UNIVERSITY OF SOUTHERN DENMARK
Environmental Engineering

ENVIRONMENTAL IMPACT ASSESSMENT OF DIFFERENT PHOSPHORUS RECOVERY TECHNOLOGIES IN EJBY MØLLE WASTEWATER TREATMENT PLANT

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ABSTRACT

Phosphorus depletion is a problem of our time with severe consequences. Being a fundamental bio element phosphorus accumulates in the food chain and eventually ends up in the sewage. Wastewater treatment has great potential in protection of natural waterbodies from nutrient overload. The awareness of this environmental problem has brought up new technologies to recover nutrients from sewage sludge. The study is a consequential life cycle assessment made for evaluate the environmental impacts of technologies that might be implemented in Ejby Mølle wastewater treatment plant operated by VandCenter Syd.

Four different scenarios were established, composting as the current recovery option. Even though composting is a common process, the product provides nutrient and fiber to the soil. There are more efficient options on the market. Sewage sludge incineration is the most controversial its product (sewage sludge ash) requires further purification for application as fertilizer in agriculture. Although, sewage sludge pyrolysis is a similar process, biochar is readily usable as fertilizer and soil amendment. While the first three technologies provide sludge management option, struvite precipitation only recovers phosphorus from the plant's supernatant. This efficient process provides struvite crystals that is clean and ready to use as fertilizer.

The models are a reference to reality, as some Danish companies who already implemented the technologies could kindly complement this study with data. The environmental impact assessment showed that sewage sludge pyrolysis has the highest avoided impact from all. Hence, the implementation of a pyrolysis unit would be the best option from an environmental perspective for VandCenter Syd. Nevertheless, when decisions are made financial factors must be deliberated. This paper serves as a strong basis for future projects in this direction.

Keywords:

Life cycle assessment; Consequential; Wastewater and sludge treatment; Phosphorus recovery;

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Author

Áron Mári

Contents

List of Figures

List of Tables

Abbreviations

AD – Anaerobic Digester

$Al_2(SO_4)_3$ - Alum

ATP – Adenosine triphosphate

BASE – Baseline scenario

$Ca(OH)_2$ - Lime

CEPT – Chemically enhanced primary treatment

CH_4 – Methane

CHP – Combined heat and power

CO_2 – Carbon dioxide

EBPR – Enhanced Biological Phosphorus Removal

FBR – Fluidized bed reactor

$Fe_2(SO_4)_3$ – Ferrous sulphate

$Fe^{2+}{}_3(PO_4)_2 * 8H_2O$ - Vivianite

$FeCl_2$ – Ferric chloride

$FeCl_3$ – Ferrous chloride

GW – Garden waste

$MgCl_2$ – Magnesium chloride

NaOH – Sodium hydroxide

NE – North East plant

$NH_4MgPO_4 \cdot 6H_2O$ - Struvite

NW – North west plant

PAOs – Phosphate accumulation organisms

PHB – Polyhydroxy butyrate

PO_4^{3-} - Phosphate

SS – Sewage sludge

SSA – Sewage sludge ash

SSB – sewage sludge biochar

SSI – Sewage sludge incineration

SSP – Sewage sludge pyrolysis

STP – Sewage Treatment Plant

STR – straws

STRUV – Struvite precipitation

TN – Total nitrogen

TOC – Total organic carbon

TP – Total phosphorus

TS – Total solids

VS – Volatile solids

WWTP – wastewater treatment plant

1. Introduction

In the 21st century, humanity is facing grave challenges. As a result of our changing climate, heavy rain events are more frequent. Average global temperature is rising leading to melting ice caps and ultimately sea level rise. Yet, our population is growing uncontrollably. The growing population causes alimentation problems and the depletion of natural resources. For better understanding, we must admit, in an ecological system everything connected. A good example of this is the phosphorus cycle.

1.1. Global Phosphorus depletion

Phosphorus is one of the most essential elements of nature. The phosphorus cycle connects all living beings in the world. There are a material (industrial) and biological (agricultural) aspect of phosphorus and these cannot be separated. Thanks to its highly reactive properties, the most generic form in nature called phosphate (PO_4^{3-}). It can be found in many different minerals, but apatite is the most important economically.

Phosphorus is the most mined mineral in the world. The last decades had a severe effect on P stock all over the world. Currently, Morocco has a state monopoly, with the highest global phosphate rock reserves. It has high export to Europe as well since the Finnish P stock was declared depleted. In 2014 the European Union declared P as a critical raw material, meaning the stocks are achieved severely small numbers. Estimations say that we have a severe problem, and the P stock depletion will be continued at the same rate. The depletion could be slowed down with higher efficiency fertilizers and the improvement of nutrient management in agriculture[1]–[5].

Some might ask, what can be the reason behind the depletion? The answer relies on P's biological properties. In the form of PO_4^{3-}, it can store energy for the cell in the form of adenosine triphosphate (ATP). It stores the in energy in its chemical bond and gives quick access to the cells in need of this energy. In addition to this phosphate is a part of our origin. Every link in a living being's DNA and RNA have phosphate. It can be said that phosphate is the key element of evolution and life itself[3].

In the middle age, at the dawn of urbanization, the concentration of people led to difficulties with alimentation. A solution to this problem appeared during the first industrial revolution. This was the discovery of chemical fertilizers. This artificial product let the farmers grow their crop into enormous yields. N fertilizers were the dominant chemical product spread on farmlands since P fertilizer was first synthesized only in the 19th century. Since then, both products are used extensively in the agricultural industry. Currently, 80% of P used in agriculture and the use of P fertilizers will increase during the upcoming decades due to the growth of the global population. Although the trends in P fertilizer use may vary in different countries, the global overuse is undebatable[1], [3], [6].

1.2. Phosphorus cycle

Before industrialization, the phosphorus cycle was not changed. Nowadays, the usage of phosphorus compounds in both agriculture and industry are linear. Only a few recycling paths exist. Figure 1 represents a simplified flow of phosphorus in our modern society, the above-mentioned recycling paths will be presented later[4], [7].

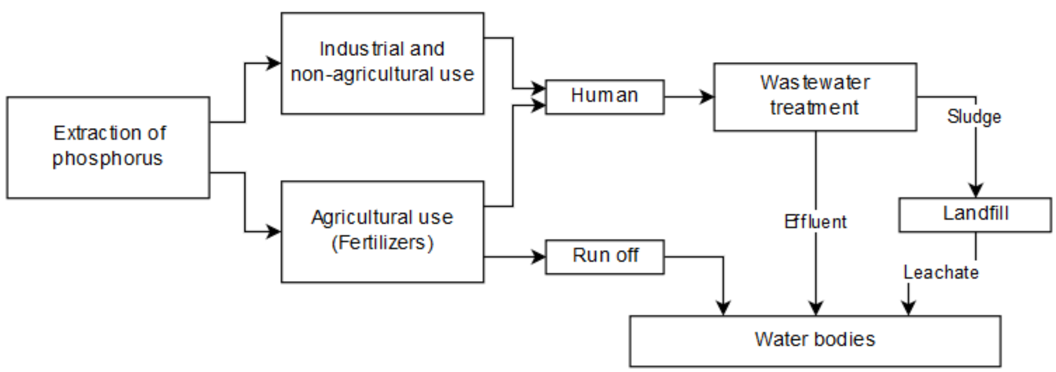

Figure 1: Modified phosphorus cycle(Based on: Desmidt *et al*., 2015*)*

After the extraction of apatite, the stock is shared between two major consumers, the industry, and the agriculture. In agriculture, phosphorus is used as fertilizer to enhance yield. In this phase, the accumulation starts because these crops will be fed to the animal livestock and humans become its consumers as well. Besides, arable lands are highly affected by precipitation and irrigation. Since these areas do not have enough potential to preserve water in the soil, phosphorus will be removed by runoff back to the water bodies.

Accumulation of phosphorus does not end with human consumption. It will leave the human body in the form of urine and excrete, which will eventually end up in wastewater treatment systems. Globally, not every treatment plant is optimised to remove all phosphorus from wastewater. However, some percentage is removed by conventional treatment plants as well. This usual rely on the country's legislation and state of development.

Depending on the treatment plants configuration some of the P will end up in the effluent, which is discharged straight to waterbodies. The other part of P can be found in sewage sludge. Usually, sewage sludge goes to landfilling, from where the precipitate slowly washes out P to natural water bodies [4].

Eutrophication was described as the natural ageing of lakes on a geological timescale. The direct translation of the expression means "well-nourished". Every natural process eutrophication also can be changed by human activity. The PO_4^{3-} rich wastewater effluent, leachate and runoff water all ending up in water bodies (Figure 1) as it was mentioned before. Since phosphate is a readily available nutrient for phytoplankton, even 0.02 mg/l P concentration in freshwaters can increase the speed of the process. The algae bloom and the increment of submerged aquatic vegetation leads to decrease of dissolved oxygen concentration and the shading of the ecosystems. Beside nutrient, light is another key part for healthy vegetation. Since there is not enough light the biomass starts to degrade. It causes the increment of sediment and hypoxia. This leads to dead benthic life, which also starts degrading. Eventually, the aquatic ecosystem stops functioning[8]–[10].

2. Literature review

To prevent a further decrease in P stocks, the current linear cycle has to be turned into a loop. There are different solutions. In this study, the centre of attention, as one of the most suitable P-recovery solution, is wastewater treatment.

To meet the strict discharge limits the last few decades has brought technical innovation in the developed countries. Thanks to the European Water Framework Directive, in EU countries the phosphorus discharge must be below 1 mg P/l and 2mg P/l depending on the population equivalent of the treatment plant. Some countries have even stricter regulation (like Denmark and other Nordic countries). As politicians debating stricter legislation, engineers are working on more environmental-friendly solutions that increase the efficiency of phosphorus recovery[11], [12].

In the following section, the basic principles of P-removal and recovery technologies will be presented. These processes work together in real-life application to enhance nutrient removal and recovery from wastewater streams. Besides, as an outlook to the future, this chapter gives insight into new recovery processes which stands for the forefront of this technology.

2.1. Phosphorus removal

The P removal processes can be divided into two main groups. First, chemical precipitation of phosphorus. Second, the biological removal of phosphorus.

The basic principle in chemical phosphorus removal is to create PO_4^{3-}precipitate with the addition of different chemicals. These chemicals can be added at various stages of the treatment processes and the P can be removed by the settlement of the insoluble phosphorus and remove it with the access sludge. The mostly used additives are lime [$Ca(OH)_2$], alum [$Al_2(SO_4)_3$] and ferric -[$FeCl_2$], ferrous chloride [$FeCl_3$] or ferrous sulphate [$Fe_2(SO_4)_3$]. Chemical P removal might seem to be the perfect process. However, there are many concerns about it. As a result of adding considerable amounts of chemicals to the process, the quality of the sludge and its reusability is significantly lower. Many treatment plants in developed countries have enhanced their removal processes addition of chemicals. It was a necessity to meet strict discharge limits[13].

Enhanced biological P removal (EBPR) is based on microorganisms able to accumulate phosphate, and they are called phosphorus accumulating organisms (PAOs). It is achieved by giving an advantageous environment to these microbes. To achieve this environment an anaerobic tank is placed in front of the aeration tank. In the anaerobic zone, the active sludge is mixed or stirred to increase the contact. Acetate is produced by fermentation of dissolved degradable organic material. Using the energy available from acetate using the energy provided by polyphosphates, PAOs assimilate volatile fatty acids and produce polyhydroxy butyrate (PHB) as an intracellular storage product. Therefore, in the cell, the amount of PHB is increased and the polyphosphate content is decreased. Later in the aerobic zone, the PHB is consumed. This supplies energy to bound orthophosphates from the solution into the cell, as polyphosphates. Eventually, the phosphorus ends up in the biomass. Part of this biomass is wasted and finally ends up in the sewage sludge[13].

Both processes produce sewage sludge which has a high concentration of different P species. Although the chemical precipitates could be readily available as a fertilizer the sludge contains pathogens and other undesired particles. This is true for the wasted activated sludge as well. To stabilize SS and release phosphate from the PAOs in many cases certain types of digestion process is used. Anaerobic digestion is not only suitable for stabilization and reduction of biomass, but it is able to produce methane. CH_4 can be burned in gas engines to produce electricity or to heat up the water in the boiler, for district heating[11], [13].

2.2. P-recovery technologies

In Denmark, organic fertilizer has a decades-old history. Using sewage sludge as fertilizer has many benefits. Although, there is one major drawback, which raises the concern of farmers. By adding sewage sludge (SS) to the farmlands, the soil could become contaminated by heavy metals and pathogens. At one-point Danish farmers even boycotted this type of sludge application[14].

There are many different options to resolve the doubt in public opinion. Both the EU and the Danish legislation are supporting the nutrient recycling scenarios. The Danish resource strategy in 2013 had set a goal to achieve at least 80% of P recycling from SS. In the document, only incineration and composting were mentioned, but there are other more efficient ways on the market[15].

2.2.1. Sewage sludge composting

SS composting is a low-cost solution for P recovery. Although it is highly dependent on regional legislation. In Denmark as well as in EU the legislation is prepared for this method. The use of sewage sludge compost is regulated by the European Commission's 86/278/EEC directive. It defines what type of lands can be fertilized with sewage sludge. According to the directive the agriculturally applied SS has to be analysed at least every six months. The frequency can be adjusted regionally by the local government or ministries[16], [17].

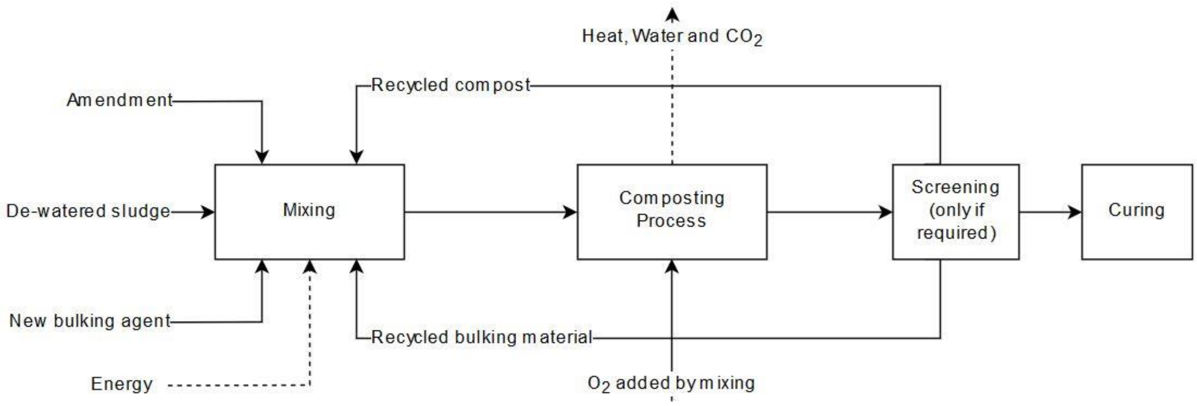

Figure 2: General composting process

The regular process of composting (Figure 2) consists of four to five parts. First, the SS is transported to a composting facility. Here SS got mixed with bulking material and some chemical amendments if it is necessary. Second, the mixed material will be placed on the open air, in the form of windrows and the maturing process begins. The microorganisms start decomposing the organic material which increases the temperature in the windrows. During the maturation, after five or seven days, the compost got mixed, to provide oxygen to the microorganisms. The composting process usually takes two months, while water and CO_2 leave the system. In some cases, the compost is screened right after to recycle bulking material. In addition, some of the compost is recycled and mixed into the raw input materials. After the composting process, the product is transferred to a maturation area. After 18 to 20 weeks the final product is stored, or used on agricultural lands right away[18].

Although, there are many concerns according to SS compost application in recent years. Some studies proved that SS compost can replace commercial fertilizers. In 2012 Ferreiro-domínguez, et al. was analysed the leachate from farmlands fertilized by SS. In the study, the group only focused on copper levels in the runoff water. They found this method to be safe. In 2018, Mañas and Heras also proved, there are no major differences between chemical fertilizers and SS fertilizer. Int his study they were focusing on the agricultural yield of winter wheat. It proves that SS fertilizer can be practical, more economical solution than chemical fertilizer. Besides the high nutrient content, it can improve the quality of the soil. This property of the compost can be useful in areas like Denmark, where the soil is low on fibres and carbon[19]–[21].

2.2.2. Sewage sludge incineration

One of the most controversial processes in sludge management is sludge incineration. In this process, the sewage sludge is converted from organic solids to biosolids, CO_2, water, and energy. The oxidisation is supported by liquid propane gas or natural gas. On the one hand, sewage sludge incineration has high potential in sterilizing the final product from toxic compounds and pathogens. Also, it has great volume reduction capability, which reduces disposal requirements. In addition, it has high potential in energy recovery.

On the other hand, SS incineration has its downsides as well. Depending on the composition of the final product (sewage sludge ash), it might be classified as a hazardous material. Even though the volume of SSA is lower, the deposition of hazardous waste can increase the operational cost. In addition, capital investment is high, due to the equipment costs and the necessity of highly trained operating staff. The overall energy recovery system is high, but the global emission of SS incineration can be harmful to the environment[13].

There are two main types of SS incineration. Co-incineration means the simultaneous combustion of solid waste and sewage sludge. This is rarely used due to the high-water content of SS. The main goal to reduce the joint cost of solid waste and SS incineration. A more common type is the mono-incineration when the sewage sludge is burned on the production site. Different approaches exist. Multiple - hearth incineration is used on large plants with highly skilled operators. In this process, the SS cakes are fed from the top of the hearth, as it lowers to the bottom it dries and burns in the system. The SSA is collected at the bottom of the furnace. Another type of SS incinerator is fluidized – bed furnace. This is a vertical, cylindrical shaped hearth. In its chamber, a sand bed is fluidized by a strong airflow from the bottom. The combustion happens, while the SS is added gradually to the system. This type of incineration is used on smaller plants[13].

The fate of SSA differs. The less appealing is landfilling. Here, only the energy recovery potential is exploited from the SS. Although, sewage sludge ash has a high concentration of nutrients and heavy metals. Due to its high heavy metal concertation, SSA is inadequate for agricultural purposes. If the legislation allows it can be used as a building material. Usually, it’s added to the cement. Application as a construction material is also bounded to heavy metal concentration.

Direct use of SSA in agriculture is often impossible and it has to be going through further purification. Such purification can be thermochemical treatment, wet phosphorus extraction or electrodialysis. Although they are existing processes, no scientific paper was found from full-scale evaluation of these systems. According to laboratory experiments, all these purification processes are a viable solution for removing heavy metal concentration. All of the phosphorus products from these were evaluated suitable for agricultural uses[22]–[24].

2.2.3. Sewage sludge Pyrolysis

Similarly, to incineration, pyrolysis is also a thermal process. Instead of total combustion of SS, this process takes place in theoretically inert atmosphere, where the organic materials decompose into vapours and solid product. The operational conditions are dependent on what type of final product must be obtained. This could be solid, biochar; liquid, bio-oil; or syn-gas, which is produced by gasification of organic materials and used as fuel. Bio-oil is produced during fast pyrolysis and used as a basis to produce other chemicals, or also as a fuel. Slow pyrolysis has higher retention times, and the solid product yield is higher in this case. Biochar, on the other hand, has different purposes. It can be used as a filter for contaminant or soil amendment to improve porosity, water retention, chemical composition[25], [26].

The composition of biochar is highly dependent on the properties of the sewage sludge. Due to its porosity and surface area, biochar efficiently absorbs toxins and pollutants from liquid and gas states. Therefore, it is possible to use as an alternative to active carbon in filtering processes. Agronomic application of biochar has been always controversial due to its heavy metal concentration. Depending on pyrolysis temperature biochar yield and composition can be different. When higher temperature and retention time is applied the heavy metals in biochar form stronger chemical bonds. Therefore, during the land application, the leaching will be less significant. To further improve biochar quality stabilizing compounds could be mixed to the material. Recent studies showed the effectiveness of supplements. However, they recommended long term investigation[26]–[29].

In contrary biochar has many positive effects on soil. Due to its high nutrient concentration, pore structure, surface area and chemistry sewage sludge biochar (SSB) increase soil quality and fertility. The different temperatures in the reactor not only helps to keep heavy metals in biochar but also increases the concentrations of P and K. Later, the nutrients in biochar released slowly into the soil. Thanks to its chemistry, SSB is inhibited the denitrification in the soil, thus reducing the N_2O emissions. In addition, its production mitigates climate change, because biomass is turned into a more stable form of carbon which can stay in the soil for decades[26], [30]–[32].

2.2.4. Struvite precipitation

Struvite [$NH_4MgPO_4 \cdot 6H_2O$] is a common mineral that occurs in biological systems. Usually, it appears in the urine, or rotting materials with high organic activity, like guano or manure. Struvite is also known in wastewater treatment as a scale problem. First descriptions were in anaerobic digesters, where a thick layer formed on the walls of the reactors. Later, it was described as struvite. It has been proved that high sheer areas (fitting of pipelines and valves) where supernatants flow with high PO_4^{3-} concentration, struvite precipitate spontaneously[33], [34].

Due to its capabilities, struvite became a new area of interest in phosphorus recovery. When a precipitation process is applied at a WWTP the product is a clean, easy to manage, slow release crystalline fertilizer. The struvite pearls are easy to store and spread on farmlands. According to Corre *et al.* the key for every precipitation process to reach 1:1:1 molar ratio of cations and the anion. There are three major categories in struvite precipitation:

a. Selective ion exchange;
b. Stirred reactors;
c. And Fluidized bed reactors.

Selective ion exchange is a process were wastewater supernatant flows through two cation columns and then two anionic columns. After the PO_4^{3-} and NO_3^- enriched liquid flows to a tank or reactor, ere with the addition of $MgCl_2$, NaOH and H_3PO_4 struvite precipitation happen. This process does not produce surplus sludge, and it runs with high (90%) removal efficiencies. The limiting factor here is the lack of phosphate is the supernatant.

In stirred reactors, the struvite precipitates using continuous chemical dosing to keep the wished molar ratio. Magnesium-chloride is added as a cation supply while NaOH is added to maintain the necessary pH for the precipitation. On one hand, this is a simple process and it has high recovery efficiencies. On the other hand, the stirring propeller could fail, and the energy demand is high in the system thanks to the high rotation speed (necessity to maintain a homogenous solution).

Fluidized bed or air-agitated reactors are the most common use of struvite precipitation processes. In this process, struvite is crystallized spontaneously from the supernatant with the addition of necessary chemicals. Usually $MgCl_2$ and NaOH. The process is also favourable because it can fit to already existing STP and operates with continuous supernatant and chemical feed[34], [35].

The greatest advantage of struvite compared to chemical fertilizers is the low solubility. Being a slow release fertilizer, struvite can be applied on a high variety of soil, preferably with neutral and low pH.

Recovery of struvite from wastewater supernatant is advantageous from an agricultural point of view. Since the product is clean, effective, and manageable. However, its economic state is questionable. Usually, the capital investment is already high. In addition, magnesium salts are expensive factors in the operation. Although, its considerable fertilizing properties, the high capex and especially its high opex can be a down-turner for companies interested in P recovery. Sadly, the value of wastewater precipitated struvite is low. Thus the economic turnover is very long[35]–[38].

2.2.5. Vivianite precipitation

Vivianite [$Fe^{2+}{}_3(PO_4)_2 * 8H_2O$], a ferrous phosphate crystal which can be found mostly in the bounded form in the Earth's crust. In the last few years researcher observed this crystal in the wastewater treatment plant. For a few years, the potential in this material was neglected. However, the urge to find new ways and methods for more efficient phosphate recovery from wastewater has driven the attention of the field to this crystal. Thanks to its new interest there is a noticeable amount of research published in recent years. Unfortunately, in these papers, there is a lot of contradiction and lack of information.

In 1997 Nancy *et al.* analysed sludge samples from different sludge treatment processes. They observed that the anaerobic digester (AD) sludge contained a high percentage of vivianite. In 2015 Wilfert *et al.*, published an article about the possibilities of iron in wastewater treatment and sludge management. They revealed that most of the current P recovery processes are not economic. On the other hand, in many treatment plants, the operation is expanded by iron dosing, to enhance the flocculation and the P removal from the sludge [40]. The next year (2016) Wilfert *et al.* have support this, when the research group published a study about two STPs in the Netherlands to examine the iron chemistry in these systems. It turned out the main precipitates in the treatment plants where the operation is enhanced by iron were vivianite and pyrite[7], [39]–[41].

Cheng *et al.* (2015) proved in laboratory experiments that AD is suitable for P recovery and it is possible via vivianite precipitation. The process can provide the basis for an economically feasible and environmentally friendly P recovery process. However, another study was published which stated that the chemistry behind is far from understood in addition to this $FeCl_2$ addition to AD digestion hampered the CH_4 yield due to the acidic pH conditions [43]. Vivianite precipitation is also proved to be sensitive on pH and the best suitable pH for the process is 7 [9]. Further, the possibility of vivianite in AD was supported by this paper[9], [42], [43].

$FeCl_2$ inhibit the methane yield in AD, thus other ways must be found. Laboratory experiments showed that adding scrap iron into AD sludge has positive effects. Sulphate can bound to scrap iron which helps to reduce the H_2S formation. In addition, when scrap iron was dosed, the CH_4 yield was raised significantly [44]. Enhancement of AD by adding scrap iron might have some positive effects on vivianite precipitations. Since the optimal conditions for vivianite formation are anoxic and non-sulphuric environment [17]. If these conditions are satisfactory, recovery efficiencies are high. Nonetheless, with purification methods, it might be increased. To achieve this goal bigger crystals are needed which makes the separation easier[17], [44], [45].

In conclusion, vivianite is a stable crystal. It can provide a possible alternative for P recovery from sludge in STPs where iron addition is used for COD and PO_4^{3-} removal in the treatment line [45]. Unluckily, there is a long way to go until a conventional process can be established.

2.3. Life cycle assessment in wastewater treatment

During the research for literature, the main goal was to keep the geological scale at least on the same continent. Most of the paper found related to the topic are from the European Union. It is easier to compare these papers since the legislation and the data bases are similar. Sadly, a limited amount of reliable research was found on the topic. Therefore, to make the literature review more comprehensive two papers from Canada and the United States were included. During the research papers were selected that are matches the technologies in this study. This helped put in context the environmental impact assessment results. In the following, the main point of the assessed literature will be concluded.

Life cycle assessment has been a proven tool in WWT decision making process during the last two decades[46]. Recent literature showed although the LCAs follows the ISO standards, the different parameters (functional unit, methodology, impact assessment categories) are distributed on a wide range. Therefore it has been recommended by Corominas *et al.* (2013) a further development in life cycle assessment standards This would help maintain the quality of the studies in the field. If a holistic view applied in the LCA modelling new technologies can be also assessed.

As it is about different technologies, the scope of the system changes. It is one of the most challenging processes of the WW LCAs. According to Chen, Ngo and Guo (2012), some studies are excluding major environmental contributors of the upstream and downstream processes. Other studies include upstream processes such as the water collection and transport as well as the core (treatment) and downstream processes (sludge management). This can lead to an intricate dataset. Managing as such, on one hand, is labour intensive and costly. On the other hand, reduce uncertainties in the study. Some studies only include operation processes [49]. In these cases, one should be careful, and keep the focus on the material and energy flows that might contribute highly to the impact categories.

Defining the functional unit is also challenging and no guideline applied on it WWT. There were four main functional units (FU) selected in the assessed studies. Two of them were only selected once, such as 1 m3 of wastewater treated, and 1 PE^{-1} a^{-1}, related to P recycling and treatment (Table 1). According to Corominas *et al.* (2013) selecting the treated volume of water isn't representative when two systems are compared. In their study, they recommend more specific characteristic chosen for the functional unit. It could be a good idea to choose a parameter with a conventional and widely accepted analytical method. From the four main FU, the most used was 1 ton of dry matter used, out of eleven studies 6 selected some type of solids. Only two of them used the amount of removed orthophosphate.

A life cycle inventory (LCI) has to be established when the scope and the FU are well defined. There are different approaches to do that. Some study used statistical data to quantify the process flows [50]. Other studies LCI are based on mathematical modelling [51], [52]. The data from mathematical simulation has also uncertainties which have to be considered. The real, full-scale applications of the systems might be different from the flows defined in the computer models.
Similarly, to the mathematical models, material and energy flow analysis also a proven tool to define upstream and downstream in a WWTP[53]. Material flow analysis can be coupled with LCA later in the impact assessment as well.

Table 1: Conclusion of life cycle assessmentstudies

Author	Country	System	Functional unit	Impact categories	Method
Niero *et al*., 2014	Italy – Denmark	Different STPs grouped in 4 different types	1 m3 of inlet wastewater	○ Global warming ○ Fossil depletion ○ Human toxicity ○ 3 eutrophication and ecotoxicity	ReCiPe
Sørensen, Dall and Habib, 2015	Denmark	Assessment of P recovery from WAS	1 ton of dry matter	○ Climate change ○ Photochemical ozone formation ○ Acidification ○ Biogenic carbon	ILCD, EDIP resource only update to 2012
Rodriguez-Garcia *et al*., 2014	Spain – Italy	Nutrient removal from AD supernatant	1 kg PO_4^{3-} removed	○ Global warming ○ Acidification potential ○ Eutrophication potential ○ POP ○ Toxicity related impacts	USEtox, CML
Gourdet *et al*., 2017	France	Combined AD and mechanical dewatering	1 ton of TS input	○ Climate Change ○ Terrestrial acidification ○ Freshwater eutrophication ○ Human toxicity ○ Ionizing radiation	ReCiPe baseline method
Hospido *et al*., 2005	Spain	Comparison of AD vs. Thermal processes	1 ton of dry mass	○ Eutrophication ○ Stratospheric ozone depletion ○ Global warming potential ○ POFP ○ Human toxicity	CML method
Heimersson *et al*., 2017	Sweden	SS anaerobic digestion and land application	1 dry tonne of sludge	○ Global warming potential ○ Acidification ○ POFP ○ Freshwater, marine, and terrestrial Eutrophication	ILCD

Willén *et al.*, 2017	Sweden	Digested sludge storage and land application	SS containing P replacing 1 kg of chemical P fertilizer	○ Global warming potential ○ Acidification potential ○ Eutrophication potential ○ Primary energy use	CML 2001
Yoshida *et al.*, 2018	Denmark	Five sludge treatment scenarios	Thousand kg of mixed sludge (treatment and disposal)	○ Human toxicity non-carcinogenic effects ○ Ecotoxicity ○ Freshwater eutrophication ○ Terrestrial eutrophication ○ Terrestrial acidification ○ Particulate matter formation ○ Climate change ○ Photochemical oxidant formation	ILCD
Barry *et al.*, 2019	Canada	Pyrolysis as sewage sludge treatment	Sludge required to produce 1 ton of biochar	○ Global warming potential over 100 years ○ Freshwater ecotoxicity	CML method 2015
Sena and Hicks, 2018	USA	Struvite precipitation LCA review	Usual used FU differ trough studies, but 1 kg PO43- recovered is common	○ Global warming potential ○ Eutrophication potential ○ Cumulative energy demand	Varies throughout studies
Amann *et al.*, 2018	Austria	Struvite recovery processes	1 PE^{-1} a^{-1}, related to P recycling and treatment	○ Cumulative energy demand ○ Acidification potential ○ Global warming potential	Ecoinvent ver. 3.3, varies in different impact categories

Figure 3concludes the main pollutants emitted to the environment. According to this figure, the main impact categories in a life cycle studies would be global warming related thanks to the greenhouse gases it emits. Due to its nutrient emissions to the water bodies and soil, the eutrophication should be also considered. In wastewater treatment to enhance its capacity and efficiency chemicals are used. Therefore, it is interesting to see how a treatment process performed in a toxicity related category [47], [61].

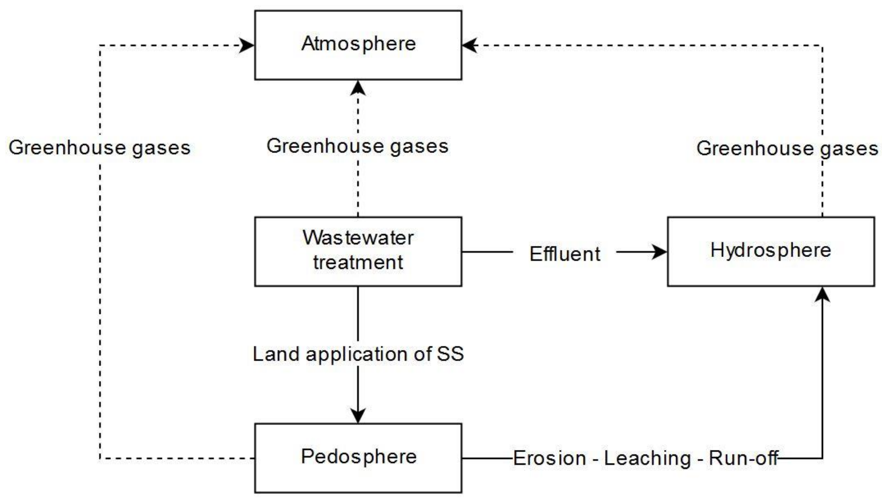

Figure 3: The main pollution flows of wastewater treatment processes (Based on Zang *et al.*, 2015)

These thoughts are justified by the assessed literature as well. All the studies included the four main impact categories in their assessment. However, to achieve a comprehensive LCA, all the impact categories has to be examined.

There is no scientific consensus in selecting the impact assessment methods. In Table 1 is it visible that five main methodologies were used. The type of methodology is also an important factor to consider. Midpoint methods are usually more precise and transparent in characterization values. Especially when climate change or acidification is assessed with it. In contrary when toxicity related categories are also in the scope midpoint methods might not perform adequate[63].
When decision support is in the goal could be a clever idea to include an endpoint method to the study. Endpoint methods might be less precise in characterization, but the results are easier to present and understand [63].

From eleven study the most used lice cycle methodologies were the different versions of CML methods. It has been used in for studies. Three of them were only using this methodology [55],

[57], [59], and one of them [49] used as a secondary method beside USEtox (which has been used to identify toxicity related categories). The second most was the ILCD method 3 study [54], [58], [64] used is as a primary method and only one [54] expanded this with the EDIP method, which is used for resource depletion analysis. Only two studies [50], [51] used ReCiPe as the main methodology.
According to Corominas *et al.* (2013), the application of the methodology is highly influenced by the geographical scope of the life cycle assessment. The choice of the method has to be a logical decision according to the scope in every case.

According to the reviewed studies in general in wastewater treatment, there is a shift of paradigm during the last decade. Wastewater treatment is not only a facility reducing the impact on eutrophication of natural water bodies, but treatment plants transform more and more into urban mines to recover precious materials from the sewage and the sludge as well [47]. The reviewed articles mostly criticize that there is no consensus and guideline. The papers also urge to form these guidelines, because LCAs can provide valuable data for the developers of new technologies [47], [65]

2.4. VandCenter Syd – Ejby Mølle

VandCenter Syd is one of the oldest water companies in Denmark, as it was founded in the mid-19th century. Currently, it operates the freshwater distribution and wastewater treatment (municipal and industrial) all over Fyn. The company runs 3 wastewater treatment plant in Odense and 5 more on the island.

Ejby Mølle is one of the biggest treatment plants the company owns. To meet the strict Danish phosphorus discharge limits the enhanced biological phosphorus removal is supplemented with chemical precipitation in the primary treatment. Last year (2018) the plant has almost reached the net zero emission profile. The sewage sludge produced is stabilized in an anaerobic digester. It produces methane which is then used for electricity and district heating production. The phosphorus rich digestate after the final dewatering is collected by Odense Miljø Nord and gets composted. The final product – compost – is spread over farmlands by farmers around the island, and some percentage on Jutland. Although, a significant amount of the nutrient of sewage sludge is salvaged this way, there are new, more efficient, and economical ways to recover P from sewage sludge.

The main goal of the study is to compare phosphorus recovery processes that are suitable for Ejby Mølle. This comparison only involves environmental aspects. The economic aspect of these installations requires further investigation. In the last decades, life cycle assessments are proved to be a reliable tool for evaluating and supporting decision making in such situations[47].

2.5. Research question and hypothesis

It is possible to improve P recovery at Ejby Mølle. In addition to this, the recovery technologies on the market are suitable for this treatment plant as well. Some of the products are more desirable than the other. Executing a life cycle assessment of the applicable processes will define their environmental impact. Therefore, the results of the paper can be used as a guide to help and support the company's decision-making procedure. Due to the limitation of the method, the study will not expand to the application of the precipitate. However, the results might be interesting for local authorities and farmers as well.

The following questions will be answered by this study:

- What is the current environmental impact of Ejby Mølle plant?
- What kind of technologies exists for phosphorus recovery? How the impacts change when the different technologies are applied?
- What is the current state in life cycle assessment in wastewater technology?

3. Materials and methods

3.1. Goal and Scope definition

The goal of the paper to provide a comprehensive environmental assessment of different phosphorus recovery processes. To achieve a robust and transparent analysis, that can be compared with other studies, the relevant ISO 14040:2006 LCA standard was followed all along with the execution. (Further information: [66]

The study carried out for support VCS' decision-making process. In developed countries the legislation promoting the application of innovative technologies. Therefore, the company looking for phosphorus recovery options.The main target of the study is the board of VCS. Additional targets, all the companies and researchers involved phosphorus recovery processes. Table 2 concludes all the influential parties, supplying all information and data for the smooth execution of the study.

Table 2: Influential parties of the study

VandCenter Syd	Providing problem basis and major datasets
Odense Miljø Nord	Datasets and other information
Biofos	Datasets for incineration scenarios
AquaGreen	Datasets for pyrolysis scenario
AarhusVand	Datasets and other information for struvite scenario

The study follows the consequential approach. It does not only consider the effect on the environment but also takes in account the changes on the market. The consequential approach is rarely used in decision support and especially in the wastewater treatment. Hence, the secondary goal of the study to increase the knowledge and experience in consequential approach.

3.1.1. Scenarios

As the purpose of the study to compare P-recovery technologies implemented to Ejby Mølle, the scenarios of the assessments were designed that way. Four main scenarios will compare the impacts of the technologies.

1. Base [Baseline]: This scenario describes the current practice of sewage treatment.
2. SSI [Sewage sludge incineration]: The scenario created as a mono-incineration plant would be implemented to the baseline system. Since it's not only a P recovery process but a sludge management option as well, composting is excluded.
3. SSP [Sewage sludge pyrolysis]: A pyrolysis unit is implemented to the system. As it is a sludge management process too, the composting is excluded.
4. STRUV [Struvite precipitation]: A precipitation unit is added to the treatment process. This unit is only for P recovery; thus, composting is still part of the system.

Originally a 5th scenario has been planned to be assessed. It would have included the vivianite precipitation. However, there was no available full-scale implementation of this process.

Different studies apply system boundaries. Some of them include the construction phase and the end of life stage in the life cycle assessment. Although it gives a more complex picture of the wastewater treatment and its life cycle, these stages are highly influencing the result of the treatment itself. This project is made for assessing different recovery technologies. It was assumed that if the construction and end of life stage would have been included in the study, the impact of the recovery processes would have been minor in comparison.

Originally the geological scope would have been narrowed down to Odense as the treatment plant is found in that city. However, during the data collection, this was widened. Therefore, the geological scope becomes Denmark. This is influenced not only the data collection but the lifecycle modelling as well.

The scenarios describe future possibilities with present technologies. The temporal scope of the study is the present situation and it point forward five years to the future. This is a timescale on one of the scenarios might become a real-life application.

3.2. Functional Unit

The functional unit of the system is "treatment of 1 ton of dry matter". This is the only parameter that provides references between the systems. According to the literature review, when two or more different technologies has to be compared selecting the treated wastewater of the system won't give a comprehensive reference. In this case, the sludge characteristic would have had to be modelled. This would increase the uncertainties of the study depending on the data quality of the sludge composition. The other possibility for the functional unit – according to other literature – would have been the amount of ortho-PO_4^{3-} removed. To keep the study more comparable, it was obvious the dry matter input is the better choice.

3.3. Modelling Framework

The life cycle modelling is based on EcoIncvent 3 library. The library was managed in SimaPro 8.5.0.0 (Student version). The software is developed in Switzerland and became a reliable interface for life cycle modelling. For impact assessment, three different methodologies were selected. First the ILCD 2011 Midpoint+ method for midpoint environmental impact assessment. Then Recipe 2016, Endpoint (H) method for endpoint assessment. In addition to this EDIP/UMIP 97 (resource only – updated) method was selected for resource analysis, because the technologies are affected by scarce materials like phosphorus and magnesium.

3.4. System description

The baseline system can be divided into three different sections. First, the wastewater treatment itself, where P is removed from the influent. Second is the combined heat and power. Here, the biogas produced during anaerobic digestion is burnt in gas engines and gas boilers. The energy produced is partly used by the treatment plant and partly fed back to the electricity grid and the district heating. The third part of the system is the sludge management. The dewatered sludge (DS) is transported to a composting plant. The compost is later used on agricultural land as fertilizer.

3.4.1. Wastewater treatment

The influent wastewater is produced by the city of Odense. At Ejby Mølle some of the industrial wastewater is also treated. In the study, the influent flow has a predetermined characteristic (Table 3) based on laboratory measurement.

Table 3: Predetermined influent characteristic

Name	Influent
	[mg/l]
NH4	26.62
TN	45.23
TP	6.61
COD	729.98
SS	337.39

The influent runs into the preliminary treatment where most of the scum (oil, grease, and rugs) is removed. After a sand filter, it flows to the next process. This process does not have major influence on the system as it only a physical treatment. Therefore, it is not represented on the process flow charts.

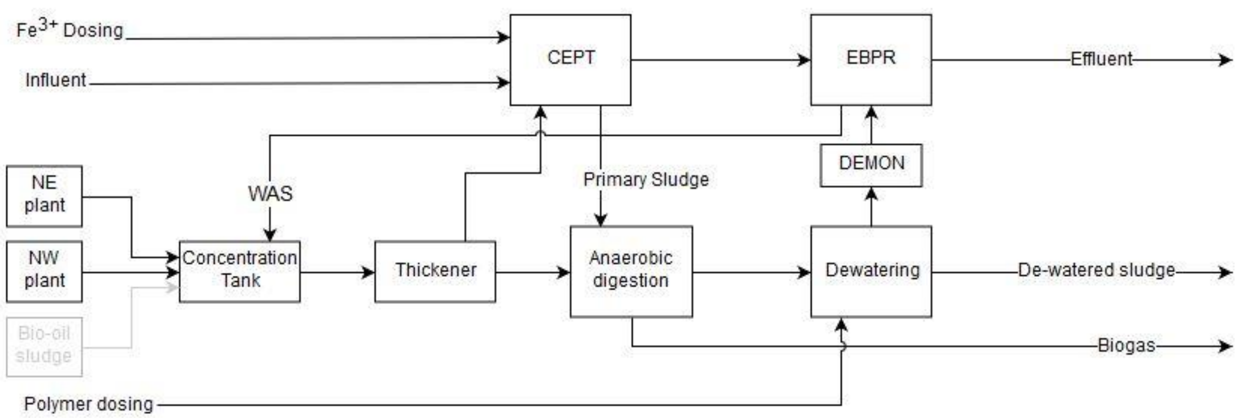

Figure 4: Wastewater treatment, process flows

In Figure 4 an input is highlighted with a light grey. This is the input of the bio-oil sludge from Emmelev. The surplus of sludge they produce in their bio-oil plant is treated in Ejby Mølle's Anaerobic digestion process. This flow became a systematic error in the wastewater treatment process. Earlier studies did not show important P flows in it. However, during the data collection process, it turned out there is a significant amount added to the system. The dataset was not consistent, it had been excluded from all the scenarios.

3.4.1.1. Primary treatment

This process removes a significant part of the suspended solids and other floating material (oil, grease, rugs) which was not eliminated in the preliminary treatment. On one hand, the removal of the scum helps to protect the plant machinery. On the other hand, the removal of bigger particles helps to reduce the load on secondary treatment. Usually, sedimentation is done by gravity. In the case of Ejby Mølle, we can talk about a chemically enhanced primary treatment (CEPT). This type of process can further improve the reduction of downstream process load [67]. In addition to this, it provides smaller and easily biodegradable particles for secondary treatment. Different flocculants exist to improve the process. In this case, iron salt [$Fe_2(SO_4)_3$] is added. This works as a flocculant and reduces the amount of soluble phosphate by precipitation. The primary sludge is taken and mixed with the other sludge flows in the anaerobic digester.

3.4.1.2. Enhanced Biological phosphorus removal

The effluent for CEPT is treated in the secondary treatment. In the enhanced biological phosphorus removal (EBPR), PAOs are binding the soluble phosphorus into their cell. It is achieved by providing them with an advantageous environment. Some of the activated sludge is recycled in this process, to maintain the efficiency. A smaller part of it is wasted and flows into a concentration tank. The effluent is released to Odense Å, and it has a predetermined characteristic throughout the scenarios (Table 4).

Table 4: Predetermined effluent characteristics

Name	Effluent
	[mg/l]
NH4	0.54
NO3	2.41
TN	4.20
TP	0.31
COD	26.11
SS	1.10

3.4.1.3. Anaerobic digestion

This one of the oldest process used for sewage sludge stabilization. Anaerobic digestion turns organic solids into biogas in the absence of oxygen. The raw 3 different sludge flows are mixed in a concentration tank and forwarded to a thickener to increase solid concentration. The reject water from here is carried to the CEPT. Thickened sludge flows into anaerobic digestion. There the raw sludge transformed into soluble organics in the hydrolysis process. These will form organic acids, hydrogen, and carbon-dioxide after the acidogenesis. Then the methanogen microorganisms turn these substances into CH_4 and CO_2[13]. Biogas with high percentages of CH_4 is carried to the Combined heat and power system.

3.4.1.4. Final dewatering

The digestate from the anaerobic digestion flows into the final dewatering. At Ejby Mølle centrifugal dewatering applied. This type of dewatering requires polymer addition. Polyacrylamide is the most widely used chemical in these processes. This compound is applied in this facility as well. After the dewatering sludge cakes has 25% dry matter. The sludge characteristics (Table 5) is also predetermined throughout the scenarios.

Table 5: Ejby Mølle dewatered sludge characteristics

NAME	UNIT	VALUE
TSS	*%*	25
VSS	*%*	59
TN	*mg/kg*	49000
K	*mg/kg*	1051
MG	*mg/kg*	7308
TP	*mg/kg*	29208

The reject water of the final dewatering process contains a high concentration of soluble nutrients. The ammonia is treated in a DEMON process. Wherefrom, the supernatant is delivered back to the EBPR process for further nutrient removal.

3.4.2. Combined heat and power

The second part of the system is straight forward and presented on Figure 5. A part of the biogas produced in the anaerobic digestion got burned in gas engines. At Ejby Mølle two engine is operational. One part of the electricity produced is used in the plant, the rest is directed to the grid. Another part of the biogas is used for heating boilers providing hot water for the district heating system. The main advantage to have a zero-emission energy source right at the facility is to further decrease the environmental impacts of it.

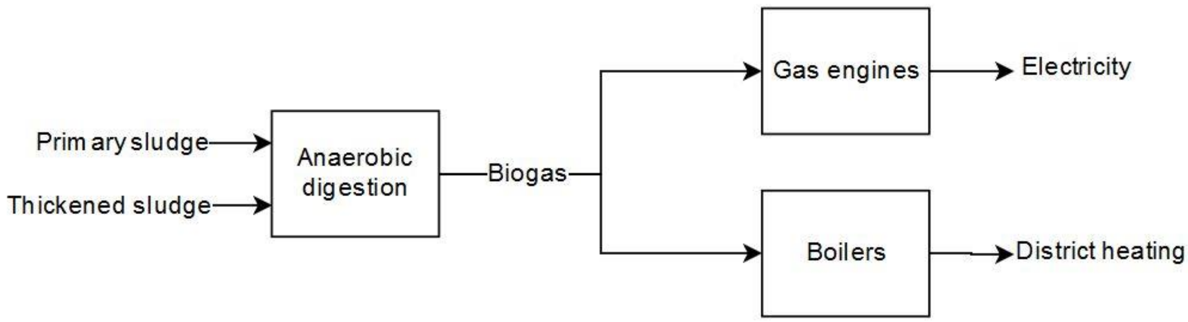

Figure 5: Combined heat and power process flows(own)

3.4.3. Composting

After the final dewatering sewage sludge cakes are loaded into a truck and transported 13 km away Ejby Mølle to the north from Odense. The company (Odense Miljø Nord) runs a composting facility, where the sewage sludge gets its last treatment before it is used on agricultural lands.

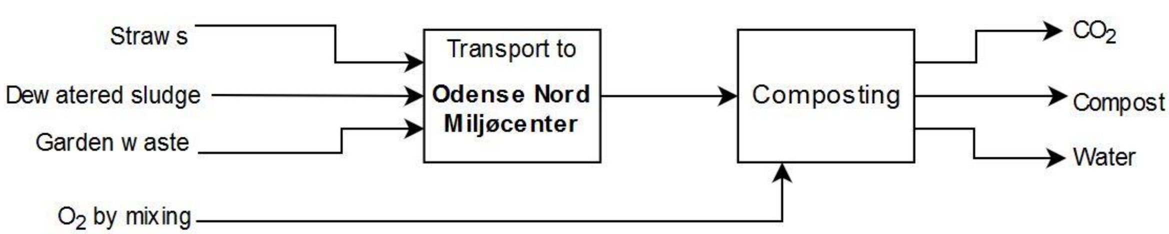

Figure 6: Composting process flows (own)

Figure 6 represents the main flows of the composting process. At the facility dewatered sludge is mixed with garden waste and straws. The ratios in the mixture are depending on temperature and humidity, and other factors as well. After the mixing, windrows are formed, and the composting process starts. After five to ten weeks, the windrows are mixed to provide O_2. During the next 8 weeks, the windrows reduce in volume, and compost will be formed. The compost is going to a maturation process for further purification. Later it will be stored until application. The complete process takes 18 to 20 weeks, and the final product is spread on arable land between April and October [18], [21]. The EU legislation is relatively strict in the application of sewage sludge application [16]. To meet the prescribed standards and meet the required quality laboratory analysis is executed on the final product.

3.5. Process Flows

According to the literature review, the scope of wastewater treatment LCAs could vary. Some studies include the construction stage and the lifetime of the plant. This process has a usual higher impact compared to the actual use phase. As this project focusing on recovery technologies the only, the use phase was considered in life cycle modelling.

3.5.1. Baseline scenario

The baseline scenario was already detailed above. Figure 7 concludes the main flows and groups of the unit process of the system. The wastewater treatment with the energy and the chemical inputs, as well as the three outputs of the system, the effluent to Odense Å, the biogas and the dewatered sludge. The biogas id turned into electricity and district heating during the combined heat and power process. And the sludge is transported to the composting facility where compost is produced from it.

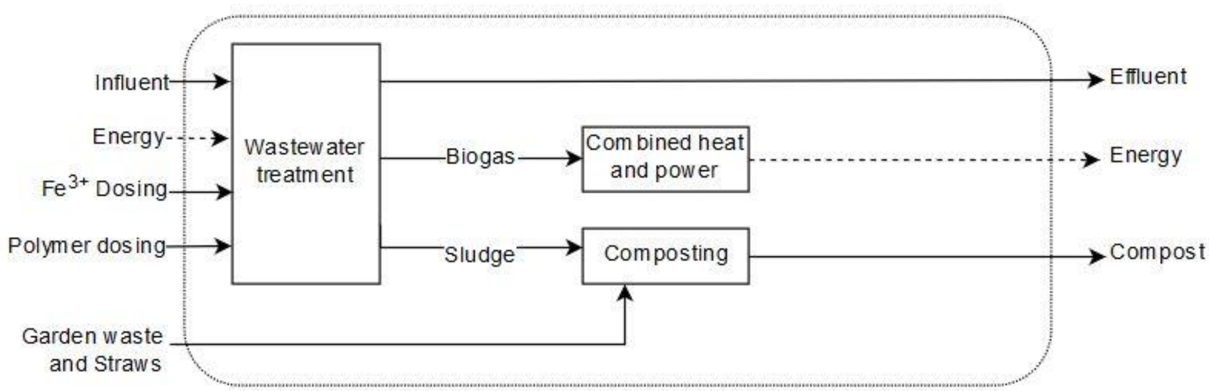

Figure 7: Baseline scenario flows (own)

3.5.2. Sewage sludge incineration

The second scenario (sewage sludge incineration) a little bit different from the other three scenarios. The main difference in the flows that biogas is used as fuel in the incineration. According to the incineration dataset to manage the whole sludge amount, all of the biogas has to be during the incineration process. Figure 8 concludes the main mass and energy flows of the scenario.

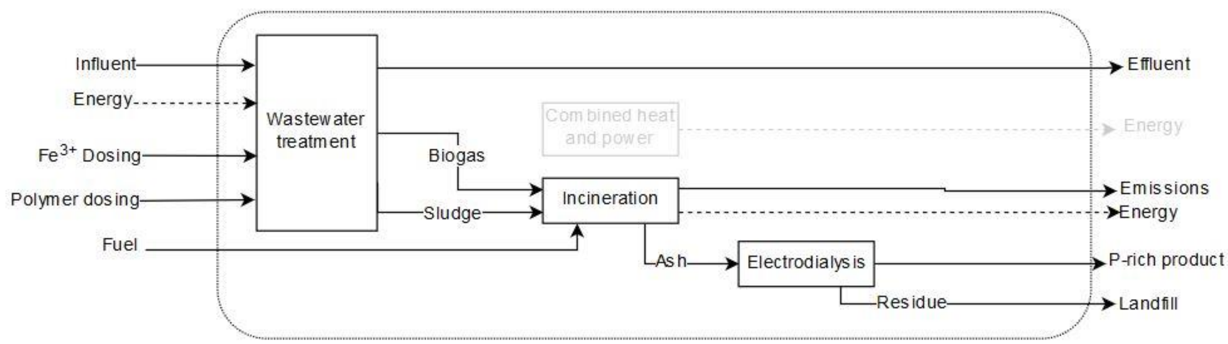

Figure 8: SSI scenario flows (own)

The incineration process (Figure 9) has been modelled based on Biofos' Avedøre and Lynette plants. The dewatered sludge enters a dryer where hot water dries the sludge further increase the dry matter content. While the sludge is drying the excess steam is cooled down in a condenser. The dried sludge enters the fluidized bed furnace. Here the sludge is floated with high air flows from the bottom of the furnace while it is combusted. On the side of the furnace, a boiler uses the same energy to produce hot water for the drying process. It also provides hot water for the district heating. The hot air and the residues after combustion are treated in filters and condensers. Wherefrom, the heat is transferred to district heating and the ash leaves the system.

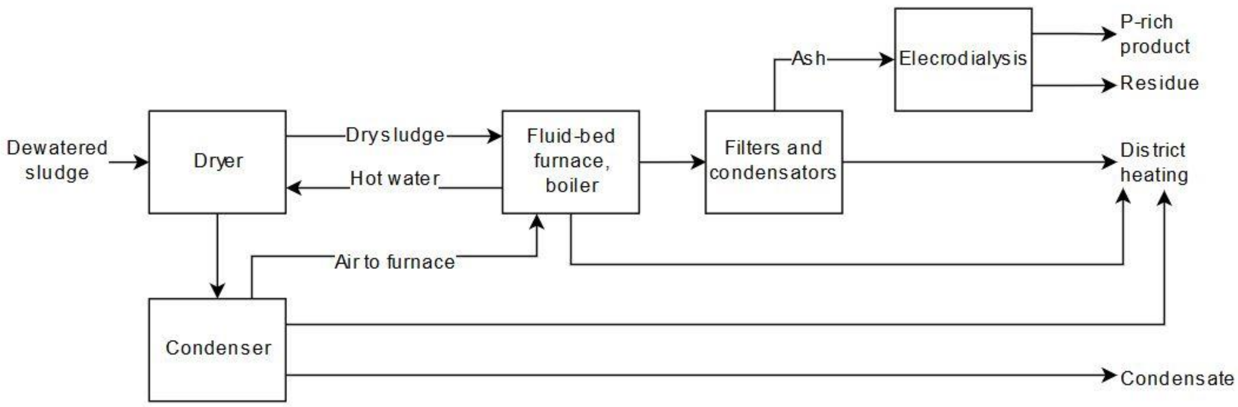

Figure 9: Simplified diagram of sewage sludge incineration (own)

To recover the valuable nutrient from the sewage sludge it requires further treatment, as SSA is not possible to apply on arable land due to its high heavy metals concentration [68]. Danish policies are preparing for the solution to eliminate general landfilling of SSA. According to Rosendal (2015), there are initiatives to handle sewage sludge ash by testing new technologies and establishing separate landfills for SSA. Commercial application of electrodialysis has not been found, it was selected because it seemed a more efficient alternative than landfill. According to Biofos and other Danish companies collaboration on resource recovery from wastewater, the VARGA project also applies this technology to produce fertilizer from SSA [70].

3.5.3. Sewage sludge pyrolysis

In Figure 10 the third scenario is concluded. Sewage sludge pyrolysis scenario is again applying combined heat and power to produce energy. Some of the biogas produced in the anaerobic digestion process is fuelling the pyrolysis process itself. After dewatering the digested sludge, it delivered to the pyrolysis process. The process is calibrated in a way that the final product will be biochar.

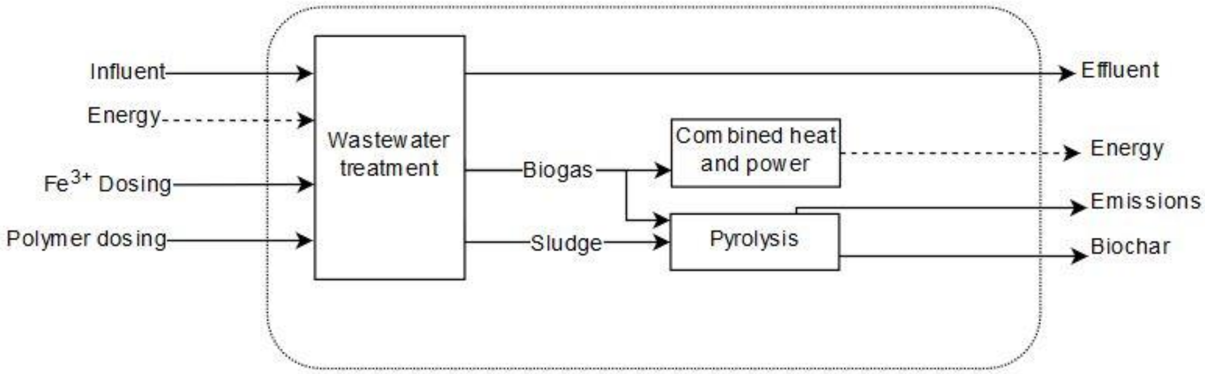

Figure 10: SSP scenario's flows (own)

Similarly to the other thermal sludge management process. The schematic description of the unit is represented in Figure 11. The first step in pyrolysis is further drying the input material. This is done by a steam dryer. Its heat is supplied by the pyrolysis unit and the excess heat of the system is delivered to the district heating through a heat exchanger. The gas burner will heat the pyrolysis unit and then the sludge is combusted in an inert environment.

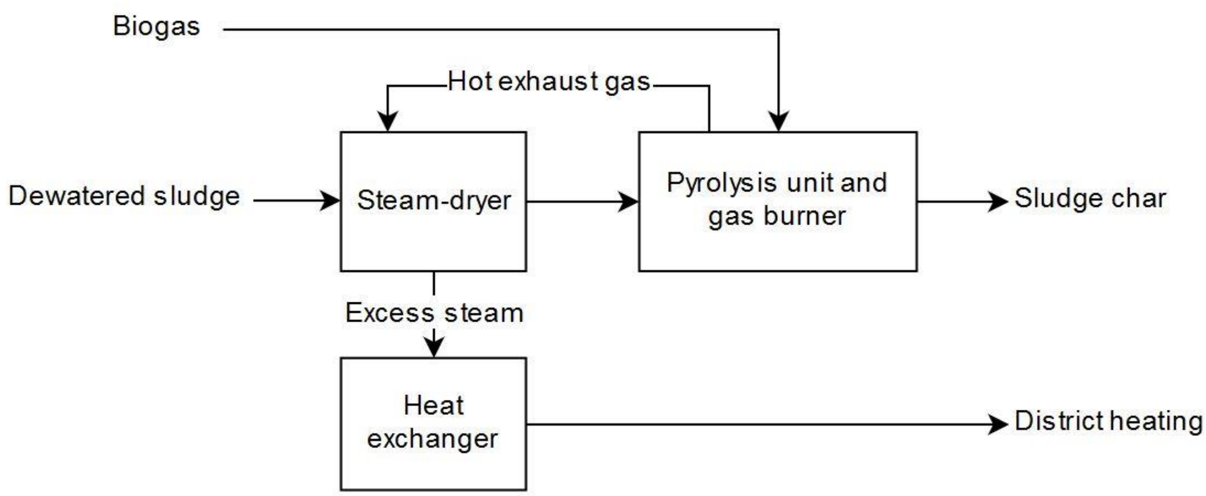

Figure 11: AquaGreen's pyrolysis solution (own)

Currently, at Ejby Mølle, AquaGreen is running a pilot unit for assessing their pyrolysis process in real life. Therefore, it was an obvious choice to include their process to life cycle modelling. The biochar is later used as soil amendment improving soil composition and nutrient capacity.

3.5.4. Struvite precipitation

In Figure 12 the last scenario and its flows are represented. Struvite precipitation is not providing a solution for sludge management. In this scenario, the management of the produced dewatered sludge is being composted as it happened in the first scenario. The supernatant from the final dewatering process is delivered to the struvite precipitation process. The product is struvite crystals which are depending on the quality is readily usable as fertilizer on agricultural land.

It is also visible that the iron salt is not added anymore into the wastewater treatment process. This is necessary to achieve higher orthophosphate concentrations in the effluent to the operation of the EBPR process, thus increase later this concentration in the supernatant.

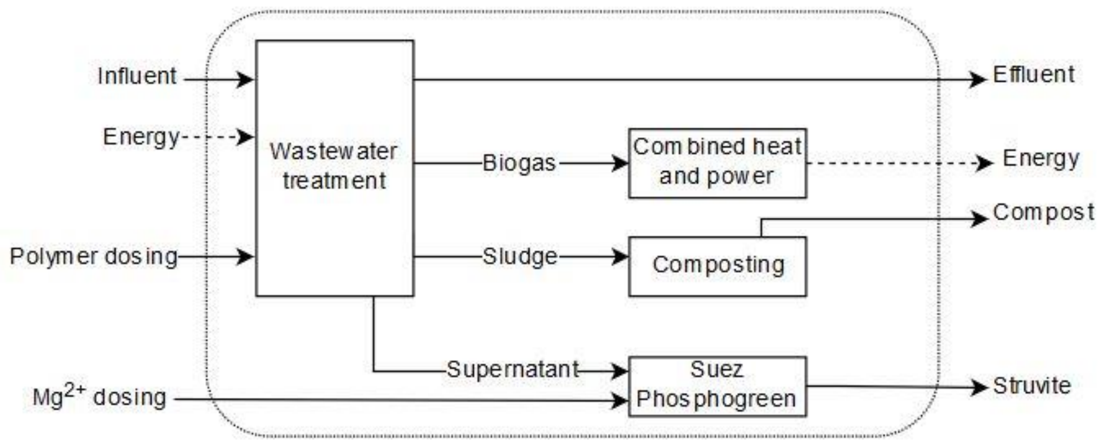

Figure 12: Struvite precipitation scenario (own)

As it was described at the background of the study there are different options for struvite precipitation. In this study, SUEZ’s Phosphogreen process (Figure 13) was applied. It was selected because in Denmark this process has the most unit in operation. Recently AarhusVand implemented a struvite precipitation unit in their Marselisborg WWTP.

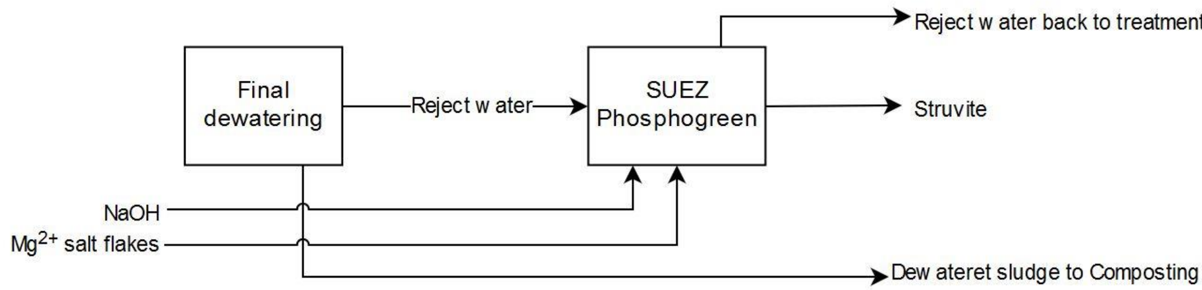

Figure 13: SUEZ Phosphogreen flows (own)

The reject water of the final dewatering enters a fluidized bed reactor, and it got mixed with the chemical amendments. Magnesium salts (MgCl2) and sodium hydroxide are added to the solution, for reaching the right ratio of nitrogen, phosphorus, and magnesium; and for maintaining the right pH. After the crystallization process, the struvite is collected at the bottom of the reactor, while the effluent leaves the system at the top of the reactor and carried back to the EBPR process.

4. Results and discussion

4.1. Inventory Analysis

When the scope and the main flows were defined, the quantification of the process flows had to be done. To set up a baseline dataset the following steps had to be taken. First, a preliminary data set about the phosphorus pools in Ejby Mølle's system had been created back in 2016, by a PhD student of the University of Southern Denmark. This mass balance becomes the basis of the study, as all the flows were defined. The input and output flows are based on measured results from the treatment plant. The definition of the internal flows was unavoidable because of one of the scenarios (STRUV) differs. To reach the right concertation for the struvite precipitation process the ferrous salt addition had to be stopped. This influenced all the flows in the WTP.
Second, the mass balance had to be updated. Originally the model was calculated from full-scale values of Ejby Mølle. To maintain the temporal scope this model was recalculated with influent and effluent data from the plant (Table 6).

Table 6: Measured values of influent and effluent flows

	Unit	Influent	Effluent
Flow	*[m^3/d]*	45703	42837
SS	*[mg/l]*	234.50	1.10
TP	*[mg/l]*	6.61	0.31

The following step in establishing the database was to identify the corresponding chemical and energy inputs of the baseline scenario. This was done by VandCenter Syd (VCS) providing access to their database. The user interface was SCADA, which a web-based platform that ties together decentralized systems and provides a graphical interface for the operation to industrial application, such as wastewater treatment. The interface has a data acquiring platform which creates reports from the logged data. This dataset was used to establish the inventory for the baseline scenario Table 7 concludes the quantified flows per FU of the **WWT process**. This process will be the same in the next two scenarios but will differ in the last one, due to the struvite precipitation process.

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Table 7: Quantification of WWT process input and output flows

Wastewater treatment					
Inputs			**Outputs**		
Name	***Unit***	**Value**	**Name**	***Unit***	**Value**
Iron (III) sulphate	*[kg/FU]*	92.7	**Biogas**	*[m^3/FU]*	1258.6
Polyacrylamide	*[kg/FU]*	11.7	**Effluent TP**	*[kg/FU]*	1.0
Electricity	*[GWh/FU]*	176.0			
Heat	*[GJ/FU]*	0.5			
Transport	*[tkm/FU]*	2.4			

Table 8 concludes the quantified flows per FU of the **CHP process**. The data was also collected from SCADA reports.

Table 8: Quantification of CHP process input and output flows

Combined heat and Power					
Inputs			**Outputs**		
Name	***Unit***	**Value**	**Name**	***Unit***	**Value**
Biogas	*[m^3/FU]*	1258.6	Electricity	*[kWh/FU]*	2225.9
			Heat	*[GJ/FU]*	12.0

Table 9 concludes the quantified flows per FU of the **composting process**. The data collection and source, however, were different in his case. After a personal interview with the operation leader of Odense’s composting facility, he provided the necessary data. The mass flows were defined by the company’s intro presentation. The compost characteristic is based on analytical measurement from last year. The measurement was done by Eurofins, and according to the company, it is done every second month [21].

Table 9: Quantification of the Composting process input and output flows

Composting					
Inputs			**Outputs**		
Name	***Unit***	**Value**	**Name**	***Unit***	**Value**
GW	*[Mg/FU]*	6.8	Compost	*[Mg/FU]*	5.6
Straw	*[Mg/FU]*	0.3	**Emissions**		
Transport	*[tkm/FU]*	140.3	**CO_2-C**	*[kg/FU]*	1325.8
			CH_4-C	*[kg/FU]*	20.0
			N_2O-N	*[kg/FU]*	0.5
			CO-C	*[kg/FU]*	1.2

The emissions of the composting facility are based on a Swedish study [71]. Although the company provided the required data, their analysis was focused on the odour composition and emissions. These emissions are not included in the study.

For more accurate modelling the composition of Danish garden waste had to be implemented. The composition as defined by the relevant study Boldrin and Christensen (2010). In this literature, the seasonal changes of the Danish garden waste were observed. Table 10 concludes the composition of the analysed garden waste.

Small stuff (flower, soil, hedge cuts) and other waste considered as grass in the LCA model. The wood and branches added to the system as a wood chip, which most likely considers the environmental impact of the shredding process as well.

Table 10: Composition of Danish garden waste(Based on Boldrin and Christensen, 2010)

Composition	**[%]**
Small stuff	75.6%
Wood and branches	24.0%
Other (less than)	0.4%

For the **incineration process,** the data collection was a bit harder nut to crack. Biofos provided some data from their facilities. The dataset was created during a collaboration with Ramboll [73]. It was presented in 2017. This presentation served as the source of most of the flows of the system. The energy demand and production of the system was calculated, as well as the produced ash. Table 11 concludes the energy input and the material and district heating output of the incineration process. All data is presented per FU. The ratios for the electrodialysis was calculated with the help of a recent study by Guedes *et al.* (2014). This study is assessing the P-recovery efficiencies in a laboratory experiment. Therefore, this data not suiting the idea of using only full-scale data during this LCA.

Table 11: Quantification of SSI input and output flows

Incineration					
Inputs			**Outputs**		
Name	***Unit***	**Value**	**Name**	***Unit***	**Value**
Biogas	*[m^3/FU]*	1258.552	**P-rich product**	*[kg/FU]*	87.4
			Residue to landfill	*[kg/FU]*	974.8
			District heating	*[kWh/FU]*	11043.3

The emissions of the SSI are concluded in Table 12. These emission values are based also on the Rambøll and Biofos collaboration dataset. The values were recalculated as if all the Ejby Mølle dewatered sludge would be burned in the furnace. This has been implemented to the emission category during the life cycle modelling.

Table 12: Emissions to air in kilogram per functional unit

Emissions to air	
	[kg/FU]
CO	1.3E-02
TOC	2.0E-06
Particles	0
HF	0
HCl	1.6E-07
SO_2	3.3E-03
NO_x	7.9E-06
Hg	7.1E-07

The first part of the data of the **pyrolysis process** collected with the help of AquaGreen. The material and energy flows of the system (Table 13) were calculated based on a recently done PI chart. This chart contains the energy flows in and out, thus the amount of biogas necessary for the system was calculated. The yearly operation time was assumed based on a recently made study on the carbon footprint of AquaGreen's pyrolysis system [74]. It was assumed that the unit operates 8000 hours per year. It means the unit operates eleven months in a year, and there is one month of maintenance time. This study does not include the fate of the sludge generated during this month. The biochar composition was defined based on analytical measurements. These measurements were done by Agrolab, in Kiel, Germany in 2017 (Table 26).

Table 13: Quantification of Pyrolysis unit input and output flows

Pyrolysis					
Inputs			**Outputs**		
Name	***Unit***	**Value**	**Name**	***Unit***	**Value**
Biogas	*[m^3/FU]*	27.5	**Biochar**	*[kg/FU]*	642.0
			District heating	*MJ/FU*	780.4

After the energy and material flows were calculated the emissions to air had to be defined. AquaGreen provided their calculations, but no analytical measurements have been done on the emissions. Table 14 concludes the assumed emission values per functional unit.

Table 14: Flue gas composition of the pyrolysis process per FU

Flue gas composition	*[Kg/FU]*
CO_2	23.7
SO_2	1.1
NO_3	5.2
H_2O	21.9
O_2	69.5
N_2	299.8

The pyrolysis unit almost runs completely self-sustained. Only a minimal amount of biogas flows into the unit. Therefore, this scenario again able to maintain a CHP unit. This will provide electricity and district heating both for the facility and the grid. Table 15 concludes the inputs and output per functional unit.

Table 15: Quantification of CHP unit input and outflows

Combined heat and Power					
Inputs			**Outputs**		
Name	***Unit***	**Value**	**Name**	***Unit***	**Value**
Biogas	*[m^3/FU]*	1231	**Electricity**	*[kWh/FU]*	2177.18
			Heat	*[GJ/FU]*	11.76

Struvite precipitation process flows have been a bit more complex to define. The mass balance of the new system had to be calculated according to the previously mentioned mass balance model. It was necessary to define the amount of orthophosphate in the supernatant. This calculation is based and verified by data provided AarhusVand. At Marselisborg the company implemented SUEZ struvite precipitation solution. SUEZ claims that its technology can produce struvite if the supernatant total phosphate concentration reaches 70 mg/l. Although the fluidized bed reactor (FBR) unit is operational, it is still in the commissioning process. For the calculation, the parameters were used that the company wished to achieve. There are chemicals and energy input of the FBR. Table 16 concludes all the changed flows of the Struvite precipitation scenario.

Table 16: Quantification of Struvite precipitation process implemented to the WWT

Wastewater treatment with SUEZ Phosphogreen					
Inputs			**Outputs**		
Name	**Unit**	**Value**	**Name**	**Unit**	**Value**
Polyacrylamide	*[kg/FU]*	11.71	**Biogas**	*[m^3/FU]*	1258.6
Electricity	*[GWh/FU]*	176.02	**Effluent TP**	*[kg/FU]*	1.0
Heat	*[GJ/FU]*	0.46	**Struvite**	*[kg/FU]*	56.9
Transport	*[tkm/FU]*	2.38	**TP**	*[kg/FU]*	15.9
Mg (II) salt	*[kg/FU]*	0.12	**TN**	*[kg/FU]*	2.8
NaOH	*[kg/FU]*	0.05	**Mg**	*[kg/FU]*	5.7
Additional electricity	*[kWh/FU]*	277.10			

The dataset is temporally and geographically consistent. The calculations mainly based on full-scale data. However, it is important that the inventory contains many assumptions about the system. These are weakening the study and the impact assessment itself. The assessment could definitely give a good basis for further investigation of the environmental impact of these systems. The ideas on how to improve will be discussed in the critical review.

4.2. Impact assessment

Three methods were selected to analyse the environmental impact of the scenarios. ILCD 2011 Midpoint+ method was selected as it was recommended by the International Reference Life Cycle Data System [66]. This method contains 14 different impact categories based on the best existing practice. ILCD method also includes normalization factors and weighting which help identify the most important impact categories.

As the study supports the decision making of VCS, for better visualization of the results an endpoint category had to be chosen. Since ILCD 2011 Midpoint does not include endpoint characterization, ReCiPe 2016 Endpoint (H) method was selected. ReCiPe Hierarchist methods are based on the most common policies with regards to the timeframe and related issues. The endpoint methodology aggregates the different midpoint categories into three indicators. For the transformation, the method uses its own characterization factor. This could increase the uncertainty in the results.

The EDIP/UMIP 97 (resource only – updated) was later added to the study after the midpoint impacts were assessed. According to the ILCD method, resource depletion was high in three scenarios. EDIP was selected to define which materials are affected by this depletion. There are a few criteria which have to be highlighted. LCA methods assess other environmental impacts more accurately than resource depletion. In EDIP resources are not evaluated by the economic importance, substitutability nor if the depletion of the certain resource is reversible or not. EDIP only weight the resources according to their scarcity levels. The original method was already outdated, thus the database had to be brought up to date. This was done by Habib (2016).

4.2.1. ILCD 2011 Midpoint+

The creation and verification of the LCA models is an iterative process. After the right processes were defined, the comparison of those scenarios had to be done. The characterization values were exported from SimaPro to Excel. All the chart in this study were created in this way.

The characterization gives the most undistorted results of the systems, but as it is visible in Figure 14 there is no emphasis on any of the indicators. All the scenarios performed well in nine out of fourteen categories.

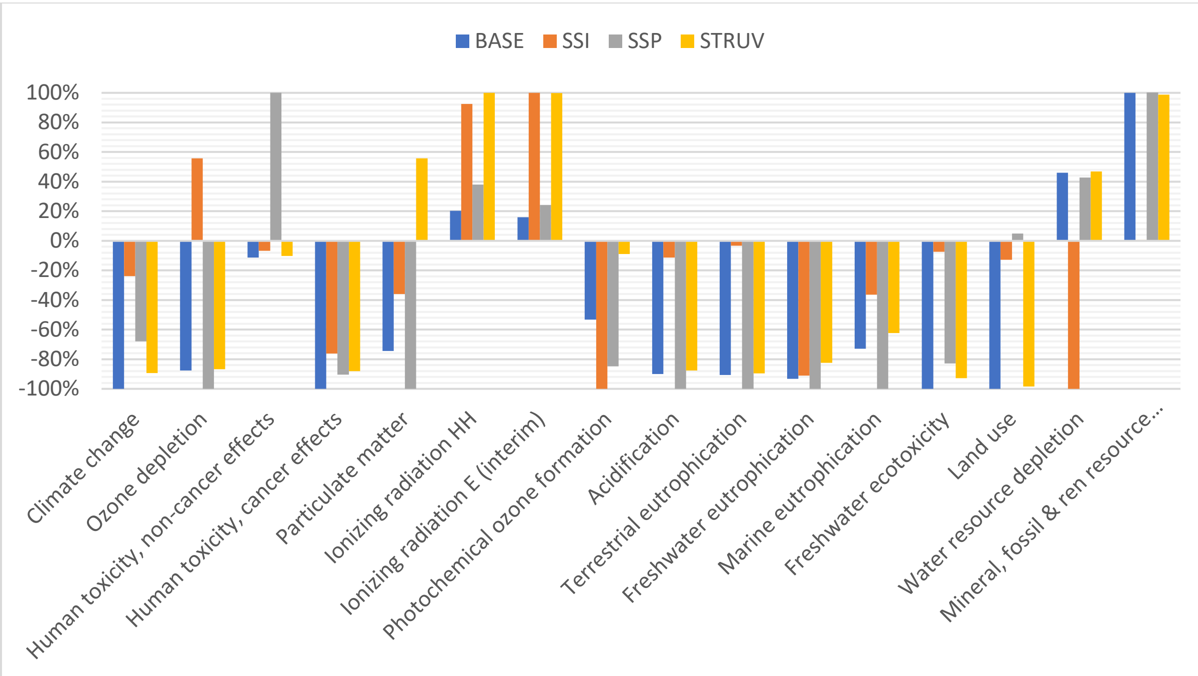

Figure 14: ILCD 2011 Midpoint+ Characterization

The normalization of the result was carried out with "EU27 2010/normal weighting" factors. It is crucial to select the right normalization factors which are geographically correct and fit the characterization method. It is visible in Figure 14 that the toxicity related impacts a relatively high. Besides the high toxification, the other impacts seem neglectable. To define the categories with a smaller impact in Figure 15 and Figure 16 the normalization results are visible. The "eutrophication", the "mineral, fossil, and renewable resource depletion" and "climate change" are the most important categories, respectively.

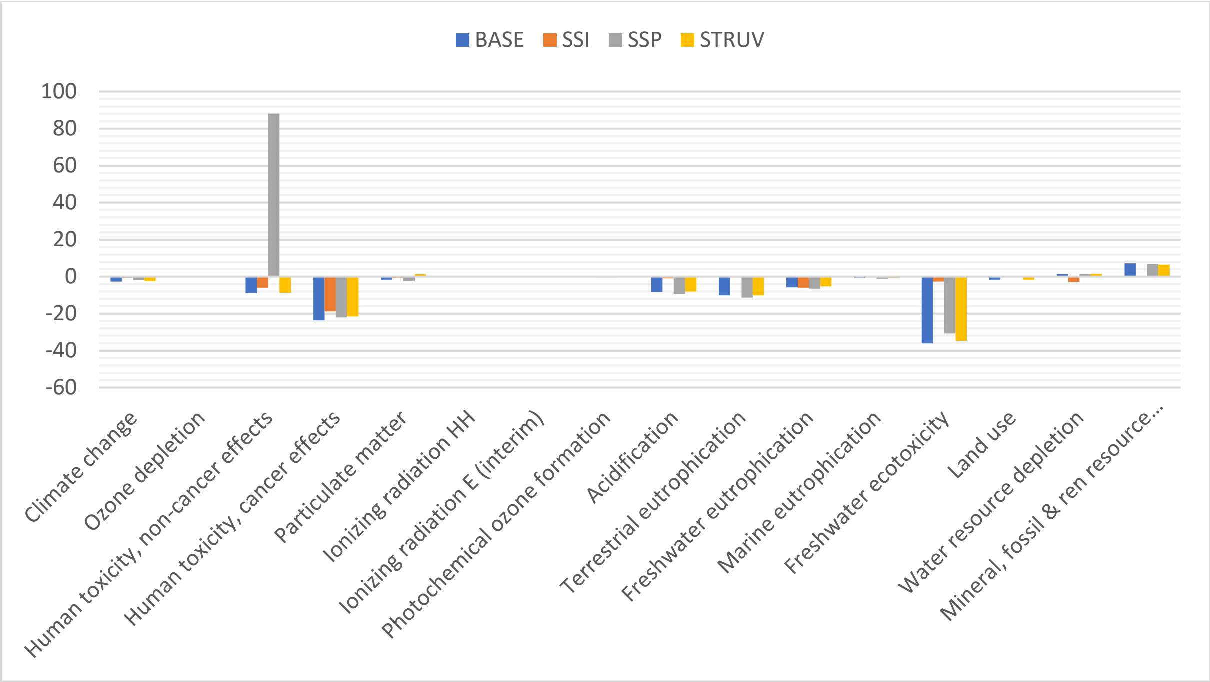

Figure 15: ILCD 2011 Midpoint+ normalisation results

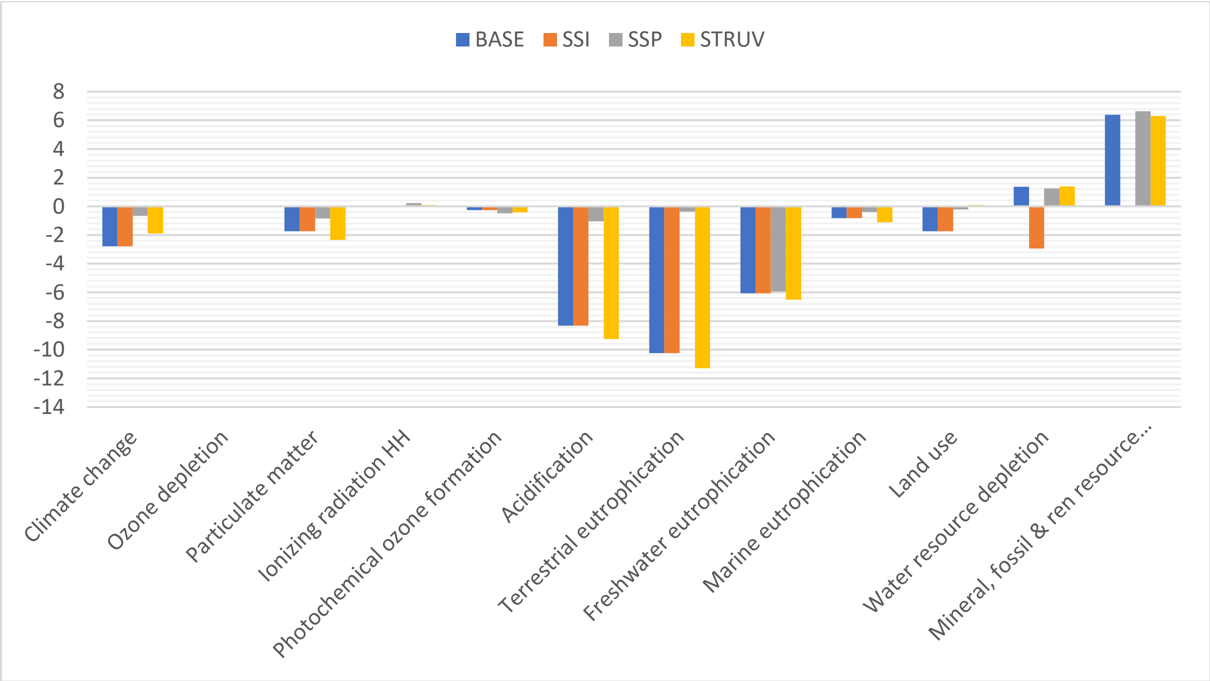

Figure 16: ILCD 2011 Midpoint+ normalization results (without toxicity related impacts)

The following impact categories are listed in the order as the method ranked them. Each column of the chart presents the impacts of the scenarios' process units. The aggregated impacts are represented with the red dots in the middle of the columns.

4.2.1.1. Climate change

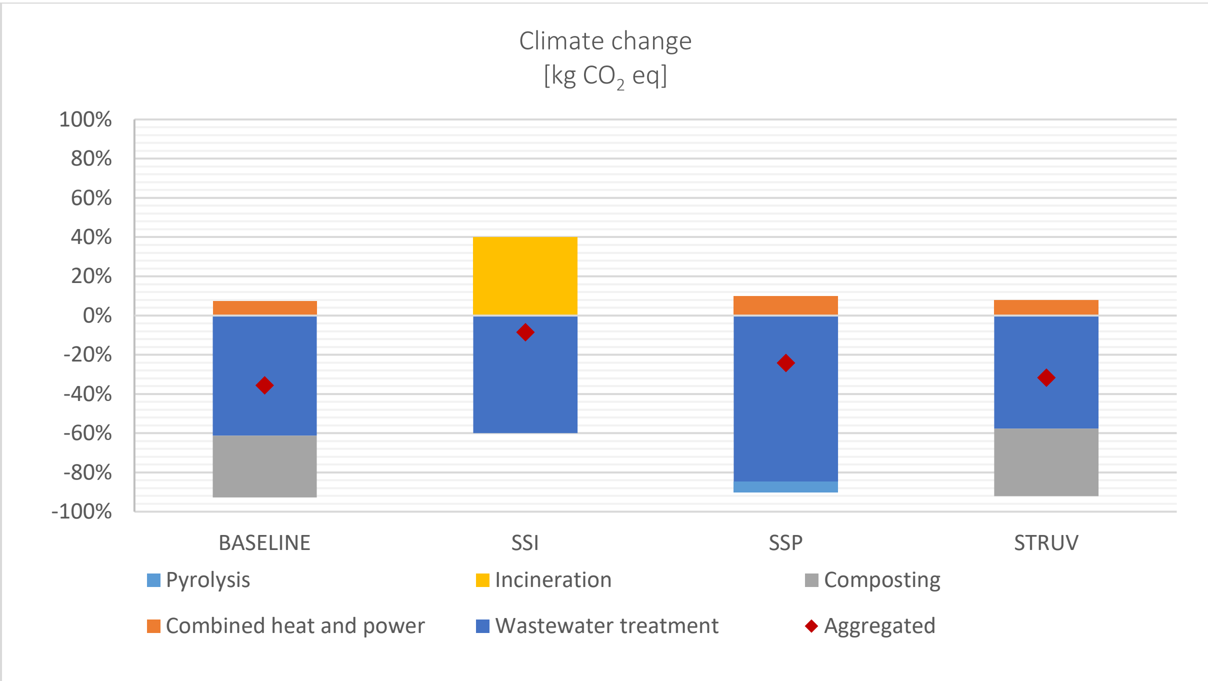

Figure 17: Characterization result and the process units' effect on climate change

The ILCD methods for climate change are to calculate the global warming potential over a 100 years time horizon. The results of this category are represented in Figure 17. Only the combined heat and power and the incineration units have an effect on the climate change. The rest of the unit processes are avoiding the impacts. The baseline scenario has the highest avoided impact, then the struvite precipitation process and the pyrolysis. Finally, the incineration has the lowest negative impact in this category.

4.2.1.2. Human toxicity

Figure 18 concludes both human toxicities related (cancer and non-cancer effects) impacts. The comparative toxic unit for humans expressing the estimated increase in human morbidity in the total population per unit mass of chemicals emitted. In this category, all the scenarios had negative impacts, except for one case. The pyrolysis unit – according to the results – has an outstanding impact on the non-cancer effects. This will be further discussed in the life cycle interpretation.

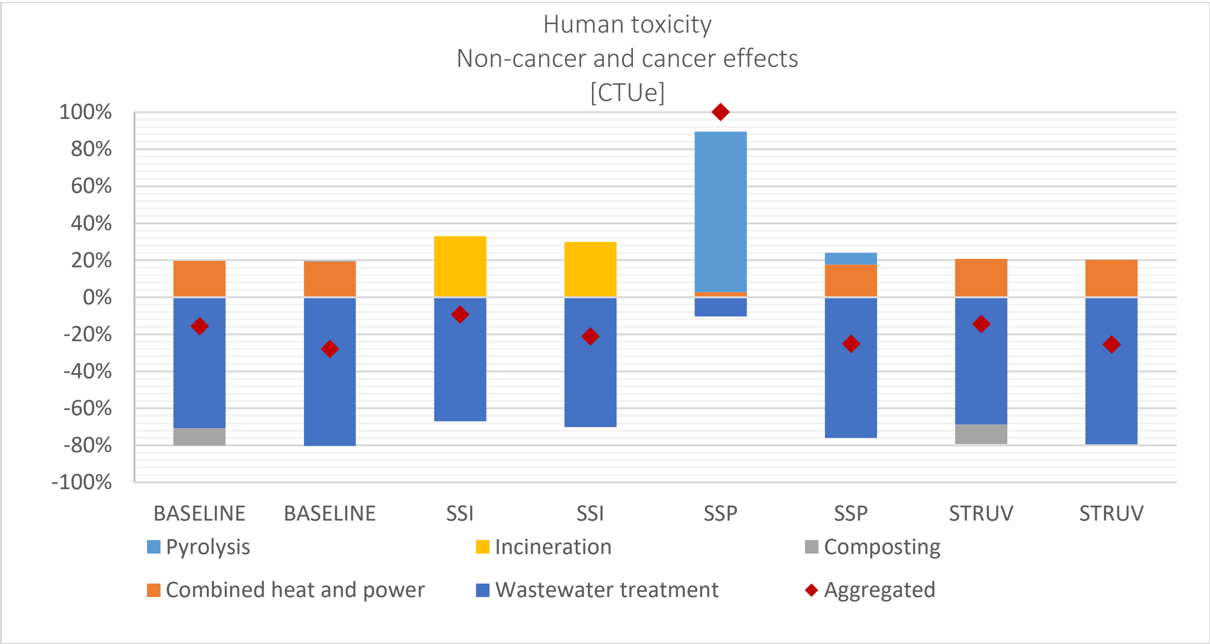

Figure 18: Characterization result and the process units' effect on human toxicity

4.2.1.3. Freshwater ecotoxicity

In Figure 19 the performance of the unit processes is visible. The aggregated result shows that three scenarios performed similarly to each other. Except for the SSI scenario which – due to the incineration – has only -3% the aggregated negative impact.

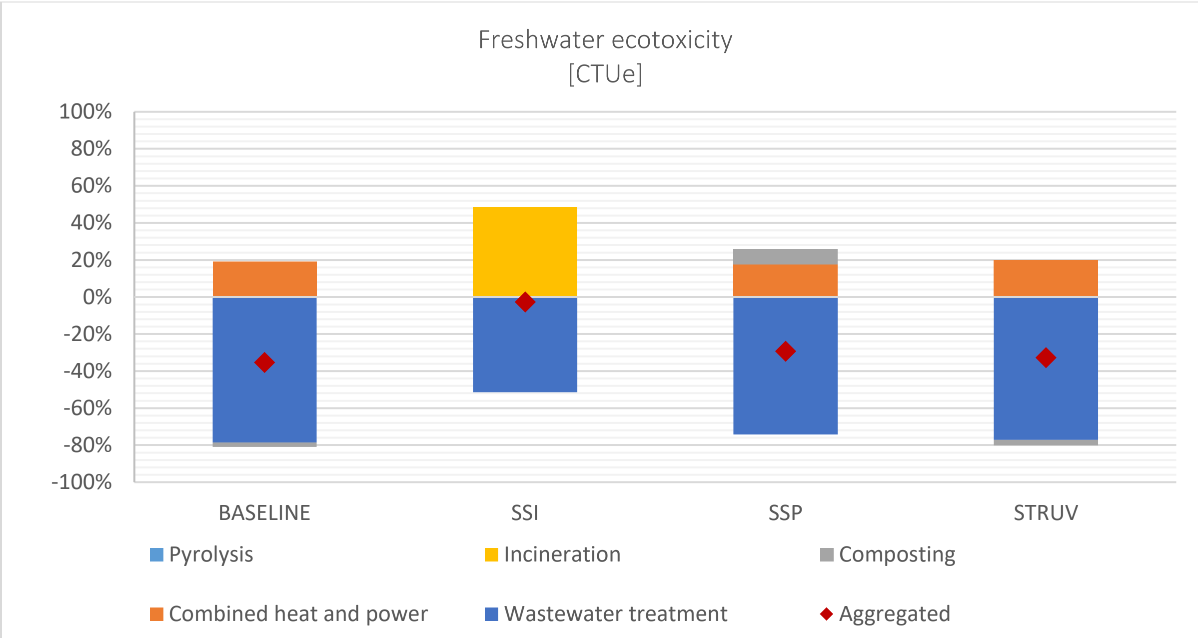

Figure 19:Characterization result and the process units' effect on freshwater ecotoxicity

4.2.1.4. Eutrophication

In Figure 20 the effects on **freshwater eutrophication** are visible. As phosphorus is considered to be a limiting factor in freshwater, the impact category represents the degree of this nutrient when it reaches the freshwater bodies. All P recovery technologies perform similarly. The pyrolysis unit has the lowest impact with -27% (aggregated), the second best are the baseline and the incineration processes. In this category, the struvite precipitation has the lowest aggregated avoided impact (-22%). The aggregated results might be similar, but the pyrolysis process is the only one with avoided impact (-0,11 kg P eq).

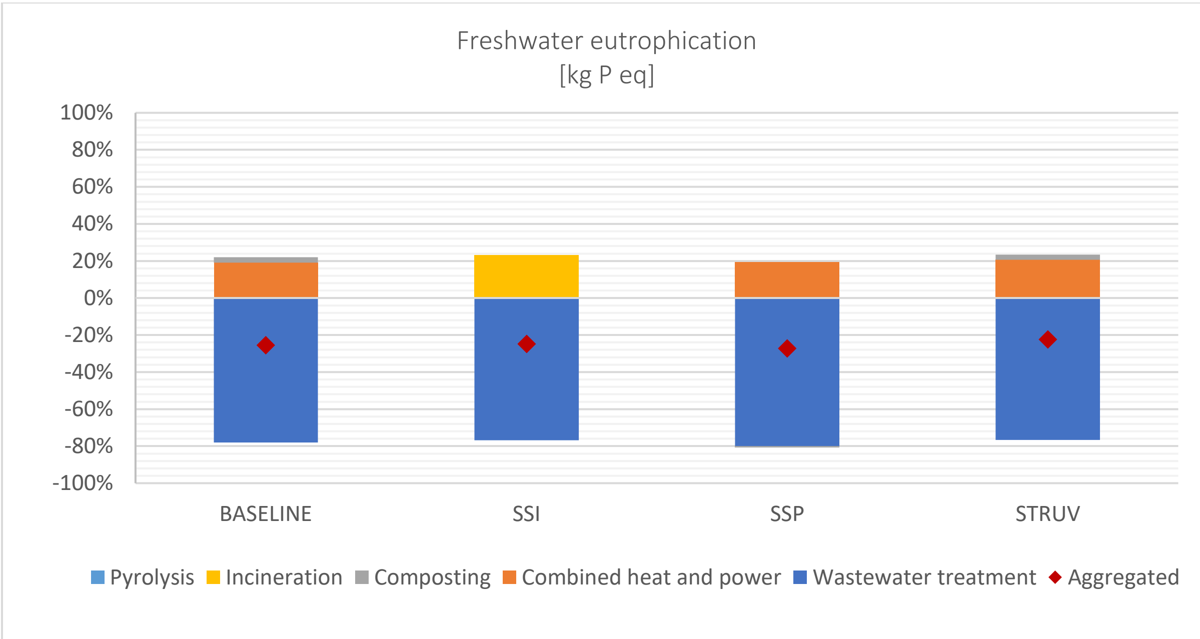

Figure 20: Characterization result and the process units' effect on freshwater eutrophication

In Figure 21 the results of the **terrestrial eutrophication** results are presented. This impact category describes the critical load of exceeding nutrient in sensitive areas. The characterization unit is defined in kg N eq. In this category the pyrolysis unit had the best performance, then struvite, baseline, and incineration followed.

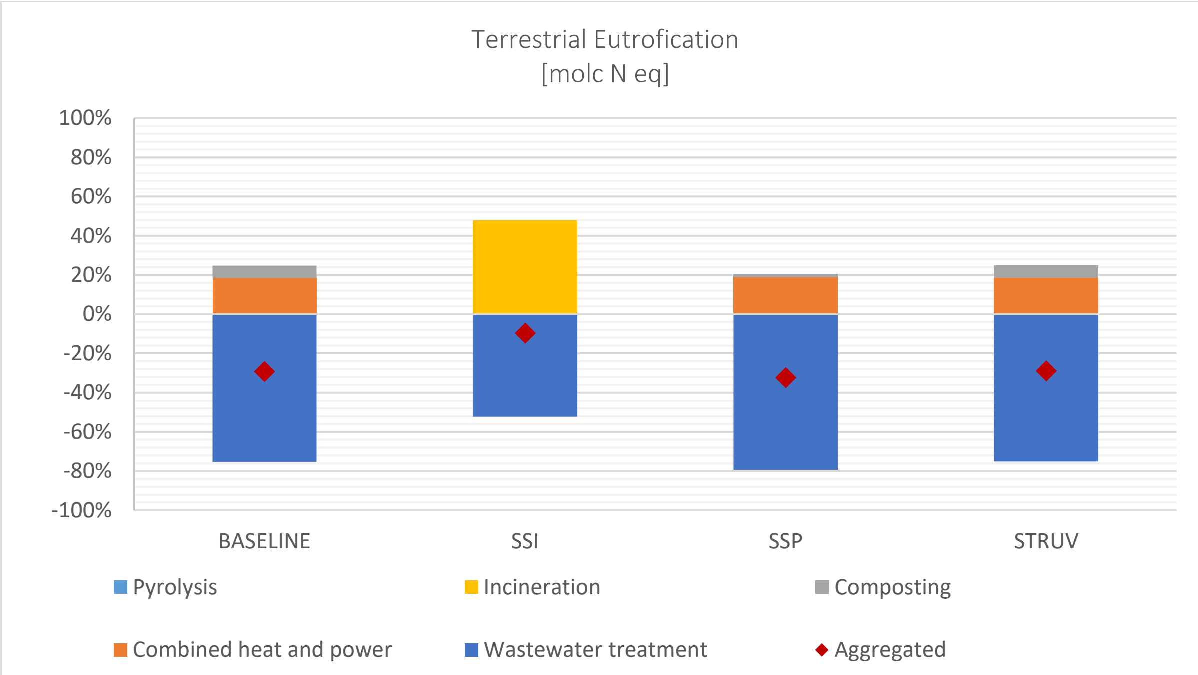

Figure 21: Characterization result and the process units' effect on terrestrial eutrophication

Marine eutrophication in Figure 22 – similarly to freshwater eutrophication – represents the degree of limiting nutrient reaching the marine end compartment. Again, the pyrolysis scenario performed with the highest avoided impact.

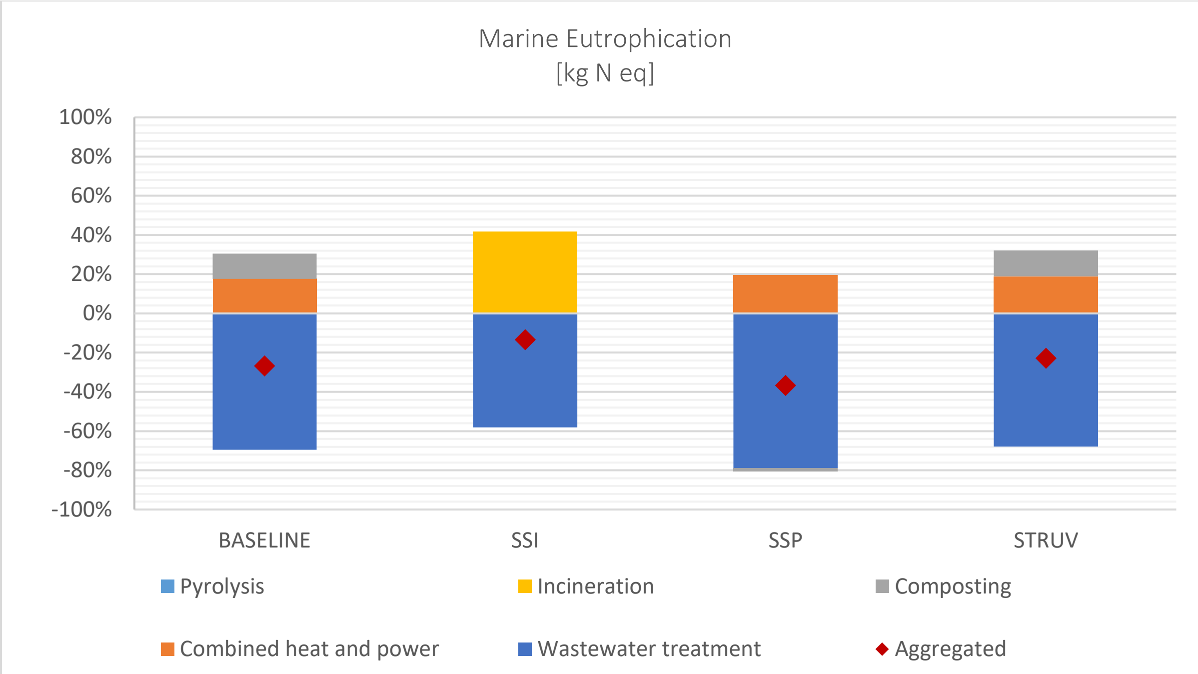

Figure 22: Characterization result and the process units' effect on Marine eutrophication

4.2.1.5. Mineral, fossil, and renewable resource depletion

The resource depletion category is not included in similar studies. The category results are presented in Figure 23. The resource depletion case was expected to be lower or even negative than it turned out to be. Therefore, further analysis of the scenarios with the EDIP method was included in the study. The best performance was provided by the SSI scenario where the impacts of the system were close to zero.

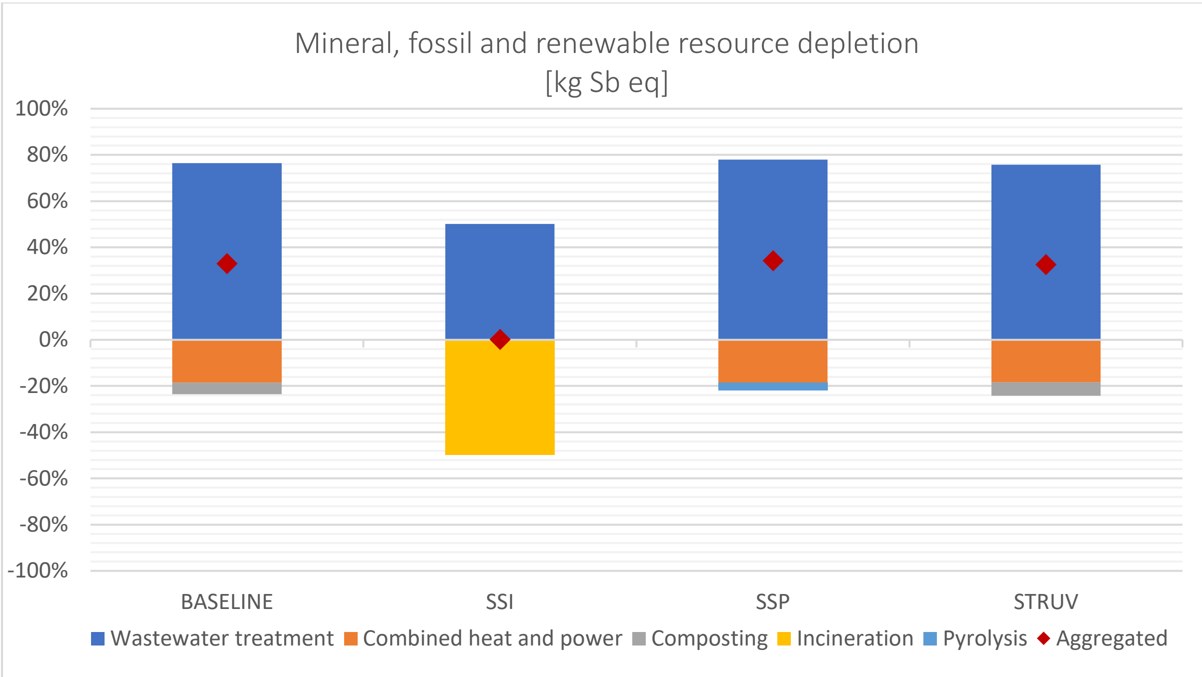

Figure 23: Characterization result and the process units' effect on Mineral, fossil, and renewable resource depletion

4.2.2. ReCiPe 2016 Endpoint, Hierarchist

In Figure 24 the damage assessment results are visible. In the first two categories all the scenarios have avoided impacts on human health and on the ecosystem as well. The baseline has the best performance for human health. Pyrolysis has the highest avoided impact considering the damage to the ecosystem. The last category shows different results than the midpoint method's resource depletion. In this case, the incineration has the highest impact on resource depletion. This contradiction might be the result of the uncertainty of the resource depletion methods in LCA or simply the different approaches in the ILCD and the ReCiPe. It will be later discussed in the interpretation chapter.

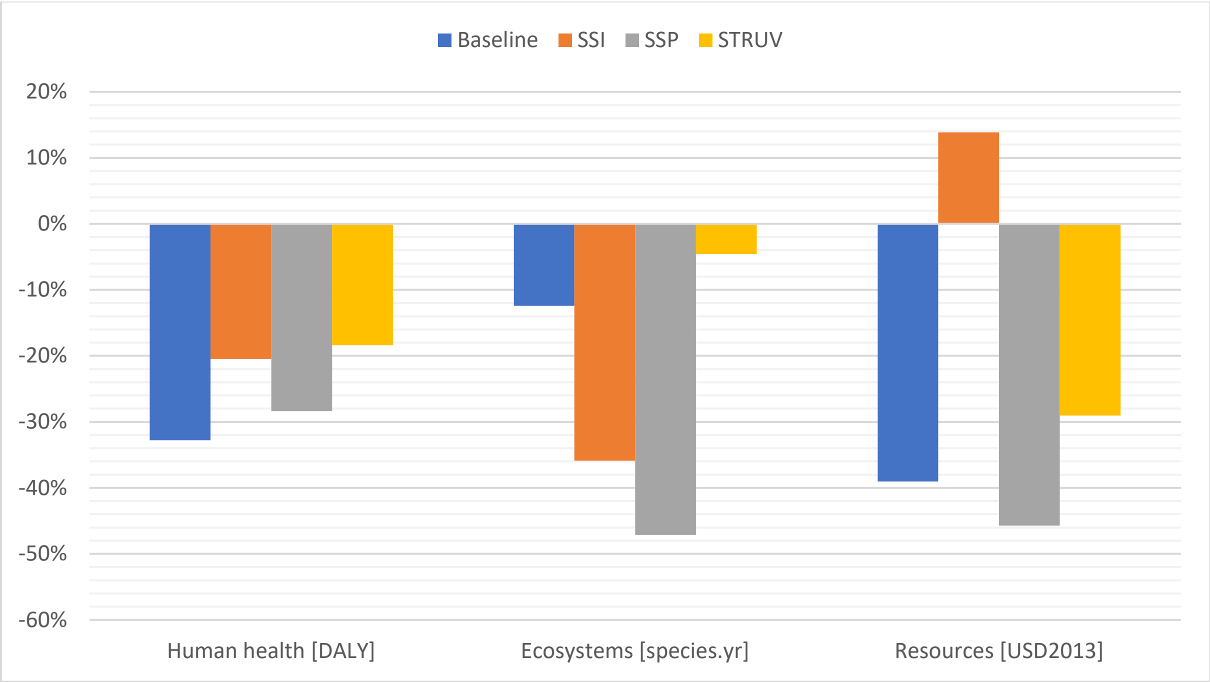

Figure 24: ReCiPe 2016 Endpoint (H) Damage Assessment

4.2.3. EDIP/UMIP 97 (resource only – updated)

The life cycle methods do not necessarily deliver the best results on resource depletion. Since the midpoint and endpoint method results turned out to be contradictive and the scenarios are affecting the resource flows on the market. It has been a reasonable choice to include a resource only method. The EDIP method factors were updated from a predetermined database [75]. This provides the accurate temporal scope of the method. The definition of the important materials depleted in the scenarios was like the ILCD method. First, the characterization values were simulated in SimaPro. In order to compare these results normalization and weighting factor must be applied. These are the normalization factor shows the magnitude of consumption of a material per global capita. The weighting factor shows the relative scarcity of the resource assumed no new reserves get discovered.

In Figure 25 the characterization values are visible, comparing the different scenarios. In Figure 26 the normalization values are visible. This chart shows that three of the four scenarios (Baseline, SSP, STRUV) have a high impact on cadmium depletion. Natural gas, brown coal, coal, and oil are also relevant categories since in every scenario thermal processes are included (CHP, Incineration, and Pyrolysis). In Figure 27 the weighting values are presented.

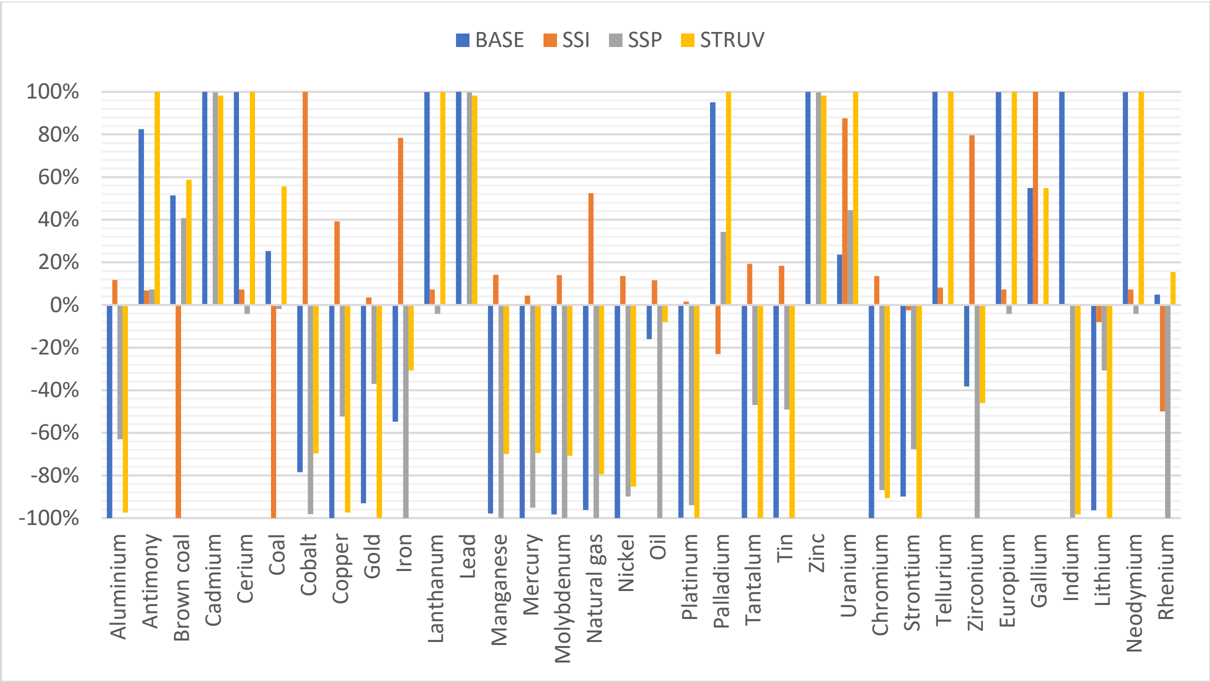

Figure 25: Characterization values of EDIP/UMIP 97 (resource only - updated) method

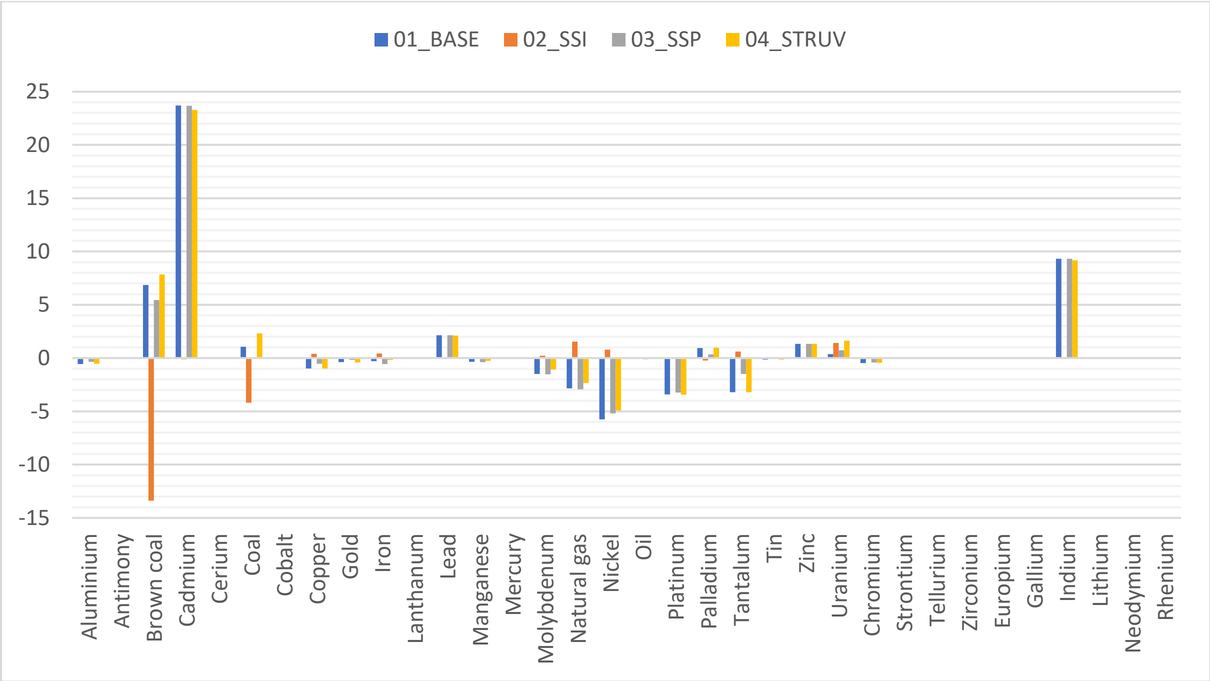

Figure 26:Normalization values of EDIP/UMIP 97 (resource only - updated) method

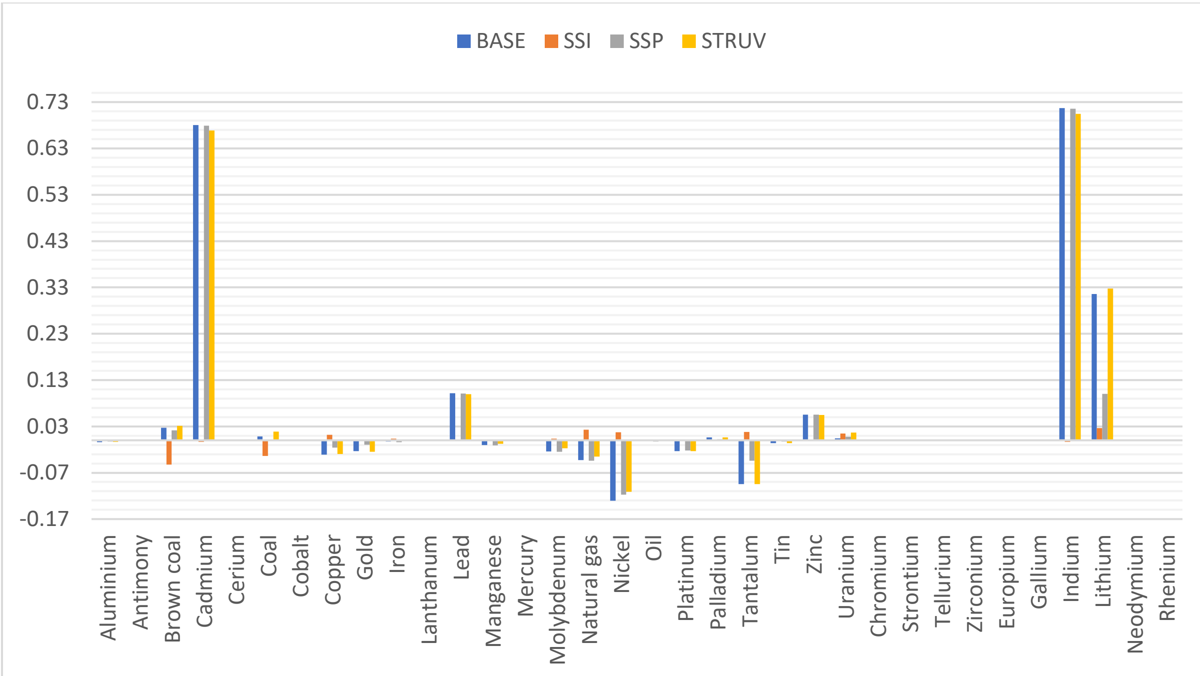

Figure 27: Weighting values of EDIP/UMIP 97 (resource only - updated) method

In Figure 28 the cadmium and zinc impacts are visible. Only the wastewater treatment processes affect these elements' depletion. According to the network analysis, the high impacts are related to biogas production. Therefore, the thermal processes are compensating this impact

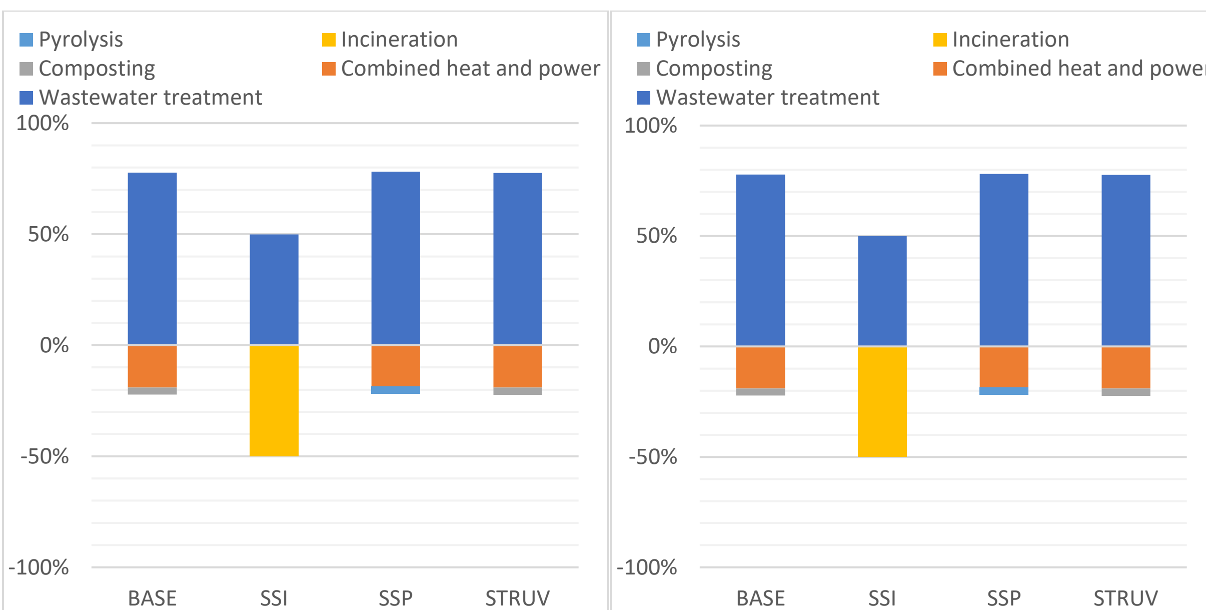

Figure 28: Cadmium (left) and Zinc (right) resource depletion (EDIP/UMIP 97 [resource only - updated])

These results could also be anomalies of the models or related to the design. No paper was found that could back these results.

In Figure 29 the natural gas and oil depletion is visible. In the case of natural gas, the combined heat and power and the incineration are the main contributors. The pyrolysis is contributing to the avoided impacts, which might be related to the self-sufficient operation.
In the case of oil again the thermal processes and the composting are the main contributors. The wastewater treatment and pyrolysis are avoiding this impact.

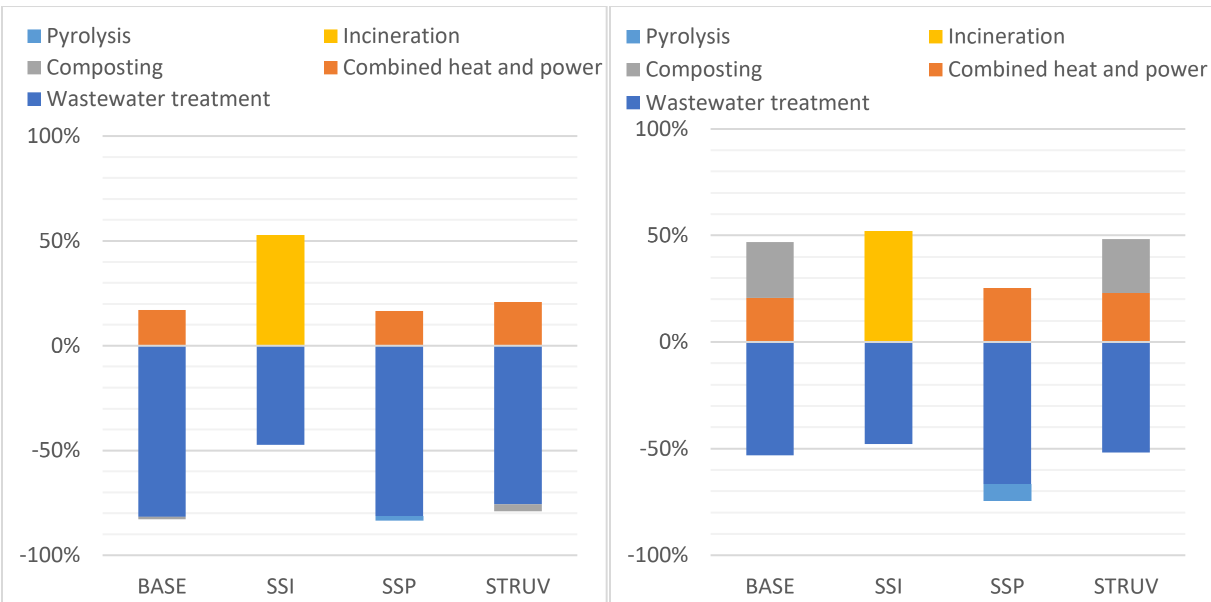

Figure 29: Natural gas (left) and Oil (right) depletion (EDIP/UMIP 97 [resource only - updated])

In Figure 30 the brown coal and coal depletion is visible. In case of the wastewater treatment and the composting processes are responsible for the impact. The thermal processes are avoiding both lignite and coal use. They produce heat, and in three cases electricity, thus they are avoiding the use of coal plants for example.

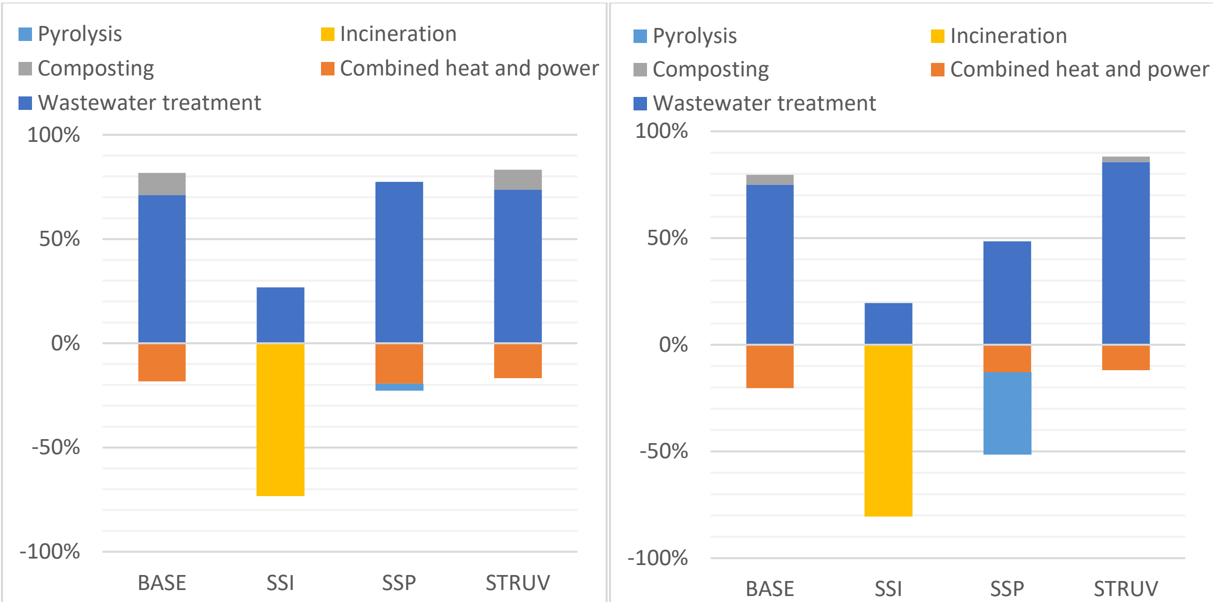

Figure 30: Lignite (left) and Coal (right) depletion (EDIP/UMIP 97 [resource only - updated])

4.3. Summary of impact assessment

Int his part a small conclusion will be presented about how the different scenarios performed during the impact assessment.

At the midpoint, the input parameters were calculated by the ILCD method characterization factors. The main categories are represented in Figure 31. It is difficult to distinguish between the different processes. But, according to the results, the good option could be the SSP. It provides P-recovery with high efficiency and it has great SS volume reduction potential as well. This technology does not exploit all the recovery potential of the system. The supernatant still has a high concentration of orthophosphate. Struvite precipitation would provide a solution for that, but the capital investment and the turnover would be high. There are recent technologies under development. Such as vivianite precipitation which is a promising P-recovery process in facilities where iron salts are applied. When a conventional process is patented or applied in full-scale the execution of another study is highly recommended.

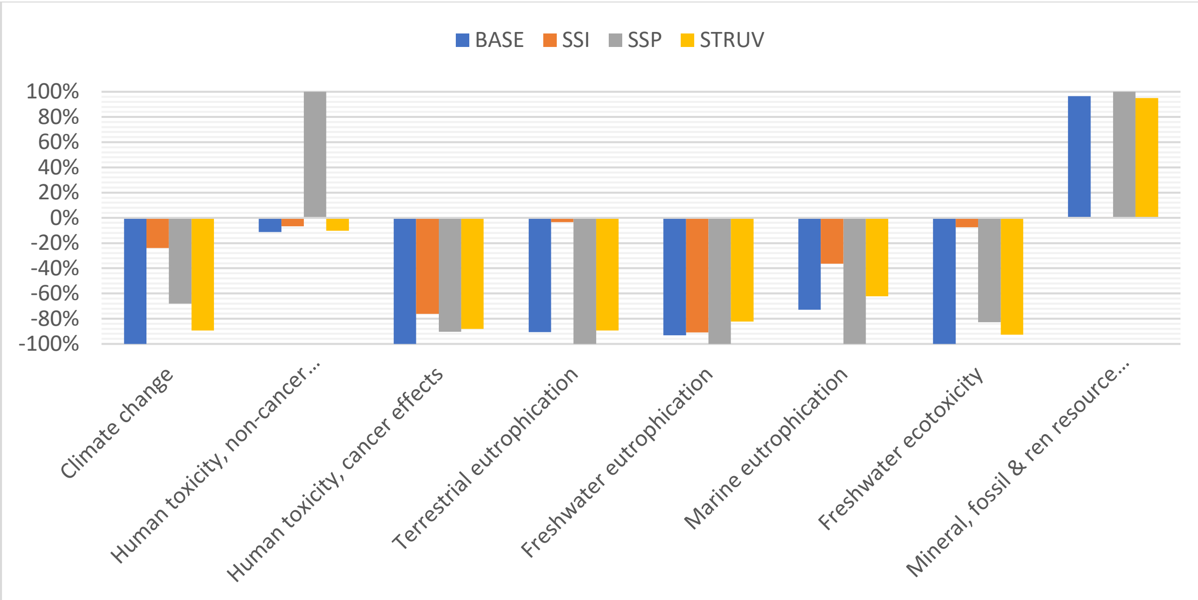

Figure 31: Comparison of characterisation results of main impact categories (ILCD 2011 Midpoint+)

At endpoint, the input parameters were calculated with the ReCiPe method and the most relevant impact categories were presented before. This time the aggregated values will be shown for better understanding. In Figure 32 the damage assessment results are presented where the different impact categories are transformed into three main damage categories. It must be kept in mind that this time the results might be more uncertain than the characterization results. The upside of the damage assessment that the results are cleaner. Overall, the results justify that the pyrolysis process could be a solution for the future.

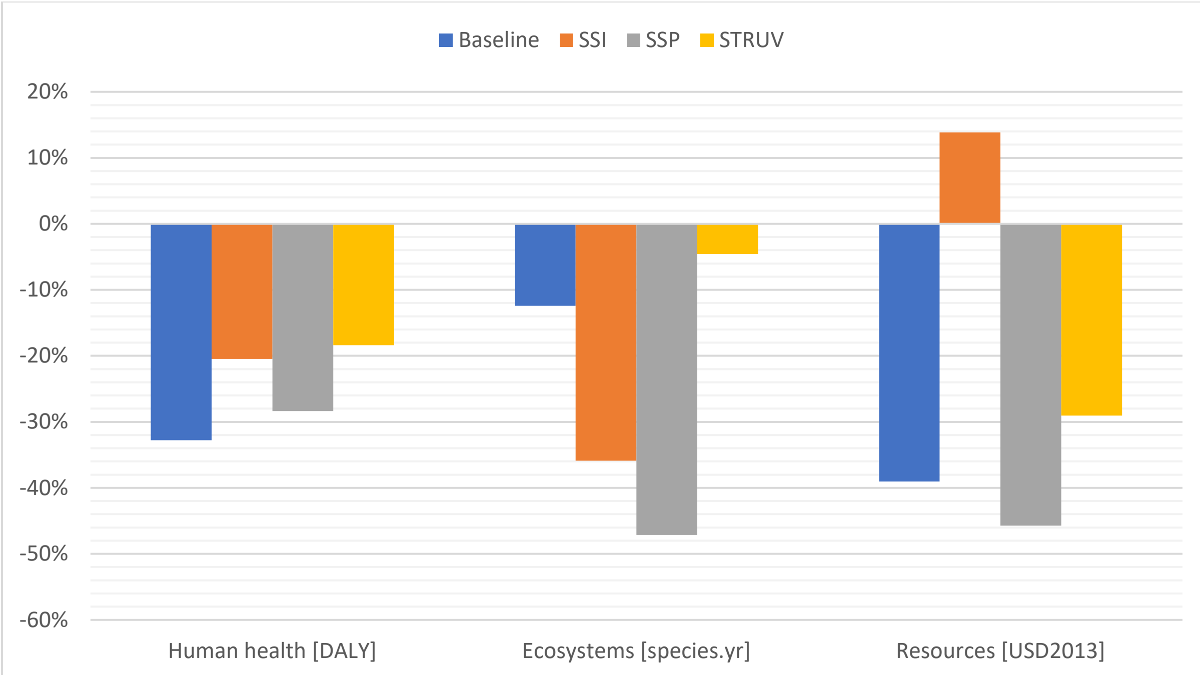

Figure 32: ReCiPe 2016 Endpoint (H) damage assessment results

The ILCD midpoint results predicted high impacts on the resource depletion. After the EDIP method was done it turned out the highest impacts were accounted for the wastewater treatment. The unit processes were acting as it would be predicted. Thus, the thermal units preventing the coal and lignite depletion.

4.4. Uncertainty and Sensitivity analysis

The goal and scope definition had to be done with great care. To create comprehensive models the scope is correctly defined. It does not include the construction phase and the end of life stage. This cannot influence the system. The definition of the functional unit also had to be chosen with caution. The dry matter as a reliable functional unit was backed up by other studies in the field. The calculation of the actual data itself can influence the results. The data was gathered from the influent analysis and then interpolate to a year. This statement was not justified when the models were run with different dry matter load. The ratios of the impacts (characterizations) showed always similar pattern as the functional unit was "treatment of 1 ton of dry matter".

The consequential approach is not yet commonly used in the field. Hence, this could also lead to distortion at the final results. During the development of the SimaPro scenario development process, the attributional approach was also tested. The different unit processes showed similar contributions. The certainty only could be proven with a deeper analysis of the attributional methods and its impacts.

The **baseline scenario** is the most exact scenario from all. The least assumptions had to be done during the development of the inventory and the SimaPro models. Nonetheless, the model of the baseline system is far from perfect. For the record, the emission in the composting process is only based on literature. The provided dataset was not including the methane, carbon dioxide and water emissions. Regarding water emission, the leachate was neglected from the study. In developed countries, the leachate from landfills and composting processes has to be collected through drainage and must be cleaned. If this assumption is correct there is no environmental impact from the leachate during the composting process.

The sewage sludge incineration scenario has the most uncertain design. The dataset of this scenario was gathered from a presentation provided by Biofos. The design of the incinerators was perfectly described, but the fictive implementation to the Ejby Mølle STP might contain issues. The data point in the presentations was mostly rounded values and most of them were proportionally augmented to the higher sludge flow. It is obvious that in real life application this is not the case. A higher load to a system could cause major changes in the system. This would probably affect the biogas consumption of the unit. If it runs more inefficiently with higher inputs, additional liquid propane gas has to be added to the system. This might lower the system's avoided impacts. If the system runs more efficiently the combined heat and power unit could provide electricity output, therefore, increasing the avoided impacts on all the important categories. The following measurements were not based on literature, they are just sheer assumption made to visualize how changes could affect the system.

In Figure 33 the comparison of the two assumptions is visible. The ILCD characterizations clearly show that the addition of propane does not influence relevantly of the system. The avoided impacts are lower by a few percent. In the case of the combined heat and power, the avoided impacts of the system are higher.

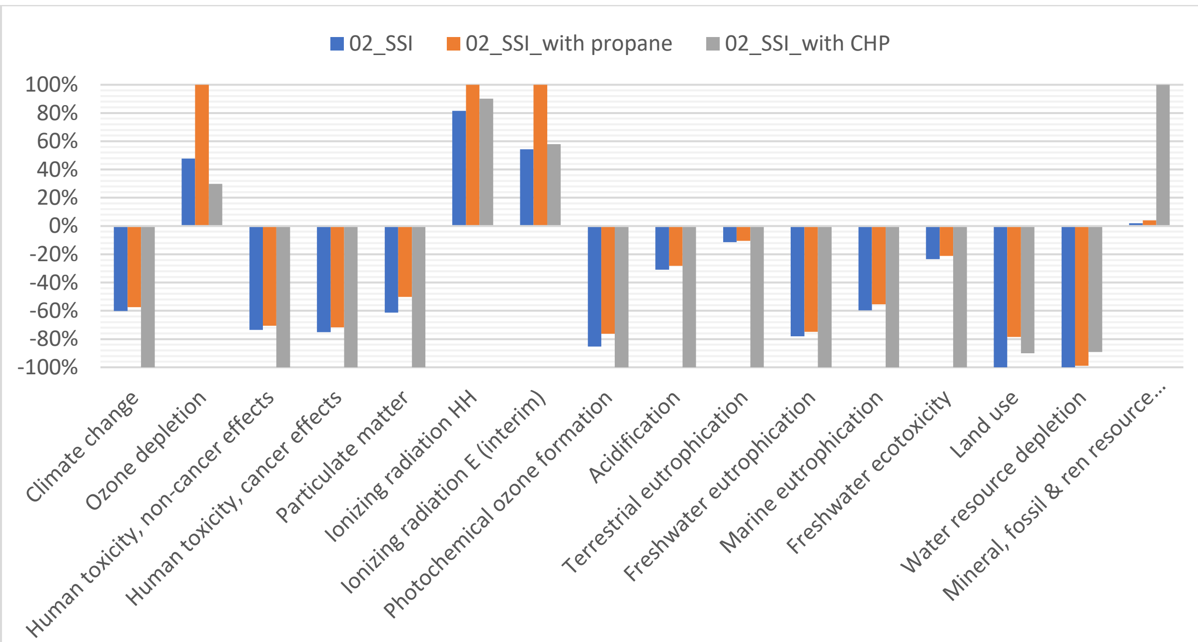

Figure 33: Comparison of SSI scenario with different incineration efficiencies

In addition to the impacts, we must be bear in mind that the impact of the electrodialysis separator is not correctly implemented due to lack of information. This could also influence the final results of the study. Besides, the residue is assumed to be landfilled. In some cases, the residue can be used as a building material. Due to its high heavy metal content usually, the ash is downcycled to roads. Although, the current legislation does not allow such a process in Denmark, in the future it might change. The following chart compares how it influences the SSI system impacts. Again, the assumptions have not been backed up with literature. The calculations are based on sheer assumption.

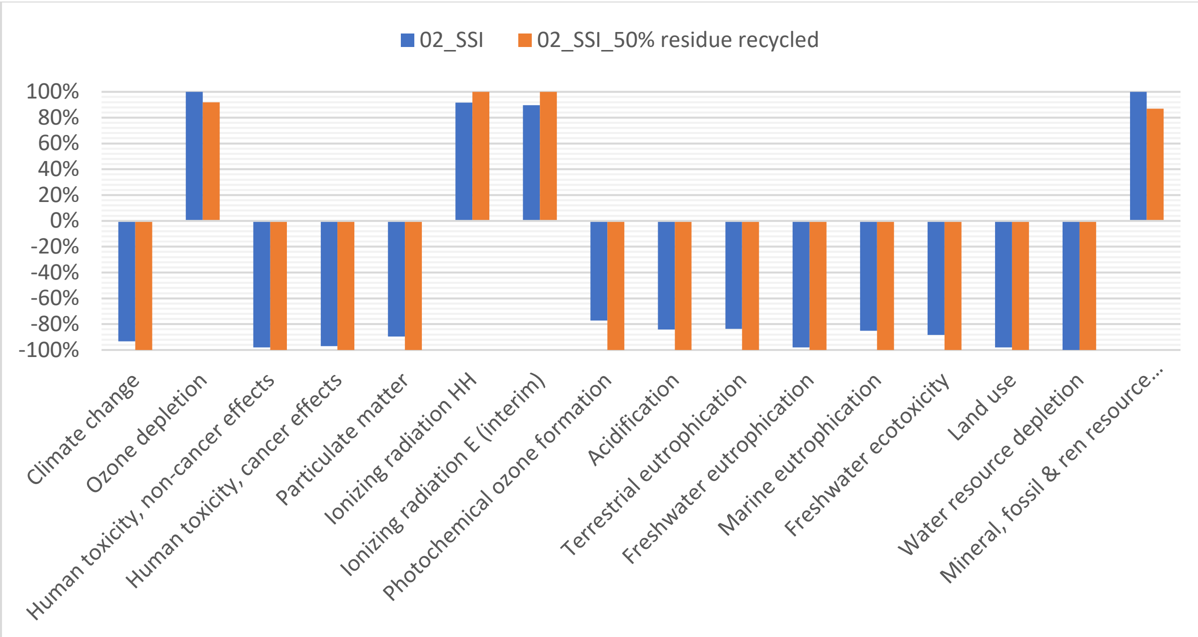

Figure 34: Comparison of SSI scenario with different residue handling

In Figure 34 compares SSI systems with different residue handling. The blue dataset represents the current progress where the residue is landfilled. The orange dataset represents a scenario when 50% of the residue is recycled as building material (cement). Even though, the calculations are based on assumptions, when the residue is recycled the impacts are lower and the avoided impacts are higher in every impact category.

Similarly to the previous scenario, **sewage sludge pyrolysis** also involves assumptions and design flaws. Even though, the provided data was more accurate. The main flows are based on a recently did PI chart. The PI chart is based on a currently working pilot system. The dataset was complete enough to define all the flows in the system, but the problem of upscale also presents itself in this scenario as well. For instance, the biogas use of the system was proportionally augmented to the ratio of dewatered sludge input. Supplementary, the working hour of the system was based on a recently did study.

During the SimaPro model development, there were design decisions that influence the results, and the model itself is based on assumptions. The composition of the pyrolysis product (biochar) was defined based on analytical measurements. In the models the carbon content of the biochar was plotted as if would avoid activated carbon production. In real life, it is usually not the case.

Even though, the effects of biochar on carbon-related emissions are favourable, is it not replacing activated carbon in the market flow.

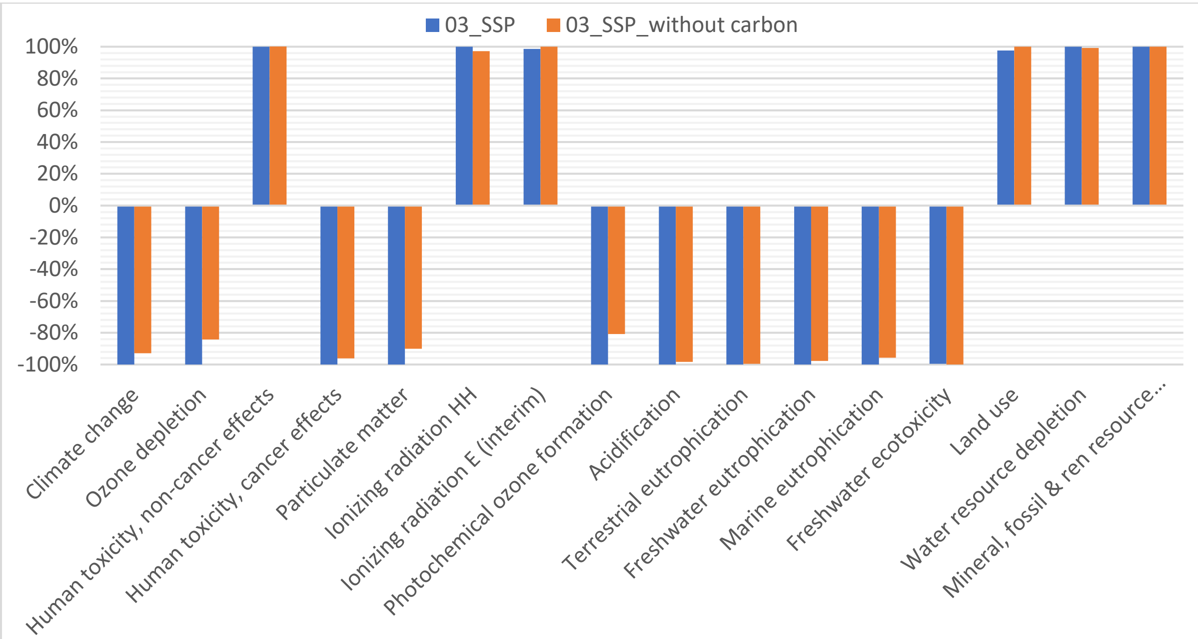

Figure 35: Comparison of SSP scenario with and without avoided activated carbon

As it can be seen in Figure 35 the activated carbon does not affect significantly the environmental impacts. The exclusion of the models does not change the overall picture.

It has to be added that the emission flows of the system are based only on assumptions. The flue gas flows from the pilot system were not measured analytically. However, the characterization had been already derived from the mass balance of the system, as it was previously done by the researchers at AquaGreen.

The most uncertain scenario is the one where **struvite precipitation** is implemented to Ejby Mølle STP. This dataset was only based on assumptions of how an optimal system would work in real life. It has to be said AarhusVand made it clear that the real scenario could be 50% less efficient then it was presented in the dataset. When the realistic values were applied to the mass balance model of the STP, the input and output flow became dissimilar. In contrary when the expected values were applied in the model the mass balance of the STP equalled out.

The second major issue with the struvite precipitation is the characterization of the struvite crystals based on literature. It was gathered from SUEZ related website. It also applies here; the values are rounded on the site and does not mirror the database.
The main difference between the three scenarios that the struvite precipitation technology only provides a solution for P-recovery. It means the P from dewatered sludge is still recovered from the compost. In this case, struvite has higher recovery efficiency than the other scenarios, but it has other negative outputs as well. For example, transportation.

In the inventory, a **systematic error** occurs. Therefore, the result has to be handled with care. During the inventory analysis and the quantification of the flows, a problematic input appeared. Another sludge flow sourced from Emmelev bio-oil plant. The sludge from here goes to the anaerobic digester. The main problem with this flow is that it was not quantified before in the mass balance model. Therefore, it was excluded from the study completely. The P flow was excluded but the amount is coming into the digester accounts as biogas later in the system.
Since this flow is badly implemented in every scenario it should not change the final result of the models. But it must be kept in mind and in further study it must be included. For the flawless quantification of this flow, it is recommended to involve Emmelev A/S to provide the necessary datasets.

A systematic error also appears in the modelling phase. The output phosphorus of the scenarios is modelled as avoided fertilizer production on the market. The process for that is "Phosphate fertilizer, as P2O5 {GLO} |market for| Coseq, U". In all scenarios, it was assumed that the amount of total phosphorus (TP) is leaving the system is equal to the amount that it replaces on the market. This is far from true in real life scenarios. In the following, the baseline model was evaluated, as if only half of the TP is used as a fertilizer.

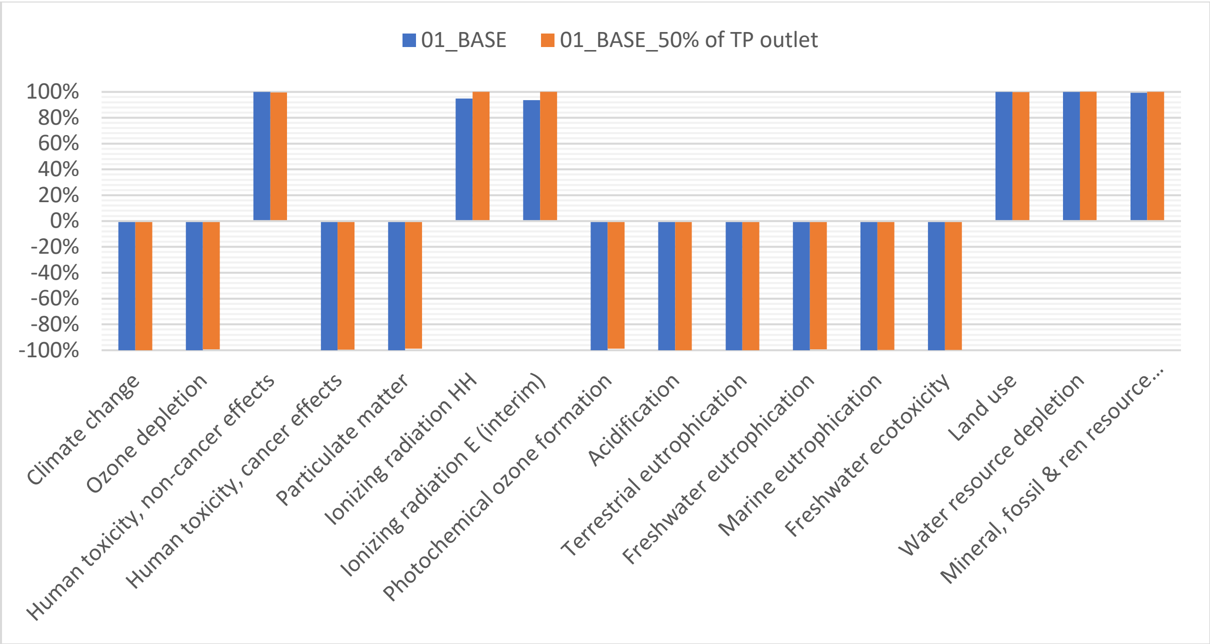

Figure 36: The effects of the changes in the amount of avoided fertilizer

In Figure 36 the comparison between the baseline scenarios is visible. The system is not sensitive to the changes in outlet P amount. On the contrary, there is one percent lower avoided impact in the freshwater eutrophication category then there was in the original system. It was assumed that the system would not be sensitive to this parameter because of the high avoided impacts from the biogas burning in the CHP.

The focus of the study was on the phosphorus flows. For the completeness sake the avoided nitrogen fertilizers were also taken to account in the models. In the following charts, the sensitivity of the system to this parameter will be presented.

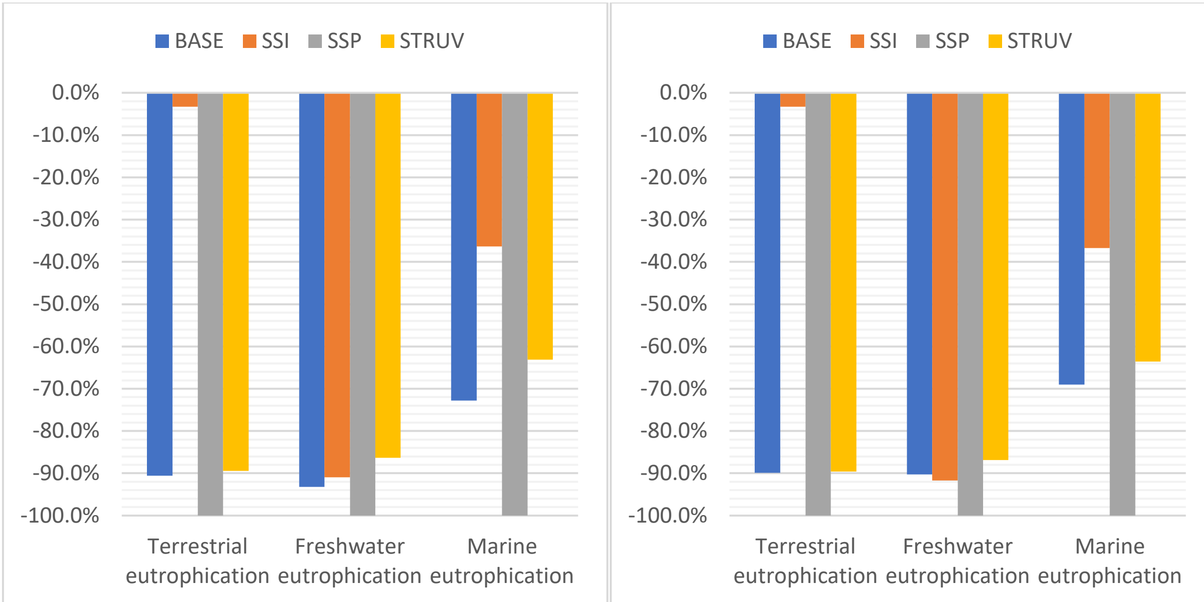

Figure 37: Comparison of scenarios of eutrophication categories standard scenarios (left) and without avoided nitrogen fertilizer (Right)

In Figure 37 the results show if nitrogen fertilizer is avoided or not. The difference is neglectable. Therefore, the system not sensitive to this parameter as well.

As a conclusion, in a future study of these systems – to achieve better comparison results – the wastewater and combined heat and power production would have to be excluded. The contribution of these unit processes is significantly higher than the impacts of the P-recovery processes. Thus, the overall result will be distorted.

4.5. Assessing the environmental impact results

Although, the study contains uncertainties about the assumptions and some design flaws during the development of the LCA models. The study is comprehensively analysing the different recovery technologies.

The study includes midpoint and endpoint characterization to increase the completeness and the representativeness of the data. It also makes easier for the reader to understand the different categories and how the different scenarios act in these groups. Overall, the midpoint and endpoint results are correlating. However, in certain categories, they might differ. This mainly caused by the different methodology and the different characterization and normalization factors used. The main dissimilarities int the ILCD and ReCiPe method occur in the toxicity and resource-related categories (Figure 38).

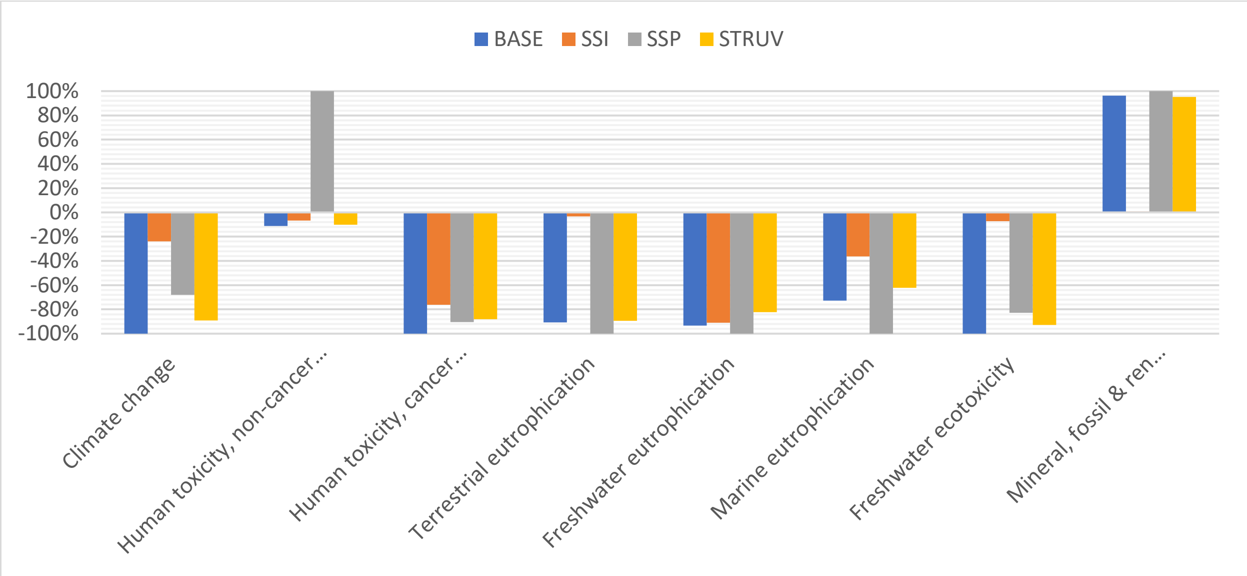

Figure 38: Most relevant impact categories (ILCD)

In the **climate change** impact category, all the scenarios had negative effects according to the models. The avoided impacts mainly related to the wastewater treatment process. Except for the SSI process, all the recovery processes showed negative effects on the environment. The only contributor to global warming was the combined heat and power process. It has to highlight in this case that the biogas was burned in the process was biogenic.

In the case of the **human toxicity non-cancer and cancer effects**, the results are questionable. There is no scientific consensus about the normalization values as well. When the normalization factors applied to a model, every impact category will have only one unit. In the case of toxicity related impacts, this factor is very ambiguous. This uncertainty weakens the decision if the toxicity related issues how relevant to the scenarios. A good solution to eliminate this problem could be the investigation of the toxicity related impact with USEtox method which is designed to define better the significance of these groups. This principal also applies to the freshwater ecotoxicity results as well.

According to the measurement in this case the wastewater treatment process avoided the most impact in this category. The struvite precipitation process also contributes to this because it is implemented to the wastewater treatment process.

The **eutrophicatio**n-related categories showed similar performance. Again, the highest negative contributor in every scenario is the wastewater treatment process in case all the eutrophication-related category. From all the scenarios SSP has the highest avoided impact in every eutrophication related impact categories.

Impacts of the **resource depletion** won't be discussed in this section. The detailed description can be found in 4.3.

The results from the ReCiPe damage assessment support the statements made during the ILCD impact assessment. On Figure 39 the conclusion of the damage assessment is visible.

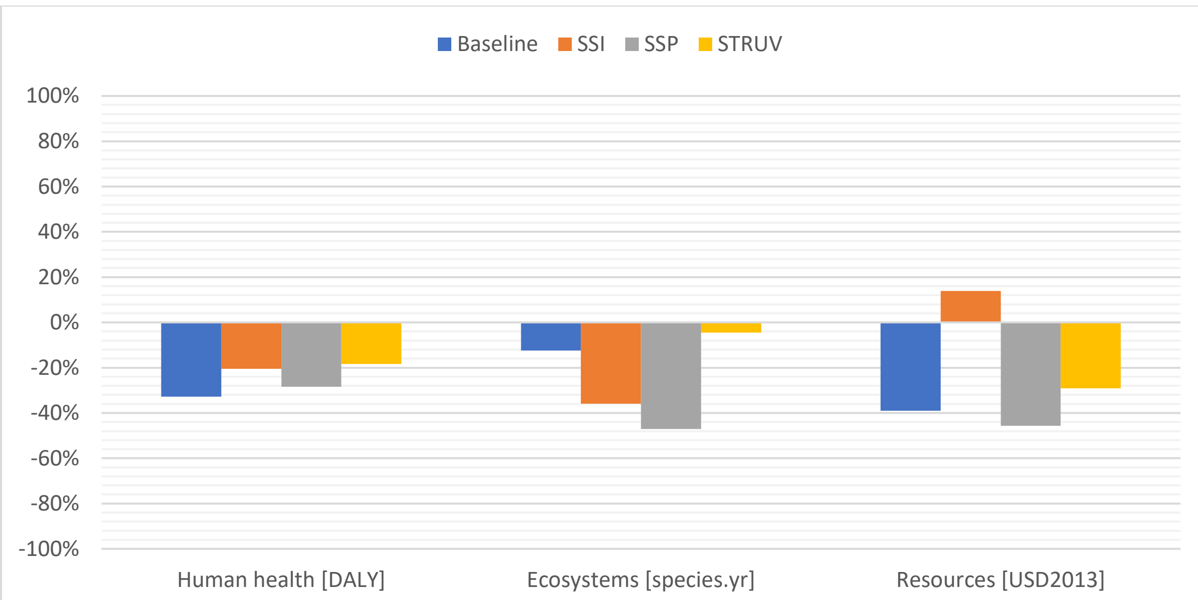

Figure 39: Damage assessment (ReCiPe)

Although the damage assessment results are highly distorted, it nicely comprehends the overall results of the scenarios. In **human health** (includes global warming and toxicity related categories) the baseline scenario has the lowest avoided impacts. Since this study looking for new options to increase the P-recovery efficiency this result is secondary. More interesting how the other scenarios performed in the damage assessment. It is evident that the pyrolysis scenario has the lowest impact on the environment (if the baseline is neglected). It was assumed that the struvite precipitation scenario has to perform similarly to the baseline scenario. It is close to half, at endpoint the magnesium addition to the struvite system cause a high impact in the global warming and toxicity related categories.

In case of the **ecosystem** related categories, the pyrolysis scenario clearly had the lowest impacts. However, this result can be also influenced by the high amount of avoided activated carbon. It is highly recommended that the characterization of the sewage sludge pyrolysis is modelled more accurate.

The **resource depletion** category at the endpoint is controversial compared to the midpoint characterization. This led to the implementation of the third EDIP method. This is discussed in the previous chapter.

4.6. Critical review

The consequential approach in wastewater treatment is not a common practice. From the analysed literature only two were applied this method. The consequential LCAs are focusing on the full share of the activities that are affecting the environment. Hence, its property it gives a broader picture of the environmental impacts. This is an advantage that might influence the outcome of the analysis, because in consequential LCAs the foreseeable consequences are rely on subjective view. Besides, there is no comparable amount of studies open to the public in the field for comparison, thus the paper can hardly refer to previously done analysis. The combination of these factors might result design errors in the life cycle modelling, which later will affect the sturdiness of the whole analysis and the value of the results.

In retrospective, more accurate planning of a life cycle assessment model is a crucial point in the execution. The author was aiming to reach a complex comparison of P-recovery technologies. But it must be admitted in some cases the less is more. It is assumed with a narrower scope on the studied processes more precise and stronger study would have been achieved. This aspect would also reduce the uncertainties and imperfections in the inventory and the life cycle modelling. In addition to this, a well thought schedule and preliminary plan on inventory development is essential for closer cooperation with experts from the involved parties.

The basis of the study is a mass balance model. This model based on calculations that have not been verified. This results a great uncertainty in the inventory. Although the model based on measurement (input and output), and there are parameters given from literature. The design of the struvite precipitation process was vaguely done. The mass balance calculation could be improved with the aid of a process engineer. Besides sampling of the different flows could help reduce the weakness of the mass balance, establishing strong background data and eliminating the assumptions. This would be only done on the baseline system, but the combination of the involvement of an expert and the sampling could reduce the chance of failures and miscalculations.

Another weak point of the study the electrolytic separation. Only few papers were found on the topic. These only included laboratory results about the recovery efficiencies. However, electricity consumption was mentioned in the paper, but the upscaling was not reasonable. Thus, this flow has been excluded. Similarly, the leachate from the composting and landfilling processes was excluded due to lack of information about the amount.

This study does not include the agricultural spreading of the final products. On one hand, the exclusion has simplified the databases and avoided a lot of assumptions. On the other hand, the study only considers the environmental impacts from the avoided fertilizers but not considers the environmental impact of the spreading of the different product. With this section added the model would have been more sophisticated, and it would have given the chance to see the end of life of the final products.

5. Conclusion

In Denmark, the water handling companies are aware of the environmental issues related to water and resource depletion. This study was executed as a decision support in collaboration with Odense's local water handling company VandCenter Syd. The assessment of the environmental impacts of these processes became essential in decision making. Life cycle assessment was developed to fill this need, and the last twenty years became a popular and proven tool for this purpose. In this consequential LCA different P-recovery methods were applied to VCS' Ejby Mølle STP. The scenarios are assessing the environmental impacts of the baseline scenario and the application of the new P-recovery processes.

In the **baseline scenario**, the currently applied P-recovery system is provided by Odense Miljø Nord composting facility. Composting is a low-cost solution which efficiently reduce SS volumes. This is used as an amendment for soil improvement and as fertilizer. This solution is not the most economical, nor the most efficient either. The life cycle model for this scenario was the most accurate one. Considering the environmental impact of the baseline system the overall result is negative according to the models. The effects on climate change the composting process was negative, although in all other impact categories it had positive impacts. Therefore, the need for new P-recovery and sludge management process was justified.

The first alternative technology was the **sewage sludge incineration**. The SSA cannot be used as fertilizer without purification. The energy production of this system is considered to be good, but it only provides district heating. The capital investment and the operation cost were reported to be high. The scenario was modelled based on Biofos' mono incineration facilities. This scenario performed with the least avoided impacts in every impact category, both in midpoint and endpoint assessment. The main contributor to the avoiding impact was the wastewater treatment process.

Sewage sludge pyrolysis is also a thermal process, providing high P-recovery efficiency. Besides, its high potential in volume reduction rates it also supplies efficient P-recovery. Depending on operation factors it can provide different products for different purposes. This case is based on the AquaGreen pilot process - running in Ejby Mølle -which is optimized to produce biochar. This product is readily available as fertilizer. Due to its properties, it can also improve the soil quality and reduce washout of nutrients from the soil. The models are based on pilot scale data and literature. It also contains several assumptions based on calculations and literature. The midpoint results are justified by the endpoint analysis. In almost all categories SSP performs the best from all the P-recovery technologies

Struvite precipitation only extracts the orthophosphate from the supernatant with high efficiencies. The capital investment and the operation cost are reported to be high. The quality of the struvite crystals is varying in every batch and the price on the market is low. . The midpoint and endpoint results of the system are in line with the baseline scenario. The reason for this is the model design. The wastewater treatment and the struvite precipitation process were not separated. Due to this issue clear definition is not possible.

Overall according to the midpoint and endpoint results, the impact assessment showed that sewage sludge pyrolysis has the highest avoided impact from all. Hence, the implementation of a pyrolysis unit would be the best option from an environmental perspective for VandCenter Syd.A better picture of the P-recovery process would have been achieved if the wastewater treatment and the combined heat and power is excluded from the study. This must be considered in a future study.

The main goal of the study is to support upcoming decisions at VandCenter Syd. It answers the research questions and gives a general overview of the possible technologies. The environmental impacts are considered more often. Nevertheless, when decisions are made the economic factors cannot be neglected. To achieve a detailed picture financial parameter are recommended to be included in future studies.

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APPENDIX

BASELINE

Table 17: Baseline scenario WWT inputs and outputs

Wastewater treatment					
Inputs			**Outputs**		
Name	**Unit**	**Value**	**Name**	**Unit**	**Value**
Iron (III) sulphate	*[ton]*	363	**Biogas**	*[m^3]*	4923457
Polyacrylamide	*[ton]*	46	**Effluent TP**	*[ton/y]*	3.89
Electricity	*[kWh]*	688607			
Heat	*[GJ]*	1786			
Transport	*[tkm]*	9318			

Inputs from technosphere: materials/fuels	Amount	Unit
Iron(III) sulfate, without water, in 12.5% iron solution state {GLO}| market for | APOS, U	363*a = 0	ton
Iron(III) sulfate, without water, in 12.5% iron solution state {GLO}| market for | Conseq, U	363*c = 363	ton
Electricity, medium voltage {DK}| market for | APOS, U	688607*a = 0	kWh
Electricity, medium voltage {DK}| market for | Conseq, U	688607*c = 6.89E5	kWh
Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | AP(	1786*a = 0	GJ
Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | Cor	1786*c = 1.79E3	GJ
Biogas {CH}| treatment of sewage sludge by anaerobic digestion | APOS, U	-4923457*a = 0	m3
Biogas {CH}| anaerobic digestion of manure | APOS, U	-4923457*a*0 = 0	m3
Biogas {CH}| anaerobic digestion of manure | Conseq, U	-4923457*c = -4.92E6	m3
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	9318*a = 0	tkm
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Conseq, U	9318*c = 9.32E3	tkm
Polyacrylamide {GLO}| market for | APOS, U	45.824*a = 0	ton
Polyacrylamide {GLO}| market for | Conseq, U	45.824*c = 45.8	ton
Add		

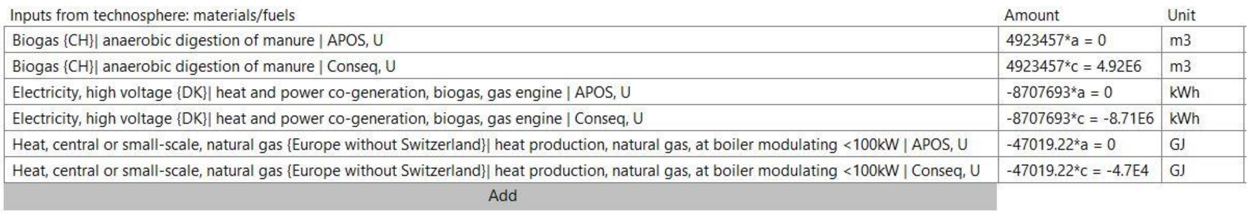
Figure 40:Baseline wastewater treatment inputs and outputs (SimaPro)

Emissions to water	Sub-compartment	Amount	Unit	Distribution
Phosphate	river	3.893	ton	Undefined
Add				

Figure 41: Baseline wastewater treatment effluent (SimaPro)

Table 18: Baseline scenario CHP inputs and outputs

Combined heat and Power					
Inputs			**Outputs**		
Name	**Unit**	**Value**	**Name**	**Unit**	**Value**
Biogas	*[m^3]*	4923457	**Electricity**	*[kWh]*	8707693
			Heat	*[GJ]*	47019



Inputs from technosphere: materials/fuels	Amount	Unit
Biogas {CH}| anaerobic digestion of manure | APOS, U	4923457*a = 0	m3
Biogas {CH}| anaerobic digestion of manure | Conseq, U	4923457*c = 4.92E6	m3
Electricity, high voltage {DK}| heat and power co-generation, biogas, gas engine | APOS, U	-8707693*a = 0	kWh
Electricity, high voltage {DK}| heat and power co-generation, biogas, gas engine | Conseq, U	-8707693*c = -8.71E6	kWh
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler modulating <100kW | APOS, U	-47019.22*a = 0	GJ
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler modulating <100kW | Conseq, U	-47019.22*c = -4.7E4	GJ
Add		

Figure 42: Baseline CHP inputs and outputs (SimaPro)

Table 19: Baseline Composting inputs and outputs

Composting					
Inputs			**Outputs**		
Name	**Unit**	**Value**	**Name**	**Unit**	**Value**
Dewatered sludge	*[ton]*	18156	**Compost**	*[ton]*	21994.77
DS TP	*[ton]*	137	**Compost TP**	*[ton]*	149.5644
Garden waste	*[ton]*	26444	**TP of GW**	*[ton]*	11.54558
Small stuff	*[ton]*	19991	**TP og straws**	*[ton]*	0.533531
Wood and Branches	*[ton]*	6346	**TN compost**	*[ton]*	241.9425
GW TP	*[ton]*	11.5			
Straws	*[ton]*	1222	**Emissions**		
STR TP	*[ton]*	0.5	**CO2-C**	*[ton]*	5187
Transport DS	*[tkm]*	243296	**CH4-C**	*[ton]*	78
Transport GW	*[tkm]*	243296	**N2O-N**	*[ton]*	2
Transport STR	*[tkm]*	243296	**CO-C**	*[ton]*	5

Inputs from technosphere: materials/fuels	Amount	Unit
Straw {GLO}| market for | APOS, U	1222*a = 0	ton
Straw {GLO}| market for | Conseq, U	1222*c = 1.22E3	ton
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	549005.6*a = 0	tkm
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Conseq, U	549005.6*c = 5.49E5	tkm
Grass, organic {GLO}| market for | APOS, U	19992*a = 0	ton
Grass, organic {GLO}| market for | Conseq, U	19992*c = 2E4	ton
Wood chips, wet, measured as dry mass {CH}| market for | Conseq, U	6347*a = 0	ton
Wood chips, wet, measured as dry mass {CH}| market for | APOS, U	6347*c = 6.35E3	ton
Add		

Figure 43: Baseline Composting inputs (SimaPro)

Outputs to technosphere: Avoided products	Amount	Unit
Compost {GLO}| market for | APOS, U	21995*a = 0	ton
Compost {GLO}| market for | Conseq, U	21995*c = 2.2E4	ton
Nitrogen fertiliser, as N {GLO}| market for | APOS, U	242*a = 0	ton
Nitrogen fertiliser, as N {GLO}| market for | Conseq, U	242*c = 242	ton
Phosphate fertiliser, as P2O5 {GLO}| market for | APOS, U	149.6*a = 0	ton
Phosphate fertiliser, as P2O5 {GLO}| market for | Conseq, U	149.6*c = 150	ton
Potassium fertiliser, as K2O {GLO}| market for | APOS, U	0*a = 0	ton
Potassium fertiliser, as K2O {GLO}| market for | Conseq, U	0*c = 0	ton
Add		

Figure 44: Baseline Composting outputs (SimaPro)

Emissions to air	Sub-compartment	Amount	Unit
Carbon dioxide, biogenic		5187	ton
Carbon monoxide, biogenic		5	ton
Methane, biogenic		78	ton
Dinitrogen monoxide		2	ton
Add			

Figure 45: Baseline Composting (SimaPro)

Table 20: Additional data for the scenarios

Additional data			
Name	**Unit**	**Value**	**Source**
NE - EM distance	*[km]*	6.7	*(Google maps, 2019)*
NW - EM distance	*[km]*	8.3	*(Google maps, 2019)*
EM - Odense Env. Nord	*[km]*	13.4	*(Google maps, 2019)*
Odense Env. Center NORD - Højme	*[km]*	10.4	*(Google maps, 2019)*
Odense Env. Center NORD - Seden	*[km]*	13.4	*(Google maps, 2019)*
Odense Env. Center NORD - Naesty	*[km]*	7.3	*(Google maps, 2019)*
Odense Env. Center NORD -Lindved	*[km]*	20.1	*(Google maps, 2019)*
Odense Env. Center NORD - Odense C	*[km]*	8.1	*(Google maps, 2019)*
Odense Env. Center NORD -Bilka	*[km]*	15	*(Google maps, 2019)*
Odense Env. Center NORD - Villestoffe	*[km]*	11.7	*(Google maps, 2019)*
Odense Env. Center NORD - Bolbro	*[km]*	10.4	*(Google maps, 2019)*
Average	*[km]*	12.05	*(Google maps, 2019)*
Straw travel	*[km]*	50	*(Google maps, 2019)*

SEWAGE SLUDGE INCINERATION

Table 21: SSI WWT inputs and outputs

Wastewater treatment					
Inputs			**Outputs**		
Name	**Unit**	**Value**	**Name**	**Unit**	**Value**
Iron (III) sulphate	*[ton]*	363	**Biogas**	*[m^3]*	4923457
Polyacrylamide	*[ton]*	46	**Effluent TP**	*[ton/y]*	3.89
Electricity	*[kWh]*	688607			
Heat	*[GJ]*	1786			
Transport	*[tkm]*	9318			

Table 22: SSI inputs and outputs

Incineration					
Inputs			**Outputs**		
Name	**Unit**	**Value**	**Name**	**Unit**	**Value**
Biogas	*[m^3]*	4923457	**P-rich product**	*[ton]*	342
			Residue to landfill	*[ton]*	3813
			District heating	*[ton]*	43201376
			Emissions to air		
			CO	*[kg/a]*	4.9E+01
			TOC	*[kg/a]*	7.8E-03
			Particles	*[kg/a]*	0.0E+00
			HF	*[kg/a]*	0.0E+00
			HCl	*[kg/a]*	6.1E-04
			SO2	*[kg/a]*	1.3E+01
			NOx	*[kg/a]*	3.1E-02
			Hg	*[kg/a]*	2.8E-03
			Sum 9 metals	*[kg/a]*	1.2E-06

Inputs from technosphere: materials/fuels	Amount	Unit
Biogas {CH}| anaerobic digestion of manure | APOS, U	4923457*a = 0	m3
Biogas {CH}| anaerobic digestion of manure | Conseq, U	4923457*c = 4.92E6	m3
Add		

Figure 46: SSI input (SimaPro)

Outputs to technosphere: Avoided products	Amount	Unit
Phosphate fertiliser, as P2O5 {GLO}| market for | APOS, U	342*a = 0	kg
Phosphate fertiliser, as P2O5 {GLO}| market for | Conseq, U	342*c = 342	kg
Heat, for reuse in municipal waste incineration only {DK}| market for | APOS, U	43201376*a = 0	kWh
Heat, for reuse in municipal waste incineration only {DK}| market for | Conseq, U	43201376*c = 4.32E7	kWh
Add		

Figure 47: SSI outputs (SimaPro)

Emissions to air	Sub-compartment	Amount	Unit	Distribution
Organic carbon		0.008	kg	Undefined
Carbon monoxide, biogenic		48.9	kg	Undefined
Hydrogen fluoride		0	kg	Undefined
Hydrogen chloride		0.001	kg	Undefined
Sulfur dioxide		13	kg	Undefined
Nitrogen oxides, DK		0.031	kg	Undefined
Mercury		0.003	kg	Undefined
Add				

Figure 48: SSI Emissions

SEWAGE SLUDGE PYROLYSIS

Table 23: SSP WWT inputs and outputs

Wastewater treatment					
Inputs			**Outputs**		
Name	**Unit**	**Value**	**Name**	**Unit**	**Value**
Iron (III) sulphate	*[ton]*	363	**Biogas**	*[m^3]*	4923457
Polyacrylamide	*[ton]*	46	**Effluent TP**	*[ton/y]*	3.89
Electricity	*[kWh]*	688607			
Heat	*[GJ]*	1786			
Transport	*[tkm]*	9318			

Table 24: SSP CHP inputs and outputs

Combined heat and Power					
Inputs			**Outputs**		
Name	**Unit**	**Value**	**Name**	**Unit**	**Value**
Biogas	*[m^3]*	4815716	**Electricity**	*[kWh]*	8517140
			Heat	*[GJ]*	45990

Table 25: SSP inputs and outputs

Pyrolysis					
Inputs			**Outputs**		
Name	**Unit**	**Value**	**Name**	***Unit***	**Value**
Biogas	*[m^3]*	107741	**Biochar**	*[ton]*	2511
			District heating	*[kWh/s]*	848000
				[GJ/a]	3053
			Emission to air		
			CO2	*[ton]*	92.8
			SO2	*[ton]*	4.1
			NO	*[ton]*	20.2

Inputs from technosphere: materials/fuels	Amount	Unit
Biogas {GLO}| market for | APOS, U	107741.34*a = 0	m3
Biogas {GLO}| market for | Conseq, U	107741.34*c = 1.08E5	m3
Add		

Figure 49: SSP input (SimaPro)

Outputs to technosphere: Avoided products	Amount	Unit
Heat, district or industrial, natural gas {DK}| heat and power co-generation, natural g	3052.8*a = 0	GJ
Heat, district or industrial, natural gas {DK}| heat and power co-generation, natural g	3052.8*c = 3.05E3	GJ
Activated carbon, granular {RER}| activated carbon production, granular from hard c	568*a = 0	ton
Activated carbon, granular {RER}| activated carbon production, granular from hard c	568*c = 568	ton
Nitrogen fertiliser, as N {GLO}| market for | APOS, U	53*a = 0	ton
Nitrogen fertiliser, as N {GLO}| market for | Conseq, U	53*c = 53	ton
Phosphate fertiliser, as P2O5 {GLO}| market for | APOS, U	125.57*a = 0	ton
Phosphate fertiliser, as P2O5 {GLO}| market for | Conseq, U	125.57*c = 126	ton
Potassium fertiliser, as K2O {GLO}| market for | APOS, U	1.60*a = 0	ton
Potassium fertiliser, as K2O {GLO}| market for | Conseq, U	1.60*c = 1.6	ton
Add		

Figure 50: SSP outputs (SimaPro)

Emissions to air	Sub-compartment	Amount	Unit	Distribution
Carbon dioxide, biogenic	low. pop.	92.802	ton	Undefined
Sulfur dioxide, DK	low. pop.	4.1465	ton	Undefined
Nitrogen dioxide, DK	low. pop.	20.1756	ton	Undefined
Add				

Figure 51: SSP Emissions (SimaPro)

Table 26: Biochar characteristic (Based on: Thomsen, (2018)

Biochar characteristic		
Name	*[ton]*	**Value**
DM		2511
Vs		1868
VS org		643
VS org		352
$CaCO_3$		568
TOC		53
TN		126
P		89
P-citric acid		2
K		24
Tot. Mg		7
Metals		1862

STRUVITE PRECIPITATION

Table 27: STRUV WWT inputs and outputs

Wastewater treatment					
Inputs			**Outputs**		
Name	**Unit**	**Value**	**Name**	**Unit**	**Value**
Polyacrylamide	*[ton]*	45.8	Biogas	*[m3]*	4923457
Electricity	*[kWh]*	688607	Effluent TP	*[ton/y]*	3.89
Heat	*[GJ]*	1785.8	Struvite	*[ton]*	222.6
Transport	*[tkm]*	9317.8	TP	*[ton]*	62.3
Mg (II) salts	*[ton]*	463	TN	*[ton]*	11.1
NaOH	*[ton]*	191	Mg	*[ton]*	22.3
Additional Electricity	*[kWh]*	1084028			

Inputs from technosphere: materials/fuels	Amount	Unit
Iron(III) sulfate, without water, in 12.5% iron solution state {GLO}| market for | APOS, U	363*a*0 = 0	ton
Iron(III) sulfate, without water, in 12.5% iron solution state {GLO}| market for | Conseq, U	363*c*0 = 0	ton
Electricity, medium voltage {DK}| market for | APOS, U	688607*a = 0	kWh
Electricity, medium voltage {DK}| market for | Conseq, U	688607*c = 6.89E5	kWh
Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | APOS, U	1786*a = 0	GJ
Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | Conseq, U	1786*c = 1.79E3	GJ
Biogas {CH}| treatment of sewage sludge by anaerobic digestion | APOS, U	-4923457*a = 0	m3
Biogas {CH}| anaerobic digestion of manure | APOS, U	-4923457*a = 0	m3
Biogas {CH}| anaerobic digestion of manure | Conseq, U	-4923457*c = -4.92E6	m3
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U	9318*a = 0	tkm
Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | Conseq, U	9318*c = 9.32E3	tkm
Polyacrylamide {GLO}| market for | APOS, U	45.824*a = 0	ton
Polyacrylamide {GLO}| market for | Conseq, U	45.824*c = 45.8	ton
Magnesium {GLO}| market for | APOS, U	463*a = 0	ton
Magnesium {GLO}| market for | Conseq, U	463*c = 463	ton
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | APOS, U	191*a = 0	ton
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Conseq, U	191*c = 191	ton
Add		

Figure 52: STRUV inputs (SimaPro)

Outputs to technosphere: Avoided products	Amount	Unit
Nitrogen fertiliser, as N {GLO}| market for | APOS, U	11.1*a = 0	ton
Nitrogen fertiliser, as N {GLO}| market for | Conseq, U	11.1*c = 11.1	ton
Phosphate fertiliser, as P2O5 {GLO}| market for | APOS, U	62.3*a = 0	ton
Phosphate fertiliser, as P2O5 {GLO}| market for | Conseq, U	62.3*c = 62.3	ton
Add		

Figure 53: STRUV outputs (SimaPro)

Emissions to water	Sub-compartment	Amount	Unit	Distribution
Phosphate	river	3.893	ton	Undefined
Add				

Figure 54: STRUV Effluent (SimaPro)

NETWORKS

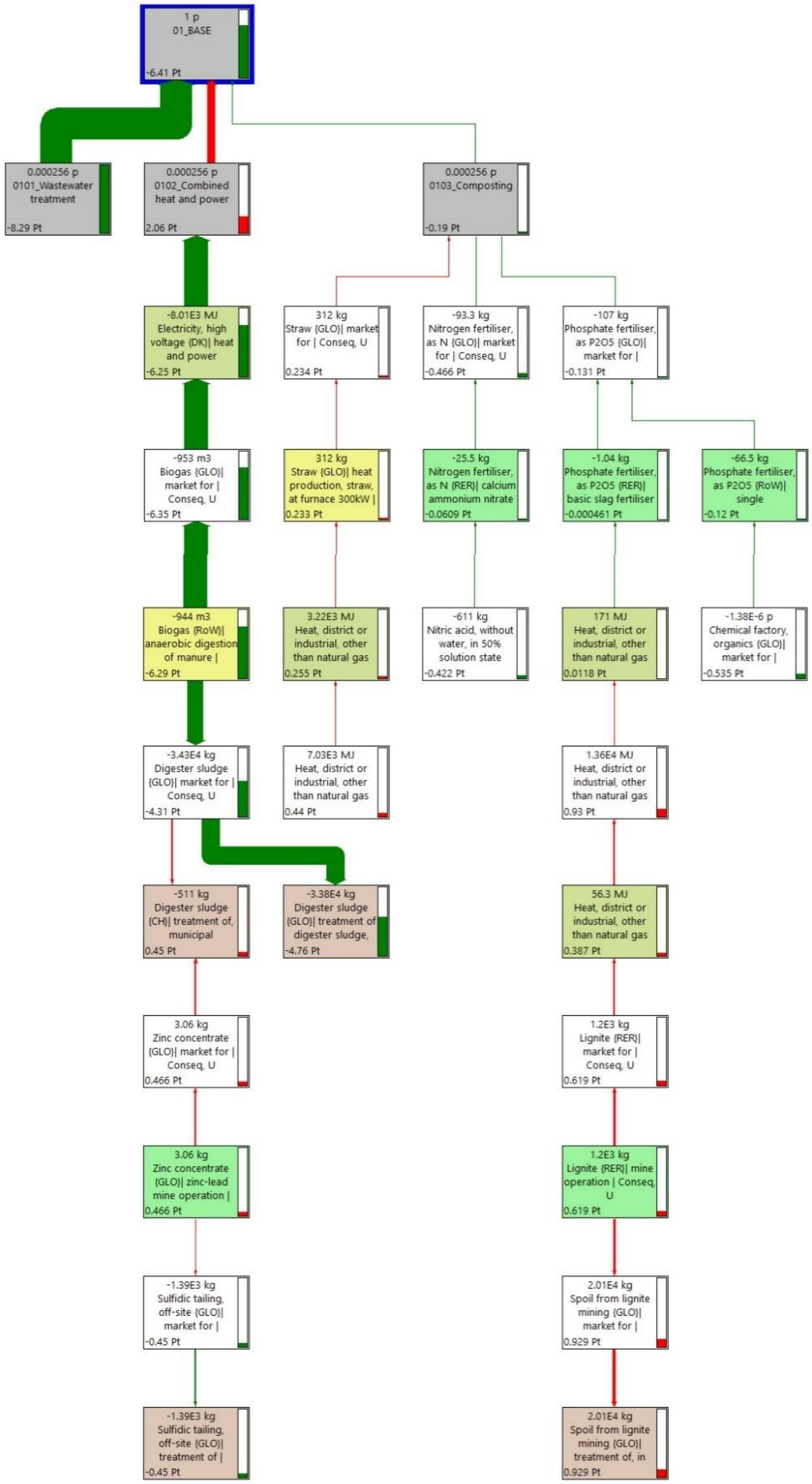


Figure 55: Baseline Single Score network with 5% cut-off

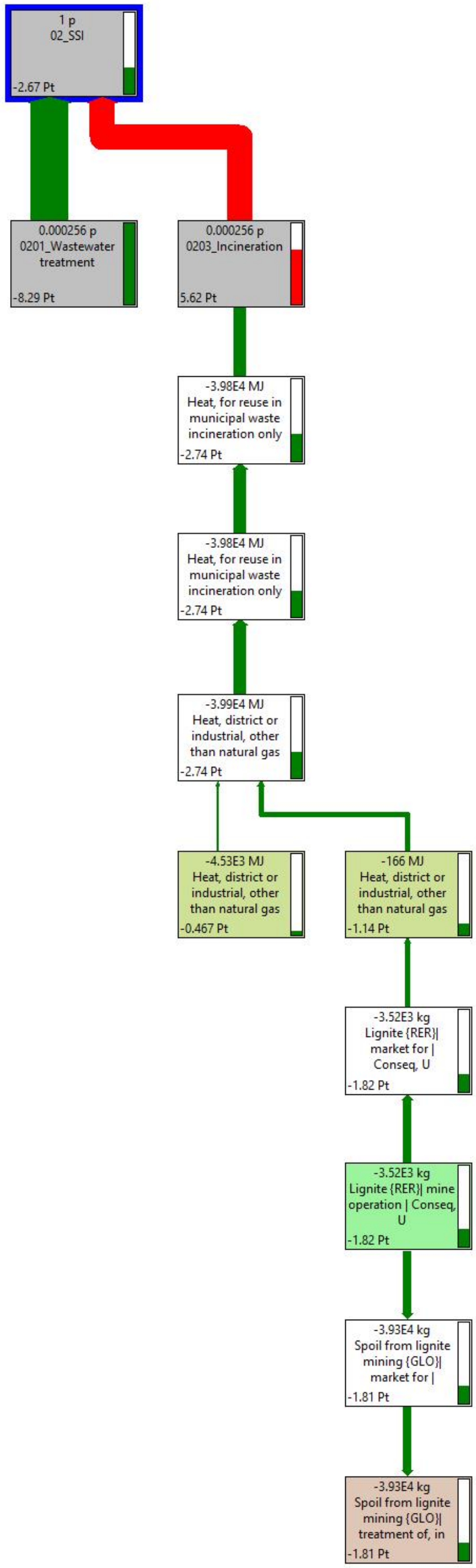


Figure 56: SSI Single Score network with 5% cut-off

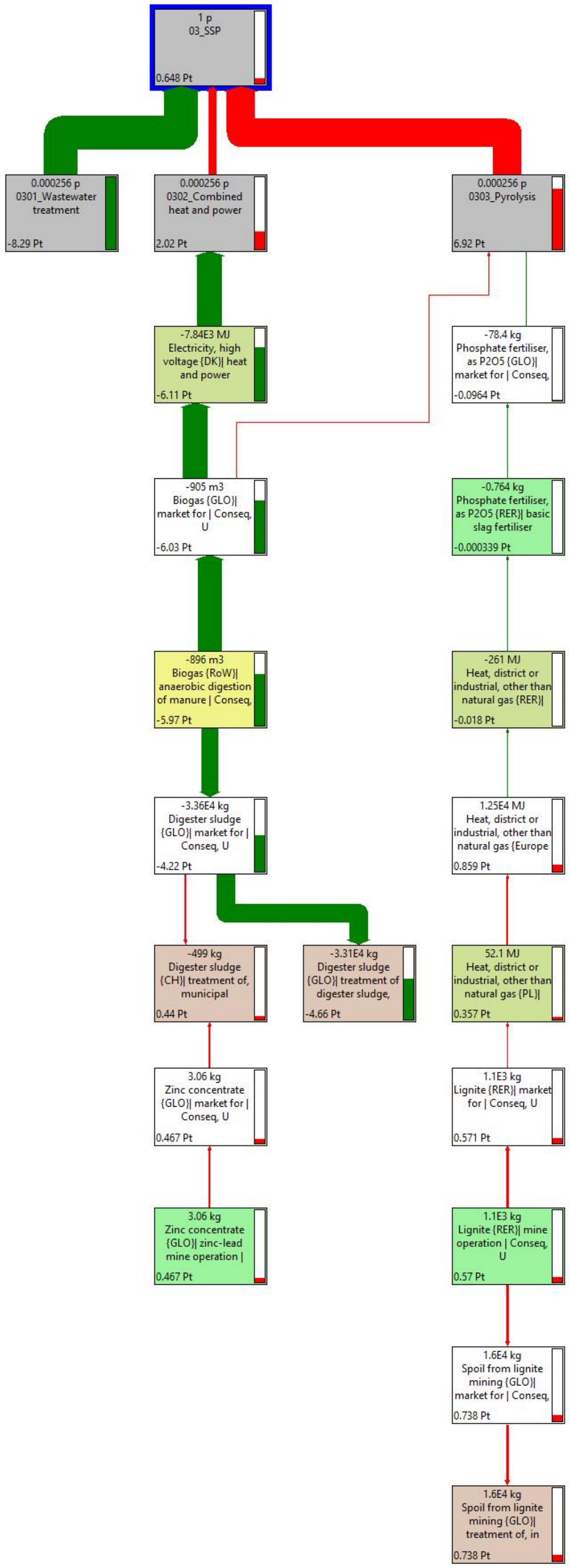


Figure 57: SSP Single Score network 5% cut-off

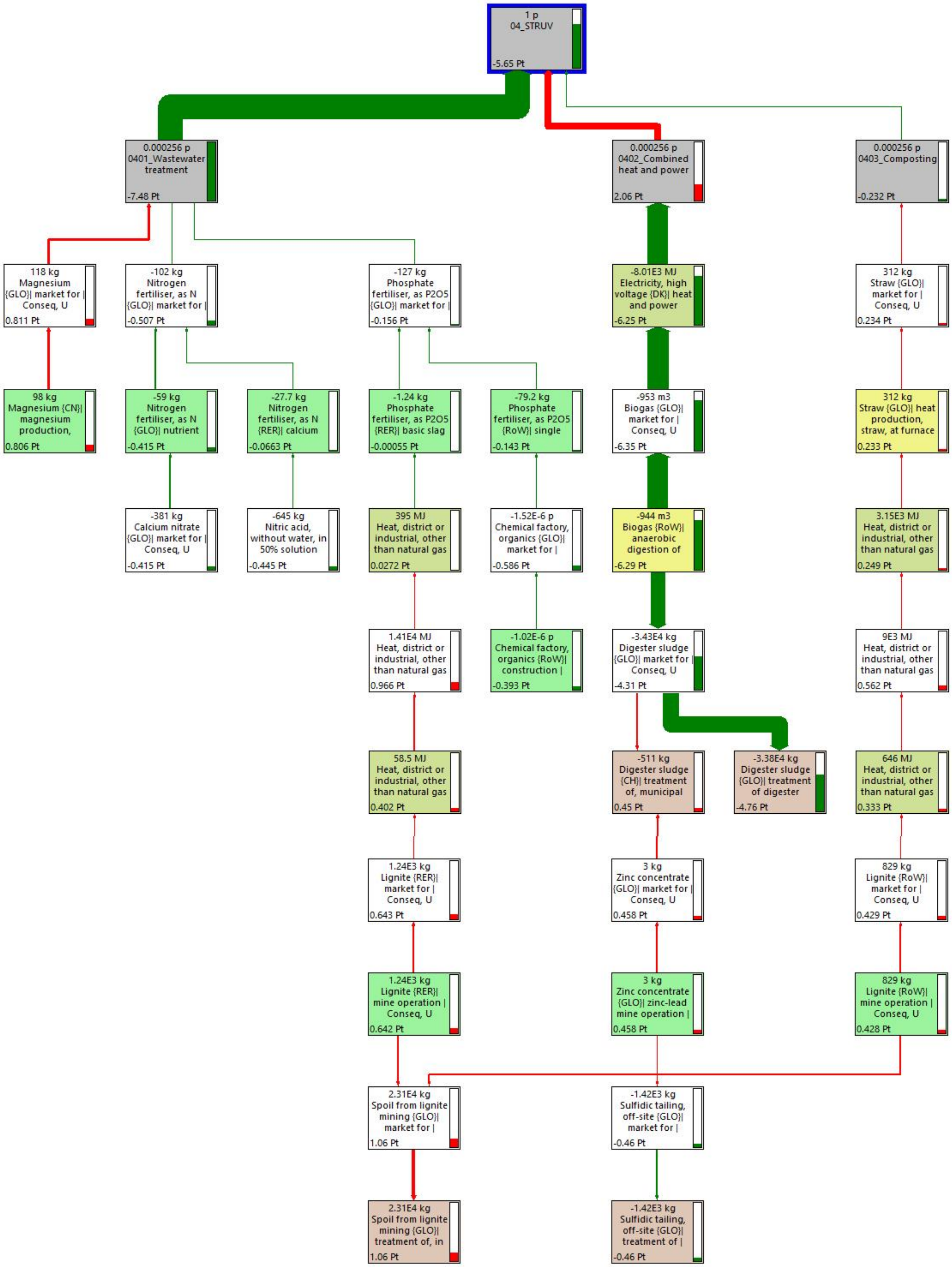


Figure 58: STRUV Single Score network with 5% cut-off