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## **LCA analysis of different WWTP processes**

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In cooperation with INCOPA

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## Preface

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# Summary

Wastewater treatment plants have the main objective to treat the incoming wastewater to meet specified discharge criteria. Different process configurations requiring different amount of resources such as energy and chemicals can be used. The selection of process configuration can also impact the amount of energy produced from digestion of the sludge to biogas.

In this study, Life Cycle Assessment (LCA) has been used to calculate the environmental impact of operation of three different process configurations for phosphorus removal from wastewater; pre-precipitation, simultaneous precipitation and enhanced biological phosphorus removal (Bio-P) to two different effluent standards regarding total phosphorus: 1 mg P/L and 0.3 mg P/L. Pre-precipitation and simultaneous precipitation are based on phosphorous removal by addition of chemicals in different locations along the treatment process, Bio-P is based on removal by additional uptake of phosphorus by specialized bacteria. Both iron and aluminium based precipitation chemicals were studied.

Operational data in the form of direct emissions to water and air, energy consumption, chemical consumption, production of sludge and biogas were generated by dynamic process simulations. The operational data were used in the LCA to calculate the environmental impact in five different impact categories, where global warming potential (GWP) also known as carbon footprint, was one.

The results show that pre-precipitation gives the lowest GWP per m<sup>3</sup> of treated water for both effluent standards. Bio-P gives the highest GWP. Pre-precipitation results in a higher removal of pollutants in the primary sedimentation which is positive from two perspectives: lower load on the biological treatments resulting in lower energy consumption in this treatment step and a higher methane production in the digestion process. Pre-precipitation had the lowest energy consumption and the highest methane production of the three configurations.

The lower effluent standard resulted in higher GWP for all three configurations with still lowest values for pre-precipitation and highest for Bio-P.

The choice of energy source is an important factor for several impact categories. A change of the source of electricity from European average electricity mix to 100% hydropower, decreases the total GWP of operating the process configuration with 50%.

# Sammanfattning

Avloppsreningsverk har som huvudsyfte att rena avloppsvatten för att uppfylla kraven på utgående vattenkvalitet. För att uppnå detta kan olika processer tillämpas. Olika processlösningar ger olika miljöpåverkan i form av bland annat energiförbrukning och kemikalieförbrukning. I tillägg kan olika mycket energi produceras från avloppsslam genom rötning till biogas, beroende på val av processlösning.

I denna studie har livscykelanalys (LCA) använts för att beräkna miljöpåverkan från tre olika processkonfigurationer för rening av fosfor från avloppsvatten; förfällning, simultanfällning och biologisk fosforrening (s.k. Bio-P) till två olika halter utgående totalfosfor; 1 mg P/L och 0,3 mg P/L. De två första konfigurationerna använder fällningskemikalier för avskiljning av fosfor, medan den tredje inte använder någon kemikalietillsats utan utnyttjar särskilda bakterier för extra upptag av fosfor. Både järnbaserad och aluminiumbaserad fällningskemikalie har studerats.

Driftdata i form av emissioner till vatten och luft, energiförbrukning, kemikalieförbrukning, produktion av slam och biogas har genererats genom dynamisk processimulering. Driftdata har sedan använts som indata till LCA:n för beräkning av miljöpåverkan i fem olika kategorier där klimatpåverkan varit en kategori.

Resultaten visar att processkonfigurationen med förfällning gav lägst klimatpåverkan per m<sup>3</sup> renat avloppsvatten medan biologisk fosforrening gav högst klimatpåverkan. Anledningen till att förfällning gav lägst miljöpåverkan beror på att mer föroreningar avskiljs i försedimenteringen vilket är positivt ut två aspekter: minskad belastning till biologin och således mindre energiförbrukning i det biologiska reningssteget och ökad biogasproduktion. Förfällning hade både lägst energiförbrukning och högst metanproduktion av de tre studerade konfigurationerna. Skillnaden mellan simultanfällning och biologisk fosforreduktion var mindre än mellan dessa och förfällning.

Den inbördes ordningen mellan konfigurationen var densamma vid båda utsläppskraven, men klimatpåverkan ökade för scenariot med hårdare utsläppskrav.

Val av energikälla är en viktig faktor för flera miljöpåverkanskategorier. En ändring i elmix från europeisk medel-el till 100 % vattenkraft gav en minskning i klimatpåverkan med 50 %.

# 1 Introduction

It is well known that municipal wastewater treatment plants (WWTPs) consume energy in their processes, but also has a potential to produce energy in the form of biogas. There are a number of “standard” process solutions when treating wastewater depending on wastewater quality, treatment requirements, available space and perception on what is a good solution or not.

With chemical treatment it is possible to remove more phosphorus, produce more biogas, reduce energy consumption in biological treatment and make a more compact plant. Still, chemical treatment is perceived as a less preferred solution in many cases as chemicals comes to a cost and an environmental footprint. Therefore, a process without chemical addition is therefore usually more attractive.

Professor Halvard Ødegaard and Ingemar Karlsson raised this question more than 20 years ago (Ødegaard & Karlsson, 1994; Ødegaard, 1995) and their conclusion was that a combined chemical/biological treatment process is more environmentally friendly than a biological process only. Since then, the Life Cycle Assessments (LCA) tools have been improved, new learnings on how to operate WWTPs are known and technologies have improved. The requirements of treated water have also become stricter in some areas. It is therefore of value to, from an LCA perspective, re-evaluate different WWTP processes with the new information available today.

Dynamic process models are advantageous for this type of evaluation as different process configurations can be simulated using the same incoming flow and pollutant load and the yearly variations can be traced. The models can give estimations of resource consumption, effluent concentrations, sludge production and quality and biogas production.

## 2 Objective

The objective of this study is to compare the environmental impact of treating wastewater to two different levels of effluent quality (total phosphorus concentration 1 mg P/L and 0.3 mg P/L) in three different process configurations using dynamic process modelling and life cycle assessment. The three different processes studied are:

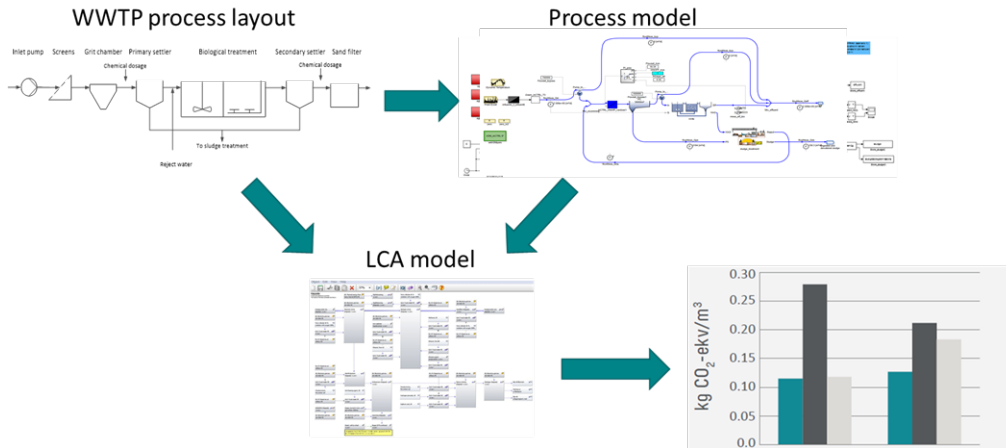
1. Pre-precipitation (PrePrec)
2. Simultaneous precipitation (SimPrec)
3. Biological Phosphorous Removal (Bio-P)

The incoming water quality is the same in all scenarios and automatic process control in the models was used to achieve similar treatment results for the different processes.

Pre-precipitation gives less load in the biological treatment step and increased biogas production, while simultaneous precipitation has the advantage that incoming carbon source can be used for pre-denitrification and it is possible to build up a buffer of precipitation metal in the sludge, but the disadvantage that larger biological volume is needed (to compensate for higher load and that metal in the sludge takes up part of the volume). Bio-P has the advantage that no chemicals are used while the configuration requires larger volumes and more pumping. The aim of the project was to quantify the differences between the configurations in the form of environmental impact in five categories.

## 3 Method

To calculate the environmental impact the process layout in combination with process modelling and LCA needs to be in place. This combination is illustrated in Figure 1.



**Figure 1. Schematic of the combinations of the different methods.**

A detailed description of the different methods is given in the sections below.

### 3.1 Process modelling

The starting point for the process modelling was a full-scale Swedish wastewater treatment plant with a simultaneous precipitation configuration (Henriksdal WWTP, 780 000 P.E. (Personal Equivalent), Inflow 250 MLD (Megaliters per Day)). Data on influent wastewater characteristics, coagulant dosage, sludge production, sludge concentrations, effluent quality, energy data and biogas production were collected and used in calibrating the model. Some adjustments to volumes and operating conditions were done to more resemble standard European conditions.

#### 3.1.1 Effluent discharge criteria

The baseline scenario for the discharge criteria is compliant with the Urban Waste Water Treatment Directive for plants larger than 100 000 P.E. releasing effluent to sensitive areas, (UWWTD, 1991). Limits for Biological Oxygen Demand (BOD), total Nitrogen (TN) and total Phosphorus (TP) are studied. All three processes are also operated to reach a lower effluent phosphorus concentration. Discharge criteria are based on yearly average concentrations. The effluent concentrations used as criteria for the simulations are presented in Table 1.

**Table 1. Effluent discharge criteria as yearly average concentrations.**

Scenario	BOD <sub>5</sub>	TN	TP
Baseline	25 g/m <sup>3</sup>	10 g/m <sup>3</sup>	1 g/m <sup>3</sup>
Stricter P	25 g/m <sup>3</sup>	10 g/m <sup>3</sup>	0.3 g/m <sup>3</sup>



It should be noted that a Phosphorus removal without chemical addition, so called Biological Phosphorus Removal (Bio-P), is difficult to control to reach a certain effluent standard regarding phosphorous concentration, without a tertiary polishing step. Chemical dosing enables a higher level of control of effluent phosphorous concentration.

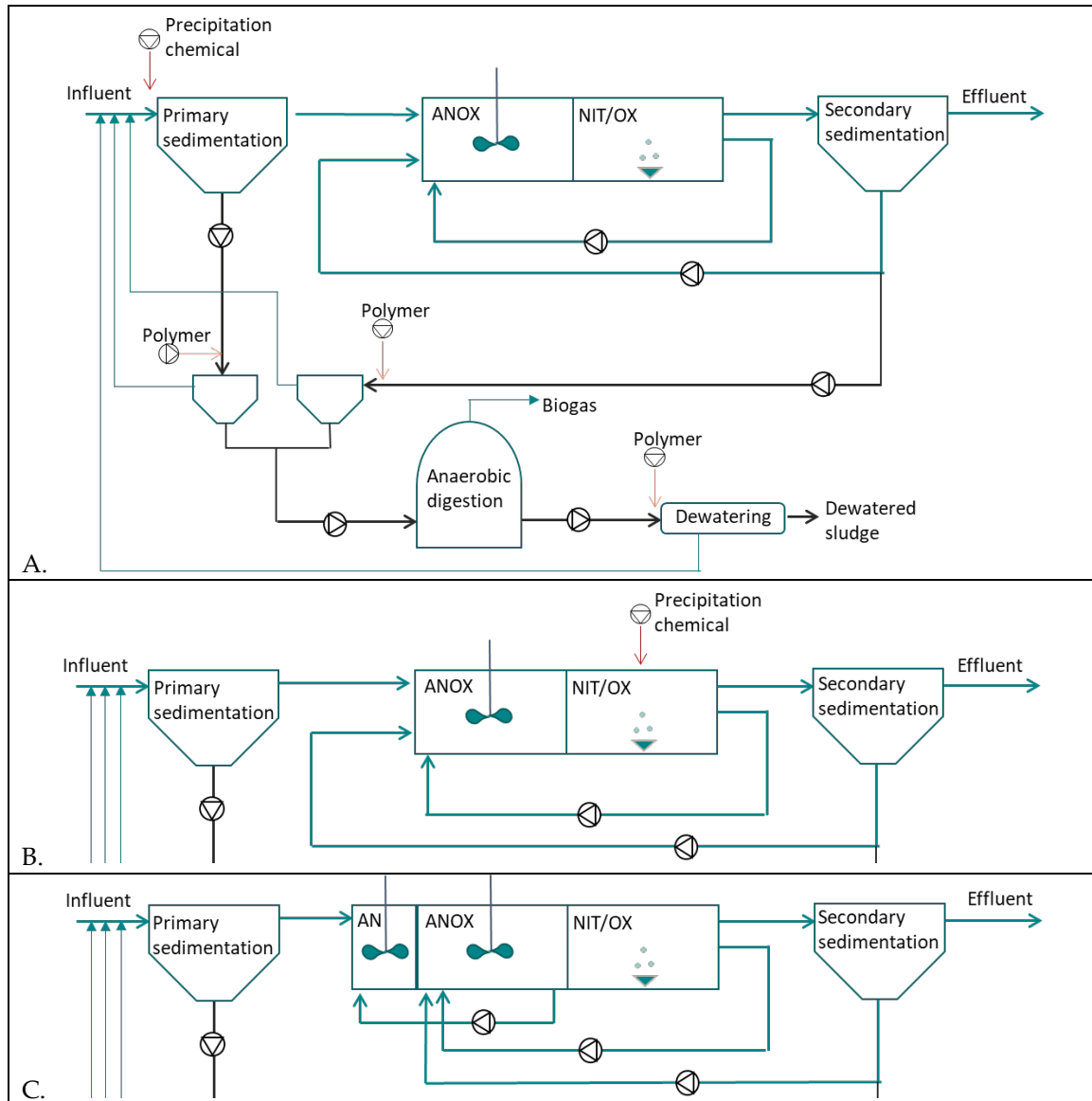
### 3.1.2 Process configuration

In this project three different processes are studied:

1. **Pre-precipitation.** Precipitation chemical is added prior to primary sedimentation.
2. **Simultaneous precipitation.** Precipitation chemical is added in the biological treatment.
3. **Biological Phosphorous Removal.** No precipitation chemical added.

The modelling of the three processes all include primary sedimentation, activated sludge process, secondary sedimentation and anaerobic digestion. Reject water from thickening and dewatering of sludge is added to the inlet (prior to pre-sedimentation). Polymers are added in both the thickening and dewatering of sludge processes. The activated sludge process is a pre-denitrification process without addition of external carbon source. Pre-treatment steps (screens, grit and grease removal) are not included in the dynamic process models.

The configurations of each alternative are presented for the Baseline scenario in Figure 2.



**Figure 2. A. Process configuration for Pre-precipitation. B. Changes in configuration to simultaneous precipitation. C. Changes in configuration to Biological phosphorus removal.**

For the Stricter phosphorus scenario, the process configuration is complemented with sand filtration as a final polishing step after secondary sedimentation. An additional flocculant dosage point is also added just before the sand filters.

### 3.1.3 Volume calculations

The volumes from Henriksdal WWTP in Sweden has been used as reference. The reference plant is operated at a sludge concentration in the biology of about 2 500 g SS/m<sup>3</sup>. This is low compared to standard European situations where 4000 g SS/m<sup>3</sup> is considered normal. Thus, the volumes for ANOX and NIT/OX has been adjusted with a factor  $2500/4000 = 0.625$  in order to resemble normal volumes required when operating at a sludge concentration of 4000 g SS/m<sup>3</sup>. In addition, the size of the secondary sedimentation tank has been designed based on surface loading rate 0.6 m/h and depth 4 m.

With pre-precipitation, the load to the biology will be lower compared to a plant with simultaneous precipitation. Therefore, this alternative has smaller volumes compared to the other two alternatives. The criteria for the new volume was to maintain the aerated sludge age. With Bio-P removal an additional anaerobic compartment has been added, resulting in a larger total volume for the Activates Sludge Process (ASP).

In the models, the anoxic volume (ANOX) is divided into two compartments and the aerated volume (NIT/OX) is divided into three compartments. The added anaerobic volume in the Bio-P alternative is modelled as one separate compartment prior to the first anoxic compartment.

**Table 2. Total volumes used in modelling of the three processes.**

Total volumes, m <sup>3</sup>	Pre-precipitation	Simultaneous precipitation	Bio-P
<b>Primary Sedimentation</b>	30 000	30 000	30 000
AN	N/A	N/A	47 000
ANOX	56 000	56 000	60 000
NIT/OX	30 240	54 000	54 000
<b>Secondary Sedimentation</b>	75 000	75 000	75 000
<b>Anaerobic digester</b>	32 000	28 500	31 000

The volume of the anaerobic digester was adjusted to maintain on average a hydraulic retention time (HRT) of 20 days.

### 3.1.4 Models used

The process modelling has been carried out in the software SIMBA#water.

For the biokinetics an extended version of ASM1 (Activated sludge model no 1, Henze et al, 2000) called ASM\_inCTRL (Schraa et. al., 2016) was used. This is a mature engineering model continuously updated and it includes biological phosphorus removal and the possibility to add both iron and aluminum-based precipitation chemicals.

Anaerobic digestion was modelled using a simple model calculating the biogas production based on biodegradable Chemical Oxygen Demand (COD), temperature, retention time and pH.

Sand filtration was modelled with a separate dosage of coagulant on the effluent followed by a small storage tank to provide a hydraulic retention time followed by a fixed separation of solids (setting 80% removal of solids). The reject water including the solids were set to have a concentration of 200 g TSS/m<sup>3</sup> resulting in a reject/wash water flowrate corresponding to 5.6% of effluent flow, which is similar as the reference plant (5.6%).

### 3.1.5 Load

Flow and load are based on data from the reference plant, see Table 3. As it is situated in Sweden, the flow is typical for Nordic conditions, with high infiltration of stormwater runoff and ground water, cold temperatures during winter and a snow-melting period in the spring. It is a combined

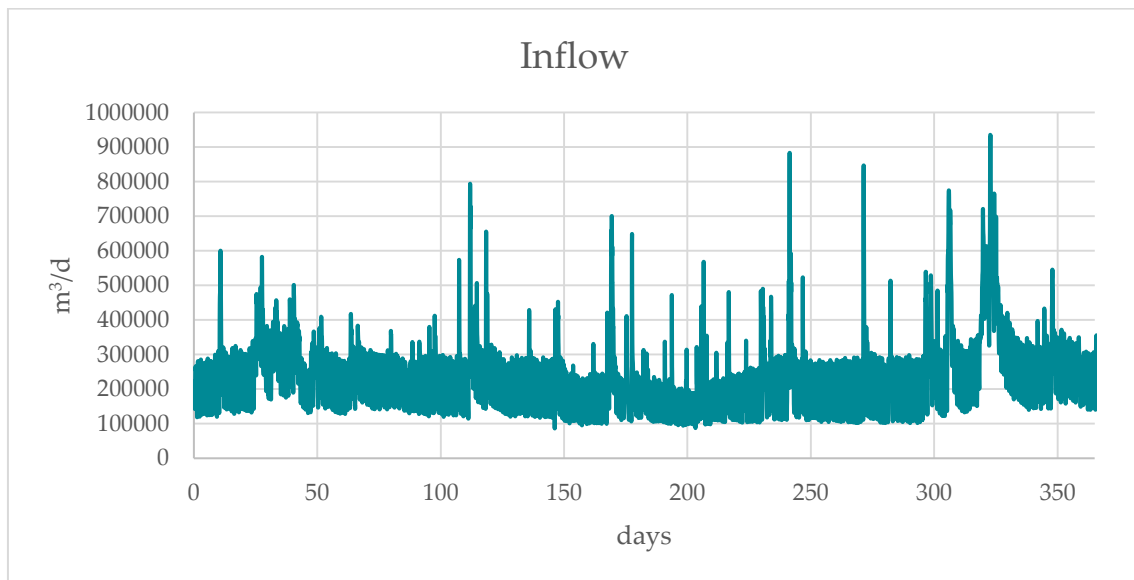
sewer system for wastewater and stormwater. In Sweden phosphorus load to treatment plants are relatively low as a result of upstream work (e.g. removal of phosphorus in detergents).

**Table 3. Flow and load to the treatment processes as yearly average.**

Parameter	Unit	Load, constant	Load, average of dynamic data
Q	m <sup>3</sup> /d	270 000	250 665
TSS	g/m <sup>3</sup>	310	313
COD	g/m <sup>3</sup>	500*	516
TN	g/m <sup>3</sup>	40	45
TP	g/m <sup>3</sup>	6	6.7

\*TOC measurements x 3.3.

The dynamic inflow for one year is presented in Figure 3.



**Figure 3. Inflow used to model the scenarios (15 min resolution).**

Influent concentrations are based on a fixed load per day for COD, TN and TP and a specific load profile for daily variation. The loads were divided by inflow to get concentrations (Figure 4).

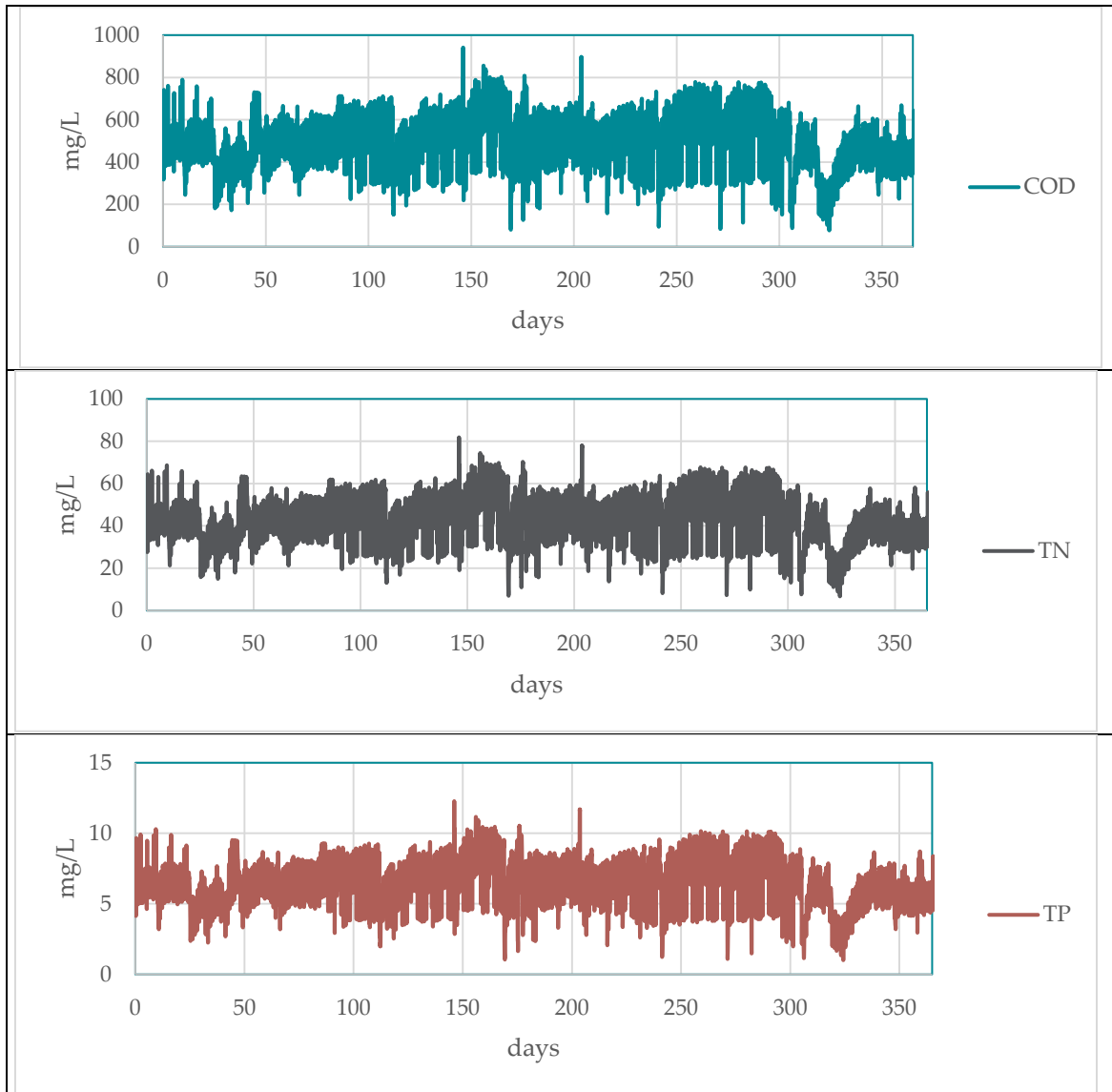


Figure 4. Influent concentrations of COD (top), TN (middle) and TP (bottom). Resolution 15 minutes.

Average temperature was 17.2 degrees C, yearly variation is shown in Figure 5.

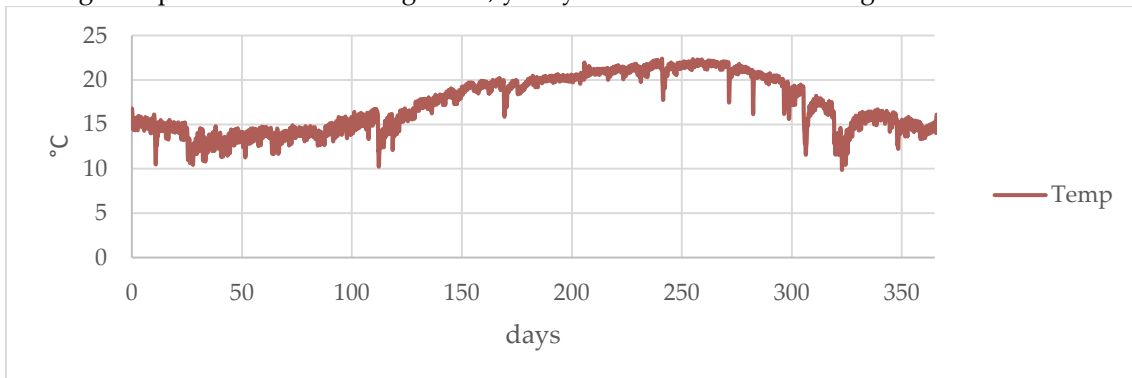


Figure 5. Temperature variations for one year. Resolution 15 minutes.

### 3.1.6 Control strategies

In order to compare the results from the different alternatives priority was set on achieving similar effluent concentrations for each modelled alternative. In order to control the effluent concentrations, the following control strategies have been implemented in the model:

1. **Ammonium based aeration control.** Effluent ammonium concentration is used to adjust the aeration in the NIT/OX compartments. Setpoint 1 g NH<sub>4</sub>-N/m<sup>3</sup>. Maximum dissolved oxygen (DO) setpoint was set to 3.5 g O<sub>2</sub>/m<sup>3</sup>.
2. **Nitrate control.** Effluent nitrate concentration is used to adjust the nitrate recirculation flowrate. Setpoint was 7 g NO<sub>3</sub>-N/m<sup>3</sup>. Nitrate recirculation maximum flowrate was set to 4xQ<sub>in</sub>.
3. **Phosphate control.** Effluent phosphate measurements are used to control dosage of precipitation chemicals. The setpoint was 0.35 g PO<sub>4</sub>-P/m<sup>3</sup> for dosage control. The effluent phosphate concentration is difficult to control when using biological phosphorous removal. For this configuration, the volumes of the different compartments and the recirculation flow rates were manually adjusted to reach close to the target effluent concentration.
4. **Sludge concentration control.** Suspended solids concentration in the biology is used to control the waste activated sludge flowrate in order to have similar solids loading rate to the secondary clarifier. In the modelling it was assumed that the sedimentation properties are similar for the different processes, i.e. that the secondary sedimentation can handle 4 000 g/m<sup>3</sup> regardless of the biological process.

In Table 4 the setpoints are summarized.

**Table 4. Different setpoints used in the control of the WWTP.**

Scenario	Setpoint TSS Bio (WAS control)	Setpoint Eff NO <sub>3</sub> (Q rec control)	Setpoint Eff PO <sub>4</sub> (Precipitation dosage control)	Setpoint Eff NH <sub>4</sub> (aeration control)
Baseline	< 4000 g/m <sup>3</sup>	7 g/m <sup>3</sup>	0.35 g/m <sup>3</sup>	1 g/m <sup>3</sup>
Stricter P	< 4000 g/m <sup>3</sup>	7 g/m <sup>3</sup>	Addition of sand filter	1 g/m <sup>3</sup>

### 3.1.7 Modelling different coagulants

Two types of coagulants are considered; iron source and aluminum source. In the models, the products will contribute to different sludge productions. This is considered in the model (g product and g Fe or Al are included). If nothing else is mentioned ferric salts are used in the chemical treatment as a coagulant.

For the thickening and dewatering different polymer dosages are used for sludge from different processes. A summary of polymer dosages used can be found in Table 5.

**Table 5. TS concentrations of sludge and dosage of polymer used for thickening and dewatering.**

	TS in sludge entering (%)	Dosage (g/kg TS)	TS and separation degree in treated sludge (%)
PS without pre-precipitation	1.5%		5%, 95% removal
PS with pre-precipitation	1.5%		5%, 95% removal
WAS, ANOX+NIT	0.8%		5%, 95% removal
WAS, Bio-P	0.8%		5%, 95% removal
Digested sludge (ANOX+NIT)		11.5*	24%* 98% removal
Digested sludge (Bio-P)		16.2*	24%* 98% removal

\*STOWA 2012

## 3.2 Life Cycle Assessment - LCA

In this study, Life Cycle Assessment (LCA) has been used to calculate the environmental impact of operation of the WWTP for one year. An LCA includes resource consumption, waste production, energy use and transport for all intermediaries. Construction and demolition of the treatment plant are thus not included.

The GaBi Professional 8.6 software tool has been used to perform the LCA modelling. GaBi Professional is one of the world's most widely used software tools for LCA. It has been developed for more than 20 years and contains a robust internal database with more than 7,000 ready-to-use life cycle inventory (LCI) profiles.

The LCA in this study includes activities that are directly related to, or a result of, wastewater treatment. Production and transport of chemicals for the purification process, as well as production of the electricity used, are also included. In this study we do not study the use phase of by-products from the process such as use of biogas and sludge.

The life cycle analysis was performed according to ISO 14044 standards.

The functional unit used in this project is 1 m<sup>3</sup> of treated wastewater fulfilling the yearly average discharge criteria specified in Table 1.

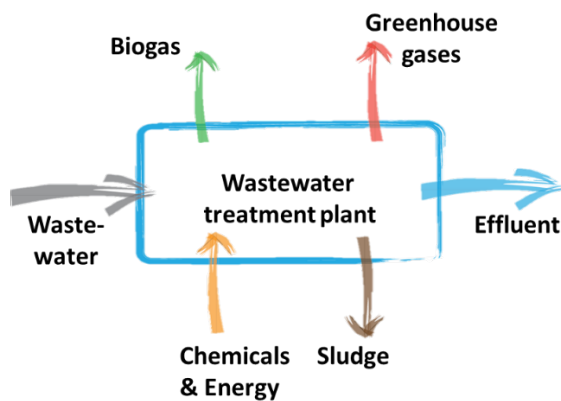
To quantify the potential environmental impact from processes, a number of environmental impact categories were selected, see Table 6. These are developed by CML (Centrum voor Milieukunde – Universiteit Leiden, 2002) and within LCA general and common use (Guinée et al., 2002). The methods are scientifically based on chemical and biological reactions in air, water and soil, as well as estimated resources on earth. The categories analyse potential environmental effects.

The units are reference units where all emissions have been normalized to the reference unit using characterization factors. Nitrous oxide is, for example, normalized to carbon dioxide equivalents by multiplying the amount of nitrous oxide emissions by a factor of 298, as nitrous oxide has a 298 times stronger impact on global warming compared with carbon dioxide, per kg of emissions of each gas (in a 100-year perspective), (CML 2002).

**Table 6. List of environmental impact categories analysed in the study. By Abiotic Depletion (ADP Fossil) is meant energy-containing fossil resources such as coal, oil and natural gas, extracted from the geosphere. Uranium is not included. ADP Elements are non-energy-containing natural resources such as metals and phosphorus, extracted from the geosphere. Uranium is included here.**

Environmental impact categories (CML2002)		
Short name	Name	Unit
Global Warming Potential (GWP)	CML2001 - Jan. 2016, Global Warming Potential, excl biogenic carbon (GWP 100 years)	kg CO <sub>2</sub> -Equiv.
Eutrophication Potential (EP)	CML2001 - Jan. 2016, Eutrophication Potential (EP)	kg PO <sub>4</sub> -Equiv.
Acidification Potential (AP)	CML2001 - Jan. 2016, Acidification Potential (AP)	kg SO <sub>2</sub> -Equiv.
Abiotic Depletion (ADP Fossil)	CML2001 - Jan. 2016, Abiotic Depletion Potential (ADP fossil)	MJ
Abiotic Depletion (ADP Elements)	CML2001 - Jan. 2016, Abiotic Depletion Potential (ADP elements)	kg Sb-Equiv.

Input data to the LCA related to the operation of the WWTP was retrieved from the process model and includes direct emissions, energy and chemical consumption, see Figure 6. Production data on coagulants and polymers used in the process were given from INCOPA. The sludge handling after the digester is not considered in this study, only amounts produced is tracked.



**Figure 6. Illustration of inputs and outputs from the WWTP that drives the LCA. Note that sludge amounts only are considered and not any further handling of this output.**

Energy production were set to be European average electricity mix and data taken from the data bases in the LCA software.

To study the effect of how different choices in the LCA impacts the result, a sensitivity analysis can be performed. In this study following sensitivity analysis were chosen:

- Change of energy source for electricity production. What will happen if European average electricity mix is replaced by 100 % hydro power?
- Usage of biogas. What is the impact if biogas replaces natural gas in the energy system?

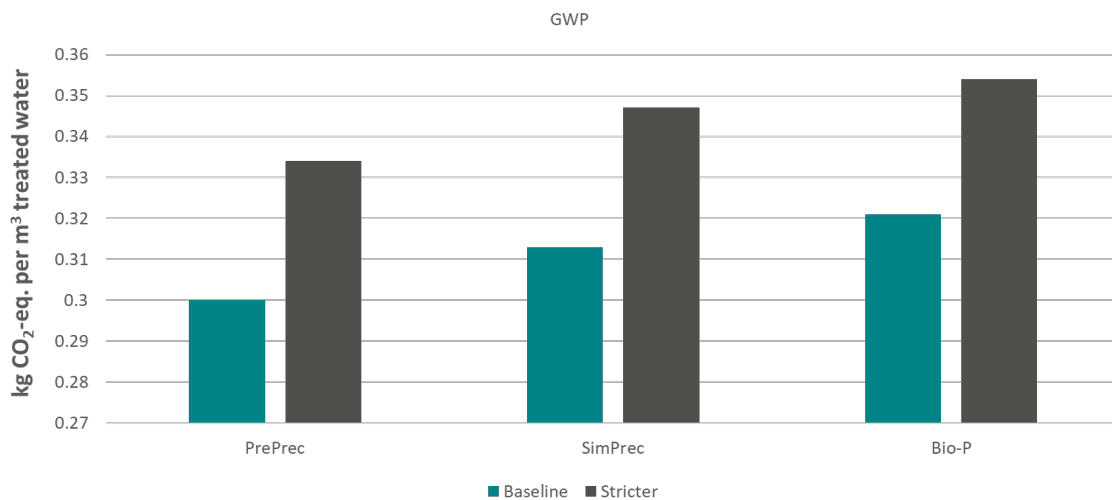


## 4 Results

Simulation of the three different process configurations were performed and data utilized in the LCA for the following scenarios:

- Baseline: Effluent standards that fulfils the criteria given.
- Stricter: More stringent limits on phosphorus.

In Figure 7 the environmental impact category global warming potential (GWP) is presented for the different process configurations and effluent criteria.

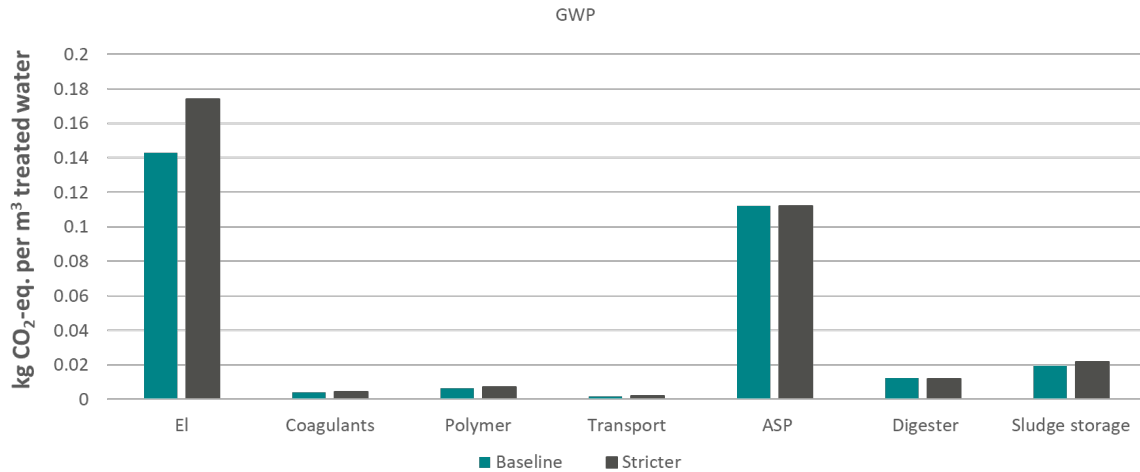


**Figure 7. Global warming potential for the different process configurations. Results coloured according to effluent criteria. Note that the usage of biogas is included in these results.**

When comparing the configurations, pre-precipitation gives the lowest GWP for both effluent scenarios. This is because the pre-precipitation configuration has the lowest load on the biological treatment and hence less energy is needed in this treatment step. Biological phosphorus removal has the highest GWP of the three configurations.

A more stringent effluent limit on phosphorus cause an increase of the GWP for all three process configurations. To fulfil the stricter limits on phosphorus there is a need for more coagulant. But that does not explain all the difference. A post precipitation step is needed in all process configurations to achieve the stricter effluent criteria. This extra step results in a higher energy usage and therefore contributes to the global warming potential.

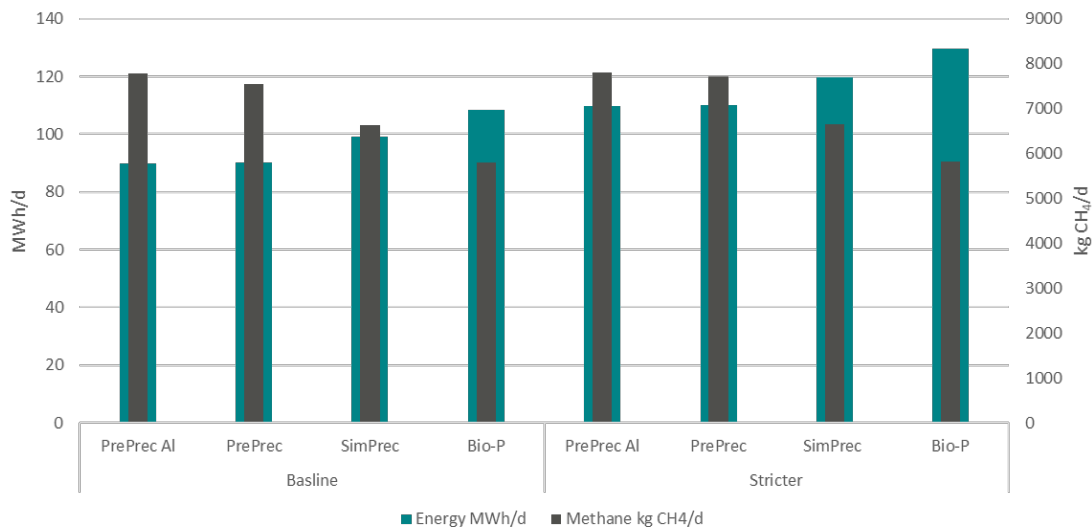
To see what affects to the GWP the figures are broken down into different resources needed and direct emissions from contributing process steps. As an example, the different contributions to GWP for the pre-precipitation step is shown in Figure 8.



**Figure 8. Contribution to the GWP for the pre-precipitation configuration. Results coloured according to effluent criteria. Note that the usage of biogas is not included. El = electricity usage, ASP=Activated Sludge Process (biological treatment).**

The two main contributors to GWP are the electricity usage and the direct emissions of nitrous oxide (laughing gas) from the biological treatment. From the digester, slip of methane contributes to the GWP. Direct emissions of methane and nitrous oxide from sludge storage are the third largest contributor to GWP. The increased dosage of chemicals in the stricter effluent criteria does not affect the GWP in any significant way. The difference is mainly from the increased energy demand by introduction of a sand filter as a final polishing treatment step. Transportation of chemicals has the least contribution to the GWP.

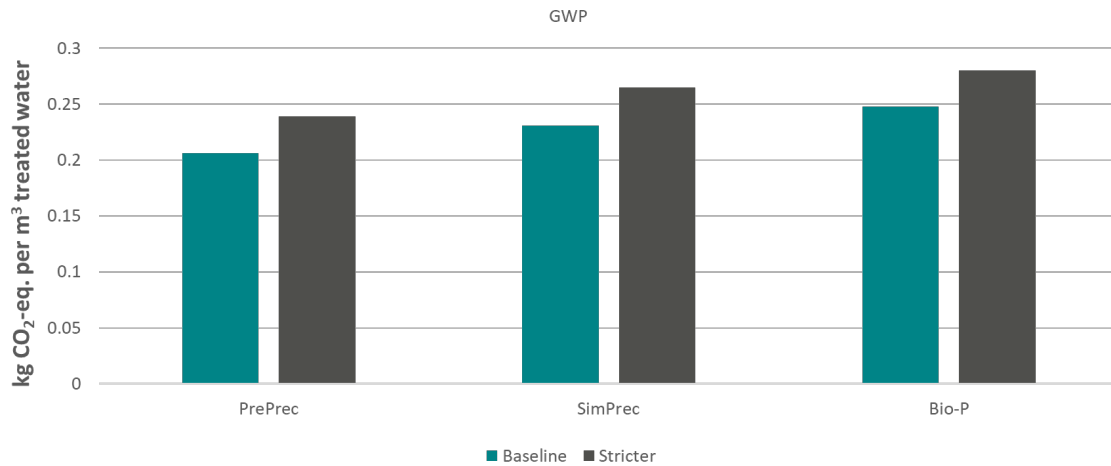
The energy demand and biogas produced is compared for the different process configurations and effluent criteria, see Figure 9.



**Figure 9. Comparison of energy demand (MWh/d) and biogas production (kg CH<sub>4</sub>/d) for the different process configurations. PrePrec Al = aluminium based precipitation chemical, PrePrec = iron based precipitation chemical.**

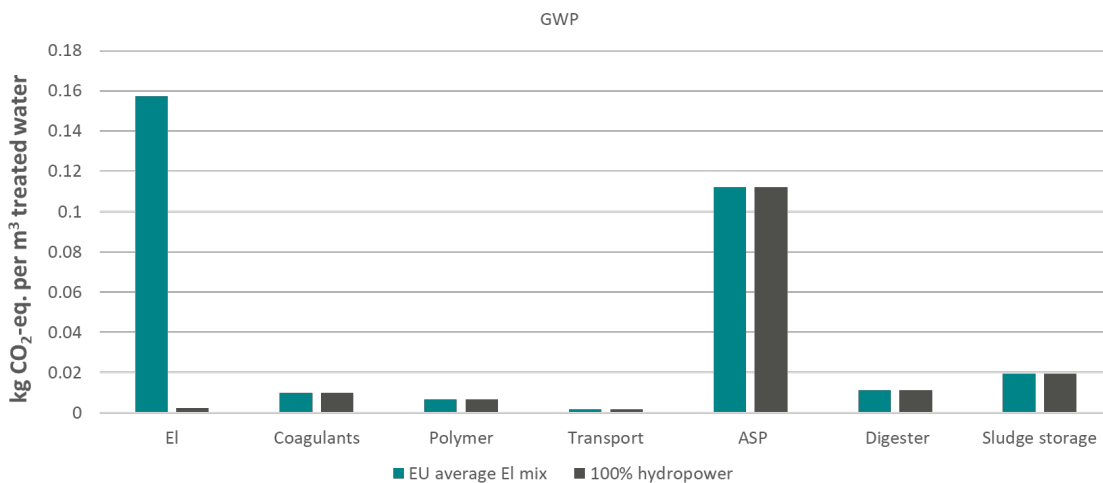
The pre-precipitation produces more biogas than the other configurations since more primary sludge is produced with this configuration. Digestion of primary sludge will generate more biogas compared to digestion of waste activated sludge and more primary sludge will lead to more biogas production.

In the scenarios presented above the biogas were not utilized in any way, only the amount of produced methane was tracked. In many WWTP the biogas is used in some way, it could be as an energy source locally at the plant or it could be upgraded to vehicle fuel. In both the given examples biogas could replace fossil fuels as energy carrier. In Figure 10 the result of this credit of biogas is shown for the GWP of the process configurations. This credit decreases the total contribution to the GWP between 30% and 20% for all the different scenarios and effluent criteria.



**Figure 10. Contribution to the GWP after the biogas has replaced natural gas in energy production for the different process configurations. Results coloured according too effluent criteria.**

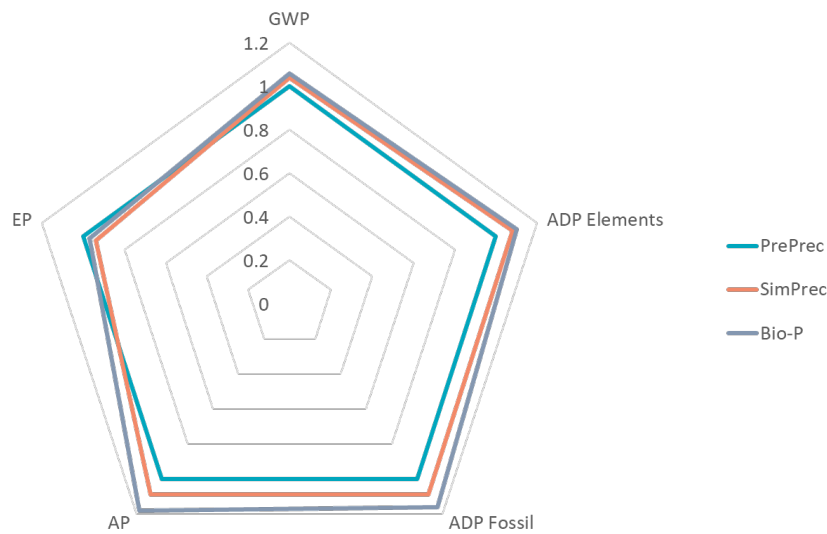
As seen in Figure 8 the electricity usage has a very large impact on the results of the GWP. A sensitivity analysis was performed replacing the original European average electricity mix with 100% hydropower (Figure 11). This change of electricity production decreases the total GWP of operating the process configuration with 50%.



**Figure 11. Sensitivity analysis of electricity production. Replacing a European average electricity mix with 100% hydropower.**

The main focus has been on the global warming potential, but to give a more detailed picture of the total environmental impact, the other impact categories is presented, together with the GWP, in Figure 12.

In Appendix 1 data for the different scenarios studied and for all impact categories are presented.



**Figure 12. Comparing all the calculated impact categories. Normalized around the pre-precipitation configuration. GWP = global warming potential, EP = Eutrophication potential, AP = Acidification potential, ADP = Abiotic Depletion Potential.**

Regarding the eutrophication potential (EP), the main contribution is the nitrogen in the effluent. The effluent criteria were reached for all the scenarios but not the same levels on the decimal and therefore the EP differ somewhat for the different configurations. Consumption of fossil resources (ADP fossil) is higher for the Bio-P due to higher energy consumption as this configuration requires more pumping. The main contribution to the acidification potential (AP), is also linked to energy consumption.

## 5 Conclusions

Three process configurations for phosphorus removal from wastewater; pre-precipitation, simultaneous precipitation and biological phosphorus removal, was evaluated using dynamic process models and LCA.

Combining dynamic process models with life cycle assessment could give insight to what is large and not in the contribution to the global warming potential from different configurations of wastewater treatment plants. The use of models is a good method when real or test data are hard to retrieve from the process.

To conclude this study the main points are summarized below:

- **Pre-precipitation clearly gives a lower GWP than the other configurations.**
- **Pre-precipitation produces the highest amounts of biogas while biological phosphorus removal produces the lowest amount of biogas.**
- **A more stringent effluent limit leads to a higher carbon footprint.**
- **Choice of energy source is an important factor for several impact categories.**

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# Appendix 1

In the following tables the results from the LCA is presented for the different scenarios and the studied environmental impact categories. All values are for the functional unit 1m<sup>3</sup> treated wastewater fulfilling the yearly average discharge criteria.

**Environmental impact categories for different process configurations and effluent criteria. Note that the usage of biogas is not included.**

	PrePrec		SimPrec		Bio-P	
	Baseline	Stricter	Baseline	Stricter	Baseline	Stricter
Abiotic Depletion (ADP elements) [kg Sb eq.]	6.71E-08	7.89E-08	7.16E-08	8.36E-08	7.31E-08	8.52E-08
Abiotic Depletion (ADP fossil) [MJ]	1.78E+00	2.14E+00	1.93E+00	2.30E+00	2.06E+00	2.41E+00
Acidification Potential (AP) [kg SO <sub>2</sub> eq.]	4.41E-04	5.32E-04	4.81E-04	5.74E-04	5.19E-04	6.09E-04
Eutrophication Potential (EP) [kg Phosphate eq.]	8.59E-03	5.65E-03	8.12E-03	5.68E-03	8.38E-03	6.09E-03
Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO <sub>2</sub> eq.]	3.00E-01	3.34E-01	3.13E-01	3.47E-01	3.21E-01	3.54E-01

**Contribution to the different environmental impact categories for the pre-precipitation configuration.**

**Divided into different process steps. Note that the usage of biogas is not included. El = electricity usage, ASP=Activated Sludge Process (biological treatment).**

PrePrec - Baseline	Abiotic Depletion (ADP elements) [kg Sb eq.]	Abiotic Depletion (ADP fossil) [MJ]	Acidification Potential (AP) [kg SO <sub>2</sub> eq.]	Eutrophication Potential (EP) [kg Phosphate eq.]	Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO <sub>2</sub> eq.]
Total	6.71E-08	1.78E+00	4.41E-04	8.59E-03	3.00E-01
El	4.54E-08	1.53E+00	3.99E-04	3.77E-05	1.43E-01
Coagulants	7.54E-09	8.28E-02	1.42E-05	2.74E-06	4.21E-03
Polymer	1.40E-08	1.52E-01	2.36E-05	2.47E-05	6.60E-03
Transport	1.34E-10	2.35E-02	3.94E-06	9.76E-07	1.74E-03
ASP	0	0	0	1.14E-04	1.12E-01
Digester	0	0	0	0.00E+00	1.25E-02

Sludge storage	0	0	0	9.48E-06	1.95E-02
Emissions	0	0	0	8.40E-03	0
<b>PrePrec -Stricter</b>					
Total	7.89E-08	2.14E+00	5.32E-04	5.65E-03	3.34E-01
El	5.55E-08	1.86E+00	4.87E-04	4.60E-05	1.74E-01
Coagulants	8.17E-09	8.97E-02	1.53E-05	2.97E-06	4.56E-03
Polymer	1.52E-08	1.64E-01	2.56E-05	2.67E-05	7.13E-03
Transport	1.46E-10	2.55E-02	4.26E-06	1.06E-06	1.89E-03
ASP	0	0	0	1.14E-04	1.12E-01
Digester	0	0	0	0	1.18E-02
Sludge storage	0	0	0	1.05E-05	2.17E-02
Emissions	0	0	0	5.45E-03	0

**Environmental impact categories for different process configurations and effluent criteria. Credit for the usage of biogas is included.**

Credit for biogas included - replacing natural gas	Baseline			Stricter		
	PrePrec	SimPrec	Bio-P	PrePrec	SimPrec	Bio-P
Abiotic Depletion (ADP elements) [kg Sb eq.]	6.43E-08	6.93E-08	7.06E-08	7.60E-08	8.11E-08	8.26E-08
Abiotic Depletion (ADP fossil) [MJ]	1.33E-01	5.00E-01	7.76E-01	4.67E-01	8.53E-01	1.12E+00
Acidification Potential (AP) [kg SO2 eq.]	4.26E-04	4.68E-04	5.04E-04	5.16E-04	5.60E-04	5.93E-04
Eutrophication Potential (EP) [kg Phosphate eq.]	8.59E-03	8.12E-03	8.38E-03	5.65E-03	5.68E-03	6.09E-03
Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.]	2.06E-01	2.31E-01	2.48E-01	2.39E-01	2.65E-01	2.80E-01

**Sensitivity analysis of electricity production. European average electricity contra electricity produced by 100% hydropower.**

<b>EU average El mix</b>	<b>Abiotic Depletion (ADP fossil) [MJ]</b>	<b>Acidification Potential (AP) [kg SO2 eq.]</b>	<b>Eutrophication Potential (EP) [kg Phosphate eq.]</b>	<b>Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.]</b>
<b>Total</b>	1.78E+00	4.41E-04	8.59E-03	3.00E-01
El	1.53E+00	3.99E-04	3.77E-05	1.43E-01
Coagulants	8.28E-02	1.42E-05	2.74E-06	4.21E-03
Polymer	1.52E-01	2.36E-05	2.47E-05	6.60E-03
Transport	2.35E-02	3.94E-06	9.76E-07	1.74E-03
ASP	0	0	1.14E-04	1.12E-01
Digester	0	0	0.00E+00	1.25E-02
Sludge storage	0	0	9.48E-06	1.95E-02
Emissions	0	0	8.40E-03	0
<b>100% hydropower</b>				
<b>Total</b>	4.02E-01	5.82E-05	8.09E-03	1.64E-01
El	8.76E-03	3.05E-06	3.99E-07	2.41E-03
Coagulants	2.15E-01	2.70E-05	5.73E-06	1.00E-02
Polymer	1.57E-01	2.44E-05	2.55E-05	6.81E-03
Transport	2.20E-02	3.68E-06	9.14E-07	1.63E-03
ASP	0	0	1.14E-04	1.12E-01
Digester	0	0	0.00E+00	1.12E-02
Sludge storage	0	0	9.53E-06	1.95E-02
Emissions	0	0	7.93E-03	0





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