an advanced WWT process at Rya WWTP.

10. References

Aho Vanhatapio, A., Wensing, K. (2021). *Beräkning av koldioxidutsläpp från frakter mellan Kina, USA och Sverige, Skillnader i koldioxidutsläpp med eller utan lagerhållning nära slutkund. [Calculations of carbon dioxide emissions from shipping between China, the US, and Sweden, Differences in carbon dioxide emissions with or without warehousing near end customer]* (E2021:071). Chalmers University of Technology. https://odr.chalmers.se/bitstream/20.500.12380/302756/1/E2021_071.pdf

Álvarez-Muñoz, D., Rodríguez-Mozaz, S., Maulvault, A.L., Tediosi, A., Fernández-Tejedor, M., Van den Heuvel, F., Kotterman, M., Marques, A., Barceló, D. (2015). Occurrence of pharmaceuticals and endocrine disrupting compounds in macroalgaes, bivalves, and fish from coastal areas in Europe. *Environmental research, 143*(B), 56-64. https://doi.org/10.1016/j.envres.2015.09.018

American Institute of Chemical Engineers [AIChE]. (n.d). *Advanced Wastewater Treatment (AWT).* https://www.aiche.org/ifs/resources/glossary/isws-water-glossary/advanced-wastewater-treatment-awt#:~:text=Any%20process%20which%20reduces%20the,high%20percentage%20of%20suspended%20solids.

Arena, N., Lee, J., Clift, R. (2016). Life Cycle Assessment of activated carbon production from coconut shells. *Journal of Cleaner Production, 125,* 68–77. https://doi.org/10.1016/j.jclepro.2016.03.073

Arnell, M., Andersson, S., Junestedt, C., Oliveira, F., Rahmberg, M., Åmand, L. (2016). *Nya utsläppskrav för Svenska reningsverk – effekter på reningsverkens totala miljöpåverkan [New emission requirements for Swedish waste water treatment plants – effects on the treatment plants' total environmental impact]* (Nr B 2246). IVL Svenska miljöinstitutet. https://www.ivl.se/download/18.694ca0617a1de98f473715/1628416844797/FULLTEXT01.pdf

Asplund, E. (2021). *Disc Filter facility at Gryaab* [photography]. Gryaab. https://www.gryaab.se/pressmeddelanden/bildarkiv/

Avloppsguiden. (n.d.). *Avloppsguidens ordlista [Sewer guide dictionary]*. https://avloppsguiden.se/informationssidor/avloppsguidens-ordlista/

Azapagic, A., Tarpani, R.R.Z. (2018). Life cycle environmental impacts of advanced wastewater treatment techniques for removal of pharmaceutical and personal care products (PPCPs). *Journal of Environmental Management, 215,* 258-272. https://doi.org/10.1016/j.jenvman.2018.03.047

Bailey, M.P. (2020). *Calgon carbon adds activated-carbon production capacity in Belgium.* Chemical Engineering Essentials for the CPI professional. https://www.chemengonline.com/calgon-carbon-adds-activated-carbon-production-capacity-in-belgium/

Baresel, C. (2020). *Riskbedömning av Ryaverkets recipient med avseende för läkemedelsemissioner. En bedömning baserat på tidigare studier och tillgänglig kunskap [A risk assessment of the recipient of Rya WWTP with respect to effluents of pharmaceutical residues. An assessment based on previous studies and available knowledge]* (U 6293). Svenska miljöinstitutet. (Internal data).

Baresel, C., Ek, M., Ejhed, H., Allard, A.S., Magnér, J., Dahlgren, L., Westling, K., Wahlberg, C., Fortkamp, U., Söhr, S. (2017). *Handbok för rening av mikroföroreningar vid avloppsreningsverk [Handbook for treatment of micro-contaminants at sewage treatment plants]* (B 2288). Svenska miljöinstitutet. https://www.ivl.se/download/18.34244ba71728fcb3f3f8e2/1591705071470/B2288.pdf

Baresel, C., Gunnarsson, A., Habagil, M., Keucken, A., Malovanyy, A., Petersén, A., Svedberg, S. (n.d.). *Läkemedelsrening vid Ullared reningsverk [Purification of pharmaceutical residues at Ullared WWTP]* (C 468). VIVAB Vatten & Miljö I Väst AB. https://www.ivl.se/download/18.694ca0617a1de98f4734d8/1628416311171/FULLTEXT01.pdf

Baresel, C., Ekengren, Ö., Filipsson, S., Karlsson, J., Winberg von Friesen, L., Blomqvist, S., Hasselgren, M., Lazic, A., Stapel, H., Feldthusen, M., Hellman, J., Nordin, A. (2020). *The municipal wastewater treatment plant of the future – A water reuse facility* (C538). IVL Swedish Environmental Research Institute. https://sjostad.ivl.se/download/18.19f66483176f7d6a18e112c/1611845125745/The%20municipal%20wastewater%20treatment%20plant%20of%20the%20future%20%E2%80%93%20A%20water%20reuse%20facility%20C538.pdf

Baumann, H., Tillman, A-M. (2004). Appendix 2: Characterisation indicators. *The Hitch Hiker's Guide to LCA* (p. 515). Studentlitteratur. ISBN 978-91-44-02364-9

Björlenius, B. (2018). *Pharmaceuticals – improved removal from municipal wastewater and their occurrence in the Baltic Sea* [Doctoral Thesis, KTH Royal Institute of Technology]. DiVA. http://www.diva-portal.org/smash/get/diva2:1264354/FULLTEXT01.pdf

Bruneau, L. (n.d.). *Industrier spridande gaser och lukt [Industries dispersing gases and odors]*. https://www.ivl.se/download/18.1ee76657178f8586dfc8d2/1619515730548/B14.pdf

Bui, X.T., Vo, T.P.T., Ngo, H.H., Guo, W.S., Nguyen, T.T. (2016). Multicriteria assessment of advanced treatment technologies for micropollutants removal at large-scale applications. *Science of The Total Environment. 563-564,* 1050-1067. https://doi.org/10.1016/j.scitotenv.2016.04.191

Čelić, M., Gros, M., Farré, M., Barceló, D., Petrović, M. (2019). Pharmaceuticals as chemical markers of wastewater contamination in the vulnerable area of the Ebro Delta (Spain). *Science of The Total Environment, 652,* 952-963. https://doi.org/10.1016/j.scitotenv.2018.10.290

Cimbritz, M., Mattsson, A. (2018). *Reningstekniker för läkemedel och mikroföroreningar i avloppsvatten [Purification techniques for pharmaceutical and micro-contaminants in wastewater]* (2018:7). Havs- och vattenmyndigheten. https://www.havochvatten.se/download/18.4c271c50163bf560e38ecf2d/1528952839153/rapport-reningstekniker-for-lakemedel-och-mikrofororeningar-i-avloppsvatten.pdf

Clerc, B., Gulde, R., McArdell, C.S, Rutsch, M., Schollée, J.E., Von Gunten, (2021). Formation of transformation products during ozonation of secondary wastewater effluent and their fate in post-treatment: From laboratory- to full-scale. *Water Research, 200*(117200), https://doi.org/10.1016/j.watres.2021.117200

Contactica S.L., Emivasa. (2018). *Portable solution for the electrochemical regeneration of activated carbon.* (768905). PORTABLECRAC. https://www.aspire2050.eu/sites/default/files/users/user735/Deliverables/WP6/D6%201_Virgin%20activated%20carbon%20%20Thermal%20regeneration_v4_FINAL.pdf

DESOTEC through Seiler. (2022). (Communication via e-mail).

Edefell, E., Ullman, R., Bengtsson, E. (2019). *Ultrafilter och granulerat aktivt kol för avskiljning av mikroföroreningar [Ultrafilter and granulated activated carbon for separation of micro-contaminants]* (2019–1). Svenskt Vatten. https://www.svensktvatten.se/contentassets/7ec170db0a6d4d8a84523b0340841755/vu-rayt-19-01.pdf

Ernst, G., Neth, M., Tumlin, S. (2020). *D1909 Läkemedelsrening: Förstudie av alternativ för läkemedelsrening på Ryaverket [Purification of pharmaceutical residues: A pre-study of alternatives for purification of pharmaceutical residues at Rya WWTP].* Gryaab. https://www.svensktvatten.se/globalassets/avlopp-och-miljo/reningsverk-och-reningsprocesser/bestallargrupp/19-slutrapporter/gryaab.pdf

Eskebaek, A. (2016). *Utvärdering av småskalig rening från läkemedelsrester i källsorterad urin [Evaluation of small-scale purification of source sorted urine]* [Examensarbete, Uppsala universitet & Sveriges Lantbruksuniversitet]. http://vav.griffel.net/filer/C_SLU2016-032.pdf

Finnson, A. (2019). *Läkemedelsrening [Purification of pharmaceutical residues]*. Svenskt vatten. https://www.svensktvatten.se/vattentjanster/avlopp-och-miljo/reningsverk-och-reningsprocesser/lakemedelsrening

Gryaab. (2020). *Basis for multicriteria-analysis*. (Internal data).

Gryaab. (n.d.a). *Avloppsvattenrening [Wastewater treatment]*. https://www.gryaab.se/vad-vi-gor/avloppsvattenrening/

Gryaab. (n.d.b). *Framtidens avloppsrening med Nya Rya [Future wastewater treatment with New Rya WWTP]*. https://www.gryaab.se/vad-vi-gor/nya-rya/

Gryaab. (n.d.c). *Gryaabs miljötillstånd [Gryaab's environmental permit]*. https://www.gryaab.se/om-gryaab/gryaabs-miljotillstand/

Gryaab. (n.d.d). *Kort om Gryaab [Short introduction of Gryaab]*. https://www.gryaab.se/vad-vi-gor/kort-om-gryaab/

Gryaab. (n.d.e). *Vatten som vatten – eller? [Water as water - or?]*. https://www.gryaab.se/hjalp-oss/klokt-avloppstank/vatten-som-vatten-eller/

Gustavsson, D.J.I, Tumlin, S. (2013). Carbon footprints of Scandinavian wastewater treatment plants. *Water Science & Technology, 68*(4), 887-893. https://doi.org/10.2166/wst.2013.318

Gålfalk, M., Johansson, C., Nilsson Påledal, S., Sehlén, R., Yngvesson, J. (2020). *Innovativ teknik för mätning av växthusgaser från avloppsreningsverk [Innovative technology for measuring greenhouse gases from sewage treatment plants]* (2020-10). Svenskt Vatten utveckling. http://vav.griffel.net/filer/svu-rapport-2020-10.pdf

Hoff, H. (2020). *Läkemedel i avloppsvatten [Pharmaceuticals in wastewater]*. Sveriges riksdag. https://www.riksdagen.se/sv/dokument-lagar/dokument/motion/_H8022492

Hörsing, M., Wahlberg, C., Falås, P., Hey, G., Ledin, A., Jansen, J.l.C. (2014). *Reduktion av läkemedel i svenska avloppsreningsverk – kunskapssammanställning [Reduction of pharmaceuticals in Swedish wastewater treatment plants – compilation of knowledge]* (2014–16). Svenskt Vatten Utveckling. http://vav.griffel.net/filer/SVU-rapport_2014-16.pdf

Karlstads Kommun. (2020). *Avancerad rening av läkemedelsrester vid Sjöstadsverket [Advanced purification of pharmaceutical residues at Sjöstadsverket]* (2). Norconsult. https://www.svensktvatten.se/globalassets/avlopp-och-miljo/reningsverk-och-reningsprocesser/bestallargrupp/19-slutrapporter/karlstad-kommun.pdf

Klimatanpassning.se. (2020). *Vatten och avlopp [Water and sewer]*. https://www.klimatanpassning.se/hur-samhallet-paverkas/vatten-och-avlopp/vatten-avlopp-1.22569

Kolrester från industrier kan designas att rena avloppsvatten [Coal residues from industries can be designed to purify wastewater]. (n.d.). forskning.se. https://www.forskning.se/2019/05/15/kolrester-fran-industrier-kan-designas-att-rena-avloppsvatten/#

Krahnstöver, T., Wintgens, T. (2018). Separating powdered activated carbon (PAC) from wastewater – Technical process options and assessment of removal efficiency. *Journal of Environmental Chemical Engineering. 6*(5), 5744-5762. https://doi.org/10.1016/j.jece.2018.09.001

Kristianstads Kommun. (2020). *Läkemedelsrening igång på Degeberga avloppsreningsverk [Purification of pharmaceutical residues underway at Degeberga wastewater treatment plant]*. https://www.kristianstad.se/sv/nyhetsarkiv/lakemedelsrening_degeberga/

Li, Y., Zhang, S., Zhang, W., Xiong, W., Ye, Q., Hou, X., Wang, C., Wang, P. (2019). Life cycle assessment of advanced wastewater treatment processes: Involving 126 pharmaceuticals and personel care products in life cycle inventory. *Journal of Environmental Management, 238*, 442-450. https://doi.org/10.1016/j.jenvman.2019.01.118

Lüdtke, M. (2019). *Läkemedelsrening och statligt stöd [Purification of pharmaceutical residues and state support]* [Conference session]. NAM19, Sundsvall. https://www.svensktvatten.se/globalassets/utbildning/konferenser-och-seminarier/2019/nam19/5-maximilian-ludtke-naturvardsverket.pdf

Martínez Bueno, M.J., Boillot, C., Munaron, D., Fenet, H., Casellas, C., Gómez, E. (2014). Occurrence of venlafaxine residues and its metabolites in marine mussels at trace levels: development of analytical method and a monitoring program. *Analytical and Bioanalytical Chemistry, 406*, 601–610. https://doi.org/10.1007/s00216-013-7477-x

Mousel, D., Palmowski, L., Pinnekamp, J. (2017). Energy demand for elimination of organic micropollutants in municipal wastewater treatment plants. *Science of The Total Environment, 575*, 1139-1149. https://doi.org/10.1016/j.scitotenv.2016.09.197

Mulder, M., Antakyali, D., Ante, S. (2015). *Costs of removal of micropollutants from effluents of municipal wastewater treatment plants – general cost estimates for the Netherlands based on implemented full scale post treatments of effluents of wastewater treatment plants in Germany and Switzerland.* STOWA and Waterboard the Dommel, The Netherlands. https://www.stowa.nl/sites/default/files/assets/PROJECTEN/Projecten%202018/Stowa%20TAPES%20Final%20report.pdf

Muñoz, I., Rodríguez, A., Rosal, R., Fernández-Alba, A.R. (2009). Life Cycle Assessment of urban wastewater reuse with ozonation as tertiary treatment: A focus on toxicity-related impacts. *Science of The Total Environment*, *407*(4), 1245–1256. https://doi.org/10.1016/j.scitotenv.2008.09.029

Nationalencyklopedin AB [NE]. (n.d.). *Verkningsgrad [Efficiency]*. https://www.ne.se/uppslagsverk/encyklopedi/l%C3%A5ng/verkningsgrad

Naturvårdsverket. (2017). *Avancerad rening av avloppsvatten för avskiljning av läkemedelsrester och andra oönskade ämnen. Behov, teknik och konsekvenser [Advanced purification of wastewater for separation of pharmaceutical residues and other unwanted substances. Need, technique, and consequences]* (Report 6766). Arkitektkopia AB. https://www.naturvardsverket.se/globalassets/media/publikationer-pdf/6700/978-91-620-6766-3.pdf

Naturvårdsverket [SEPA]. (2021). *Läkemedel i miljön [Pharmaceuticals in the environment]*. https://sverigesmiljomal.se/etappmalen/lakemedel-i-miljon/

Naturvårdsverket. (n.d.a). *Läkemedel i miljön [Pharmaceuticals in the environment]*. https://www.naturvardsverket.se/amnesomraden/miljofororeningar/organiska-miljogifter/lakemedel-i-miljon/

Naturvårdsverket. (n.d.b). *Natura 2000-områden [Natura 2000 areas]*. https://www.naturvardsverket.se/amnesomraden/skyddad-natur/olika-former-av-naturskydd/natura-2000-omraden/

Naturvårdsverket. (n.d.c). *Rekommenderade ämnen för analys [Recommended substances for analysis]*. https://www.naturvardsverket.se/bidrag/lakemedelsrening-vid-avloppsreningsverk/rekommenderade-amnen-for-analys/

Neth at Gryaab. (2022). (Personal communication).

New standard for hospital wastewater treatment. (2015). *Elsevier*, *52*(3), 44-45. https://doi.org/10.1016/S0015-1882(15)30141-5

Niinipuu, M. (2019). *Tailoring residue-derived carbon materials for the removal of wastewater contaminants: Adsorption and surface properties* [Dissertation for PhD, Umeå University]. DiVA. http://umu.diva-portal.org/smash/get/diva2:1307880/FULLTEXT01.pdf

Operating data Gryaab. (2020). (Internal data).

Pesqueira, J.F.F.R., Pereira, M.F.R., Silva, A.M.T. (2020). Environmental impact assessment of advanced urban wastewater treatment technologies for the removal of priority substances and contaminants of emerging concern: A review. *Journal of Cleaner Production, 261,* 121078. https://doi.org/10.1016/j.jclepro.2020.121078

Ports.com. (n.d.). *Sea route & distance.* http://ports.com/sea-route/port-of-shanghai,china/port-of-antwerp,belgium/

Rahman, S.M., Eckelman, M.J., Onnis-Hayden, A., Gu, A.Z. (2018). Comparative Life Cycle Assessment of Advanced Wastewater Treatment Processes for Removal of Chemicals of Emerging Concern. *Environmental Science & Technology*, *52*(19), 11346-11358. https://doi.org/10.1021/acs.est.8b00036

Reports from Sweco to Gryaab. (2020). (Internal data).

Research Institute of Sweden [RISE]. (2021). *Ersättning av fossil aktivt kol [Replacement of fossil activated carbon]*. https://www.ri.se/sv/vad-vi-gor/projekt/ersattning-av-fossilt-aktivt-kol

Sehlén, R., Nilsson, J., Stapf, M., Schütz, J., Bester, K., Kharnel, S., Lukas, M., Bogusz, A., Putna-Nimane, I. (2020). *Evaluation and experiences of full-scale ozonation followed by MBBR post-treatment and comparison with previous pilot tests*. CWPharma. https://doi.org/10.5281/zenodo.4032487

Sphera. (n.d.a). *GaBi LCA Databases.* Sphera. https://gabi.sphera.com/sweden/databases/gabi-databases/

Sphera. (n.d.b). *GaBi LCIA Documentations*. Sphera. https://gabi.sphera.com/support/gabi/gabi-lcia-documentation/

Supplier of polymer. (2022). (Communication via e-mail).

Svenskt Vatten. (2016). *Hur renas avloppsvattnet [How to purify wastewater]*. https://www.svensktvatten.se/fakta-om-vatten/avloppsfakta/hur-renas-avloppsvattnet/

Tekniska verken. (n.d). *Rening av läkemedelsrester [Purification of pharmaceutical residues]*. https://www.tekniskaverken.se/om-oss/innovation/innovativa-projekt/rening-av-lakemedelsrester/

Tierps Energi & Miljö AB. (2020). *Implementering av fullskalig läkemedelsrening vid Tierps reningsverk [Implementation of full-scale purification of pharmaceuticals at Tierps wastewater treatment plant]*. https://www.svensktvatten.se/globalassets/avlopp-och-miljo/reningsverk-och-reningsprocesser/bestallargrupp/19-slutrapporter/tierp-energi-och-miljo-ab.pdf

Wahlberg, C., Björlenius, B., Paxéus, N. (n.d.). *Läkemedelsrester i Stockholms vattenmiljö [Pharmaceutical residues in Stockholm's aquatic environment]*. Stockholm Vatten. https://www.stockholmvattenochavfall.se/globalassets/pdf1/rapporter/avlopp/avloppsrening/lakemedelsrapport_slutrapport.pdf

Walldén, M. (2020). *Slam föreslås bara få användas i jordbruket [A suggestion of only using sludge in agriculture]*. Sveriges Natur. https://www.sverigesnatur.org/aktuellt/slam-foreslas-bara-fa-anvandas-i-jordbruket/

Westling, K. (2021a). *Läkemedelsrester och andra föroreningar – minskade utsläpp via avloppsreningsverk [Pharmaceutical residues and other contaminants – reduced effluents via wastewater treatment plants]*. Svenskt Vatten. https://www.svensktvatten.se/vattentjanster/avlopp-och-miljo/reningsverk-och-reningsprocesser/bestallargrupp-lakemedelsrester-mikroplaster-och-andra-fororeningar/lakemedelsrester-och-andra-fororeningar/

Westling, K. (2021b). *Naturvårdsverket – pågående bidragsprojekt läkemedelsrening [The Swedish Environmental Agency Protection – ongoing grant projects for purification of pharmaceutical residues]*. Svenskt Vatten. https://www.svensktvatten.se/vattentjanster/avlopp-och-miljo/reningsverk-och-reningsprocesser/bestallargrupp-lakemedelsrester-mikroplaster-och-andra-fororeningar/lakemedelsrening/

Xing, W., Ngo, H.H., Kim, S.H., Guo, W.S., Hagare, P. (2020). Adsorption and bioadsorption of granular activated carbon (GAC) for dissolved organic carbon (DOC) removal in wastewater. *Bioresource Technology, 99*(18), 8674-8678. https://doi.org/10.1016/j.biortech.2008.04.012

Zhulincarbon. (n.d.). *Powdered Activated Carbon*. https://www.activatedcarbon.net/powdered-activated-carbon

Appendix 1 – LCIA Methods

Table A.1. A brief description of the LCIA methods used in the study, i.e., CML 2001, EN 15804+A1, and ReCiPe (Sphera, (n.d.b).

Database	Description
CML 2001 (2016)	An impact assessment method which restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties. Results are grouped in midpoint categories according to common mechanisms (e.g. climate change) or commonly accepted groupings (e.g. ecotoxicity).
EN 15804+A1 (2013)	The standard EN 15804 is used to calculate environmental indicators to use in Environmental Product Declaration (EPDs). The introduction of EN 15804 as a separate group of characterization factors is meant to align more specifically to the EN 15804 standard without additional calculations done by thinkstep as is the case with the CML values.
ReCiPe (2016)	ReCiPe can be seen as a fusion of the two methodologies CML 2001 and Ecoindicator 99, taking the midpoint indicators from CML and the endpoint indicators from Ecoindicator. All mid- and endpoint indicators are available in three versions taking into account three different cultural perspectives: Individualist (I) is based on the short-term interest, undisputed impact types, and technological optimism as regards human adaptation. Uses the shortest timeframe e.g. a 20 year timeframe for global warming, GWP20 Hierarchist (H) is based on the most common policy principles with regard to the timeframe and other issues. Uses the medium timeframe e.g. a 100 year timeframe for global warming, GWP100 Egalitarian (E) is the most precautionary perspective, taking into account the longest timeframe, impact types that are not yet fully established but for which some indication is available, etc. Uses the longest timeframe e.g. a 1000 year timeframe for global warming, (GWP1000) and infinite time for ozone depletion (ODPInf)

Appendix 2 – Concentrations of Pharmaceutical Residues in Effluent Treated Wastewater from the Existing WWTP

Table B.1. Concentration of different pharmaceutical residues in the effluent wastewater at Rya WWTP (Baresel, 2020).

Substance	Concentration (ng/l)
Estrone (E1)	10
Atenolol	600
Carbamazepine	300
Citalopram	26
Diclofenac	600
Ibuprofen	100
Metoprolol	1100
Naproxen	600
Oxazepam	400
Paracetamol	20
Propranolol	100
Sertraline	40
Ciprofloxacin	5
Clarithromycin	20
Erythromycin	100
Sulfamethoxazole	100
Trimethoprim	100

Appendix 3 – Chosen Flows in GaBi

For Tables C.1-C.6, bolded text means tracked flows in GaBi, i.e., flows that can be linked to another activity. Italicized text means waste flows in GaBi and normal text means untracked flows that are not linked to another activity. Lastly, underlined text defines activities that are linked to a tracked flow.

Table C.1. Chosen flows in GaBi for all activities within the system boundary for the ozonation process.

Activity		Chosen flows and activities in GaBi
Oxygen production (VPSA)	Inflow	• **SE: electricity, production mix SE [production mix]** linked to SE: Electricity grid mix • **Heat (consumption mix, at consumer | from residential heating systems from wood) [Thermal energy]** linked to EU-28: Heat ts (residential heating systems from wood pellets)
	Outflow	• **Oxygen [renewable resources]**
Ozone production	Inflow	• **SE: electricity, production mix SE [production mix]** linked to SE: Electricity grid mix • **Heat (consumption mix, at consumer | from residential heating systems from wood) [Thermal energy]** linked to EU-28: Heat ts (residential heating systems from wood pellets) • **Oxygen [renewable resources]**
	Outflow	• **Ozone [inorganic intermediate products]**
Ozonation and other installations *(Was fixed to one)*	Inflow	• **Ozone [inorganic intermediate products]** • **SE: electricity, production mix SE [production mix]** linked to SE: Electricity grid mix • CH: treatment, sewage, to wastewater treatment, class 2 [wastewater treatment]
	Outflow	• CH: treatment, sewage, to wastewater treatment, class 3 [wastewater treatment]

Bolded text=tracked flows, normal text=untracked flows, underlined text=linked activities

Table C.2. Chosen flows in GaBi for all activities within the system boundary for the process of PAC.

Activity		Chosen flows and activities in GaBi
Production of hard coal (China)	Inflow	• **CN: hard coal supply mix [Appropriation]** linked to CN: Hard coal mix ts
	Outflow	• **CN: hard coal supply mix [Appropriation]**
Transport (China to Belgium)	Type	GLO: Container ship, 5,000 to 200,000 dwt payload capacity, ocean going ts
	Inflow	• **CN: hard coal supply mix [Appropriation]** linked to **Cargo [Others]** • **Heavy fuel oil (1.0 wt. % S) [Refinery products]** linked to EU-28: Heavy fuel oil at refinery (1.0wt.% S)
	Outflow	• **CN: hard coal supply mix [Appropriation]** linked to **Cargo [Others]**
Production (activation) of virgin PAC (Belgium)	Inflow	• **BE: electricity, production mix BE [production mix]** linked to BE: electricity grid mix ts • **CN: hard coal supply mix [Appropriation]** • **Natural gas, at consumer Belgium [Natural gas, at consumer]** linked to BE: Natural gas mix ts • Water (decarbonised, softened) [Operating materials]
	Outflow	• **Activated carbon [organic intermediate products]** • Emissions (See Table D.7 in Appendix 4)
Transport (Belgium to Rya WWTP)	Type	GLO: Truck-trailer, Euro 5, 34 – 40t gross weight / 27t payload capacity
	Inflow	• **Activated carbon [organic intermediate products]** linked to **Cargo [Others]** • **Diesel [Refinery products]** linked to EU-28: Diesel mix at refinery ts
	Outflow	• **Activated carbon [organic intermediate products]** linked to **Cargo [Others]**
Addition of PAC to nitrifying MBBR and other installations *(Was fixed to one)*	Inflow	• CH: treatment, sewage, to wastewater treatment, class 2 [wastewater treatment] • **Activated carbon [organic intermediate products]** • **SE: electricity, production mix SE [production mix]** linked to SE: Electricity grid mix
	Outflow	• **CH: treatment, sewage, to wastewater treatment, class 3 [wastewater treatment]** • **Activated carbon [organic intermediate products]**
Production of polymer for the PAC process	Inflow	• **IT: electricity, production mix IT [production mix]** linked to IT: Electricity grid mix • **Acrylic acid [Organic intermediate products]** linked to DE: Acrylic acid (Propene) ts [Organic intermediate products] • **Acrylonitrile [Organic intermediate products]** linked to RER: Acrylonitrile (AN) PlasticsEurope
	Outflow	• **Polyacrylamide [Plastics]**
Transport (Italy to Rya WWTP) (PAC process)	Type	GLO: Truck-trailer, Euro 5, 34 – 40t gross weight / 27t payload capacity
	Inflow	• **Polyacrylamide [Plastics]** linked to **Cargo [Others]** • **Diesel [Refinery products]** linked to EU-28: Diesel mix at refinery ts
	Outflow	• **Polyacrylamide [Plastics]** linked to **Cargo [Others]**
Addition of polymer to the PAC process	Inflow	• **Activated carbon [organic intermediate products]** • **Polyacrylamide [Plastics]** • **CH: treatment, sewage, to wastewater treatment, class 3 [wastewater treatment]**
	Outflow	• **Sewage sludge (wastewater processing) [Waste for disposal]** • CH: treatment, sewage, to wastewater treatment, class 3 [wastewater treatment]

Production of polymer for treatment of PAC sludge	Inflow	• **IT: electricity, production mix IT [production mix]** linked to IT: Electricity grid mix • **Acrylic acid [Organic intermediate products]** linked to DE: Acrylic acid (Propene) ts [Organic intermediate products] • **Acrylonitrile [Organic intermediate products]** linked to RER: Acrylonitrile (AN) PlasticsEurope
	Outflow	• **Polyacrylamide [Plastics]**
Transport (Italy to Rya WWTP) (treatment of PAC sludge)	Type	GLO: Truck-trailer, Euro 5, 34 – 40t gross weight / 27t payload capacity
	Inflow	• **Polyacrylamide [Plastics]** linked to **Cargo [Others]** • **Diesel [Refinery products]** linked to EU-28: Diesel mix at refinery ts
	Outflow	• **Polyacrylamide [Plastics]** linked to **Cargo [Others]**
Treatment of PAC sludge	Inflow	• **SE: electricity, production mix SE [production mix]** linked to SE: Electricity grid mix • **Polyacrylamide [Plastics]** • **Sewage sludge (wastewater processing) [Waste for disposal]**
	Outflow	• **Sewage sludge (wastewater processing) [Waste for disposal]**
Transport (Rya WWTP to Sävenäs)	Type	GLO: Truck-trailer, Euro 5, 34 – 40t gross weight / 27t payload capacity
	Inflow	• **Sewage sludge (wastewater processing) [Waste for disposal]** linked to **Cargo [Others]** • **Diesel [Refinery products]** linked to EU-28: Diesel mix at refinery ts
	Outflow	• **Sewage sludge (wastewater processing) [Waste for disposal]** linked to **Cargo [Others]**
Incineration	Inflow	• **Sewage sludge (wastewater processing) [Waste for disposal]**
	Outflow	• **Heat (consumption mix, at consumer | from residential heating systems from wood) [Thermal energy]** linked to EU-28: Heat ts (residential heating systems from wood pellets) • **Sewage sludge (wastewater processing) [Waste for disposal]** linked to DE: Municipal waste water treatment (sludge incineration) ts [wastewater treatment]

Bolded text=tracked flows, normal text=untracked flows, underlined text=linked activities

Table C.3. Change of flows in GaBi for the sensitivity analyses of the PAC process: Wind power, Activation in China, Activation in China with wind power, and Renewable PAC (coconut shells).

Sensitivity analyses	Information	Chosen flows and activities in GaBi for sensitivity analyses
Wind power	Based on the main case but all electricity mixes are replaced by wind power.	• **Electricity from wind power [System-dependent]** linked to BE: Electricity from wind power ts/SE: Electricity from wind power ts/IT: Electricity from wind power ts
Activation in China	Based on the main case but both the production and activation occur in China.	Production (activation) of Virgin PAC (China): • **CN: hard coal supply mix [Appropriation]** linked to CN: Hard coal mix ts • **CN: electricity, production mix CN [production mix]** linked to CN: Electricity grid mix ts • **Natural gas, at consumer China [Natural gas, at consumer]** linked to CN: Natural gas mix ts Transport (Shanghai port to Gothenburg port): GLO: Container ship, 5,000 to 200,000 dwt payload capacity, ocean going ts • **Activated carbon [Organic intermediate products]** linked to **Cargo [Others]** inflow/outflow • **Heavy fuel oil (1.0 wt. % S) [Refinery products]** linked to EU-28: Heavy fuel oil at refinery (1.0wt.% S) Shift from ship to truck: • **Activated carbon [Organic intermediate products]** inflow/outflow Transport (Gothenburg port to Rya WWTP): GLO: Truck-trailer, Euro 5, 34 – 40t gross weight / 27t payload capacity • **Activated carbon [Organic intermediate products]** linked to **Cargo [Others]** inflow/outflow • **Diesel [Refinery products]** linked to EU-28: Diesel mix at refinery ts
Activation in China with wind power	Based on activation in China but all electricity mixes are replaced by wind power.	• **Electricity from wind power [System-dependent]** linked to CN: Electricity from wind power ts/SE: Electricity from wind power ts/ IT: Electricity from wind power ts
Renewable PAC (coconut shells)	Based on activation in China, hard coal is replaced by coconut shells.	• Coconuts with shell (1.5 kg DM per piece, 50% H2O) [Renewable primary products] • Excluding the manually added emissions for production (activation) of PAC, see Table D.7 in Appendix 4

Bolded text=tracked flows, normal text=untracked flows, underlined text=linked activities

Table C.4. Chosen flows in GaBi for all activities within the system boundary for the process of GAC.

Activity		Chosen flows and activities in GaBi
Production of hard coal (China)	Inflow	• **CN: hard coal supply mix [Appropriation]** linked to CN: Hard coal mix ts
	Outflow	• **CN: hard coal supply mix [Appropriation]**
Transport (China to Belgium)	Type	GLO: Container ship, 5,000 to 200,000 dwt payload capacity, ocean going ts
	Inflow	• **CN: hard coal supply mix [Appropriation]** linked to **Cargo [Others]** • **Heavy fuel oil (1.0 wt. % S) [Refinery products]** linked to EU-28: Heavy fuel oil at refinery (1.0wt.% S)
	Outflow	• **CN: hard coal supply mix [Appropriation]** linked to **Cargo [Others]**
Production (activation) of virgin GAC (Belgium)	Inflow	• **BE: electricity, production mix BE [production mix]** linked to BE: electricity grid mix ts • **CN: hard coal supply mix [Appropriation]** • **Natural gas, at consumer Belgium [Natural gas, at consumer]** linked to BE: Natural gas mix ts • Water (decarbonised, softened) [Operating materials]
	Outflow	• **Activated carbon [organic intermediate products]** • Emissions (See Table D.7 in Appendix 4)
Transport (Belgium to Rya WWTP)	Type	GLO: Truck-trailer, Euro 5, 34 – 40t gross weight / 27t payload capacity
	Inflow	• **Activated carbon [organic intermediate products]** linked to **Cargo [Others]** • **Diesel [Refinery products]** linked to EU-28: Diesel mix at refinery ts
	Outflow	• **Activated carbon [organic intermediate products]** linked to **Cargo [Others]**
GAC process and other installations (Rya WWTP, Sweden) *(Was fixed to one)*	Inflow	• **Activated carbon [organic intermediate products]** • **Recycled GAC [non-renewable resources]** • **SE: electricity, production mix SE [production mix]** linked to SE: Electricity grid mix ts • CH: treatment, sewage, to wastewater treatment, class 2 [wastewater treatment]
	Outflow	• **Activated carbon [organic intermediate products]** • CH: treatment, sewage, to wastewater treatment, class 3 [wastewater treatment]
Transport (GAC to regeneration in Belgium)	Type	GLO: Truck-trailer, Euro 5, 34 – 40t gross weight / 27t payload capacity
	Inflow	• **Activated carbon [organic intermediate products]** linked to Cargo [Others] • **Diesel [Refinery products]** linked to EU-28: Diesel mix at refinery ts
	Outflow	• **Activated carbon [organic intermediate products]** linked to Cargo [Others]
Regeneration (Belgium)	Inflow	• **Activated carbon [organic intermediate products]** • **BE: electricity, production mix BE [production mix]** linked to BE: Electricity grid mix ts • **Natural gas, at consumer Belgium [Natural gas, at consumer]** linked to BE: Natural gas mix ts • Water (decarbonised, softened) [Operating materials]
	Outflow	• **Recycled GAC [non-renewable resources]** • *Activated carbon (charged) [Hazardous waste for recovery]* • Emissions (See Table D.8 in Appendix 4)
Transport (regenerated GAC back to Rya WWTP)	Type	GLO: Truck-trailer, Euro 5, 34 – 40t gross weight / 27t payload capacity
	Inflow	• **Recycled GAC [non-renewable resources]** linked to **Cargo [Others]** • **Diesel [Refinery products]** linked to EU-28: Diesel mix at refinery ts

	Outflow	• **Recycled GAC [non-renewable resources]** linked to **Cargo [Others]**

Bolded text=tracked flows, italicized text=waste flows, normal text=untracked flows, underlined text=linked activities

Table C.5. Change of flows in GaBi for the sensitivity analyses of the GAC process: Wind power, Activation in China, Activation in China with wind power, Main case accounting for credited heat from regeneration, Regeneration plant at Rya WWTP, Credited heat from regeneration plant at Rya WWTP, Credited heat from regeneration plant at Rya WWTP with natural gas, Renewable GAC (coconut shells), 30 000 bed volumes, and 10 000 bed volumes.

Sensitivity analyses	Information	Chosen flows and activities in GaBi for the sensitivity analyses
Wind power	Based on the main case but all electricity mixes are replaced by wind power.	• **Electricity from wind power [System-dependent]** linked to BE: Electricity from wind power ts/SE: Electricity from wind power ts
Activation in China	Based on the main case but both the production and activation occur in China.	Production (activation) of Virgin GAC (China): • **CN: hard coal supply mix [Appropriation]** linked to CN: Hard coal mix ts • **CN: electricity, production mix CN [production mix]** linked to CN: Electricity grid mix ts • **Natural gas, at consumer China [Natural gas, at consumer]** linked to CN: Natural gas mix ts Transport (Shanghai port to Gothenburg port): GLO: Container ship, 5,000 to 200,000 dwt payload capacity, ocean going ts • **Activated carbon [Organic intermediate products]** linked to **Cargo [Others]** inflow/outflow • **Heavy fuel oil (1.0 wt. % S) [Refinery products]** linked to EU-28: Heavy fuel oil at refinery (1.0wt.% S) Shift from ship to truck: • **Activated carbon [Organic intermediate products]** inflow/outflow Transport (Gothenburg port to Rya WWTP): GLO: Truck-trailer, Euro 5, 34 – 40t gross weight / 27t payload capacity • **Activated carbon [Organic intermediate products]** linked to **Cargo [Others]** inflow/outflow • **Diesel [Refinery products]** linked to EU-28: Diesel mix at refinery ts
Activation in China with wind power	Based on activation in China but all electricity mixes are replaced by wind power.	• **Electricity from wind power [System-dependent]** linked to CN: Electricity from wind power ts/BE: Electricity from wind power ts/SE: Electricity from wind power ts
Main case accounting for credited heat from regeneration	Based on the main case but heat is added as a negative inflow to regeneration.	• **Heat (consumption mix, at consumer | from residential heating systems from wood) [Thermal energy]** linked to EU-28: Heat ts (residential heating systems from wood pellets)
Regeneration plant at Rya WWTP	Based on the main case but all transports to and from regeneration are removed. The flows connected to regeneration are switched to occur in Sweden. Natural gas at regeneration is replaced by biogas and the loss of biogas as vehicle fuel is replaced by diesel.	• **SE: electricity, production mix SE [production mix]** linked to SE: Electricity grid mix ts • **Diesel [Refinery products]** linked to EU-28: Diesel mix at refinery ts

Credited heat from regeneration plant at Rya WWTP	Based on regeneration plant at Rya WWTP but heat is added as a negative inflow to regeneration.	• **Heat consumption mix, at consumer | from residential heating systems from wood [Thermal energy]** linked to EU-28 Heat ts (residential heating systems from wood pellets)
Credited heat from regeneration plant at Rya WWTP with natural gas	Based on the main case but all transports to and from regeneration are removed. The flows connected to regeneration are switched to occur in Sweden. Heat is added as a negative inflow to regeneration.	• **SE: electricity, production mix SE [production mix]** linked to SE: Electricity grid mix ts • **Heat consumption mix, at consumer | from residential heating systems from wood [Thermal energy]** linked to EU-28 Heat ts (residential heating systems from wood pellets)
Renewable GAC (coconut shells)	Based on activation in China, hard coal is replaced by coconut shells.	• Coconuts with shell (1.5 kg DM per piece, 50% H2O) [Renewable primary products] • Excluding the manually added emissions for production (activation) of GAC and regeneration, see Table D.7 and Table D.8 in Appendix 4
30 000 bed volumes	Based on the main case but all flows are divided with the ratio (30 000/20 000).	-
10 000 bed volumes	Based on the main case but all flows are divided with the ratio (10 000/20 000).	-

Bolded text=tracked flows, normal text=untracked flows, underlined text=linked activities

Table C.6. Chosen flows in GaBi for all activities within the system boundary for the existing sludge treatment.

Activity		Chosen flows and activities in GaBi
Primary settling *(Was fixed to one)*	Inflow	• CH: treatment, sewage, to wastewater treatment, class 3 [wastewater treatment] • **Sewage sludge (wastewater processing) [Waste for disposal]**
	Outflow	• CH: treatment, sewage, to wastewater treatment, class 3 [wastewater treatment]
Polymer production	Inflow	• **IT: electricity, production mix IT [production mix]** linked to IT: Electricity grid mix • **Acrylic acid [Organic intermediate products]** linked to DE: Acrylic acid (Propene) ts [Organic intermediate products] • **Acrylonitrile [Organic intermediate products]** linked to RER: Acrylonitrile (AN) PlasticsEurope
	Outflow	• **Polyacrylamide [Plastics]**
Transport (Italy to Rya WWTP)	Type	GLO: Truck-trailer, Euro 5, 34 - 40t gross weight / 27t payload capacity
	Inflow	• **Polyacrylamide [Plastics]** linked to **Cargo [Others]** • **Diesel [Refinery products]** linked to EU-28: Diesel mix at refinery ts
	Outflow	• **Polyacrylamide [Plastics]** linked to **Cargo [Others]**
Existing sludge treatment	Inflow	• **Polyacrylamide [Plastics]** • **Sewage sludge (wastewater processing) [Waste for disposal]** • **SE: electricity, production mix SE [production mix]** linked to SE: Electricity grid mix ts
	Outflow	• *Sludge for use as fertilizer [Waste for recovery]*

Bolded text=tracked flows, italicized text=waste flows, normal text=untracked flows, underlined text=linked activities

Appendix 4 – Inventory Data

Table D.1. Flows of wastewater per year and m^3 for the ozonation process. The values in m^3 constitute the basis for the calculations in GaBi for the ozonation process.

Ozonation process

Yearly flows of wastewater					Flows per m3 wastewater				
	Oxygen production (VPSA)		Unit			Oxygen production (VPSA)		Unit	
	Inflow	Outflow				Inflow	Outflow		
Electricity	7750000		kWh/year		Electricity	0,060233061		kWh/m3	
Heat		1076000	kWh/year		Heat		0,00836	kWh/m3	
Oxygen		12807120	kg/year		Oxygen		0,09954	kg/m3	
	Ozone production		Unit	Including heat pumps for ozone production		Ozone production		Unit	Including heat pumps for ozone production
	Inflow	Outflow				Inflow	Outflow		
Electricity	10125000		kWh/year	10940000	Electricity	0,078691579		kWh/m3	0,085025766
Oxygen	12807120		kg/year		Oxygen	0,099537037		kg/m3	
Heat		10354000	kWh/year		Heat		0,08047	kWh/m3	
Ozone		1287720	kg/year		Ozone		0,01001	kg/m3	
	Ozonation and other installations		Unit			Ozonation and other installations		Unit	
	Inflow	Outflow				Inflow	Outflow		
Ozone	1287720		kg/year		Ozone	0,01000817		kg/m3	
Wastewater	128666880	128666880	m3/year		Wastewater	1	1	m3	
Electricity	3510000		kWh/year		Electricity	0,027279748		kWh/m3	
	Heatpumps for ozone production		Unit			Heatpumps for ozone production		Unit	
	Inflow	Outflow				Inflow	Outflow		
Electricity	815000		kWh/year		Electricity	0,006334186		kWh/m3	

	Price	Unit
Electricity	0,8	kr/kWh

Reference: Ozonation report from Sweco to Gryaab, 2020

The price of electricity in kr/kWh was used to calculate the total electricity in kWh/year. The cost for the total electricity demand in kr/year was known and the total electriciy (kWh/year) could thus be calculated by dividing the cost in kr/year with the price of electricity in kr/kWh.

Table D.2. Flows of wastewater per year and m^3 for the sensitivity analysis with wind power for the ozonation process. The values in m^3 constitute the basis for the calculations in GaBi for the ozonation process with wind power.

Sensitivity analysis for the ozonation process

				Sensitivity analysis							
				Wind power							
	Electricity	Unit (yearly)			Electricity	Unit (m3)					
Oxygen production	7750000	kWh/year		Oxygen production	0,06023306	kWh/m3					
Ozone production	10940000	kWh/year		Ozone production	0,08502577	kWh/m3					
Ozonation and other installations	3510000	kWh/year		Ozonation and other installations	0,02727975	kWh/m3					

Table D.3. Flows of wastewater per year and m^3 for the PAC process. The values in m^3 constitute the basis for the calculations in GaBi for the PAC process.

PAC process												
Yearly flows of wastewater								Flows per m3 wastewater				
	Production (activation) of virgin PAC (Belgium)		Unit						Production (activation) of virgin PAC (Belgium)		Unit	
	Inflow	Outflow							Inflow	Outflow		
Electricity industrial furnace	3556720		kWh/year					Electricity industrial furnace	0,027642856		kWh/m3	
Hard coal (3 kg)	5799000		kg/year					Hard coal	0,045069873		kg/m3	
	25708900		MJ/year						0,199809772		MJ/m3	
Heat (natural gas)	7141932,42		kWh/year					Heat (natural gas)	0,055507155		kWh/m3	
Softened water (from decarbonized water)	24027190		kg/year					Softened water (from decarbonized water)	0,186739509		kg/m3	
Virgin PAC		1933000	kg/year					Virgin PAC		0,015023291	kg/m3	
	Transport (b-c) container ship	Unit										
Nautical miles (nm)	1,852	km										
	11908	nm										
Distance	22053,616	km										
Amount	1											
Total distance	22053,616	km										
	Transport (d-e) pre-study 40 ton payload	Unit		Diesel consumption (transport d-e) calculated based on pre-study and GaBi values		Unit			Transport (d-e) distance in GaBi	Unit		
Distance	1250	km		Payload truck	27000	kg		Ratio	1,81150847			
Amount	48			Amount	71,59259259			Distance	690,0326554	km		
Total distance	60000	km/year		Total distance	89490,74074	km						
					0,3	l/km						
				Diesel	0,246	kg/km						
				Density	0,82	kg/dm3						
				Total diesel consumption	22014,72222	kg						

	Addition of PAC to nitrifying MBBR and other installations		Unit
	Inflow	Outflow	
Wastewater	128666880	128666880	m3/year
PAC (activated carbon)	1933000	1933000	kg/year
Electricity other installations	1000000		kWh/year

	Production of polymer for the PAC process		Unit
	Inflow	Outflow	
Electricity	44100		kWh/year
Acrylonitrile (50%)	73500		kg/year
Acrylic acid (50%)	73500		kg/year
Polyacrylamide		147000	kg/year

	Transport (h-i) pre-study 40 ton payload	Unit
Distance	2000	km
Amount	4	
Total distance	8000	km/year

	Diesel consumption (transport h-i) calculated based on pre-study and		Unit
Payload truck	27000		kg
Amount	5,444444444		
Total distance	10888,88889		km
	0,3		l/km
Diesel	0,246		kg/km
Density	0,82		kg/dm3
Total diesel consumption	2678,666667		kg

	Addition of PAC to nitrifying MBBR and other installations		Unit
	Inflow	Outflow	
Wastewater	1	1	m3
PAC (activated carbon)	0,015023291	0,015023291	kg/m3
Electricity other installations	0,007772008		kWh/m3

	Production of polymer for the PAC process		Unit
	Inflow	Outflow	
Electricity	0,000342746		kWh/m3
Acrylonitrile (50%)	0,000571243		kg/m3
Acrylic acid (50%)	0,000571243		kg/m3
Polyacrylamide		0,001142485	kg/m3

	Transport (h-i) distance in GaBi	Unit
Ratio	1,81150847	
Distance	1104,052249	km

	Addition of polymer to the PAC process		Unit
	Inflow	Outflow	
Wastewater	128666880	128666880	m3/year
PAC (activated carbon)	1933000		kg/year
Polyacrylamide	147000		kg/year
PAC sludge		21000000	kg/year

	Addition of polymer to the PAC process		Unit
	Inflow	Outflow	
Wastewater	1	1	m3
PAC (activated carbon)	0,015023291		kg/m3
Polyacrylamide	0,001142485		kg/m3
PAC sludge		0,163212165	kg/m3

	Production of polymer for treatment of PAC sludge		Unit
	Inflow	Outflow	
Electricity	60165		kWh/year
Acrylonitrile (50%)	100275		
Acrylic acid (50%)	100275		
Polyacrylamide		200550	kg/year

	Production of polymer for treatment of PAC sludge		Unit
	Inflow	Outflow	
Electricity	0,000467603		kWh/m3
Acrylonitrile (50%)	0,000779338		kg/m3
Acrylic acid (50%)	0,000779338		kg/m3
Polyacrylamide		0,001558676	kg/m3

	Transport (l-m) pre-study 40 ton payload	Unit
Distance	2000	km
Amount	4	
Total distance	8000	km/year

	Diesel consumption (l-m) calculated based on pre-study and GaBi values		Unit
Payload truck		27000	kg
Amount		7,427777778	
Total distance		14855,55556	km
		0,3	l/km
Diesel		0,246	kg/km
Density		0,82	kg/dm3
Total diesel consumption		3654,466667	kg

	Transport (l-m) distance in GaBi	Unit
Ratio	1,81150847	
Distance	1104,052249	km

	Treatment of PAC sludge		Unit
	Inflow	Outflow	
Electricity	462000		kWh/year
PAC sludge	21000000	21000000	kg/year
Polyacrylamide	200550		kg/year

	Treatment of PAC sludge		Unit
	Inflow	Outflow	
Electricity	0,003590668		kWh/m3
PAC sludge	0,163212165	0,163212165	kg/m3
Polyacrylamide	0,001558676		kg/m3

	Transport (o-p) pre-study 40 ton payload	Unit
Distance	30	km
Amount	525	
Total distance	15750	km/year

	Diesel consumption (o-p) calculated based on pre-study and GaBi values	Unit
Payload truck	27000	kg
Amount	777,7777778	
Total distance	23333,33333	km
Diesel	0,3	l/km
	0,246	kg/km
Density	0,82	kg/dm3
Total diesel consumption	5740	kg

	Transport (o-p) distance in GaBi	Unit
Ratio	1,81150847	
Distance	16,56078373	km

	Incineration		Unit
	Inflow	Outflow	
Heat		5444444	kWh/year
PAC sludge	21000000		kg/year

	Incineration		Unit
	Inflow	Outflow	
Heat		0,042314261	kWh/m3
PAC sludge	0,163212165		kg/m3

Table D.4. Flows of wastewater per year and m^3 for the sensitivity analyses of the PAC process: Wind power, Activation in China, Activation in China with wind power, and Renewable PAC (coconut shells). The values in m^3 constitute the basis for calculations in GaBi for the sensitivity analyses of the PAC process.

Sensitivity analyses for the PAC process						
Sensitivity analyses						
				Wind power		
	Electricity	Unit (yearly)		Electricity	Unit (m3)	
Activation in Belgium	3556720	kWh/year	Activation in Belgium	0,027642856	kWh/m3	
Activation in China	3556720	kWh/year	Activation in China	0,027642856	kWh/m3	
Other installations in Sweden	1000000	kWh/year	Other installations in Sweden	0,007772008	kWh/m3	

Activation in China												
Production (activation) of virgin PAC												
	Inflow	Outflow	Unit (yearly)			Inflow	Outflow	Unit (m3)				
Electricity industrial furnace	3556720		kWh/year		Electricity industrial furnace	0,027642856		kWh/m3				
Hard coal (3kg)	5799000		kg/year		Hard coal	0,045069873		kg/m3				
Heat (natural gas)	25708900		MJ/year		Heat (natural gas)	0,199809772		MJ/m3				
	7141932,42		kWh/year			0,055507155		kWh/m3				
Softened water (from decarbonized water)	24027190		kg/year		Softened water (from decarbonized water)	0,186739509		kg/m3				
Virgin PAC		1933000	kg/year		Virgin PAC		0,015023291	kg/m3				
	Transport (container ship) from Shanghai port to Gothenburg port	Unit										
Distance	26444	km										
Amount	1											
Total distance	26444	km										
	Transport (truck) from Gothenburg port to Gryaab pre-study 40 ton payload	Unit					Diesel consumption (transport truck) from Gothenburg port to Gryaab) calculated based on pre-study and GaBi values	Unit		Transport (transport truck) distance in GaBi	Unit	
Distance	7	km			Payload truck		27000	kg	Ratio	1,81150847		
Amount	8,05				Amount		11,92592593		Distance	3,86418287	km	
Total distance	56,35	km			Total distance		83,48148148	km				
					Diesel		0,3	l/km				
							0,246	kg/km				
					Density		0,82	kg/dm3				
					Total diesel consumption		20,53644444	kg				

Renewable PAC (coconut shells)																		
Production (activation) of virgin PAC																		
	Inflow	Outflow		Unit (yearly)				Inflow	Outflow	Unit (m3)								
Electricity industrial	3556720			kWh/year			Electricity industrial furnace	0,027642856		kWh/m3								
Coconut shell	5799000			kg/year			Coconut shell	0,045069873		kg/m3								
	25708900			MJ/year			Heat (natural gas)	0,199809772		MJ/m3								
Heat (natural gas)	7141932,42			kWh/year				0,055507155		kWh/m3								
Softened water (from decarbonized water)	24027190			kg/year			Softened water (from decarbonized water)	0,186739509		kg/m3								
Virgin GAC		1933000		kg/year			Virgin GAC		0,01502	kg/m3								
	Transport (container ship) from Shanghai port to Gothenburg port	Unit																
Distance	26444	km																
Amount	1																	
Total distance	26444	km																
	Transport (truck) from Gothenburg port to Gryaab pre-study 40 ton payload	Unit						Diesel consumption (transport truck) from Gothenburg port to Gryaab) calculated based on pre-study and GaBi values	Unit						Transport (transport truck) distance in GaBi	Unit	
Distance	7	km					Payload truck	27000	kg				Ratio	1,81150847		
Amount	8,05						Amount	11,92592593					Distance	3,86418287	km	
Total distance	56,35	km					Total distance	83,48148148	km							
							Diesel	0,3	l/km							
								0,246	kg/km							
							Density	0,82	kg/dm3							
							Total diesel consumption	20,53644444	kg							

Table D.5. Flows of wastewater per year and m^3 for the GAC process. The values in m^3 constitute the basis for the calculations in GaBi for the GAC process.

GAC process							
Yearly flows of wastewater				Flows per m3 wastewater			
	Production (activation) of virgin GAC (Belgium)		Unit		Production (activation) of virgin GAC (Belgium)		Unit
	Inflow	Outflow			Inflow	Outflow	
Electricity industrial furnace	592480		kWh/year	Electricity industrial furnace	0,004604759		kWh/m3
Hard coal (3kg)	966000		kg/year	Hard coal	0,00750776		kg/m3
	4282600		MJ/year		0,033284401		MJ/m3
Heat (natural gas)	1189706,28		kWh/year	Heat (natural gas)	0,009246407		kWh/m3
Softened water (from decarbonized water)	4002460		kg/year	Softened water (from decarbonized water)	0,03110715		kg/m3
Virgin GAC		322000	kg/year	Virgin GAC		0,002502587	kg/m3
	Transport (b-c) container ship		Unit				
Nautical miles (nm)	1,852		km				
	11908		nm				
Distance	22053,616		km				
Amount	1						
Total distance	22053,616		km				

	Transport (d-e) pre-study 40 ton payload	Unit
Distance	1250	km
Amount	8	
Total distance	10000	km/year

		Diesel consumption (transport d-e) calculated based on pre-study and GaBi values	Unit
Payload truck	27000	kg	
Amount	11,92592593		
Total distance	14907,40741	km	
	0,3	l/km	
Diesel	0,246	kg/km	
Density	0,82	kg/dm3	
Total diesel consumption	3667,222222	kg	

	Transport (d-e) distance in GaBi	Unit
Ratio	1,81150847	
Distance	690,0326554	km

	GAC process and other installations		Unit
	Inflow	Outflow	
Virgin GAC	322000		kg/year
Recycled GAC	2878000		kg/year
Electricity other installations	3000000		kWh/year
Wastewater	128666880	128666880	m3/year
GAC for regeneration		5800000	kg/year

	GAC process and other installations		Unit
	Inflow	Outflow	
Virgin GAC	0,002502587		kg/m3
Recycled GAC	0,022367839		kg/m3
Electricity other installations	0,023316024		kWh/m3
Wastewater	1	1	m3
GAC for regeneration		0,045077645	kg/m3

	Transport (g-h) pre-study 40 ton payload	Unit
Distance	1250	km
Amount	145	
Total distance	181250	km/year

Diesel consumption (transport g-h) calculated based on pre-study and GaBi values		Unit
Payload truck	27000	kg
Amount	214,8148148	
Total distance	268518,5185	km
	0,3	l/km
Diesel	0,246	kg/km
Density	0,82	kg/dm3
Total diesel consumption	66055,55556	kg

Ratio	1,81150847	
Distance	690,0326554	km

	Regeneration 20000 bed volumes (Belgium)		Unit
	Inflow	Outflow	
Activated carbon for regeneration	5800000		kg/year
	4,93		MJ/0,9 kg regenerated activated carbon
	1,369554		kWh/ 0,9 regenerated activated carbon
Natural gas	3941576,412		kWh/year
	0,61		kWh/0,9 kg regenerated activated carbon
Electricity	1755580		kWh/year
	4,47		kg/0,9 kg regenerated activated carbon
Softened water	12864660		kg/year
Lost of GAC		322000	kg/year
GAC transported back to Rya WWTP		2878000	kg/year

	Regeneration 20000 bed volumes (Belgium)		Unit
	Inflow	Outflow	
Activated carbon for regeneration	0,045077645		kg/m3
Natural gas	0,030633963		kWh/m3
Electricity	0,013644382		kWh/m3
Softened water	0,099984238		kg/m3
Lost of GAC		0,002502587	kg/m3
GAC transported back to Rya WWTP		0,022367839	kg/m3

	Transport (j-k) pre-study 40 ton payload	Unit			Diesel consumption (transport j-k) calculated based on pre-study and GaBi values		Unit			Transport (j-k) distance in GaBi	Unit
Distance	1250	km			Payload truck	27000	kg		Ratio	1,81150847	
Amount	71,175				Amount	106,5925926			Distance	690,0326554	km
Total distance	88968,75	km/year			Total distance	133240,7407	km				
						0,3	l/km				
					Diesel	0,246	kg/km				
					Density	0,82	kg/dm3				
					Total diesel consumption	32777,22222	kg				

Table D.6. Flows of wastewater per year and m^3 for the sensitivity analyses of the GAC process: Wind power, Activation in China, Activation in China with wind power, Main case accounting for credited heat from regeneration, Regeneration plant at Rya WWTP, Credited heat from regeneration plant at Rya WWTP, Credited heat from regeneration plant at Rya WWTP with natural gas, Renewable GAC (coconut shells), 30 000 bed volumes, and 10 000 bed volumes. The values in m^3 constitute the basis for calculations in GaBi for the sensitivity analyses of the GAC process.

Sensitivity analyses for the GAC process						
	Sensitivity analyses					
	Wind power					
	Electricity	Unit (yearly)		Electricity	Unit (m3)	
Activation in Belgium	592480	kWh/year	Activation in Belgium	0,004604759	kWh/m3	
Activation in China	592480	kWh/year	Activation in China	0,004604759	kWh/m3	
Other installations in Sweden	3000000	kWh/year	Other installations in Sweden	0,023316024	kWh/m3	
Regeneration in Belgium	1755580	kWh/year	Regeneration in Belgium	0,013644382	kWh/m3	

Activation in China																		
	Production (activation) of virgin GAC																	
	Inflow	Outflow	Unit (yearly)			Inflow	Outflow	Unit (m3)										
Electricity industrial furnace	592480		kWh/year			Electricity industrial furnace	0,004604759		kWh/m3									
Hard coal (3kg)	966000		kg/year			Hard coal	0,00750776		kg/m3									
Heat (natural gas)	4282600		MJ/year			Heat (natural gas)	0,033284401		MJ/m3									
	1189706,28		kWh/year				0,009246407		kWh/m3									
Softened water (from decarbonized water)	4002460		kg/year			Softened water (from decarbonized	0,03110715		kg/m3									
Virgin GAC		322000	kg/year			Virgin GAC		0,002502587	kg/m3									
	Transport (d-e) container ship from Shanghai port to Gothenburg port	Unit																
Distance	26444	km																
Amount	1																	
Total distance	26444	km																
	Transport (d-e, truck from Gothenburg port to Gryaab) pre-study 40 ton payload	Unit					Diesel consumption (transport d-e truck from Gothenburg port to Gryaab) calculated based on pre-study and GaBi values	Unit						Transport (d-e) distance in GaBi	Unit			
Distance	7	km				Payload truck	27000	kg			Ratio	1,81150847						
Amount	8,05					Amount	11,92592593				Distance	3,86418287	km					
Total distance	56,35	km				Total distance	83,48148148	km										
						Diesel	0,3	l/km										
							0,246	kg/km										
						Density	0,82	kg/dm3										
						Total diesel consumption	20,53644444	kg										

Regeneration plant at Rya WWTP

	Inflow	Outflow	Unit (yearly)		Inflow	Outflow	Unit (m3)
Activated carbon for regeneration	5800000		kg/year	Activated carbon for regeneration	0,045077645		kg/m3
Diesel (replacement fuel due to loss of biogas)	4368580,523		kWh/year	Diesel (replacement fuel due to loss of biogas)	0,033952642		kWh/m3
Electricity	1755580		kWh/year	Electricity	0,013644382		kWh/m3
Lost of GAC		322000	kg/year	Lost of GAC		0,00250259	kg/m3
Recycled GAC		2878000	kg/year	Recycled GAC		0,02236784	kg/m3

1 litre of diesel contains 9,8kWh
-->
9,8(kWh/litre)/0,82(kg/litre)=12kWh/kg

Natural gas = 13,3kWh/kg

https://www.energigas.se/fakta-om-gas/biogas/faq-om-biogas/vad-ar-energiinnehallet-i-naturgas-biogas-och-fordonsgas/

Credited heat from regeneration plant at Rya WWTP (similar heat is generated in Belgium for the main case accounting for credited heat from regeneration)

	Inflow	Outflow	Unit (yearly)		Inflow	Outflow	Unit (m3)
Activated carbon for regeneration	5800000		kg/year	Activated carbon for regeneration	0,045077645		kg/m3
Diesel (replacement fuel due to loss of biogas)	4368580,523		kWh/year	Diesel (replacement fuel due to loss of biogas)	0,033952642		kWh/m3
Electricity	1755580		kWh/year	Electricity	0,013644382		kWh/m3
Lost of GAC		322000	kg/year	Lost of GAC		0,00250259	kg/m3
GAC transported back to Rya WWTP		2878000	kg/year	GAC transported back to Rya WWTP		0,02236784	kg/m3
Heat generated		3900000	kWh/year	Heat generated		0,03031083	kWh/m3

Credited heat from regeneration plant at Rya WWTP with natural gas for regeneration instead of biogas (no need for substitution of diesel due to loss of biogas)

	Inflow	Outflow	Unit (yearly)		Inflow	Outflow	Unit (m3)
Activated carbon for regeneration	5800000		kg/year	Activated carbon for regeneration	0,045077645		kg/m3
Natural gas (used in regeneration, all biogas for fuel)	3941576,412		kWh/year	Natural gas (used in regeneration, all biogas for fuel)	0,030633963		kWh/m3
Electricity	1755580		kWh/year	Electricity	0,013644382		kWh/m3
Lost of GAC		322000	kg/year	Lost of GAC		0,00250259	kg/m3
GAC transported back to Rya WWTP		2878000	kg/year	GAC transported back to Rya WWTP		0,02236784	kg/m3
Heat generated		3900000	kWh/year	Heat generated		0,03031083	kWh/m3

Biogas= 13 kWh/kg

Natural gas = 13,3kWh/kg

https://www.energigas.se/fakta-om-gas/biogas/faq-om-biogas/vad-ar-energiinnehallet-i-naturgas-biogas-och-fordonsgas/

Renewable GAC (coconut shells)																
Production (activation) of virgin GAC																
	Inflow	Outflow		Unit (yearly)				Inflow	Outflow	Unit (m3)						
Electricity industrial furnace	592480			kWh/year			Electricity industrial furnace	0,004604759		kWh/m3						
Coconut shell	966000			kg/year			Coconut shell	0,00750776		kg/m3						
	4282600			MJ/year				0,033284401		MJ/m3						
Heat (natural gas)	1189706,28			kWh/year			Heat (natural gas)	0,009246407		kWh/m3						
Softened water (from decarbonized water)	4002460			kg/year			Softened water (from decarbonized water)	0,03110715		kg/m3						
Virgin GAC		322000		kg/year			Virgin GAC		0,00250259	kg/m3						
	Transport (d-e) container ship from Shanghai port to Gothenburg port	Unit														
Distance	26444	km														
Amount	1															
Total distance	26444	km														
	Transport (d-e, truck from Gothenburg port to Gryaab) pre-study 40 ton payload	Unit						Diesel consumption (transport d-e truck from Gothenburg port to Gryaab) calculated based on pre-study and GaBi values	Unit				Transport (d-e) distance in GaBi	Unit		
Distance	7	km					Payload truck	27000	kg			Ratio	1,81150847			
Amount	8,05						Amount	11,92592593				Distance	3,86418287	km		
Total distance	56,35	km					Total distance	83,48148148	km							
							Diesel	0,3	l/km							
								0,246	kg/km							
							Density	0,82	kg/dm3							
							Total diesel	20,53644444	kg							

30000 bed volumes

Production (activation) of virgin GAC (Belgium)

	Inflow	Outflow	Unit (yearly)
Electricity industrial furnace	394986,6667		kWh/year
Hard coal	644000		kg/year
	2855066,667		MJ/year
Heat (natural gas)	793137,52		kWh/year
Softened water (from decarbonized water)	2668306,667		kg/year
Virgin GAC		214666,6667	kg/year

	Inflow	Outflow	Unit (m3)
Electricity industrial furnace	0,003069839		kWh/m3
Hard coal	0,005005173		kg/m3
	0,022189601		MJ/m3
Heat (natural gas)	0,006164271		kWh/m3
Softened water (from decarbonized water)	0,0207381		kg/m3
Virgin GAC		0,0016684	kg/m3

	Transport (b-c) container	Unit
Nautical miles (nm)	1,852	km
Distance	11908	nm
	22053,616	km
Amount	1	
Total distance	22053,616	km

	Transport (d-e) pre-study fuel consumption	Unit
Distance	1250	km
Amount	5	
Total distance	6250	km

	Diesel consumption (transport d-e) calculated based on pre-study and GaBi values	Unit
Payload truck	27000	kg
Amount	7,950617284	
Total distance	9938,271605	km
Diesel	0,3	l/km
	0,246	kg/km
Density	0,82	kg/dm3
Total diesel	2444,814815	kg

	Transport (d-e) distance in GaBi	Unit
Ratio	1,81150847	
Distance	690,0326554	km

GAC process and other installations

	Inflow	Outflow	Unit (yearly)
Virgin GAC	214666,6667		kg/year
Recycled GAC	1918666,667		kg/year
Electricity other installations	2000000		kWh/year
Wastewater	128666880	128666880	m3/year
GAC for regeneration		3866666,667	kg/year

	Inflow	Outflow	Unit (m3)
Virgin GAC	0,001668391		kg/m3
Recycled GAC	0,014911892		kg/m3
Electricity other installations	0,015544016		kWh/m3
Wastewater	1	1	m3
GAC for regeneration		0,030051764	kg/m3

	Transport (g-h) pre-study fuel consumption	Unit
Distance	1250	km
Amount	96,66666667	
Total distance	120833,3333	km

	Diesel consumption (transport g-h) calculated based on pre-study and GaBi values	Unit
Payload truck	27000	kg
Amount	143,2098765	
Total distance	179012,3457	km
Diesel	0,3	l/km
	0,246	kg/km
Density	0,82	kg/dm3
Total diesel	44037,03704	kg

	Transport (g-h) distance in GaBi	Unit
Ratio	1,81150847	
Distance	690,0326554	km

Regeneration (Belgium)								
	Inflow	Outflow	Unit (yearly)			Inflow	Outflow	Unit (m3)
Activated carbon for regeneration	3866666,667		kg/year		Activated carbon for regeneration	0,030051764		kg/m3
Natural gas	4,93		MJ/0,9 kg regenerated activated carbon		Natural gas	0,020422642		kWh/m3
Electricity	1,369554		kWh/0,9 kg regenerated activated carbon		Electricity	0,009096254		kWh/m3
	2627717,608		kWh/year		Softened water (from decarbonized	0,066656159		kg/m3
Softened water (from decarbonized water)	0,61		kWh/0,9 kg regenerated activated carbon		Lost of GAC		0,001668391	kg/m3
	1170386,667		kWh/year		GAC transported back to Rya WWTP		0,014911892	kg/m3
	4,47		kg/0,9 kg regenerated activated carbon					
	8576440		kg/year					
Lost of GAC		214666,6667	kg/year					
GAC transported back to Rya WWTP		1918666,667	kg/year					

	Transport (j-k) pre-study fuel consumption	Unit
Distance	1250	km
Amount	47,45	
Total distance	59312,5	km

	Diesel consumption (transport j-k) calculated based on pre-study and GaBi values	Unit
Payload truck	27000	kg
Amount	71,0617284	
Total distance	88827,16049	km
Diesel	0,3	l/km
	0,246	kg/km
Density	0,82	kg/dm3
Total dieesel consumption	21851,48148	kg

	Transport (j-k) distance in GaBi	Unit
Ratio	1,81150847	
Distance	690,0326554	km

10000 bed volumes

Production (activation) of virgin GAC (Belgium)

	Inflow	Outflow	Unit (yearly)
Electricity industrial furnace	1184960		kWh/year
Hard coal	1932000		kg/year
Heat (natural gas)	8565200		MJ/year
	2379412,56		kWh/year
Softened water (from decarbonized water)	8004920		kg/year
Virgin GAC		644000	kg/year

	Inflow	Outflow	Unit (m3)
Electricity industrial furnace	0,009209518		kWh/m3
Hard coal	0,015015519		kg/m3
Heat (natural gas)	0,066568802		MJ/m3
	0,018492813		kWh/m3
Softened water (from decarbonized water)	0,062214301		kg/m3
Virgin GAC		0,0050052	kg/m3

	Transport (b-c) container ship	Unit
Nautical miles (nm)	1,852	km
Distance	11908	nm
	22053,616	km
Amount	1	
Total distance	22053,616	km

	Transport (d-e) pre-study fuel consumption	Unit
Distance	1250	km
Amount	5	
Total distance	6250	km

	Diesel consumption (transport d-e) calculated based on pre-study and GaBi values	Unit
Payload truck	27000	kg
Amount	23,85185185	
Total distance	29814,81481	km
Diesel	0,3	l/km
	0,246	kg/km
Density	0,82	kg/dm3
Total diesel	7334,444444	kg

	Transport (d-e) distance in GaBi	Unit
Ratio	1,81150847	
Distance	690,0326554	km

GAC process and other installations								
	Inflow	Outflow	Unit (yearly)			Inflow	Outflow	Unit (m3)
Virgin GAC	644000		kg/year		Virgin GAC	0,005005173		kg/m3
Recycled GAC	5756000		kg/year		Recycled GAC	0,044735677		kg/m3
Electricity other installations	6000000		kWh/year		Electricity other installations	0,046632047		kWh/m3
Wastewater	128666880	128666880	m3/year		Wastewater	1	1	m3
GAC for regeneration		11600000	kg/year		GAC for regeneration		0,090155291	kg/m3

	Transport (g-h) pre-study fuel consumption	Unit
Distance	1250	km
Amount	290	
Total distance	362500	km

	Diesel consumption (transport g-h) calculated based on pre-study and GaBi values	Unit
Payload truck	27000	kg
Amount	429,6296296	
Total distance	537037,037	km
Diesel	0,3	l/km
	0,246	kg/km
Density	0,82	kg/dm3
Total diesel	132111,1111	kg

	Transport (g-h) distance in GaBi	Unit
Ratio	1,81150847	
Distance	690,0326554	km

Regeneration (Belgium)								
	Inflow	Outflow	Unit (yearly)			Inflow	Outflow	Unit (m3)
Activated carbon for regeneration	11600000		kg/year		Activated carbon for regeneration	0,090155291		kg/m3
Natural gas	4,93		MJ/0,9 kg regenerated activated carbon		Natural gas	0,061267926		kWh/m3
Electricity	1,369554		kWh/0,9 kg regenerated activated carbon		Electricity	0,027288763		kWh/m3
	7883152,824		kWh/year		Softened water (from decarbonized	0,199968477		kg/m3
Softened water (from decarbonized water)	0,61		kWh/0,9 kg regenerated activated carbon		Lost of GAC		0,005005173	kg/m3
	3511160		kWh/year		GAC transported back to Rya WWTP		0,044735677	kg/m3
	4,47		kg/0,9 kg regenerated activated carbon					
	25729320		kg/year					
Lost of GAC		644000	kg/year					
GAC transported back to Rya WWTP		5756000	kg/year					

	Transport (j-k) pre-study fuel consumption	Unit
Distance	1250	km
Amount	290	
Total distance	362500	km

	Diesel consumption (transport j-k) calculated based on pre-study and GaBi values	Unit
Payload truck	27000	kg
Amount	429,6296296	
Total distance	537037,037	km
Diesel	0,3	l/km
	0,246	kg/km
Density	0,82	kg/dm3
Total dieesel consumption	132111,1111	kg

	Transport (j-k) distance in GaBi	Unit
Ratio	1,81150847	
Distance	690,0326554	km

Table D.7. Manually added emissions in GaBi for the activation of GAC and the activation of PAC.

	Activation of GAC				Activation of PAC			
Emissions		Unit		Unit		Unit		Unit
Hard coal ash	0,17	kg/kg	0,00042544	kg/m3	0,17	kg/kg	0,002553959	kg/m3
Aluminium	0,000618	kg/kg	1,5466E-06	kg/m3	0,000618	kg/kg	9,28439E-06	kg/m3
Antimony	9,13E-08	kg/kg	2,28486E-10	kg/m3	9,13E-08	kg/kg	1,37163E-09	kg/m3
Arsenic	0,00000146	kg/kg	3,65378E-09	kg/m3	1,46E-06	kg/kg	2,1934E-08	kg/m3
Barium	0,00000728	kg/kg	1,82188E-08	kg/m3	7,28E-06	kg/kg	1,0937E-07	kg/m3
Benzene	0,0000289	kg/kg	7,23248E-08	kg/m3	2,89E-05	kg/kg	4,34173E-07	kg/m3
Benzo(a)pyrene	5,78E-10	kg/kg	1,4465E-12	kg/m3	5,78E-10	kg/kg	8,68346E-12	kg/m3
Beryllium	7,28E-08	kg/kg	1,82188E-10	kg/m3	7,28E-08	kg/kg	1,0937E-09	kg/m3
Boron	0,0000274	kg/kg	6,85709E-08	kg/m3	2,74E-05	kg/kg	4,11638E-07	kg/m3
Bromine	0,000000548	kg/kg	1,37142E-09	kg/m3	5,48E-07	kg/kg	8,23276E-09	kg/m3
Cadmium	9,13E-08	kg/kg	2,28486E-10	kg/m3	9,13E-08	kg/kg	1,37163E-09	kg/m3
Calcium	0,0000728	kg/kg	1,82188E-07	kg/m3	7,28E-05	kg/kg	1,0937E-06	kg/m3
Carbon dioxide, fossil	7	kg/kg	0,017518106	kg/m3	7	kg/kg	0,105163038	kg/m3
Carbon monoxide, fossil	0,00578	kg/kg	1,4465E-05	kg/m3	0,00578	kg/kg	8,68346E-05	kg/m3
Chromium	0,0000013	kg/kg	3,25336E-09	kg/m3	1,3E-06	kg/kg	1,95303E-08	kg/m3
Chromium VI	0,000000161	kg/kg	4,02916E-10	kg/m3	1,61E-07	kg/kg	2,41875E-09	kg/m3
Cobalt	0,000000183	kg/kg	4,57973E-10	kg/m3	1,83E-07	kg/kg	2,74926E-09	kg/m3
Copper	0,00000096	kg/kg	2,40248E-09	kg/m3	9,6E-07	kg/kg	1,44224E-08	kg/m3
Dinitrogen monoxide	0,0000578	kg/kg	1,4465E-07	kg/m3	5,78E-05	kg/kg	8,68346E-07	kg/m3
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	1,16E-12	kg/kg	2,903E-15	kg/m3	1,16E-12	kg/kg	1,7427E-14	kg/m3
Ethane	0,0000867	kg/kg	2,16974E-07	kg/m3	8,67E-05	kg/kg	1,30252E-06	kg/m3
Ethene	0,000173	kg/kg	4,32947E-07	kg/m3	0,000173	kg/kg	2,59903E-06	kg/m3
Ethyne	0,0000289	kg/kg	7,23248E-08	kg/m3	2,89E-05	kg/kg	4,34173E-07	kg/m3
Formaldehyde	0,00000462	kg/kg	1,15619E-08	kg/m3	4,62E-06	kg/kg	6,94076E-08	kg/m3
Hydrocarbons, aliphatic, alkanes, unspecified	0,0000289	kg/kg	7,23248E-08	kg/m3	2,89E-05	kg/kg	4,34173E-07	kg/m3
Hydrocarbons, aliphatic, unsaturated	0,0000289	kg/kg	7,23248E-08	kg/m3	2,89E-05	kg/kg	4,34173E-07	kg/m3
Hydrogen chloride	0,00234	kg/kg	5,85605E-06	kg/m3	0,00234	kg/kg	3,51545E-05	kg/m3
Hydrogen fluoride	0,0000728	kg/kg	1,82188E-07	kg/m3	7,28E-05	kg/kg	1,0937E-06	kg/m3
Iodine	0,000000659	kg/kg	1,6492E-09	kg/m3	6,59E-07	kg/kg	9,90035E-09	kg/m3
Iron	0,000255	kg/kg	6,3816E-07	kg/m3	0,000255	kg/kg	3,83094E-06	kg/m3
Lead	0,00000438	kg/kg	1,09613E-08	kg/m3	4,38E-06	kg/kg	6,5802E-08	kg/m3
Lead-210	0,00269	kBq/kg	6,73196E-06	kBq/m3	0,00269	kBq/kg	4,04127E-05	kBq/m3
Magnesium	0,000219	kg/kg	5,48066E-07	kg/m3	0,000219	kg/kg	3,2901E-06	kg/m3
Manganese	0,00000128	kg/kg	3,20331E-09	kg/m3	1,28E-06	kg/kg	1,92298E-08	kg/m3
Mercury	0,000000164	kg/kg	4,10424E-10	kg/m3	1,64E-07	kg/kg	2,46382E-09	kg/m3
Methane, fossil	0,000578	kg/kg	1,4465E-06	kg/m3	0,000578	kg/kg	8,68346E-06	kg/m3
Molybdenum	0,000000274	kg/kg	6,85709E-10	kg/m3	2,74E-07	kg/kg	4,11638E-09	kg/m3
Nickel	0,0000011	kg/kg	2,75285E-09	kg/m3	1,1E-06	kg/kg	1,65256E-08	kg/m3
Nitrogen oxides	0,0116	kg/kg	2,903E-05	kg/m3	0,0116	kg/kg	0,00017427	kg/m3
NMVO, non-methane volatiel organic compounds	0,0000994	kg/kg	2,48757E-07	kg/m3	9,94E-05	kg/kg	1,49332E-06	kg/m3
Particulates < 2.5 um	0,00116	kg/kg	2,903E-06	kg/m3	0,00116	kg/kg	1,7427E-05	kg/m3
Particulates > 10 um	0,000578	kg/kg	1,4465E-06	kg/m3	0,000578	kg/kg	8,68346E-06	kg/m3
Particulates > 2.5 um, and < 10um	0,00116	kg/kg	2,903E-06	kg/m3	0,00116	kg/kg	1,7427E-05	kg/m3
Phosphorus	0,00000365	kg/kg	9,13444E-09	kg/m3	3,65E-06	kg/kg	5,4835E-08	kg/m3
Polonium-210	0,00491	kBq	1,22877E-05	kBq/m3	0,00491	kBq	7,37644E-05	kBq/m3
Potassium	0,0000728	kg/kg	1,82188E-07	kg/m3	7,28E-05	kg/kg	1,0937E-06	kg/m3
Potassium-40	0,00078	kBq/kg	1,95202E-06	kBq/m3	0,00078	kBq/kg	1,17182E-05	kBq/m3

Propane	0,0000578	kg/kg	1,4465E-07	kg/m3	5,78E-05	kg/kg	8,68346E-07	kg/m3
Propene	0,0000289	kg/kg	7,23248E-08	kg/m3	2,89E-05	kg/kg	4,34173E-07	kg/m3
Radium-226	0,000694	kBq/kg	1,7368E-06	kBq/m3	0,000694	kBq/kg	1,04262E-05	kBq/m3
Radium-228	0,00376	kBq/kg	9,40973E-06	kBq/m3	0,00376	kBq/kg	5,64876E-05	kBq/m3
Radon-220	0,0000578	kBq/kg	1,4465E-07	kBq/m3	5,78E-05	kBq/kg	8,68346E-07	kBq/m3
Radon-222	0,0000578	kBq/kg	1,4465E-07	kBq/m3	5,78E-05	kBq/kg	8,68346E-07	kBq/m3
Scandium	7,28E-08	kg/kg	1,82188E-10	kg/m3	7,28E-08	kg/kg	1,0937E-09	kg/m3
Selenium	0,000000548	kg/kg	1,37142E-09	kg/m3	5,48E-07	kg/kg	8,23276E-09	kg/m3
Silicon	0,000913	kg/kg	2,28486E-06	kg/m3	0,000913	kg/kg	1,37163E-05	kg/m3
Sodium	0,0000365	kg/kg	9,13444E-08	kg/m3	3,65E-05	kg/kg	5,4835E-07	kg/m3
Strontium	0,000011	kg/kg	2,75285E-08	kg/m3	0,000011	kg/kg	1,65256E-07	kg/m3
Sulphur dioxide	0,0289	kg/kg	7,23248E-05	kg/m3	0,0289	kg/kg	0,000434173	kg/m3
Thallium	9,13E-08	kg/kg	2,28486E-10	kg/m3	9,13E-08	kg/kg	1,37163E-09	kg/m3
Thorium	0,00000011	kg/kg	2,75285E-10	kg/m3	1,1E-07	kg/kg	1,65256E-09	kg/m3
Thorium-228	0,000318	kBq/kg	7,95823E-07	kBq/m3	0,000318	kBq/kg	4,77741E-06	kBq/m3
Thorium-232	0,000202	kBq/kg	5,05522E-07	kBq/m3	0,000202	kBq/kg	3,0347E-06	kBq/m3
Tin	3,65E-08	kg/kg	9,13444E-11	kg/m3	3,65E-08	kg/kg	5,4835E-10	kg/m3
Titanium	0,0000219	kg/kg	5,48066E-08	kg/m3	2,19E-05	kg/kg	3,2901E-07	kg/m3
Toulene	0,00000578	kg/kg	1,4465E-08	kg/m3	5,78E-06	kg/kg	8,68346E-08	kg/m3
Uranium	0,000000146	kg/kg	3,65378E-10	kg/m3	1,46E-07	kg/kg	2,1934E-09	kg/m3
Uranium-238	0,000578	kBq/kg	1,4465E-06	kBq/m3	0,000578	kBq/kg	8,68346E-06	kBq/m3
Vanadium	0,00000219	kg/kg	5,48066E-09	kg/m3	2,19E-06	kg/kg	3,2901E-08	kg/m3
Water/m3	0,00186	m3/kg	4,65481E-06		0,00186	m3/kg	2,79433E-05	
Xylene	0,00000578	kg/kg	1,4465E-08	kg/m3	5,78E-06	kg/kg	8,68346E-08	kg/m3
Zinc	0,000000183	kg/kg	4,57973E-10	kg/m3	1,83E-07	kg/kg	2,74926E-09	kg/m3

Table D.8. Manually added emissions in GaBi for the regeneration.

	Regeneration					
Emissions		Unit		Unit		Unit
Hard coal ash	0,00931	kg/0,9kg	0,010344444	kg/kg	0,000231383	kg/m3
Aluminium	0,0000344	kg/0,9kg	3,82222E-05	kg/kg	8,54948E-07	kg/m3
Antimony	5,07E-09	kg/0,9kg	5,63333E-09	kg/kg	1,26005E-10	kg/m3
Arsenic	8,12E-08	kg/0,9kg	9,02222E-08	kg/kg	2,01808E-09	kg/m3
Barium	0,000000405	kg/0,9kg	0,00000045	kg/kg	1,00655E-08	kg/m3
Benzene	0,00000161	kg/0,9kg	1,78889E-06	kg/kg	4,00136E-08	kg/m3
Benzo(a)pyrene	3,21E-11	kg/0,9kg	3,56667E-11	kg/kg	7,97786E-13	kg/m3
Beryllium	4,05E-09	kg/0,9kg	4,5E-09	kg/kg	1,00655E-10	kg/m3
Boron	0,00000152	kg/0,9kg	1,68889E-06	kg/kg	3,77768E-08	kg/m3
Bromine	3,04E-08	kg/0,9kg	3,37778E-08	kg/kg	7,55536E-10	kg/m3
Cadmium	5,07E-09	kg/0,9kg	5,63333E-09	kg/kg	1,26005E-10	kg/m3
Calcium	0,00000405	kg/0,9kg	0,0000045	kg/kg	1,00655E-07	kg/m3
Carbon dioxide, fossil	2	kg/0,9kg	2,222222222	kg/kg	0,049706308	kg/m3
Carbon monoxide, fossil	0,000321	kg/0,9kg	0,000356667	kg/kg	7,97786E-06	kg/m3
Chromium	7,23E-08	kg/0,9kg	8,03333E-08	kg/kg	1,79688E-09	kg/m3
Chromium VI	8,93E-09	kg/0,9kg	9,92222E-09	kg/kg	2,21939E-10	kg/m3
Cobalt	1,01E-08	kg/0,9kg	1,12222E-08	kg/kg	2,51017E-10	kg/m3
Copper	5,33E-08	kg/0,9kg	5,92222E-08	kg/kg	1,32467E-09	kg/m3
Dinitrogen monoxide	0,00000321	kg/0,9kg	3,56667E-06	kg/kg	7,97786E-08	kg/m3
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	6,42E-14	kg/0,9kg	7,13333E-14	kg/kg	1,59557E-15	kg/m3
Ethane	0,00000482	kg/0,9kg	5,35556E-06	kg/kg	1,19792E-07	kg/m3
Ethene	0,00000963	kg/0,9kg	0,0000107	kg/kg	2,39336E-07	kg/m3
Ethyne	0,00000161	kg/0,9kg	1,78889E-06	kg/kg	4,00136E-08	kg/m3
Formaldehyde	0,000000257	kg/0,9kg	2,85556E-07	kg/kg	6,38726E-09	kg/m3
Hydrocarbons, aliphatic, alkanes, unspecified	0,00000161	kg/0,9kg	1,78889E-06	kg/kg	4,00136E-08	kg/m3
Hydrocarbons, aliphatic, unsaturated	0,00000161	kg/0,9kg	1,78889E-06	kg/kg	4,00136E-08	kg/m3
Hydrogen chloride	0,00013	kg/0,9kg	0,000144444	kg/kg	3,23091E-06	kg/m3
Hydrogen fluoride	0,00000405	kg/0,9kg	0,0000045	kg/kg	1,00655E-07	kg/m3
Iodine	3,66E-08	kg/0,9kg	4,06667E-08	kg/kg	9,09625E-10	kg/m3
Iron	0,0000142	kg/0,9kg	1,57778E-05	kg/kg	3,52915E-07	kg/m3
Lead	0,000000243	kg/0,9kg	0,00000027	kg/kg	6,03932E-09	kg/m3
Lead-210	0,000149	kgBq/0,9kg	0,000165556	kgBq/kg	3,70312E-06	kgBq/m3
Magnesium	0,0000122	kg/0,9kg	1,35556E-05	kg/kg	3,03208E-07	kg/m3
Manganese	0,000000071	kg/0,9kg	7,88889E-08	kg/kg	1,76457E-09	kg/m3
Mercury	9,12E-09	kg/0,9kg	1,01333E-08	kg/kg	2,26661E-10	kg/m3
Methane, fossil	0,0000321	kg/0,9kg	3,56667E-05	kg/kg	7,97786E-07	kg/m3
Molybdenum	1,52E-08	kg/0,9kg	1,68889E-08	kg/kg	3,77768E-10	kg/m3
Nickel	0,000000061	kg/0,9kg	6,77778E-08	kg/kg	1,51604E-09	kg/m3
Nitrogen oxides	0,000642	kg/0,9kg	0,000713333	kg/kg	1,59557E-05	kg/m3
NMVO, non-methane volatiel organic compounds	0,00000552	kg/0,9kg	6,13333E-06	kg/kg	1,37189E-07	kg/m3
Particulates < 2.5 um	0,0000642	kg/0,9kg	7,13333E-05	kg/kg	1,59557E-06	kg/m3
Particulates > 10 um	0,0000321	kg/0,9kg	3,56667E-05	kg/kg	7,97786E-07	kg/m3
Particulates > 2.5 um, and < 10um	0,0000642	kg/0,9kg	7,13333E-05	kg/kg	1,59557E-06	kg/m3
Phosphorus	0,000000203	kg/0,9kg	2,25556E-07	kg/kg	5,04519E-09	kg/m3
Polonium-210	0,000273	kgBq/0,9kg	0,000303333	kgBq/kg	6,78491E-06	kgBq/m3
Potassium	0,00000405	kg/0,9kg	0,0000045	kg/kg	1,00655E-07	kg/m3
Potassium-40	0,0000434	kgBq/0,9kg	4,82222E-05	kgBq/kg	1,07863E-06	kgBq/m3
Propane	0,00000321	kg/0,9kg	3,56667E-06	kg/kg	7,97786E-08	kg/m3
Propene	0,00000161	kg/0,9kg	1,78889E-06	kg/kg	4,00136E-08	kg/m3
Radium-226	0,0000385	kgBq/0,9kg	4,27778E-05	kgBq/kg	9,56846E-07	kgBq/m3
Radium-228	0,000209	kgBq/0,9kg	0,000232222	kgBq/kg	5,19431E-06	kgBq/m3
Radon-220	0,00000321	kgBq/0,9kg	3,56667E-06	kgBq/kg	7,97786E-08	kgBq/m3
Radon-222	0,00000321	kgBq/0,9kg	3,56667E-06	kgBq/kg	7,97786E-08	kgBq/m3
Scandium	4,05E-09	kg/0,9kg	4,5E-09	kg/kg	1,00655E-10	kg/m3

Selenium	3,04E-08	kg/0,9kg	3,37778E-08	kg/kg	7,55536E-10	kg/m3
Silicon	0,0000507	kg/0,9kg	5,63333E-05	kg/kg	1,26005E-06	kg/m3
Sodium	0,00000203	kg/0,9kg	2,25556E-06	kg/kg	5,04519E-08	kg/m3
Strontium	0,00000061	kg/0,9kg	6,77778E-07	kg/kg	1,51604E-08	kg/m3
Sulphur dioxide	0,00161	kg/0,9kg	0,001788889	kg/kg	4,00136E-05	kg/m3
Thallium	5,07E-09	kg/0,9kg	5,63333E-09	kg/kg	1,26005E-10	kg/m3
Thorium	6,1E-09	kg/0,9kg	6,77778E-09	kg/kg	1,51604E-10	kg/m3
Thorium-228	0,0000177	kgBq/0,9kg	1,96667E-05	kgBq/kg	4,39901E-07	kgBq/m3
Thorium-232	0,0000112	kgBq/0,9kg	1,24444E-05	kgBq/kg	2,78355E-07	kgBq/m3
Tin	2,03E-09	kg/0,9kg	2,25556E-09	kg/kg	5,04519E-11	kg/m3
Titanium	0,00000122	kg/0,9kg	1,35556E-06	kg/kg	3,03208E-08	kg/m3
Toulene	0,000000321	kg/0,9kg	3,56667E-07	kg/kg	7,97786E-09	kg/m3
Uranium	8,21E-09	kg/0,9kg	9,12222E-09	kg/kg	2,04044E-10	kg/m3
Uranium-238	0,0000321	kgBq/0,9kg	3,56667E-05	kgBq/kg	7,97786E-07	kgBq/m3
Vanadium	0,000000122	kg/0,9kg	1,35556E-07	kg/kg	3,03208E-09	kg/m3
Water/m3	0,00323	m3/0,9kg	0,003588889	m3/kg	8,02757E-05	
Xylene	0,000000321	kg/0,9kg	3,56667E-07	kg/kg	7,97786E-09	kg/m3
Zinc	1,01E-08	kg/0,9kg	1,12222E-08	kg/kg	2,51017E-10	kg/m3

Table D.9. Flows of wastewater per year and m^3 for how the existing sludge treatment would be for the ozonation process and the GAC process. The values in m^3 constitute the basis for the calculations in GaBi for the existing sludge treatment process.

Yearly flows of wastewater					Flows per m3 wastewater			
Existing sludge treatment for ozonation and the GAC process								
Polymer production	Inflow	Outflow	Unit		Polymer production	Inflow	Outflow	Unit
Electricity	114600		kWh/year		Electricity	0,00089067		kWh/m3
Acrylonitrile (50%)	191000		kg/year		Acrylonitrile (50%)	0,00148445		kg/m3
Acrylic acid (50%)	191000		kg/year		Acrylic acid (50%)	0,00148445		kg/m3
Polyacrylamide		382000	kg/year		Polyacrylamide		0,00296891	kg/m3
Primary settling	Inflow	Outflow	Unit		Primary settling	Inflow	Outflow	Unit
Wastewater	128666880	128666880	m3/year		Wastewater	1	1	m3
Sludge		40000000	kg/year		Sludge		0,31088031	kg/m3
Existing sludge treatment	Inflow	Outflow	Unit		Existing sludge treatment	Inflow	Outflow	Unit
Sludge to agriculture	40000000	40000000	kg/year		Sludge to agriculture	0,31088031	0,31088031	kg/m3
Electricity	2340000		kWh/year		Electricity	0,0181865		kWh/m3
Polacrylamide	382000		kg/year		Polyacrylamide	0,00296891		kg/m3
Transports of polymer for GAC/ozonation (40 ton payload)			Unit		Diesel consumption (transports of polymer for GAC/ozonation) calculated based on pre-study and GaBi values		Unit	
Distance	2000		km		Payload truck	27000	kg	
Amount	9,55				Amount	14,1481481		
Total distance	19100		km/year		Total distance	28296,2963	km	
						0,3	l/km	
					Diesel	0,246	kg/km	
					Density	0,82	kg/dm3	
					Total diesel consumption	6960,88889	kg	
					Diesel	0,44563108	kg/km	
					consumption truck	0,54345254	l/km	

Transport (polymer for GAC/ozonation) distance in GaBi		Unit
Ratio	1,81150847	
Distance	1104,052249	km

Table D.10. Flows of wastewater per year and m^3 for how the existing sludge treatment would be for the PAC process. The values in m^3 constitute the basis for the calculations in GaBi for the existing sludge treatment process.

Yearly flows of wastewater					Flows per m3 wastewater			
Existing sludge treatment for the PAC process								
Polymer production	Inflow	Outflow	Unit		Polymer production	Inflow	Outflow	Unit
Electricity	103140		kWh/year		Electricity	0,0008016		kWh/m3
Acrylonitrile (50%)	171900		kg/year		Acrylonitrile (50%)	0,00133601		kg/m3
Acrylic acid (50%)	171900		kg/year		Acrylic acid (50%)	0,00133601		kg/m3
Polyacrylamide		343800	kg/year		Polyacrylamide		0,00267202	kg/m3
Primary settling	Inflow	Outflow	Unit		Primary settling	Inflow	Outflow	Unit
Wastewater	128666880	128666880	m3/year		Wastewater	1	1	m3
Sludge		36000000	kg/year		Sludge		0,27979228	kg/m3
Existing sludge treatment	Inflow	Outflow	Unit		Existing sludge treatment	Inflow	Outflow	Unit
Sludge to agriculture	36000000	36000000	kg/year		Sludge to agriculture	0,27979228	0,27979228	kg/m3
Electricity	2105072,713		kWh/year		Electricity	0,01636064		kWh/m3
Polyacrylamide	343800		kg/year		Polyacrylamide	0,00267202		kg/m3
Transports of polymer for PAC (40 ton payload)			Unit		Diesel consumption (transports of polymer for PAC) calculated based on pre-study and GaBi values		Unit	
Distance	2000		km		Payload truck	27000	kg	
Amount	8,595				Amount	12,7333333		
Total distance	17190		km/year		Total distance	25466,6667	km	
						0,3	l/km	
					Diesel	0,246	kg/km	
					Density	0,82	kg/dm3	
					Total diesel consumption	6264,8	kg	
					Diesel consumption truck	0,44563108	kg/km	
						0,54345254	l/km	

			Transport (transports of polymer for PAC) distance in GaBi	Unit
Ratio	1,81150847			
Distance	1104,052249	km		

Appendix 5 – Example of Calculations

Example calculation of fuel consumption for the PAC process, the GAC process, and the existing sludge treatment

Fuel consumption in GaBi (calculated based on values for transport of virgin GAC)		
Diesel consumption	0,000000744	kg
Transport of activated carbon	0,045077645	kg
	0,445631084	kg/km
Diesel consumption truck	0,543452541	l/km

In the pre-study, it was assumed a truck with a payload of 40 tonnes. The largest truck in GaBi has a payload of 27 tonnes. Therefore, the first step was to calculate the total distance and amount of transports based on the difference in payload. Thereafter, the total diesel consumption could be calculated based on the assumed fuel consumption from the pre-study.

In GaBi, the fuel consumption is not presented. Therefore, it was calculated based on the following example in red:

Distance: 1 km
Diesel consumption: 7,44*10^-7 kg
Amount product transported: 0,045 kg
Diesel consumption truck=(7,44*10^-7/0,045)*27000=0,44kg/km
Density diesel: 0,82 kg/dm3
--> Diesel consumption truck=0,44/0,82=0,54l/km

The ratio of the fuel consumption from the pre-study and the fuel consumption in GaBi could then be calculated as in red below:

(0,3l/km)/(0,54l/km)=1,81

Based on the ratio, the distance for each transport was calculated.

Figure E.13. Example calculation of the fuel consumption in GaBi for all transports in the PAC process, the GAC process, and the existing sludge treatment.

Example calculation of loss of biogas production for the PAC process

Loss of biogas production (in existing sludge treatment for PAC)		Unit
	1000	kg/day
	365000	kg/year
Loss of sludge by using PAC	365	m3/year
Sludge to biogas	574687	m3/year
Total electricity for biogas prod.	1460000	kWh/year
Density of sludge (assumes the same value as for water)	1000	kg/m3
Electricity for loss of biogas	927,2873756	kWh/year

By implementing the PAC process, less biogas is produced since sludge contaminated of PAC is incinerated. The environmental impact for the existing sludge treatment in the PAC process will therefore be a bit different in comparison to the existing sludge treatment for ozonation and the GAC process. To know how much less electricity is used when having the PAC process, the following calculations have been made in red:

Loss of sludge by using PAC: 1000 kg/day --> 365000 kg/year
Density of sludge (assumes the same value as for water) = 1000kg/m3
--> loss of sludge by using PAC = (365000kg/year)/(1000kg/m3)=365m3/year
Sludge to biogas for the current sludge treatment=1004712-430025=574687m3/year
Total electricity for biogas production=146000kWh/year
Electricity for loss of

Figure E.2. Example calculation of loss of biogas production and thereby less electricity used for the existing sludge treatment in the PAC process.

Appendix 6 – GaBi Modelling

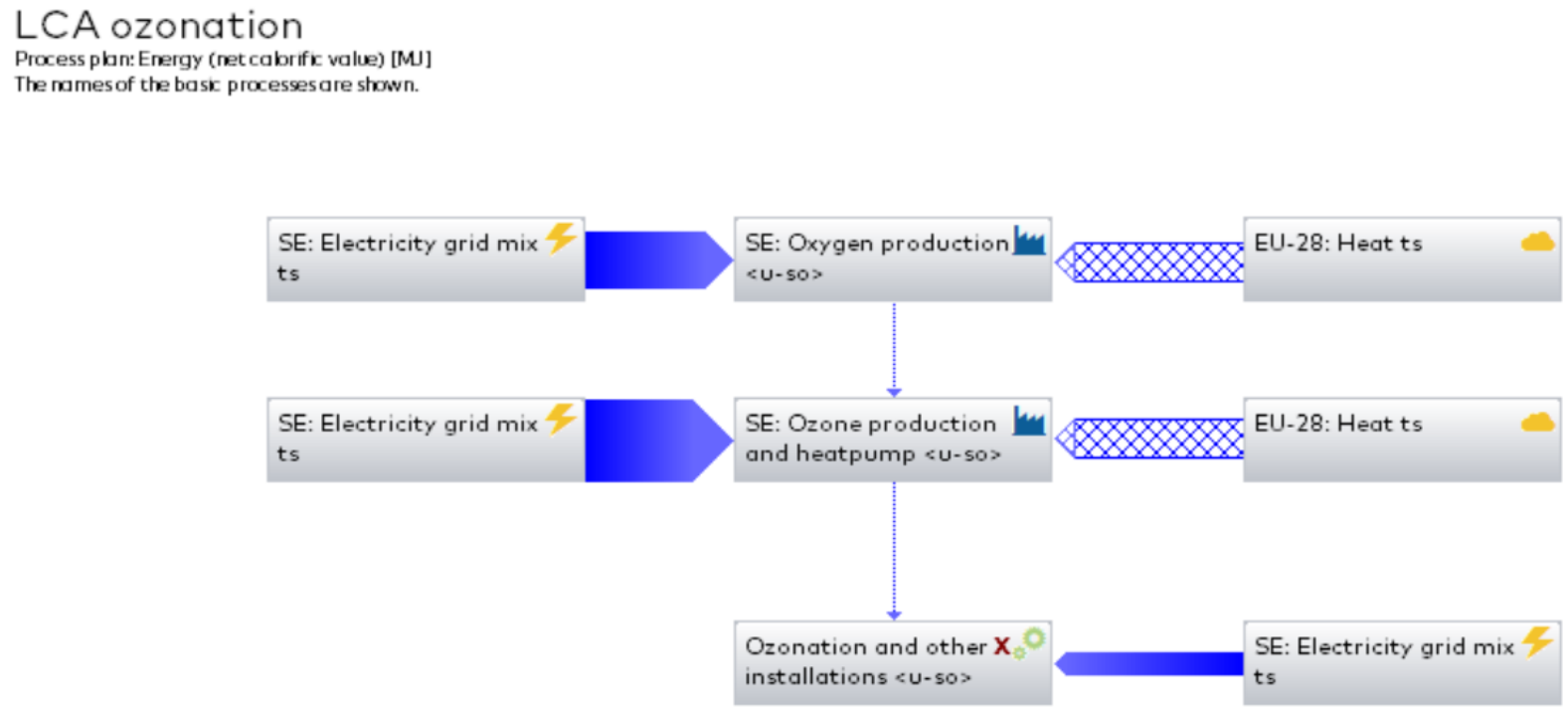


Figure F.1. A visualization of the modelling in GaBi for the main case of the ozonation process.

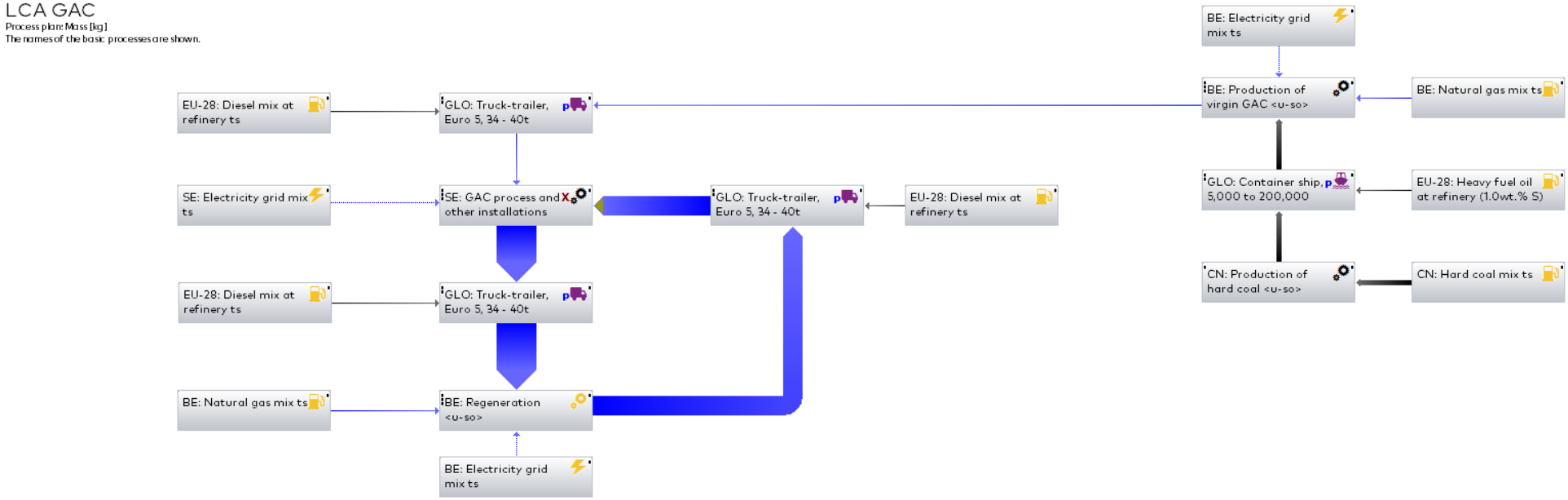


Figure F.2. A visualization of the modelling in GaBi for the main case of the GAC process.

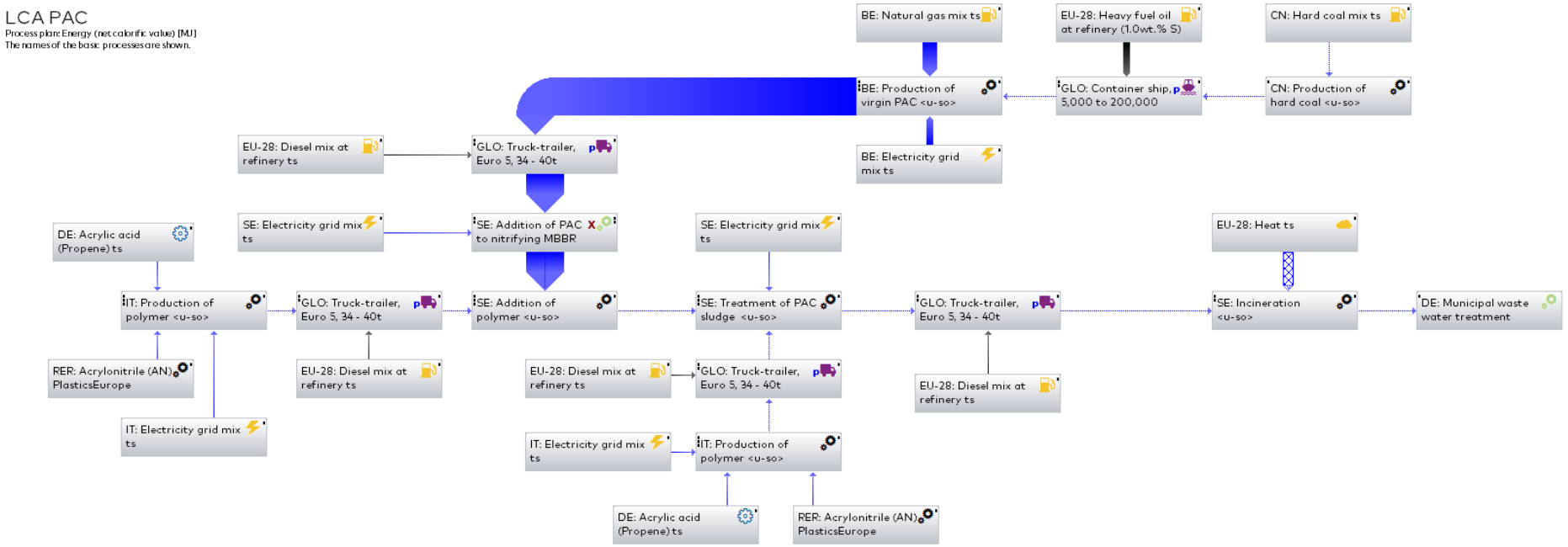


Figure F.3. A visualization of the modelling in GaBi for the main case of the PAC process.

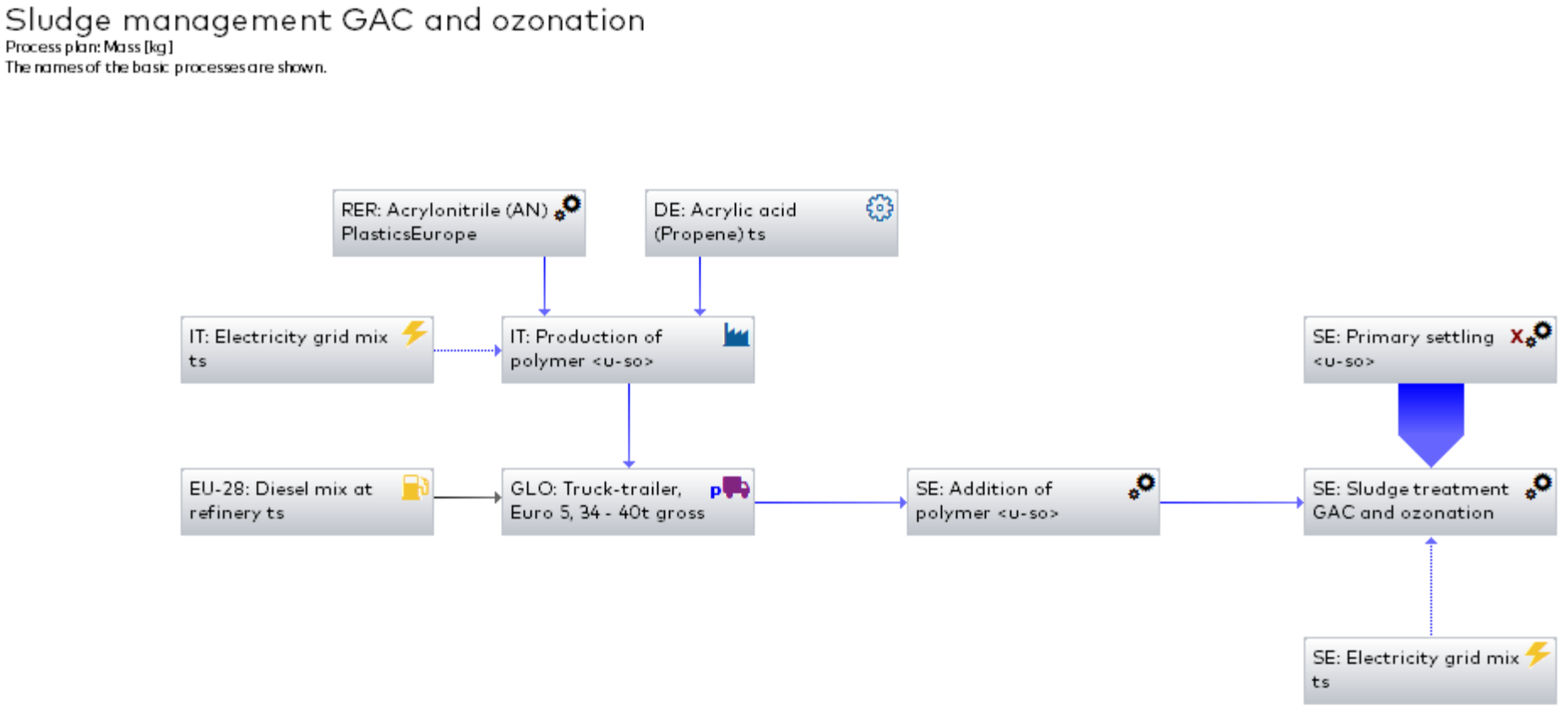


Figure F.4. A visualization of the modelling in GaBi for the existing sludge treatment. The including activities and the design are equal for the ozonation process, the PAC process, and the GAC process.

Appendix 7 – Results

Global Warming Potential

Table G.1. Results in tonnes CO_2-eq per year from the hot spot analysis for the ozonation process for the main case and the sensitivity analysis.

	Hot spot analysis detail ozonation					
Ozonation (t CO2-eq/year)	Credited heat of oxygen production	Credited heat of ozone production	SE: Electricity of other installations	SE: Electricity of oxygen production	SE: Electricity of ozone production	Total
Electricity (SE)	-32,68	-314,59	163,02	327,19	193,42	684
Windpower (SE)	-32,68	-314,59	24,39	21,16	-308,58	-263

Table G.2. Results in kg CO_2-eq per year from the hot spot analysis for the PAC process for the main case and the four sensitivity analyses.

	Hot spot analysis detail PAC																												
PAC (kg CO2-eq/year)	Hard coal, production of virgin PAC	Natural gas, production of virgin PAC	Electricity, production of virgin PAC	Production (activation) of virgin PAC	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Diesel, virgin PAC to Rya WWTP	Truck-trailer, virgin PAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Acrylic acid, PAC process	Acrylonitrile, PAC process	Electricity, polymer for PAC process	Diesel, polymer for PAC process	Truck-trailer, polymer for PAC process	Acrylic acid, sludge treatment	Acrylonitrile, sludge treatment	Electricity, polymer for sludge treatment	Diesel, polymer for sludge treatment	Truck-trailer, polymer for sludge treatment	Electricity, sludge treatment	Diesel, sludge to incineration	Truck-trailer, sludge to incineration	Incineration of sludge	Heat, incineration
Main case, β	1722706,46	147348,40	727847,65	13591891,41	930017,41	129639,82	6526,42	71216,02			46444,69	96365,92	240608,22	19473,20	794,11	8665,29	131470,54	328258,08	26566,98	1083,39	11821,93	21457,45	1746,88	19061,85	26252,37	-165454,09
Main case, γ	1722706,46	147348,40	45033,91	13591891,41	930017,41	129639,82	6526,42	71216,02			6949,08	96365,92	240608,22	430,51	794,11	8665,29	131470,54	328258,08	587,34	1083,39	11821,93	3210,47	1746,88	19061,85	26252,37	-165454,09
Prod. in China, δ	1722706,46	462748,04	2889476,85	13591891,41			37,83	412,85	371714,58	51815,17	46444,69	96365,92	240608,22	19473,20	794,11	8665,29	131470,54	328258,08	26566,98	1083,39	11821,93	21457,45	1746,88	19061,85	26252,37	-165454,09
Prod. in China, η	1722706,46	462748,04	45033,91	13591891,41			37,83	412,85	371714,58	51815,17	6949,08	96365,92	240608,22	430,51	794,11	8665,29	131470,54	328258,08	587,34	1083,39	11821,93	3210,47	1746,88	19061,85	26252,37	-165454,09
Coconut shells, δ		462748,04	2889476,85				37,83	412,85	371714,58	51815,17	46444,69	96365,92	240608,22	19473,20	794,11	8665,29	131470,54	328258,08	26566,98	1083,39	11821,93	21457,45	1746,88	19061,85	26252,37	-165454,09

Table G.3. Results in kg CO_2-eq per year from the hot spot analysis for the GAC process for the main case and the ten sensitivity analyses.

	Hot spot analysis detail GAC																		
GAC (kg CO2-eq/year)	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Electricity, production of virgin GAC	Natural gas, production of virgin GAC	Production (activation) of virgin GAC	Diesel, virgin GAC to Rya WWTP	Truck-trailer, virgin GAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Diesel, GAC to regeneration in Belgium	Truck-trailer, GAC to regeneration in Belgium	Diesel, regenerated GAC to Rya WWTP	Truck-trailer, regenerated GAC to Rya WWTP	Electricity, regeneration	Natural gas, regeneration	Regeneration	Heat generated during regeneration	Diesel, fuel for regeneration
Main case, α	154922,72	21595,46	121245,18	24545,36	2264143,40	1087,17	11863,20			139334,06	19582,63	213684,89	9717,04	106031,92	359262,08	81320,43	6401149,92		
Main case, μ	154922,72	21595,46	4253,85	24545,36	2264143,40	1087,17	11863,20			20847,23	19582,63	213684,89	9717,04	106031,92	12604,59	81320,43	6401149,92		
Prod. in China, ε			481330,31	77084,78	2264143,40	6,30	68,77	61920,39	8631,40	139334,06	19582,63	213684,89	9717,04	106031,92	359262,13	81320,43	6401149,92		
Prod. in China, π			7501,77	77084,78	2264143,40	6,30	68,77	61920,39	8631,40	20847,23	19582,63	213684,89	9717,04	106031,92	12604,59	81320,43	6401149,92		
Main case-credited heat, α	154922,72	21595,46	121245,18	24545,36	2264143,40	1087,17	11863,20			139334,06	19582,63	213684,89	9717,04	106031,92	359262,08	81320,43	6401149,92	-118519,17	
Reg. at Rya WWTP, diesel, α	154920,03	21595,08	121245,18	24545,36	2264154,30	1087,17	11863,20			139334,06					81537,35		6401149,21		108174,57
Reg. at Rya WWTP, diesel-credited heat, α	154920,03	21595,08	121245,18	24545,36	2264154,30	1087,17	11863,20			139334,06					81537,35		6401149,21	-118519,03	108174,57
Reg. at Rya WWTP, natural gas-credited heat, α	154920,03	21595,08	121245,18	24545,36	2264154,30	1087,17	11863,20			139334,06					81537,35	57297,51	6401149,21	-118519,03	
Coconut shells, ε			481330,31	77084,78		6,30	68,77	61920,39	8631,40	139334,06	19582,63	213684,89	1408,27	15366,94	359262,13	81320,43			
30000 bed volumes, α	103281,81	14396,97	80830,11	16363,57	1509428,93	724,78	7908,80			92889,37	13055,09	142456,60	6478,02	70687,94	239508,07	54213,62	4267433,28		
10000 bed volumes, α	309845,61	43190,94	242490,50	49090,75	4528289,51	2174,35	23726,39			278668,11	39165,26	427369,79	19434,07	212063,84	718524,23	162640,85	12802299,83		

Fossil depletion

Table G.4. Results in Mg oil-eq per year from the hot spot analysis for the ozonation process for the main case and the sensitivity analysis.

	Hot spot analysis detail ozonation					
Ozonation (Mg oil-eq/year)	Credited heat of oxygen production	Credited heat of ozone production	SE: Electricity of other installations	SE: Electricity of oxygen production	SE: Electricity of ozone production	Total
Electricity (SE)	-10,56	-101,70	313,87	682,31	876,40	1873
Windpower (SE)	-10,56	-101,70	7,15	5,23	-79,40	-67

Table G.5. Results in kg oil-eq per year from the hot spot analysis for the PAC process for the main case and the four sensitivity analyses.

	Hot spot analysis detail PAC																							
PAC (kg oil-eq/year)	Hard coal, production of virgin PAC	Natural gas, production of virgin PAC	Electricity, production of virgin PAC	Production (activation) of virgin PAC	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Diesel, virgin PAC to Rya WWTP	Truck-trailer, virgin PAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Acrylic acid, PAC process	Acrylonitrile, PAC process	Electricity, polymer for PAC process	Diesel, polymer for PAC process	Truck-trailer, polymer for PAC process	Acrylic acid, sludge treatment	Acrylonitrile, sludge treatment	Electricity, polymer for sludge treatment	Diesel, polymer for sludge treatment	Truck-trailer, polymer for sludge treatment	Electricity, sludge treatment	Diesel, sludge to incineration	Truck-trailer, sludge to incineration	Incineration of sludge	Heat, incineration
Main case, β	3547089,08	638029,15	577103,65			304373,11	24656,26				89422,12	79627,14	145524,21	6509,98	3000,08		108634,08	198536,43	8881,46	4092,96		41313,02	6599,55		2102,37	-53486,12
Main case, γ	3547089,08	638029,15	13191,06			304373,11	24656,26				2038,25	79627,14	145524,21	126,06	3000,08		108634,08	198536,43	171,99	4092,96		941,67	6599,55		2102,37	-53486,12
Prod. in China, δ	3547089,08	757226,25	688948,77				142,93			121653,56	89422,12	79627,14	145524,21	6509,98	3000,08		108634,08	198536,43	8881,46	4092,96		41313,02	6599,55		2102,37	-53486,12
Prod. in China, η	3547089,08	757226,25	13191,06				142,93			121653,56	2038,25	79627,14	145524,21	126,06	3000,08		108634,08	198536,43	171,99	4092,96		941,67	6599,55		2102,37	-53486,12
Coconut shells, δ		757226,25	688948,77				142,93			121653,56	89422,12	79627,14	145524,21	6509,98	3000,08		108634,08	198536,43	8881,46	4092,96		41313,02	6599,55		2102,37	-53486,12

Table G.6. Results in kg oil-eq per year from the hot spot analysis for the GAC process for the main case and the ten sensitivity analyses.

	Hot spot analysis detail GAC																			
GAC (kg oil-eq/year)	Hard coal, production of virgin GAC	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Electricity, production of virgin GAC	Natural gas, production of virgin GAC	Production (activation) of virgin GAC	Diesel, virgin GAC to Rya WWTP	Truck-trailer, virgin GAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Diesel, GAC to regeneration in Belgium	Truck-trailer, GAC to regeneration in Belgium	Diesel, regenerated GAC to Rya WWTP	Truck-trailer, regenerated GAC to Rya WWTP	Electricity, regeneration	Natural gas, regeneration	Regeneration	Heat generated during regeneration	Diesel, fuel for regeneration
Main case, α	590875,72		50702,61	96134,18	106283,19		4107,25				268266,36	73981,53		36710,15		284855,57	352123,28			
Main case, μ	590875,72		50702,61	1266,93	106283,19		4107,25				6114,76	73981,53		36710,15		3754,05	352123,28			
Prod. in China, ε	590875,72			114765,39	126139,09		23,81			20265,11	268266,36	73981,53		36710,15		284855,61	352123,28			
Prod. in China, π	590875,72			2197,37	126139,09		23,81			20265,11	6114,76	73981,53		36710,15		3754,05	352123,28			
Main case-credited heat, α	590875,72		50702,61	96134,18	106283,19		4107,25				268266,36	73981,53		36710,15		284855,57	352123,28		-38313,53	
Reg. at Rya WWTP, diesel, α	590875,72		50701,73	96134,18	106283,19		4107,25				268266,36					156987,67				408674,52
Reg. at Rya WWTP, diesel-credited heat, α	590875,72		50701,73	96134,18	106283,19		4107,25				268266,36					156987,67			-38313,48	408674,52
Reg. at Rya WWTP, natural gas-credited heat, α	590875,72		50701,73	96134,18	106283,19		4107,25				268266,36					156987,67	355546,06		-38313,48	
Coconut shells, ε				114765,39	126139,09		23,81			20265,11	268266,36	73981,53		5320,31		284855,61	352123,28			
30000 bed volumes, α	393917,12		33801,74	64089,44	70855,45		2738,17				178844,24	49321,02		24473,43		189903,73	234748,85			
10000 bed volumes, α	1181752,06		101405,28	192268,47	212566,49		8214,50				536532,71	147963,07		73420,29		569711,20	704246,56			

Total use of primary renewable energy resources

Table G.7. Results in GWh per year from the hot spot analysis for the ozonation process for the main case and the sensitivity analysis.

	Hot spot analysis detail ozonation					
Ozonation (GWh/year)	Credited heat of oxygen production	Credited heat of ozone production	SE: Electricity of other installations	SE: Electricity of oxygen production	SE: Electricity of ozone production	Total
Electricity (SE)	-1,64	-15,75	3,44	7,60	10,73	4
Windpower (SE)	-1,64	-15,75	8,79	19,41	27,40	38

Table G.8. Results in MJ per year from the hot spot analysis for the PAC process for the main case and the four sensitivity analyses.

	Hot spot analysis detail PAC																										
PAC (MJ/year)	Hard coal, production of virgin PAC	Natural gas, production of virgin PAC	Electricity, production of virgin PAC	Production (activation) of virgin PAC	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Diesel, virgin PAC to Rya WWTP	Truck-trailer, virgin PAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Acrylic acid, PAC process	Acrylonitrile, PAC process	Electricity, polymer for PAC process	Diesel, polymer for PAC process	Truck-trailer, polymer for PAC process	Acrylic acid, sludge treatment	Acrylonitrile, sludge treatment	Electricity, polymer for sludge treatment	Diesel, polymer for sludge treatment	Truck-trailer, polymer for sludge treatment	Electricity, sludge treatment	Diesel, sludge to incineration	Truck-trailer, sludge to incineration	Incineration of sludge	Heat, incineration
Main case, β	764939,08	56184,97	7488353,89			42612,17	59114,38				3531397,35	203999,17	21363,75	200139,08	7192,81		278312,91	29146,24	273046,61	9813,05		1631505,71	15822,69		33035,18	-29818422,32
Main case, γ	764939,08	56184,97	32121176,23			42612,17	59114,38				9017160,95	203999,17	21363,75	397958,83	7192,81		278312,91	29146,24	542929,00	9813,05		4165928,71	15822,69		33035,18	-29818422,32
Prod. in China, δ	764939,08	18550,32	6193850,42				342,69			17031,47	3531397,35	203999,17	21363,75	200139,08	7192,81		278312,91	29146,24	273046,61	9813,05		1631505,71	15822,69		33035,18	-29818422,32
Prod. in China, η	764939,08	18550,32	32121176,23				342,69			17031,47	9017160,95	203999,17	21363,75	397958,83	7192,81		278312,91	29146,24	542929,00	9813,05		4165928,71	15822,69		33035,18	-29818422,32
Coconut shells, δ		18550,32	6193850,42				342,69			17031,47	3531397,35	203999,17	21363,75	200139,08	7192,81		278312,91	29146,24	273046,61	9813,05		1631505,71	15822,69		33035,18	-29818422,32

Table G.9. Results in MJ per year from the hot spot analysis for the GAC process for the main case and the ten sensitivity analyses.

	Hot spot analysis detail GAC																			
GAC (MJ/year)	Hard coal, production of virgin GAC	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Electricity, production of virgin GAC	Natural gas, production of virgin GAC	Production (activation) of virgin GAC	Diesel, virgin GAC to Rya WWTP	Truck-trailer, virgin GAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Diesel, GAC to regeneration in Belgium	Truck-trailer, GAC to regeneration in Belgium	Diesel, regenerated GAC to Rya WWTP	Truck-trailer, regenerated GAC to Rya WWTP	Electricity, regeneration	Natural gas, regeneration	Regeneration	Heat generated during regeneration	Diesel, fuel for regeneration
Main case, α	127423,90		7098,35	1247413,26	9359,32		9847,30				10594192,05	177373,73		88014,07		3696215,26	31008,04			
Main case, μ	127423,90		7098,35	5343149,78	9359,32		9847,30				27051482,84	177373,73		88014,07		15832308,71	31008,04			
Prod. in China, ε	127423,90			1031774,30	3090,12		57,09			2837,11	10594192,05	177373,73		88014,07		3696215,80	31008,04			
Prod. in China, π	127423,90			5350759,54	3090,12		57,09			2837,11	27051482,84	177373,73		88014,07		15832311,03	31008,04			
Main case-credited heat, α	127423,90		7098,35	1247413,26	9359,32		9847,30				10594192,05	177373,73		88014,07		3696215,26	31008,04		-21359729,28	
Reg. at Rya WWTP, diesel, α	127423,90		7098,23	1247413,26	9359,32		9847,30				10594192,05					6199649,96				979813,72
Reg. at Rya WWTP, diesel-credited heat, α	127423,90		7098,23	1247413,26	9359,32		9847,30				10594192,05					6199649,96			-21359705,06	979813,72
Reg. at Rya WWTP, natural gas-credited heat, α	127423,90		7098,23	1247413,26	9359,32		9847,30				10594192,05					6199649,96	7712,87		-21359705,06	
Coconut shells, ε				1031774,30	3090,12		57,09			2837,11	10594192,05	177373,73		12755,66		3696215,80	31008,04			
30000 bed volumes, α	84949,26		4732,24	831608,75	6239,54		6564,87				7062794,70	118249,15		58676,04		2464143,69	20672,03			
10000 bed volumes, α	254847,94		14196,72	2494828,01	18718,64		19694,60				21188383,65	354747,45		176028,13		7392431,33	62016,08			

Total use of primary non-renewable energy resources

Table G.10. Results in GWh per year from the hot spot analysis for the ozonation process for the main case and the sensitivity analysis.

	Hot spot analysis detail ozonation					
Ozonation (GWh/year)	Credited heat of oxygen production	Credited heat of ozone production	SE: Electricity of other installations	SE: Electricity of oxygen production	SE: Electricity of ozone production	Total
Electricity (SE)	-0,13	-1,21	3,97	8,76	12,37	24
Windpower (SE)	-0,13	-1,21	0,08	0,19	0,26	-1

Table G.11. Results in MJ per year from the hot spot analysis for the PAC process for the main case and the four sensitivity analyses.

	Hot spot analysis detail PAC																									
PAC (MJ/year)	Hard coal, production of virgin PAC	Natural gas, production of virgin PAC	Electricity, production of virgin PAC	Production (activation) of virgin PAC	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Diesel, virgin PAC to Rya WWTP	Truck-trailer, virgin PAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Acrylic acid, PAC process	Acrylonitrile, PAC process	Electricity, polymer for PAC process	Diesel, polymer for PAC process	Truck-trailer, polymer for PAC process	Acrylic acid, sludge treatment	Acrylonitrile, sludge treatment	Electricity, polymer for sludge treatment	Diesel, polymer for sludge treatment	Truck-trailer, polymer for sludge treatment	Electricity, sludge treatment	Diesel, sludge to incineration	Truck-trailer, sludge to incineration	Incineration of sludge	Heat, incineration
Main case, β	156022803,60	26360084,87	25550649,76			12996179,19	1052688,77				4070134,29	3354039,87	6138484,87	276006,57	128087,10		4575864,77	8374640,08	376551,45	174747,41		1880402,20	281765,14		89324,49	-2289979,21
Main case, γ	156022803,60	26360084,87	561619,04			12996179,19	1052688,77				86777,29	3354039,87	6138484,87	5367,33	128087,10		4575864,77	8374640,08	7322,57	174747,41		40091,11	281765,14		89324,49	-2289979,21
Prod. in China, δ	156022803,60	31286908,38	30286112,37				6102,54			5194385,94	4070134,29	3354039,87	6138484,87	276006,57	128087,10		4575864,77	8374640,08	376551,45	174747,41		1880402,20	281765,14		89324,49	-2289979,21
Prod. in China, η	156022803,60	31286908,38	561619,04				6102,54			5194385,94	86777,29	3354039,87	6138484,87	5367,33	128087,10		4575864,77	8374640,08	7322,57	174747,41		40091,11	281765,14		89324,49	-2289979,21
Coconut shells, δ		31286908,38	30286112,37				6102,54			5194385,94	4070134,29	3354039,87	6138484,87	276006,57	128087,10		4575864,77	8374640,08	376551,45	174747,41		1880402,20	281765,14		89324,49	-2289979,21

Table G.12. Results in MJ per year from the hot spot analysis for the GAC process for the main case and the ten sensitivity analyses.

	Hot spot analysis detail GAC																		
GAC (MJ/year)	Hard coal, production of virgin GAC	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Electricity, production of virgin GAC	Natural gas, production of virgin GAC	Production (activation) of virgin GAC	Diesel, virgin GAC to Rya WWTP	Truck-trailer, virgin GAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Diesel, GAC to regeneration in Belgium	Truck-trailer, GAC to regeneration in Belgium	Diesel, regenerated GAC to Rya WWTP	Truck-trailer, regenerated GAC to Rya WWTP	Electricity, regeneration	Natural gas, regeneration	Regeneration	Heat generated during regeneration	Diesel, fuel for regeneration
Main case, α	25990349,78		2164909,46	4256238,37	4391074,87		175357,40				12210402,86	3158610,90		1567324,56		12611677,12	14547923,86			
Main case, μ	25990349,78		2164909,46	53919,69	4391074,87		175357,40				260331,86	3158610,90		1567324,56		159769,66	14547923,86			
Prod. in China, ε	25990349,78			5045073,80	5211787,36		1016,56			865283,29	12210402,86	3158610,90		1567324,56		12611678,97	14547923,86			
Prod. in China, π	25990349,78			93554,74	5211787,36		1016,56			865283,29	260331,86	3158610,90		1567324,56		159769,69	14547923,86			
Main case-credited heat, α	25990349,78		2164909,46	4256238,37	4391074,87		175357,40				12210402,86	3158610,90		1567324,56		12611677,12	14547923,86		-1640373,04	
Reg. at Rya WWTP, diesel, α	25990349,78		2164871,76	4256238,37	4391074,87		175357,40				12210402,86					7145445,66				17448189,17
Reg. at Rya WWTP, diesel-credited heat, α	25990349,78		2164871,76	4256238,37	4391074,87		175357,40				12210402,86					7145445,66			-1640371,18	17448189,17
Reg. at Rya WWTP, natural gas-credited heat, α	25990349,78		2164871,76	4256238,37	4391074,87		175357,40				12210402,86					7145445,66	14686459,06		-1640371,18	
Coconut shells, ε				5045073,80	5211787,36		1016,56			865283,29	12210402,86	3158610,90		227148,49		12611678,97	14547923,86			
30000 bed volumes, α	17326898,70		1443272,87	2837491,94	2927383,09		116904,91				8140268,57	2105740,65		1044882,99		8407785,36	9698615,90			
10000 bed volumes, α	51980727,26		4329821,22	8512481,85	8782154,52		350714,73				24420805,20	6317221,87		3134649,05		25223357,01	29095847,71			

Energy use

Table G.13. Results in GWh per year from the hot spot analysis for the ozonation process for the main case and the sensitivity analysis. The values present the total energy use and thus the sum of the total primary renewable energy resources in Table E.7 and total primary non-renewable energy resources in Table E.10.

	Hot spot analysis detail ozonation					
Ozonation (GWh/year)	Credited heat of oxygen production	Credited heat of ozone production	SE: Electricity of other installations	SE: Electricity of oxygen production	SE: Electricity of ozone production	Total
Electricity (SE)	-1,76	-16,96	7,41	14,60	6,14	28
Windpower (SE)	-1,76	-16,96	8,88	17,83	10,70	37

Table G.14. Results in MJ per year from the hot spot analysis for the PAC process for the main case and the four sensitivity analyses. The values present the total energy use and thus the sum of the total primary renewable energy resources in Table E.8 and total primary non-renewable energy resources in Table E.11.

	Hot spot analysis detail PAC																										
PAC (MJ/year)	Hard coal, production of virgin PAC	Natural gas, production of virgin PAC	Electricity, production of virgin PAC	Production (activation) of virgin PAC	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Diesel, virgin PAC to Rya WWTP	Truck-trailer, virgin PAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Acrylic acid, PAC process	Acrylonitrile, PAC process	Electricity, polymer for PAC process	Diesel, polymer for PAC process	Truck-trailer, polymer for PAC process	Acrylic acid, sludge treatment	Acrylonitrile, sludge treatment	Electricity, polymer for sludge treatment	Diesel, polymer for sludge treatment	Truck-trailer, polymer for sludge treatment	Electricity, sludge treatment	Diesel, sludge to incineration	Truck-trailer, sludge to incineration	Incineration of sludge	Heat, incineration
Main case, β	156787742,68	26416269,83	33039003,65			13038791,35	1111803,15				7601531,64	3558039,03	6159848,62	476145,65	135279,91		4854177,69	8403786,32	649598,05	184560,46		3511907,91	297587,84		122359,67	-32108401,52
Main case, γ	156787742,68	26416269,83	32682795,27			13038791,35	1111803,15				9103938,23	3558039,03	6159848,62	403326,17	135279,91		4854177,69	8403786,32	550251,57	184560,46		4206019,82	297587,84		122359,67	-32108401,52
Prod. in China, δ	156787742,68	31305458,70	36479962,79				6445,24			5211417,41	7601531,64	3558039,03	6159848,62	476145,65	135279,91		4854177,69	8403786,32	649598,05	184560,46		3511907,91	297587,84		122359,67	-32108401,52
Prod. in China, η	156787742,68	31305458,70	32682795,27				6445,24			5211417,41	9103938,23	3558039,03	6159848,62	403326,17	135279,91		4854177,69	8403786,32	550251,57	184560,46		4206019,82	297587,84		122359,67	-32108401,52
Coconut shells, δ	0,00	31305458,70	36479962,79				6445,24			5211417,41	7601531,64	3558039,03	6159848,62	476145,65	135279,91		4854177,69	8403786,32	649598,05	184560,46		3511907,91	297587,84		122359,67	-32108401,52

Table G.15. Results in MJ per year from the hot spot analysis for the GAC process for the main case and the ten sensitivity analyses. The values present the total energy use and thus the sum of the total primary renewable energy resources in Table E.9 and total primary non-renewable energy resources in Table E.12.

	Hot spot analysis detail GAC																			
GAC (MJ/year)	Hard coal, production of virgin GAC	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Electricity, production of virgin GAC	Natural gas, production of virgin GAC	Production (activation) of virgin GAC	Diesel, virgin GAC to Rya WWTP	Truck-trailer, virgin GAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Diesel, GAC to regeneration in Belgium	Truck-trailer, GAC to regeneration in Belgium	Diesel, regenerated GAC to Rya WWTP	Truck-trailer, regenerated GAC to Rya WWTP	Electricity, regeneration	Natural gas, regeneration	Regeneration	Heat generated during regeneration	Diesel, fuel for regeneration
Main case, α	26117773,68		2172007,81	5503651,63	4400434,18		185204,70				22804594,91	3335984,63	0,00	1655338,63		16307892,38	14578931,90			
Main case, μ	26117773,68		2172007,81	5397069,48	4400434,18		185204,70				27311814,70	3335984,63	0,00	1655338,63		15992078,37	14578931,90			
Prod. in China, ε	26117773,68		0,00	6076848,10	5214877,48		1073,65			868120,40	22804594,91	3335984,63	0,00	1655338,63		16307894,77	14578931,90			
Prod. in China, π	26117773,68		0,00	5444314,28	5214877,48		1073,65			868120,40	27311814,70	3335984,63	0,00	1655338,63		15992080,72	14578931,90			
Main case-credited heat, α	26117773,68		2172007,81	5503651,63	4400434,18		185204,70				22804594,91	3335984,63	0,00	1655338,63		16307892,38	14578931,90		-23000102,31	
Reg. at Rya WWTP, diesel, α	26117773,68		2171969,99	5503651,63	4400434,18		185204,70				22804594,91					13345095,62				18428002,89
Reg. at Rya WWTP, diesel-credited heat, α	26117773,68		2171969,99	5503651,63	4400434,18		185204,70				22804594,91					13345095,62			-23000076,24	18428002,89
Reg. at Rya WWTP, natural gas-credited heat, α	26117773,68		2171969,99	5503651,63	4400434,18		185204,70				22804594,91					13345095,62	14694171,93		-23000076,24	
Coconut shells, ε	0,00		0,00	6076848,10	5214877,48		1073,65			868120,40	22804594,91	3335984,63	0,00	239904,15		16307894,77	14578931,90			
30000 bed volumes, α	17411847,96		1448005,11	3669100,69	2933622,63		123469,78				15203063,28	2223989,80	0,00	1103559,04		10871929,05	9719287,93			
10000 bed volumes, α	52235575,20		4344017,94	11007309,85	8800873,17		370409,33				45609188,85	6671969,33	0,00	3310677,18		32615788,34	29157863,80			

Eutrophication Potential

Table G.16. Results in tonnes PO_4-eq per year from the hot spot analysis for the ozonation process for the main case and the sensitivity analysis.

	Hot spot analysis detail ozonation					
Ozonation (t PO4-eq/year)	Credited heat of oxygen production	Credited heat of ozone production	SE: Electricity of other installations	SE: Electricity of oxygen production	SE: Electricity of ozone production	Total
Electricity (SE)	-0,08	-0,80	0,10	0,14	-0,49	-0,3
Windpower (SE)	-0,08	-0,80	0,01	-0,07	-0,78	-0,8

Table G.17. Results in tonnes PO_4-eq per year from the hot spot analysis for the PAC process for the main case and the four sensitivity analyses.

	Hot spot analysis detail PAC																								
PAC (t PO4-eq/year)	Hard coal, production of virgin PAC	Natural gas, production of virgin PAC	Electricity, production of virgin PAC	Production (activation) of virgin PAC	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Diesel, virgin PAC to Rya WWTP	Truck-trailer, virgin PAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Acrylic acid, PAC process	Acrylonitrile, PAC process	Electricity, polymer for PAC process	Diesel, polymer for PAC process	Truck-trailer, polymer for PAC process	Acrylic acid, sludge treatment	Acrylonitrile, sludge treatment	Electricity, polymer for sludge treatment	Diesel, polymer for sludge treatment	Truck-trailer, polymer for sludge treatment	Electricity, sludge treatment	Diesel, sludge to incineration	Truck-trailer, sludge to incineration	Incineration of sludge	Heat, incineration
Main case, β	474,29	41,12	172,93	2966,72	3471,84	37,71	6,74	37,81			28,38	34,03	107,76	4,30	0,82	4,60	46,43	147,01	5,87	1,12	6,28	13,11	1,81	10,12	103,54	-422,59
Main case, γ	474,29	41,12	14,10	2966,72	3471,84	37,71	6,74	37,81			2,18	34,03	107,76	0,13	0,82	4,60	46,43	147,01	0,18	1,12	6,28	1,01	1,81	10,12	103,54	-422,59
Prod. in China, δ	474,29	118,85	810,89	2966,72			0,04	0,22	1387,64	15,07	28,38	34,03	107,76	4,30	0,82	4,60	46,43	147,01	5,87	1,12	6,28	13,11	1,81	10,12	103,54	-422,59
Prod. in China, η	474,29	118,85	14,10	2966,72			0,04	0,22	1387,64	15,07	2,18	34,03	107,76	0,13	0,82	4,60	46,43	147,01	0,18	1,12	6,28	1,01	1,81	10,12	103,54	-422,59
Coconut shells, δ		118,85	810,89				0,04	0,22	1387,64	15,07	28,38	34,03	107,76	4,30	0,82	4,60	46,43	147,01	5,87	1,12	6,28	13,11	1,81	10,12	103,54	-422,59

Table G.18. Results in kg PO_4-eq per year from the hot spot analysis for the GAC process for the main case and the ten sensitivity analyses.

	Hot spot analysis detail GAC																			
GAC (kg PO4-eq/year)	Hard coal, production of virgin GAC	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Electricity, production of virgin GAC	Natural gas, production of virgin GAC	Production (activation) of virgin GAC	Diesel, virgin GAC to Rya WWTP	Truck-trailer, virgin GAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Diesel, GAC to regeneration in Belgium	Truck-trailer, GAC to regeneration in Belgium	Diesel, regenerated GAC to Rya WWTP	Truck-trailer, regenerated GAC to Rya WWTP	Electricity, regeneration	Natural gas, regeneration	Regeneration	Heat generated during regeneration	Diesel, fuel for regeneration
Main case, α	79,01	578,34	6,28	28,81	6,85	494,20	1,12	6,30			85,15	20,24	113,44	10,04	56,29	85,36	22,70	271,64		
Main case, μ	79,01	578,34	6,28	1,34	6,85	494,20	1,12	6,30			6,53	20,24	113,44	10,04	56,29	3,97	22,70	271,64		
Prod. in China, ε	79,01			135,08	19,80	494,20	0,01	0,04	231,15	2,51	85,15	20,24	113,44	10,04	56,29	85,36	22,70	271,64		
Prod. in China, π	79,01			2,35	19,80	494,20	0,01	0,04	231,15	2,51	6,53	20,24	113,44	10,04	56,29	3,97	22,70	271,64		
Main case-credited heat, α	79,01	578,34	6,28	28,81	6,85	494,20	1,12	6,30			85,15	20,24	113,44	10,04	56,29	85,36	22,70	271,64	-302,71	
Reg. at Rya WWTP, diesel, α	79,01	578,33	6,28	28,81	6,85	493,71	1,12	6,30			85,15					49,83		271,64		111,79
Reg. at Rya WWTP, diesel-credited heat, α	79,01	578,33	6,28	28,81	6,85	493,71	1,12	6,30			85,15					49,83		271,64	-302,71	111,79
Reg. at Rya WWTP, natural gas-credited heat, α	79,01	578,33	6,28	28,81	6,85	493,71	1,12	6,30			85,15					49,83	8,15	271,64	-302,71	
Coconut shells, ε				135,08	19,80		0,01	0,04	231,15	2,51	85,15	20,24	113,44	1,46	8,16	85,36	22,70			
30000 bed volumes, α	52,67	385,56	4,19	19,20	4,57	329,47	0,75	4,20			56,77	13,49	75,62	6,69	37,53	56,91	15,13	181,10		
10000 bed volumes, α	158,01	1156,68	12,56	57,61	13,70	988,40	2,25	12,60			170,31	40,47	226,87	20,08	112,58	170,72	45,39	543,29		

Acidification Potential

Table G.19. Results in tonnes SO_4-eq per year from the hot spot analysis for the ozonation process for the main case and the sensitivity analysis.

	Hot spot analysis detail ozonation					
Ozonation (t SO2-eq/year)	Credited heat of oxygen production	Credited heat of ozone production	SE: Electricity of other installations	SE: Electricity of oxygen production	SE: Electricity of ozone production	Total
Electricity (SE)	-0,37	-3,52	0,53	0,81	-1,86	-0,5
Windpower (SE)	-0,37	-3,52	0,07	-0,22	-3,31	-3,5

Table G.20. Results in kg SO_2-eq per year from the hot spot analysis for the PAC process for the main case and the four sensitivity analyses.

	Hot spot analysis detail PAC																											
PAC (kg SO2-eq/year)	Hard coal, production of virgin PAC	Natural gas, production of virgin PAC	Electricity, production of virgin PAC	Production (activation) of virgin PAC	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Diesel, virgin PAC to Rya WWTP	Truck-trailer, virgin PAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Acrylic acid, PAC process	Acrylonitrile, PAC process	Electricity, polymer for PAC process	Diesel, polymer for PAC process	Truck-trailer, polymer for PAC process	Acrylic acid, sludge treatment	Acrylonitrile, sludge treatment	Electricity, polymer for sludge treatment	Diesel, polymer for sludge treatment	Truck-trailer, polymer for sludge treatment	Electricity, sludge treatment	Diesel, sludge to incineration	Truck-trailer, sludge to incineration	Incineration of sludge	Heat, incineration
Main case, β	2750,33	430,77	924,36	81827,04	30991,44	456,52	41,67	139,58			151,53	193,66	980,48	34,94	5,07	16,98	264,21	1337,66	47,67	6,92	23,17	70,01	11,15	37,36	27,02	-1851,00
Main case, γ	2750,33	430,77	123,47	81827,04	30991,44	456,52	41,67	139,58			19,04	193,66	980,48	1,18	5,07	16,98	264,21	1337,66	1,61	6,92	23,17	8,80	11,15	37,36	27,02	-1851,00
Prod. in China, δ	2750,33	746,19	8514,33	81827,04			0,24	0,81	12386,83	182,46	151,53	193,66	980,48	34,94	5,07	16,98	264,21	1337,66	47,67	6,92	23,17	70,01	11,15	37,36	27,02	-1851,00
Prod. in China, η	2750,33	746,19	123,47	81827,04			0,24	0,81	12386,83	182,46	19,04	193,66	980,48	1,18	5,07	16,98	264,21	1337,66	1,61	6,92	23,17	8,80	11,15	37,36	27,02	-1851,00
Coconut shells, δ		746,19	8514,33				0,24	0,81	12386,83	182,46	151,53	193,66	980,48	34,94	5,07	16,98	264,21	1337,66	47,67	6,92	23,17	70,01	11,15	37,36	27,02	-1851,00

Table G.21. Results in kg SO_2-eq per year from the hot spot analysis for the GAC process for the main case and the ten sensitivity analyses.

	Hot spot analysis detail GAC																			
GAC (kg SO2-eq/year)	Hard coal, production of virgin GAC	Container ship, hard coal to Belgium	Heavy fuel oil ship, hard coal to Belgium	Electricity, production of virgin GAC	Natural gas, production of virgin GAC	Production (activation) of virgin GAC	Diesel, virgin GAC to Rya WWTP	Truck-trailer, virgin GAC to Rya WWTP	Container ship, activated carbon Shanghai port to Gothenburg port	Heavy fuel oil ship, activated carbon Shanghai port to Gothenburg port	Electricity of other installations	Diesel, GAC to regeneration in Belgium	Truck-trailer, GAC to regeneration in Belgium	Diesel, regenerated GAC to Rya WWTP	Truck-trailer, regenerated GAC to Rya WWTP	Electricity, regeneration	Natural gas, regeneration	Regeneration	Heat generated during regeneration	Diesel, fuel for regeneration
Main case, α	458,15	5162,57	76,05	153,98	71,76	13630,80	6,94	23,25			454,60	125,04	418,80	62,04	207,81	456,26	237,74	7533,57		
Main case, μ	458,15	5162,57	76,05	11,58	71,76	13630,80	6,94	23,25			57,12	125,04	418,80	62,04	207,81	34,30	237,74	7533,57		
Prod. in China, ε	458,15			1418,32	124,30	13630,80	0,04	0,13	2063,40	30,39	454,60	125,04	418,80	62,04	207,81	456,26	237,74	7533,57		
Prod. in China, π	458,15			20,57	124,30	13630,80	0,04	0,13	2063,40	30,39	57,12	125,04	418,80	62,04	207,81	34,30	237,74	7533,57		
Main case-credited heat, α	458,15	5162,57	76,05	153,98	71,76	13630,80	6,94	23,25			454,60	125,04	418,80	62,04	207,81	456,26	237,74	7533,57	-1325,92	
Reg. at Rya WWTP, diesel, α	458,15	5162,48	76,05	153,98	71,76	13629,21	6,94	23,25			454,60					266,03		7533,57		690,71
Reg. at Rya WWTP, diesel-credited heat, α	458,15	5162,48	76,05	153,98	71,76	13629,21	6,94	23,25			454,60					266,03		7533,57	-1325,92	690,71
Reg. at Rya WWTP, natural gas-credited heat, α	458,15	5162,48	76,05	153,98	71,76	13629,21	6,94	23,25			454,60					266,03	100,90	7533,57	-1325,92	
Coconut shells, ε				1418,32	124,30		0,04	0,13	2063,40	30,39	454,60	125,04	418,80	8,99	30,12	456,26	237,74			
30000 bed volumes, α	305,43	3441,71	50,70	102,65	47,84	9087,20	4,63	15,50			303,07	83,36	279,20	41,36	138,54	304,17	158,49	5022,38		
10000 bed volumes, α	916,30	10325,14	152,09	307,96	143,52	27261,61	13,88	46,50			909,21	250,08	837,60	124,09	415,62	912,52	475,48	15067,14		

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY