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Brief Description	This report analyses a number of processes for material recovery at municipal wastewater treatment plants in their environmental impacts. Based on the method of Life Cycle Assessment, the analysis shows that material recovery can yield environmental benefits by reducing primary energy demand and related greenhouse gas emissions during operation. This is mainly due to operational savings in energy, chemicals or sludge amount which come in association with material recovery. Product quality assessment for potential contamination showed no unacceptable risks for human health or ecosystems during the application and use of recovered materials.
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EXECUTIVE SUMMARY

Following the circular economy approach as a new paradigm for the water sector, the project SMART-PLANT demonstrated a variety of options ("SMARTechs") to recover valuable materials from municipal wastewater and thus improve the traditional scheme of wastewater treatment. Recovering secondary resources such as biogas, nutrients, cellulose or bioplastic from wastewater will lead to the substitution of primary products such as fossil fuels, mineral fertilizer, wood fibres, or bioplastic from agricultural substrates, avoiding their environmental footprint of production. However, material recovery at WWTPs is also associated with additional efforts in treatment and processing of water and products, which will increase the environmental footprint of the treatment process. The question remains open if the circular economy approaches of SMART-PLANT are able to reduce the overall environmental footprint of WWTPs, considering all consequences of material recovery which are relevant for this system.

Life Cycle Assessment of global environmental impacts

This report provides an environmental assessment for all SMARTechs, using a holistic and global perspective to include all relevant processes and systems. They are analysed at their respective sites of demonstration (as "case study"), taking the existing WWTP of the site as reference for the comparison. Downstream SMARTechs are included where appropriate to process recovered materials into valuable end-products.

Overall, the results show that material recovery can lead to environmental benefits for WWTP operation if assessed over the entire value chain, i.e. including the valorisation of valuable end-products. In particular, efforts for wastewater treatment in terms of primary energy demand and related greenhouse gas emissions can be reduced without compromising the treatment quality of the plants. From this study, some general conclusions can be drawn:

- Depending on the SMARTech and material recovered, **up to 68% of primary energy demand and 71% of greenhouse gas emissions could be mitigated by integration of material recovery at a municipal WWTP**. The different SMARTechs and materials recovered show a wide range of potential improvement, ranging from savings in the lower % range for sidestream SMARTechs (e.g. SCENA and SCEPPHAR) up to significant improvements for mainline SMARTechs (e.g. CELLVATION, Anaerobic bilfilter, or Ion exchange).
- These savings relate not only to the credits for recovered materials, but **predominantly to operational savings at the WWTP** (reduced energy demand, less chemicals, or less sludge to be disposed). It seems **crucial for the environmental benefits of material recovery that it is also connected to operational improvements at the plant**. Avoided impacts from **substitution of primary products with recovered resources alone do not justify the efforts required for material recovery at WWTPs**.
- Another crucial point for environmental benefits of material recovery is a **low-impact downstream processing into valuable end products**. As an example, PHA-rich sludge should have a high concentration of PHA (> 20% of dry matter) to justify the efforts of chemical extraction in the overall balance. Likewise, **thermal energy requirements for processing of products should be minimised** by using excess heat at the site or low-impact processes such as bio-drying to end up with a favourable energy and GHG balance for the recovered material.
- Direct emission of greenhouse gases at WWTPs such as **N_2O and CH_4 are a relevant contribution for the overall GHG footprint** and should not be increased at all by processes for material recovery. Otherwise, potential life-cycle **benefits from reduced energy consumption are easily off-set by increased direct emissions of GHGs** and will then lead to an overall increase in the impact of WWTPs on climate change. This is especially important for short-cut nitrogen removal processes prone to increased N_2O emissions (SCENA, SCEPPHAR) and anaerobic processes releasing CH_4 to atmosphere (anaerobic biofilter). **Mitigation measures to avoid excessive emission of GHGs should be integrated** for those SMARTechs to minimise the risk of increasing the overall carbon footprint with material

recovery. In addition, a **close monitoring of direct GHG emissions** of SMARTechs should be targeted for the first full-scale references to collect more data on this aspect from full-scale plants.
- Some SMARTechs reduced water emissions below the level of the existing WWTP, thus having a **potential to improve the treatment performance of the plant**. For other SMARTechs, their impact on water quality could not be predicted with the available data. However, for these cases it is expected that a comparable effluent quality can be reached after SMARTech integration, i.e. the **primary function of the WWTP is not compromised by material recovery**.

Due to the prospective nature of the LCA case studies analysed in SMART-PLANT, a number of inherent limitations are connected to the outcomes of this report and should be carefully reflected in the interpretation of the results:

- Environmental benefits of material recovery often depend on the extent of operational savings at the WWTP. However, these **operational savings have not been monitored or quantified with real data** in this study, as most SMARTechs have been demonstrated in pilot-scale only. Finally, **mainline impacts of SMARTech integration have been estimated for all case studies** by project partners based on their experience of the WWTP processes.
- The potential **impact of SMARTech integration on the biological performance of the WWTP could not be validated** here.
- **GHG emission factors are based on pilot monitoring results combined with expert judgement, but are affected with some uncertainty.** In particular, N_2O emissions of existing WWTPs have not been monitored but for one WWTP, so that **baseline N_2O emissions have been estimated for most WWTPs from literature.**
- The LCA outcomes for selected SMARTechs **depend on the local conditions at the respective WWTP**, such as the existing process configuration in the baseline, the sludge disposal route, or the actual energy balance at the plant.

Product quality assessment

Selected samples of recovered materials from all SMARTechs have been analysed for a wide range of inorganic and organic contaminants to assess potential risks of SMART products application for human health and ecosystems during their application. In total, 15 samples have been analysed for a wide range of contaminants. These substances included heavy metals, polycyclic aromatic hydrocarbons (PAH), chloroalkanes, pesticides, and also contaminants of emerging concern (EU watch list 2018).

Results show that low contamination of SMART products can be detected for selected contaminants, which is of course due to their origin from municipal wastewater. In particular, sludge and sludge-based products such as compost contain a range of inorganic and organic substances which may pose a potential hazard for human health or ecosystems during their application in agriculture.

Overall, no excessive transfer of hazardous pollutants from wastewater into SMART products could be detected. Detected risk potentials from heavy metals or organic compounds in SMART products used on agriculture are low, but should be further investigated and legally regulated in the future. In general, new legislation in this sector is required to define acceptable levels of contamination in recovered materials from municipal wastewater, especially for application as fertilizer in agriculture.

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ABBREVIATIONS

Ac – acetate
AFA – acceptable field application
BACS – bio-available carbon source
BOD – biological oxygen demand
CEC – contaminants of emerging concern
CED – cumulative energy demand
CHP – combined heat and power
COD – chemical oxygen demand
DAS – diammonium sulfate
DM – dry matter
DS – digested sludge
FEP – freshwater eutrophication potential
GHG – greenhouse gases
GLO - global
GWP – global warming potential
HAIX – hybrid anion exchange resin
IEX – ion exchange
IPCC – international panel on climate change
LCA – life cycle assessment
LOD – limit of detection
LOQ – limit of quantification
MEP – marine eutrophication potential
PACl – polyaluminium chloride
PAH – polycyclic aromatic hydrocarbons
pe – population equivalent
PE - polyethylene
PHA – poly-hydroxy-alkanoate
PNEC – predicted no effect concentration
PS – primary sludge
PT – primary treatment
RoW – rest of world
SCENA – short-cut enhanced nutrient abatement
SCEPPHAR – short-cut phosphorus and PHA recovery
SPC – sludge plastic composite
SS – suspended solids
TAP – terrestrial acidification potential
TH – thermal hydrolysis
TN – total nitrogen
TP – total phosphorus
TS – total solids
TSS – total suspended solids
VFA – volatile fatty acids
VOC – volatile organic carbon
VS – volatile solids
WAS – waste activated sludge
WPC – wood plastic composite
WWTP – wastewater treatment plant

1. INTRODUCTION

The treatment of municipal wastewater is associated with a considerable effort in energy, chemicals and infrastructure to build and operate wastewater treatment plants (WWTPs). From an environmental perspective, cleaning the wastewater to protect receiving waters from excessive loads of organic and inorganic pollution and nutrients is the primary function of WWTPs and justifies the additional environmental impacts in terms of energy demand and related emissions such as greenhouse gases (GHG). However, the minimisation of these negative environmental impacts of wastewater treatment has been targeted in recent years in many WWTPs to respond to climate change mitigation policies, reducing energy demand and greenhouse gas emissions without compromising the effluent water quality of the systems.

Following the circular economy approach as a new paradigm for the water sector, the project SMART-PLANT demonstrated a variety of options ("SMARTechs") to recover valuable materials from municipal wastewater and thus improve the traditional scheme of wastewater treatment. Recovering secondary resources such as biogas, nutrients, cellulose or bioplastic from wastewater will lead to the substitution of primary products such as fossil fuels, mineral fertilizer, wood fibres, or bioplastic from agricultural substrates, avoiding their environmental footprint of production. However, material recovery at WWTPs is also associated with additional efforts in treatment and processing of water and products, which will increase the environmental footprint of the treatment process. The question remains open if the circular economy approaches of SMART-PLANT are able to reduce the overall environmental footprint of WWTPs, considering all consequences of material recovery which are relevant for this system.

The following report provides an environmental assessment for all SMARTechs, using a holistic and global perspective to include all relevant processes and systems. A suitable method for this task is the tool of Life Cycle Assessment (LCA) as defined in the related ISO standard (ISO 14040, 2006; ISO 14044, 2006). LCA takes into account all direct and indirect environmental impacts of a product or service, and the system boundaries can be set to include all relevant processes that are affected by the system under study. In addition, the quantitative relation of all results to a common functional unit allows for the comparative analysis of different scenarios based on the same function. LCA has been used extensively for the environmental assessment of WWTPs and disposal of sewage sludge in many studies (Corominas et al., 2013; Yoshida et al., 2013) and also in the field of resource recovery (Fang et al., 2016; Lam et al., 2020) and has shown to be a suitable tool for this type of systematic environmental assessment.

General framework of Life Cycle Assessment in this study

When applying LCA in the field of material recovery from municipal WWTPs, the system boundaries should include the entire system affected (**Figure 1-1**):

- The WWTP process
- Disposal of sewage sludge as the major waste from WWTPs
- Processes required to recover materials at the WWTP ("SMARTechs")
- Downstream processing of the intermediate materials into valuable end-products
- Valorisation of end products, e.g. in form of credits accounted for the substitution of primary products which are equivalent to the products recovered
- Electricity, fuels, chemicals, and infrastructure required for operation of the system

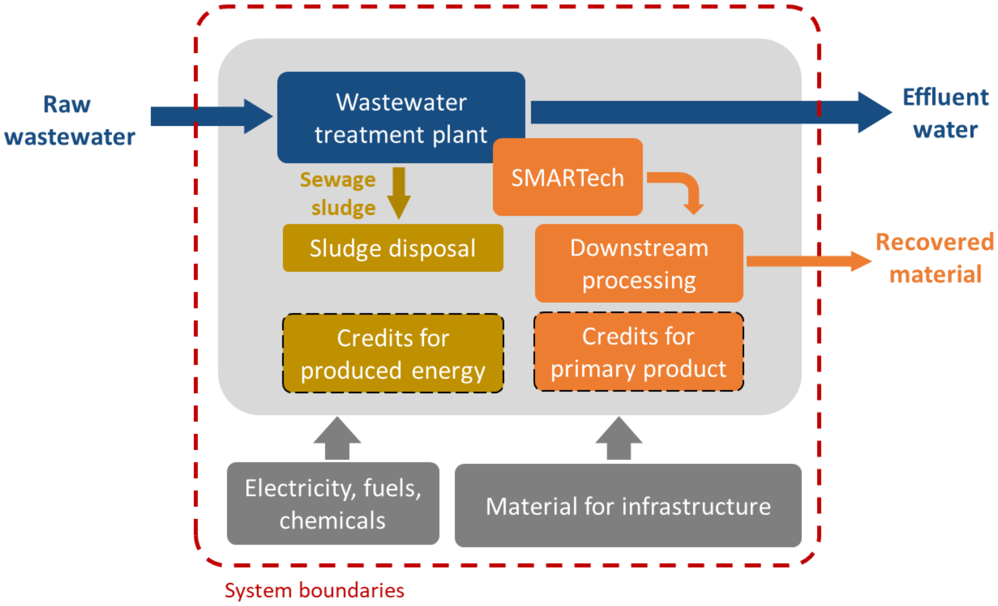

Figure 1-1: System boundaries of LCA for material recovery from wastewater treatment plants

Taking this wide system view, all relevant aspects of material recovery from WWTPs can be reflected in the LCA study:

- Efforts for material recovery at the WWTP (here: energy, chemicals and infrastructure of SMARTechs)
- Efforts for downstream material processing to end up with a marketable end-product (e.g. extraction, processing, cleaning, …)
- Upstream and downstream effects of material recovery on the WWTP process itself and the sludge disposal (e.g. savings in energy or chemicals for treatment, change of sludge amount to dispose)
- Avoided impacts of primary products which can be substituted by recovered materials in the circular economy approach.

Based on this general LCA framework, the present report analyses all SMARTechs demonstrated in the project in their environmental impacts (**Table 1-1**). They are analysed at their respective sites of demonstration, taking the existing WWTP of the site as reference for the comparison. This localized “case study” approach was applied to be able to use the data from pilot demonstration of the SMARTechs without having to transfer process data to another site with different conditions (e.g. different water quality). Downstream SMARTechs are included where appropriate to process recovered materials into valuable end-products.

Results of the LCA and their limitations

A focus is laid on those environmental categories which represent the required efforts for treatment and recovery (i.e. primary energy demand and greenhouse gas emissions), while other environmental indicators are included in the LCA if relevant for the respective case study. Impact of material recovery on WWTP effluent quality has been assessed if major changes can be expected for these parameters from the implementation of SMARTechs. In the other cases, effluent quality of the WWTP is supposed to be at least equal to the reference, i.e. material recovery is realized without compromising the primary function of the WWTP.

Table 1-1: Case studies for environmental assessment with LCA

Case study location	SMARTechs	Material recovered	Downstream valorisation	Project partners involved
Geest-merambacht (NL)	Cellvation + Biodrying or bio-composites	Cellulose	Biofuel or bio-composite	CIRTEC + SALSNES, UVIC for biodrying, ECODEK for bio-composite
Karmiel (IL)	Anaerobic biofilter	Biogas	CHP plant	AGROBICS + MEKOROT
Manresa (ES)	SCEPPHAR mainstream + PHA extraction	PHA + struvite	CHP plant or bioplastic + fertilizer	UAB + AIGUES DE MANRESA, BIOTREND for PHA extraction
Model WWTP (UK)	Ion exchange	Ca-P + NH_3 water or DAS	Fertilizer	CRANFIELD + SEVERN TRENT
Carbonera (IT)	SCENA + Dynamic composting	P-rich compost	Compost as fertilizer	UNIVR + ATS, UVIC for composting
Carbonera (IT)	SCEPPHAR sidestream + PHA extraction	PHA + struvite	Bioplastic + fertilizer	UNIVR + ATS, BIOTREND for PHA extraction
Psyttalia (GR)	SCENA after TH	-	-	NTUA + AKTOR +EYDAP

Results of each LCA case study are discussed in relation to the existing WWTP as reference, reporting the relative change in environmental impacts induced by material recovery. Naturally, reference WWTPs of all case studies have different environmental footprints as baseline due to specific process layout of the individual WWTPs, local influent water quality and treatment targets, but also different background data such as the national electricity mix. Hence, the absolute indicator results of each LCA case study are not comparable between the cases and should not be directly used to extrapolate or scale-up the LCA results to a wider scale. However, the relative changes in indicators [%] could be used to estimate a potential of material recovery to improve the environmental footprint of the wastewater sector. Further limitations of each LCA case study are discussed in the results section and should be carefully analysed and reflected for the interpretation of the LCA results.

Product quality assessment

Apart from the global environmental impacts which can be derived from an LCA study of material recovery, another important aspect of environmental concern is connected to the quality of the recovered products in terms of potential toxicological risks associated with their use. As recovered materials originate from municipal wastewater, potentially hazardous contaminants present in this matrix could be transferred into the final end-products and thus could negatively affect downstream users or the environment. This relates to a wide range of inorganic and organic trace pollutants which can be found in municipal wastewater, posing a potential risk for both ecosystems or human health during the use of recovered materials in the value chain. This potential risk should be quantitatively assessed and checked against existing benchmarks such as legal standards or other available scientific information to demonstrate that the use of recovered materials is not associated with an unacceptable hazard for humans or the environment. This task is especially relevant for recovered nutrients or fertilizers applied in agriculture, as these materials are directly applied in nature and may also affect human health via the food chain.

Therefore, product samples of all SMARTechs have been analysed for a range of potential contaminants such as heavy metals, polycyclic aromatic hydrocarbons (PAH), chloroalkanes, pesticides, and a selection of organic contaminants of emerging concern (CEC) as defined in the EU watch list 2018 (EC, 2018) (**Table 1-2**). The resulting analytical data has been assessed against existing legal benchmarks where possible, or a chemical risk assessment has been carried out in relation to existing scientific studies on the identified contaminants.

Table 1-2: Analysed contaminants in SMART products

SMART product	Heavy metals	Polycyclic aromatic hydrocarbons	Chloro-alkanes	Pesti-cides	Contaminants of emerging concern (EC, 2018)
Calcium phosphate	X	X	X	X	X
Struvite	X	X	X	X	X
P-rich sludge	X	X	X	X	X
P-rich compost	X	X	X	X	X
PHA-rich sludge	X	X	X	X	X
PHA	X	X	X	X	-
Cellulose	X	X	X	X	X
Sludge plastic composite	X	X	X	X	-

Results of this quality check give an indication on product contamination with hazardous substances and also an assessment if the detected concentration may pose any unacceptable risk for human health or ecosystems during their application. Finally, this information is crucial for the public acceptance of material recovery from municipal wastewater and the successful commercial exploitation of this concept in the future.

All data on SMARTechs and products presented in this report has been produced during the project and has been discussed and validated with the respective project partners. As such, the report represents the collaborative work of many people beyond the main authors listed, and their input is greatly acknowledged and appreciated by the authors of this study.

2. LCA OF CELLULOSE RECOVERY (SMARTECH 1 + DOWNSTREAM SMARTECH A/B)

Municipal wastewater contains cellulosic fibres, which can be separated by a fine-sieve with suitable mesh size (~ 158-350 µm) at the inflow of a WWTP instead of primary sedimentation. After separation, cellulosic sludge can be easily dewatered and further valorised for different purposes, e.g. as structural fibre material in the production of bio-composites and for applications in construction and building industry, as carbon source after fermentation to VFA, or - after further drying – for energy recovery as biofuel.
In the SMART-Plant project, the recovery of cellulose and its valorisation has been tested in industrial scale at WWTP Geestmerambacht in the Netherlands (SMARTech 1). For cellulose recovery, incoming raw wastewater undergoes grit and grease removal, a pre-screening to separate larger particles, and then a rotating belt filter (Salsnes) with a defined mesh size for separation of cellulosic sludge. The cellulosic sludge is dewatered in an integrated screw press to 30-50% total solids (TS) content, before it can be further processed in different routes for valorisation of the material. This process for cellulose recovery from sewage is called "Cellvation®". Two of these routes have also been demonstrated with the cellulose material from Geestmerambacht: a) thermal drying, pelletizing and use as structural material in the production of bio-composites (Downstream SMARTech A) and b) bio-drying (Downstream SMARTech B) and use as biofuel.

In its current configuration, the WWTP Geestmerambacht has no dedicated primary treatment, and the influent wastewater goes directly into the biological stage after bar screens (6mm). Hence, the separation of solids in the pre-treatment for cellulose recovery will have an impact on the operation of the downstream biological process and related sludge treatment. In particular, the following effects of implementing a fine sieve upstream the biological stage are anticipated:

- Savings in aeration energy for biological stage due to lower load of total suspended solids (TSS) and chemical oxygen demand (COD)
- Lower production of excess sludge from biological stage
- Lower demand of polymer for sludge dewatering
- Lower volume and TS amount of sludge to be disposed

As the systems have been tested in industrial scale but not in full-scale, pilot data will be up-scaled and extrapolated to reflect a full-scale installation of cellulose recovery at WWTP Geestmerambacht. It is important to notice that downstream impacts of cellulose recovery on the biological stage could not be quantified for the demonstration unit (due to the smaller scale), but are transferred from related studies of other WWTPs (e.g. WWTP Aarle-Rixtel in ScreenCap project (Roest, 2018)). The inherent uncertainty of this data transfer is addressed by calculating with a range of minimum, mean, and maximum expected effects of the cellulose recovery in terms of cellulose yield (TSS and COD removal) and related downstream impacts.

The goal of this LCA is to illustrate all direct and indirect impact of introducing a system for cellulose recovery at WWTP Geestmerambacht and show its environmental effect with a focus on primary energy demand and related greenhouse gas (GHG) emissions. For valorisation of cellulosic material, two different routes will be considered with a) use as structural material for bio-composite production and b) bio-drying and use as biofuel. The LCA perspective will be used to quantify both additional efforts for treatment (e.g. energy for fine-sieving, cellulose processing, etc.) and also positive impacts on the downstream system (e.g. savings in aeration energy, lower amount of sludge for disposal) and from the valorisation route (e.g. credits for energy recovery, substitution of primary material in bio-composite production). Finally, results will show a net overall impact of cellulose recovery within the life cycle of the WWTP, including all direct and indirect effects that can be attributed to this system upgrade.

The introduction of an additional treatment step in the WWTP mainline will most likely have an impact also on the performance of the WWTP (e.g. effluent quality) and its capacity. However, this LCA is focussed on energy demand and GHG emissions and will not address potential changes in effluent quality and their effect on the environmental footprint of the plant.

2.1 Goal and scope definition

2.1.1 Goal of the study

The goal of this LCA is to calculate the potential environmental impacts of the annual operation of WWTP Geestmerambacht (NL) without and with a prospective full-scale system for cellulose recovery, including potential valorisation routes for the recovered material in bio-composite production and as biofuel. All direct and indirect effects of implementing a cellulose recovery system will be quantified in the life cycle of the WWTP, focussing on primary energy demand and GHG emissions as major environmental impacts. Any potential effect of cellulose recovery on the WWTP capacity or performance in terms of effluent quality is not addressed in this LCA.

The target group of this LCA are mainly WWTP experts, planners, market parties and practitioners which should be informed about the holistic environmental impacts of cellulose recovery at a WWTP.

2.1.2 Function and functional unit

The primary function of the system under study is the treatment of municipal wastewater to defined local standards, including the final disposal of generated sewage sludge. As a secondary function, some scenarios recover cellulose as a valuable material which is further processed and valorised downstream.

Consequently, the functional unit is defined as “treatment of municipal wastewater per population equivalent (pe) and year” or $[pe*a]^{-1}$. WWTP Geestmerambacht treats raw wastewater with a load of 200.000 pe based on a daily COD load of 120 g/pe. All direct and indirect impacts of the system are related to this functional unit.

2.1.3 Scenarios

Seven scenarios have been defined for this LCA, as listed in **Table 2-1** below. In detail, the scenarios can be described as follows:

0 Baseline: this scenario reflects the situation before implementation of the cellulose recovery system, using operational data of WWTP Geestmerambacht from 2017 and 2018. The system consists of a bar screen (6 mm), a biological stage and a clarifier in the mainline. Excess sludge is thickened and dewatered on-site, before it is transported to sludge drying at a central drying facility in Beverwijk. From there, dried sludge granules are transported to the waste-to-energy incineration plant at Amsterdam West, where the dried sludge is energetically valorised to produce electricity and heat.

1a – 1c for biofuel route: these scenarios represent the implementation of a system for cellulose recovery after bar screen, consisting of grit and grease removal, pre-screening for separation of larger particles, and a rotating belt filter (Salsnes) for separation of cellulosic sludge. The belt filter has an integrated screw press to dewater the cellulosic sludge to 30% dry matter (DM), before it is further treated in a bio-drying process on-site. Dried cellulosic sludge is finally used as biofuel in a model biofuel incineration plant, recovering energy in the form of electricity and heat. Within this set of scenarios, sub-variants a to c reflect minimum, mean, and maximum data of performance for the cellulose recovery unit in terms of cellulose yield, TSS and COD removal, and also the corresponding range of effects on the downstream biological process in terms of energy savings in aeration, lower amount of excess sludge production, and lower use of polymer for dewatering.

2a – 2c for bio-composite route: these scenarios represent the same system for cellulose recovery as in 1a-1c with a range of min-mean-max effects at the WWTP, but combined with a different route for material valorisation. Here, the cellulosic sludge is thermally dried on-site using available excess heat, before it is pelletized and used as structural material in bio-composite production. The related changes in bio-composite production such as substitution of alternative structural material (i.e. wood flour) and energy needs in the production process are included in these scenarios.

Table 2-1: Scenarios for cellulose recovery at WWTP Geestmerambacht (see text for details)

Scenario	Description	Remarks
0 Baseline	WWTP Geestmerambacht	Data of 2017/18
1a CELLmin biofuel	WWTP Geestmerambacht with cellulose recovery, bio-drying and use as biofuel	Minimum performance data for cellulose recovery unit and mainstream impact
1b CELLmean biofuel		Mean performance data for cellulose recovery unit and mainstream impact
1c CELLmax biofuel		Maximum performance data for cellulose recovery unit and mainstream impact
2a CELLmin biocomposite	WWTP Geestmerambacht with cellulose recovery and use in bio-composite production	Minimum performance data for cellulose recovery unit and mainstream impact
2b CELLmean biocomposite		Mean performance data for cellulose recovery unit and mainstream impact
2c CELLmax biocomposite		Maximum performance data for cellulose recovery unit and mainstream impact

2.1.4 System boundaries

The system boundaries of this LCA include all relevant processes at the WWTP for water and sludge treatment, including the sludge disposal with transport, drying and incineration (**Figure 2-1**). For cellulose recovery scenarios, the study includes the recovery unit and the respective valorisation routes of bio-drying and incineration as biofuel (scenarios 1a-c) or thermal drying, pelletizing and use in bio-composite production. For background processes, the demand of electricity, fuel and chemicals is included, as well as basic materials for the infrastructure of the cellulose recovery unit. Infrastructure of the baseline WWTP and any other process is not included in this study. Secondary functions such as the provision of electricity and heat from incineration or the substitution of primary materials in bio-composite production (i.e. wood flour) are reflected by crediting the avoided impacts of conventional production routes ("avoided-burden approach").

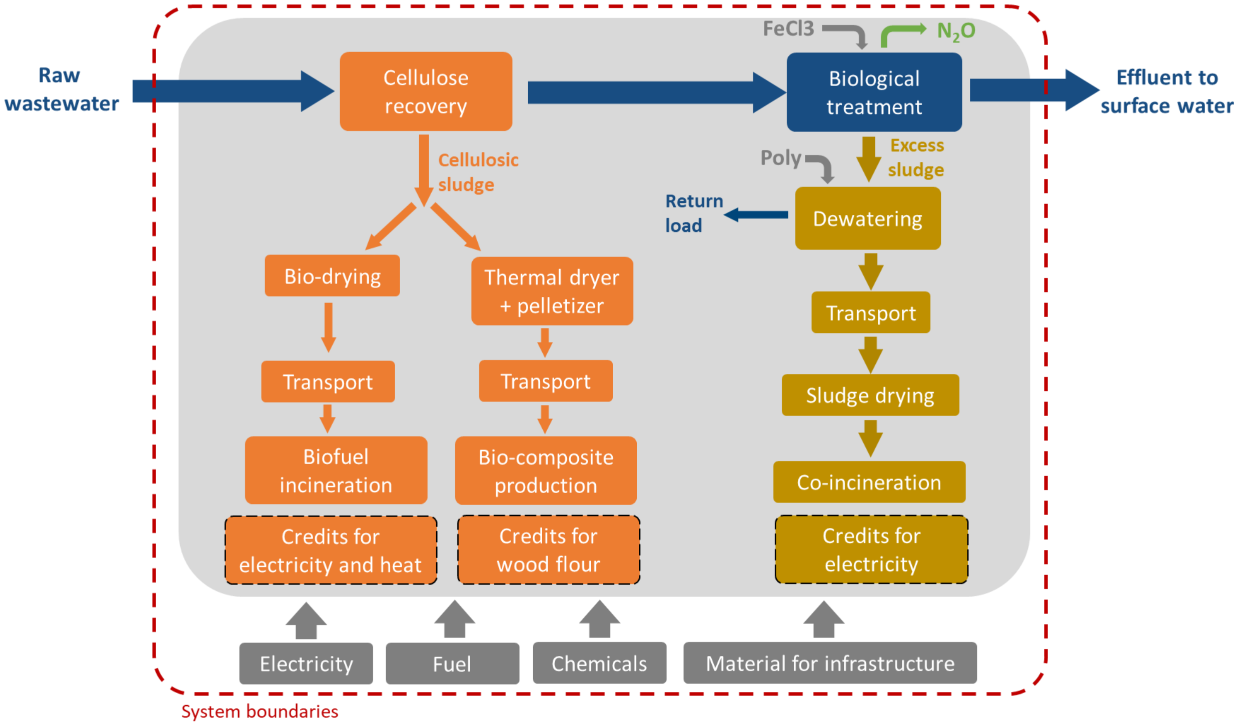

Figure 2-1: System boundaries of LCA study for cellulose recovery and downstream valorisation

2.1.5 Data sources and quality

Input data for the baseline operation of WWTP Geestmerambacht is collected from operators via project partner CirTec, and represents full-scale operational data of the years 2017/2018. For sludge disposal, data of sludge drying and incineration has been compiled from available literature. For the performance of the cellulose recovery system, pilot data of SMART-Plant trials has been extrapolated and interpreted by CirTec with a range of min-mean-max values, also taking into account comparable full-scale systems and experience at other WWTPs. Operational efforts for cellulose recovery system (e.g. electricity demand) has been up-scaled from pilot trials and available data of process suppliers by CirTec. Mainstream effects of cellulose extraction on energy demand and sludge production have been estimated with min-mean-max values by CirTec, mainly based on comparable full-scale systems at other locations such as WWTP Aarle-Rixtel (Roest, 2018).

Input data for bio-drying has been generated by project partner UVIC based on pilot trials of the process with cellulosic sludge and previous experience, up-scaling process performance and operational efforts to a full-scale system. Data for incineration of biofuel is based on estimates from UVIC (energy recovery) and KWB (emission data). Input data for bio-composite production is collected from project partner ECODEK and represents experience from pilot trials in UK.

Overall, data quality of this LCA can be described as high for most of the input data (**Table 2-2**). Uncertainty in up-scaling and data transfer for cellulose recovery and related mainstream impacts from other sites is addressed by calculating with a set of min-mean-max values. Both valorisation routes have been assessed in pilot trials, generating representative data with sufficient quality for a prospective LCA.

Table 2-2: Data quality for LCA of cellulose recovery

Process	Data source	Responsible partner	Data quality
WWTP Geestmerambacht: influent, effluent, sludge, energy and chemical demand	Full-scale data of operator	CirTec	High
Sludge drying and incineration	Literature	KWB	Medium - high
Cellulose recovery system	Pilot data (WP2) + other installations	CirTec	High (range of performance)
Mainstream effects of cellulose extraction	Other full-scale installations	CirTec	High (range of performance)
Bio-drying	Pilot data (WP3) extrapolated to full-scale	UVIC	High
Incineration as biofuel	Literature	UVIC + KWB	Medium
Bio-composite production	Pilot data (WP3) extrapolated to full-scale	ECODEK	High

2.1.6 Indicators for impact assessment

This study focusses on two specific environmental impacts: primary energy demand and greenhouse gas emissions. For primary energy demand, the indicator of cumulative energy demand (CED) for non-renewable fuels as defined in VDI 4600 (VDI, 2012) is used, adding up fossil and nuclear fuels to a single score. For greenhouse gas emissions, factors of IPCC are used to calculate the global warming potential (GWP) for a time horizon of 100 years (IPCC, 2014). Long-term emissions > 100a are neglected ("without LT").

For the biofuel scenarios, an additional indicator for terrestrial acidification is calculated to check whether gaseous emissions of bio-drying and incineration have a significant negative impact on the environmental footprint. For this purpose, the study makes use of the terrestrial acidification potential (TAP) at midpoint level (Hierarchist perspective) as defined in the ReCiPe method (Huijbregts et al., 2017), also neglecting long-term emissions > 100a.

2.2 Input data (Life Cycle Inventory)

2.2.1 Data of WWTP Geestmerambacht and sludge disposal

Data for mass flows, electricity and chemicals demand of WWTP Geestmerambacht was collected for the years 2017/2018 from WWTP operators via the project partner CirTec. Data for sludge disposal route (transport, drying, incineration) has been compiled from available literature.

Mass flow data for water and sludge line of WWTP Geestmerambacht

Relevant data for volume, TSS, COD, total nitrogen, and total phosphorus for WWTP influent and effluent is reported in **Table 2-3** below. The annual COD influent load amounts to 8726 t/a, which corresponds to around 200.000 pe when assuming a daily COD load of 120 g/pe (ATV, 2000), confirming the number defined for the functional unit. TSS concentration in WWTP influent is 290 mg/L in annual average, which determines the total yield of cellulosic sludge as this is correlated to the TSS removal. Effluent quality shows a high removal of TSS (>97%), COD (>93%), TN (> 86%) and TP (> 93%) at the WWTP. Return load from sludge thickening and dewatering is estimated and adds around 10% of TSS to the influent WWTP.

Direct gaseous emissions of the WWTP process are estimated to 0.19% of N input as N_2O based on a linear correlation between total N removal and N_2O emission factors (Parravicini et al., 2016).

Table 2-3: Input data for WWTP Geestmerambacht: influent and effluent quality and return load with sludge liquor

Parameter	*Unit*	Influent of WWTP	Effluent of WWTP	Sludge liquor from thickening	Sludge liquor from dewatering
Volume	*m^3/d*	43,390	43,264	225#	342#
Total suspended solids	*g/m^3*	290	8.3	3760*	2350*
COD	*g/m^3*	551	35.6	35*	35*
Total nitrogen	*g/m^3*	53.8	7.05	7*	7*
Total phosphorus	*g/m^3*	7.3	0.47	0.5*	0.5*

**estimated*

 # calculated with model

Mixed sludge amounts to 628 t/d with a dry matter (DM) load of 17 t DM/d (**Table 2-4**). Subtracting the loads in sludge liquor, around 70 t/d of dewatered sludge with 22% DM (15.4 t DM/d) have to be disposed.

Table 2-4: Input data for WWTP Geestmerambacht: mixed sludge and dewatered sludge for disposal

Parameter	*Unit*	Mixed sludge to thickening	Dewatered sludge to disposal
Mass	*t/d*	628	69.6*
Dry matter content	*% DM*	0.27	22
Volatile solids	*% of DM*	78.2	78*
Total nitrogen	*% of DM*	3.7*	4.1*
Total phosphorus	*% of DM*	1.7*	1.9*

**estimated by modelling, difference originates from sludge liquor*

Electricity and chemicals demand

Total electricity demand for WWTP operation amounts to 7400 MWh/a or 0.47 kWh/m^3 influent. 79% of this electricity demand is for the activated sludge process, while the remaining is for sludge thickening, dewatering, and other consumers. For P removal, the WWTP requires 487.5 t $FeCl_3$-Solution (40%) per year, resulting in a coagulant dosing of 4.3 g Fe/m^3 influent. Polymer use for dewatering amounts to 172 t/a or 18 g active substance per kg DM.

Sludge drying and incineration

For sludge drying in Beverwijk, a transport distance of 32km is estimated from the WWTP to the drying facility. Here, heat is supplied via firing CHPs with natural gas, co-producing electricity and using the heat for drying. A total input of natural gas has been calculated to 6700 kWh/t DM, with a net electricity output of 1475 kWh/t DM (Kiesewetter, 2002). The final DM content of the dried sludge is 90% DM.

For incineration at Amsterdam West, a lower heating value of 15.8 MJ/kg has been calculated for the dried sludge at 80% DM and 78% VS. The facility recovers 30% of the energetic content as electricity, which amounts to 1,300 kWh/t input sludge (Van Berlo, 2011). 20% of the input has to be disposed of as incineration ash (no transport, only landfill). Emissions of incineration are estimated based on previous studies of sludge co-incineration, not accounting the CO_2 to GWP as it is of renewable origin. Emission data is calculated per ton of DM as 2.5 g CO, 125 g NO_x, 100 g N_2O, 25 g NH_3, 0.5 g HCl, 8 g Dust, and 10 g SO_2.

2.2.2 Data for cellulose recovery system and impact on WWTP operation

Data for the cellulose recovery system is delivered by CirTec based on pilot trials at WWTP Geestmerambacht and experience from other full-scale installations, demonstration projects or supplier information.

Performance of cellulose recovery system and downstream impacts on the WWTP operation

For the performance of the prospective full-scale cellulose recovery system, TSS and COD removal has been estimated with minimum, mean, and maximum values by project partner CirTec (**Table 2-5**). TSS removal for the rotating belt filter is between 10 and 35% of influent TSS, but 10% of the separated TSS is lost back to the mainline with the filtrate of the integrated screw press. Finally, 29 – 100 g TSS of cellulosic sludge can be harvested with the system per m^3 of WWTP influent.

Cellulosic sludge is dewatered to 30% DM in the integrated screw press before further processing. In the LCA model, removed grit and sludge of pre-screening is sent to sludge disposal directly (grit) or via thickening and dewatering (pre-screening sludge).

Downstream effects of cellulose recovery are estimated to 10-20% of savings in aeration energy, 10-30% less DM for sludge production to disposal, and 5-15% savings in polymer for dewatering. Relative savings for polymer are not directly correlated to lower sludge production, as the missing fibre content in the thickened sludge can lead to a slightly higher relative polymer demand for dewatering.

Table 2-5: Input data for performance of cellulose recovery system and its downstream impact on WWTP operation

Parameter	Unit	Min value (scenarios 1a, 2a)	Mean value (scenarios 1b, 2b)	Max value (scenarios 1c, 2c)
TSS removal	%	-25	-40	-55
Grit removal	%	-5	-5	-5
Pre-screening	%	-10	-10	-15
*Rotating belt filter**	%	-10	-25	-35
COD removal		-10	-20	-30
Grit removal	%	-3	-5	-8
Pre-screening	%	-2	-5	-7
*Rotating belt filter**	%	-5	-10	-15
Sludge production to disposal (DM amount)	%	-10	-20	-30
Savings in aeration energy	%	-10	-15	-20
Savings in polymer for sludge dewatering	%	-5	-10	-15

** process stage for cellulose recovery*

Electricity and heat demand

Electricity demand for the cellulose recovery system is estimated to 4.6 Wh/m³ for grit removal, 10 Wh/m³ for the pre-screening, and 40 Wh/m³ for the rotating belt filter with integrated screw press. For regular cleaning of the rotating belt filter, hot water at 85°C is required with a total amount of 3600 L per day for the full-scale unit. Hot water is assumed to be heated using 70 kWh of heat per m³ of water originating from natural gas.
For thermal drying of cellulosic sludge (scenarios 2a-c), 320 kWh of heat is required per ton of cellulosic sludge at 50% DM. In this study, it is assumed here that this heat will usually be available on-site as excess heat (e.g. from a CHP plant), so that no external fuel is required to cover this heat demand. The drying process delivers a dried cellulosic material with 90% DM. The final pelletizer uses 50 kWh/t for producing dry cellulose pellets.

Infrastructure

As a rough estimate for infrastructure material of the cellulose recovery system (including grit removal, pre-screening, rotating belt filter, thermal dryer, and pelletizer), 50 tons stainless steel and 10 tons PE are assumed for the full-scale system. The corresponding lifetime of the equipment is estimated to 20 years.

2.2.3 Data for bio-drying and incineration

Data for bio-drying is delivered by project partner UVIC based on pilot trials of bio-drying of cellulosic sludge and experience from other projects on bio-drying (**Table 2-6**).

Cellulosic sludge at 30% DM is mixed with bulk material to enable good aeration of the mixture, and bulk material is recovered after bio-drying with a sieving stage and recycled to the input. Although a part of the bulk material remains in the product (~ 12% mass increase), this LCA does not account for the footprint of bulk material production as it is assumed that it will be mostly waste biomass with negligible impact.
DM of the output biofuel is 54% after forced aeration over 12 days, resulting in a final lower heating value (LHV) of 7.2 MJ/kg. Gaseous emission factors for NH_3, N_2O, CH_4, and VOCs from bio-drying are estimated based on results of pilot trials. A bio-filter is planned for the full-scale system for emission control, reducing 90% of NH_3 emissions, 10% of CH_4 emissions, and 70% of VOC emissions of the bio-drying system.
Electricity demand for aeration and sieving is calculated to 125 kWh per ton of input cellulosic sludge, and another 34.2 kWh/t is needed for the bio-filter. Mechanical turning during the process is done by machinery using 2.7 L Diesel/t. Final pelletizing of the dried biofuel needs another 60 kWh/t of electricity.

Table 2-6: Input data for bio-drying

Parameter	Unit	Value	Remark
DM after drying	%	54	Data from pilot trials
Lower heating value of product	MJ/kg	7.2	Data from pilot trials
Aeration demand	Nm³/t	8.550	Forced aeration for 12 days
Mass increase from bulking material	%	12	Fraction of bulking material remains in product after bio-drying
TS increase from bulking material	%	13	
NH_3 emission factor	mg/kg TS	315	before bio-filter, -90% in bio-filter
N_2O emission factor	mg/kg TS	26	before bio-filter, no change in bio-filter
CH_4 emission factor	mg/kg TS	8	before bio-filter, -10% in bio-filter
VOC emission factor	mg/kg TS	41	before bio-filter, -70% in bio-filter
Electricity for bio-drying	kWh/t	125	Related to input of wet cellulosic sludge
Electricity for bio-filter	kWh/t	34.2	
Diesel for bio-drying	l/t	2.7	
Electricity for pelletizer	kWh/t	60	Related to dried cellulosic sludge

Biofuel incineration

Dried cellulose pellets are transported to a biofuel incineration facility (estimate: 100 km by truck) where energy is recovered in the form of electricity (26% of LHV or 520 kWh/t) and heat (50% of LHV or 1000 kWh/t). Emissions from incineration are assumed to be comparable to emission factors of co-incineration of sludge (see 2.2.1), and ash (2% of DM) is disposed in landfill.

Infrastructure

The infrastructure for the bio-drying plant is roughly estimated from a dataset on open composting plant infrastructure of ecoinvent ("composting facility construction"), recalculating total material demand linearly to the amount of treated input material. For a bio-drying plant of 5000 t input per year, a total amount of 183 m^3 concrete, 10 t reinforcing steel, 18 t low-alloyed steel, and 25t cast iron is assumed. The lifetime of the plant is estimated with 20 years.

2.2.4 Data for bio-composite production

After on-site drying and pelletizing (see chapter 2.2.2), cellulose pellets are transported to a production plant for bio-composite materials (100 km by truck). At this plant, cellulose substitutes a fraction of the wood flour which is the original structural material used in the bio-composites. Two effects of this valorisation route are reflected in this LCA: a) the avoided consumption of wood flour and b) energy savings in the bio-composite production process when using cellulose as structural material.

Data for bio-composite production is delivered by project partner Ecodek (SBPL Ltd) based on pilot trials with cellulose pellets (ReCell®) recovered by CirTec (**Table 2-7**). Cellulose pellets can replace up to 50% of wood flour in the bio-composite production process without negative impacts on product quality. The substitution leads to credits of avoided production of wood flour (related ecoinvent dataset: "shavings, softwood"), accounting 1 ton of saved wood shavings per ton per ton of cellulose at 90% DM.
In the bio-composite production process, the use of cellulose leads to savings of electricity for wood-related aggregates (i.e. wood bin for feeding of material with 7.1 kW, and heated wood screw for transport and pre-drying of wood with 2.4 kW). In addition, the use of cellulose enables a higher production volume in the production line (~ 14% more material throughput per hour), so that the total electricity savings amount to 170 kWh per ton of cellulose input. All other parameters of the production process (e.g. the type and amount of chemical additives needed for bio-composite production) are assumed to stay constant. Although additives may change when using cellulose as structural material, related information was deemed confidential by the project partner, and thus cannot be included in this LCA. The final bio-composite product made with cellulose is assumed as fully equivalent to the product based on 100% wood flour.

Table 2-7: Input data for production of bio-composite with cellulose pellets

Parameter	Unit	Value	Remark
Substitution of wood flour	t/t cellulose	1.0	1:1 replacement of wood shavings with cellulose pellets at 90% DM
Electricity savings	kWh/t cellulose	170	No wood-related aggregates needed, plus higher throughput possible with cellulose

Infrastructure

No infrastructure is accounted for cellulose valorisation in bio-composite production, as the cellulose pellets can be directly fed into the existing production process without the need of additional aggregates.

2.2.5 Background data

Background processes are modelled with datasets from ecoinvent database v3.4 (Ecoinvent, 2017). The related datasets are listed below (**Table 2-8**), mainly relating to European or global markets. For electricity, the market mix of the Netherlands is applied. For transport of chemicals to the WWTP, a distance of 300km has been estimated.

Table 2-8: Datasets for background data

Process	Dataset from ecoinvent v3.4	Remarks
Energy		
Electricity	market for electricity, medium voltage [NL]	For all operational electricity demand and credits from incineration or in bio-composite production
Heat for drying	heat production, natural gas, at industrial furnace low-NOx >100kW [Europe without Switzerland]	Heat supply for sludge drying or hot water for cleaning of fine sieve
Heat credits	market for heat, district or industrial, natural gas [Europe without Switzerland]	Heat credits from biofuel incineration
Transport and fuels		
Truck transport	transport, freight, lorry 16-32 metric ton, EURO5 [RER]	300 km for chemicals, 32km for sludge to drying and disposal, 100km for biofuel pellets to incineration
Diesel	market for diesel, burned in agricultural machinery [GLO]	Diesel used in bio-drying process
Chemicals		
FeCl3	market for iron (III) chloride, without water, in 40% solution state [GLO]	Coagulant for WWTP operation
Polymer	market for acrylonitrile [GLO]	746 g acrylonitrile + water = 1kg of polymer active substance
Materials		
Stainless steel	steel production, electric, chromium steel 18/8 [RoW]	Infrastructure material for cellulose recovery unit
PE	polyethylene production, low density, granulate [RER]	Infrastructure material for cellulose recovery unit
Concrete	market for concrete, for de-icing salt contact [RoW]	Infrastructure material for bio-drying unit
Reinforcing steel	reinforcing steel production [RoW]	Infrastructure material for bio-drying unit
Steel low alloyed	steel production, low-alloyed, hot rolled [RoW]	Infrastructure material for bio-drying unit
Cast iron	cast iron production [RoW]	Infrastructure material for bio-drying unit
Wood flour	market for shavings, softwood, measured as dry mass [GLO]	Credits for use of cellulose in bio-composite production
Ash disposal	treatment of average incineration residue, residual material landfill [RoW]	Disposal of incineration ash

2.3 Results of environmental indicators (Life Cycle Impact Assessment)

Results of this LCA are presented separately for the scenarios 1a-c and 2a-c to differentiate the two potential valorisation routes of the recovered cellulosic material. This chapter presents total results for each indicator, relative change in indicator due to the implementation of cellulose recovery, and a separate impact only for the valorisation route.

2.3.1 Cellulose valorisation in bio-drying and biofuel

Cumulative energy demand (CED)

For the baseline scenario, the total net CED amounts to 623 MJ/(pe*a) (**Figure 2-2**). A gross CED of 1396 MJ/(pe*a) for WWTP operation and sludge disposal is partially compensated (55%) by energy recovered in drying and incineration facilities (-773 MJ/(pe*a)). From this sum, the operation of the WWTP with electricity and chemicals demand requires only 406 MJ/(pe*a), so the majority of the CED originates from sludge disposal. This can be explained by the high amount of energy required for drying the dewatered sludge (non-digested sludge at 22% DM). However, a major part of the invested energy in drying can be recovered by producing electricity, both at the drying facility (heat is supplied by CHP plant with co-production of electricity) and at the final incineration of the dried sludge. Overall, the sludge disposal with transport, drying, and incineration has a net CED balance of +217 MJ/(pe*a), showing that the drying and incineration of raw sludge with high water content is not energetically favourable.

Introducing a cellulose recovery system reduces total net CED of the system in scenarios 1a-1c by 4-23% depending on the efficiency of the cellulose recovery unit, including the valorisation route with bio-drying and biofuel. This illustrates that the additional efforts for cellulose recovery and processing are fully compensated by credits from material valorisation, but also from positive effects of the system on the overall energy balance of the WWTP operation. For a detailed analysis, the relative changes of CED due to cellulose recovery are analysed below.

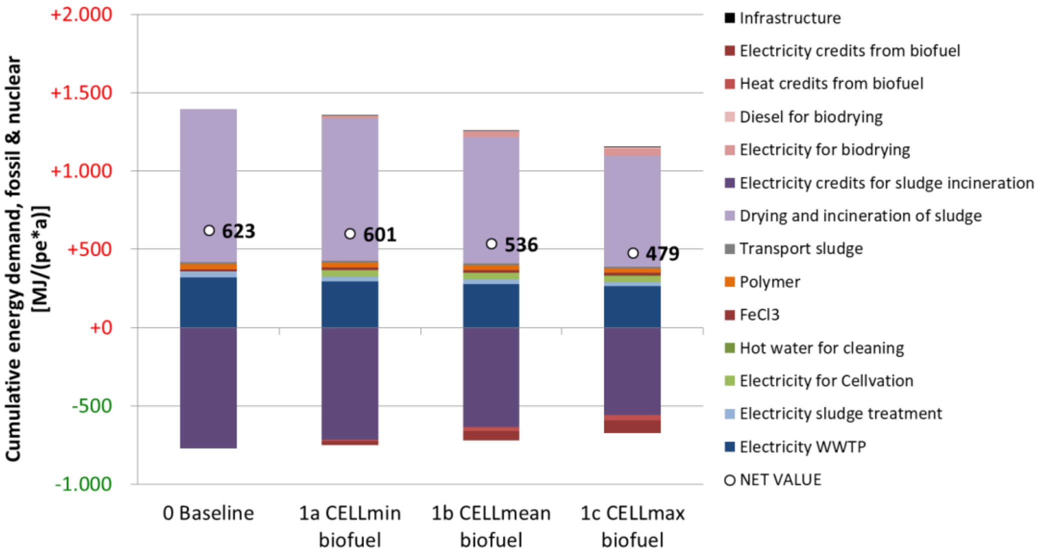

Figure 2-2: Total cumulative energy demand for baseline and cellulose recovery scenarios at WWTP Geestmerambacht. Valorisation route is bio-drying and use as biofuel

The relative CED changes of cellulose recovery scenarios 1a-1c compared to the baseline situation amount to -22 to -144 MJ/(pe*a) with valorisation route included or -5 to -85 MJ/(pe*a) without valorisation route (**Figure 2-3**). While the recovery system itself comes with an additional CED of 43 MJ/(pe*a) for electricity, hot water supply for cleaning, and infrastructure, positive effects at the WWTP and in the sludge disposal route fully compensate this energy demand. Beside the savings in aeration energy and polymer consumption (-29 to -60 MJ/(pe*a) for scenarios 1a-1c depending on the efficiency of cellulose removal), another significant factor for the positive balance is the lower sludge amount for disposal (**Table 2-5**), saving -15 to -56 MJ/(pe*a) in the different scenarios. The remaining effect in net CED is caused by the valorisation route for the recovered cellulose, which is analysed in detail below.

Related to the total amount of recovered cellulosic dry matter (462, 1134, and 1576 tons of DM per year for scenarios 1a, 1b, and 1c), the net CED footprint of cellulose recovery is calculated to -9.5, -15.3, and -18.3 GJ per ton of cellulose DM at the WWTP Geestmerambacht depending on the efficiency of the cellulose recovery process.

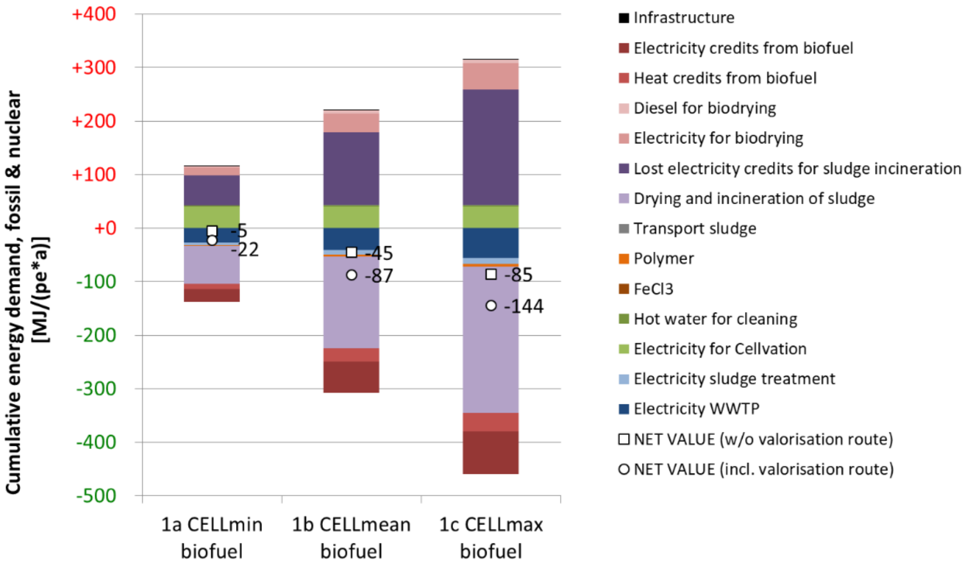

Figure 2-3: Change in cumulative energy demand for cellulose recovery scenarios at WWTP Geestmerambacht compared to baseline. Valorisation route is bio-drying and use as biofuel

Bio-drying of the cellulosic sludge requires an additional CED of 16-56 MJ/(pe*a) for electricity and diesel consumption and generates credits in incineration of -34 to -115 MJ/(pe*a) (**Figure 2-4**). Hence, around 50% of the energy credits in cellulosic pellets are used for the bio-drying process. Related to a ton of input cellulosic DM at 30% DM, this valorisation route generates a CED credit of -7.5 GJ/ton DM for the recovered cellulose.

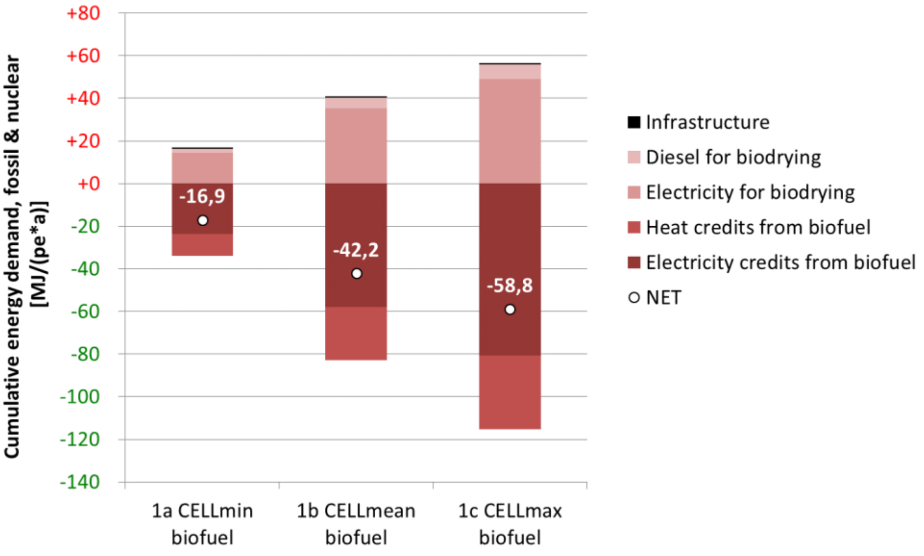

Figure 2-4: Balance of cumulative energy demand for valorisation route of cellulosic sludge (30% DM) in bio-drying and use as biofuel

Global warming potential (GWP)

The total net GWP of the baseline scenario amounts to 36.7 kg CO_2-eq/(pe*a) (**Figure 2-5**). Thereof, the system has a gross GWP impact of 86 kg CO_2-eq/(pe*a) and receives credits for energy recovery of -49 kg CO_2-eq/(pe*a), compensating 57% of its GWP. The operation of the WWTP itself with electricity, chemicals demand, and some direct emissions of N_2O accounts for the major share of the total GWP, summing up to 28 kg CO_2-eq/(pe*a). The sludge disposal route with transport, drying, and incineration adds a net GWP of 8 kg CO_2-eq/(pe*a) to the entire system, mainly due to high energy demand for drying which is larger than the energy recovered from incineration.

The implementation of a cellulose recovery unit reduces net GWP of the system by 2 to 19% for scenarios 1a to 1c, depending on the efficiency of the cellulose recovery process. A detailed profile of the changes in GWP due to cellulose recovery and valorisation as biofuel is provided below.

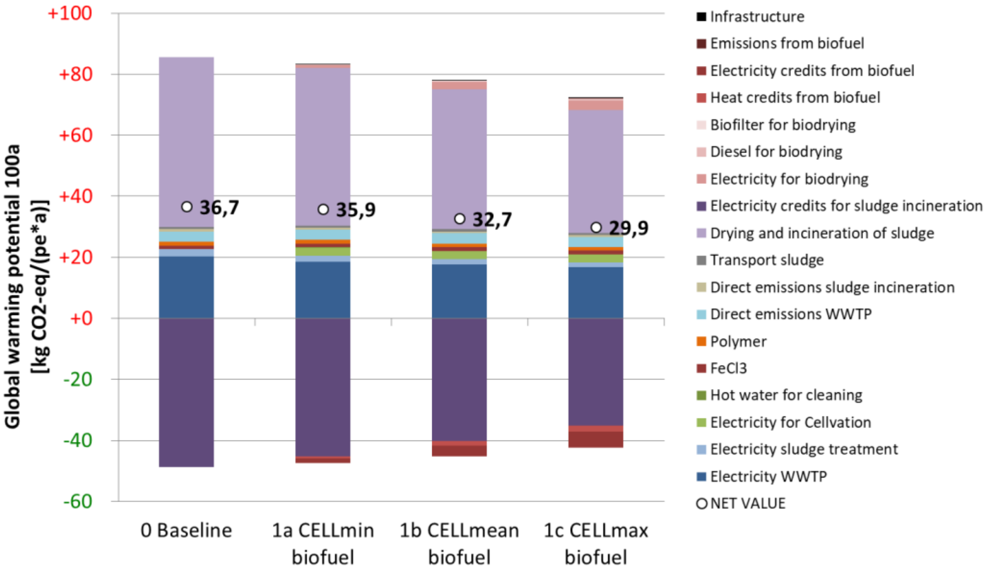

Figure 2-5: Total global warming potential for baseline and cellulose recovery scenarios at WWTP Geestmerambacht. Valorisation route is bio-drying and use as biofuel

In scenarios 1a to 1c, net GWP of the system is reduced by -0.8 to -6.8 kg CO_2-eq/(pe*a), indicating that the additional efforts for cellulose extraction and processing are fully compensated by credits for material recovery, but also due to savings in the WWTP and sludge disposal route (**Figure 2-6**). Without valorisation route, the GWP savings are reduced to +0.1 to -3.7 kg CO2-eq/(pe*a), indicating that the recovery system with lowest efficiency ("1a CELLmin biofuel") will even increase GHG emissions without valorisation of cellulose.

Additional GWP for the operation and infrastructure of the cellulose recovery system accounts for 2.7 kg CO_2-eq/(pe*a). In analogy to the CED profile, GWP benefits originate mainly from savings at the WWTP in electricity and polymer of -2.1 to -4.4 kg CO_2-eq/(pe*a), while impacts of the sludge disposal route amount to -0.5 to -2.0 kg CO_2-eq/(pe*a).

Related to the total amount of recovered cellulosic DM, the net GWP footprint of cellulose recovery is calculated to -0.3 to -0.9 ton CO_2-eq per ton of cellulose DM at the WWTP Geestmerambacht depending on the efficiency of the cellulose recovery process, including the valorisation route as biofuel.

Bio-drying of the cellulosic sludge causes 1.2 to 3.9 kg CO2-eq/(pe*a) for electricity, fuel demand and N_2O emissions from incineration (**Figure 2-7**) or ca. 0.5 t CO_2-eq per ton of cellulosic DM. Energy recovery from biofuel incineration yields -2.1 to -7.1 kg CO2-eq/(pe*a) or -0.9 t CO_2-eq per ton cellulosic DM. Overall, the valorisation of cellulosic sludge at 30% DM via bio-drying and incineration as biofuel results in a GWP credit of -0.9 to -3.1 kg CO_2-eq/(pe*a) or -390 kg CO_2-eq per ton of cellulosic DM.

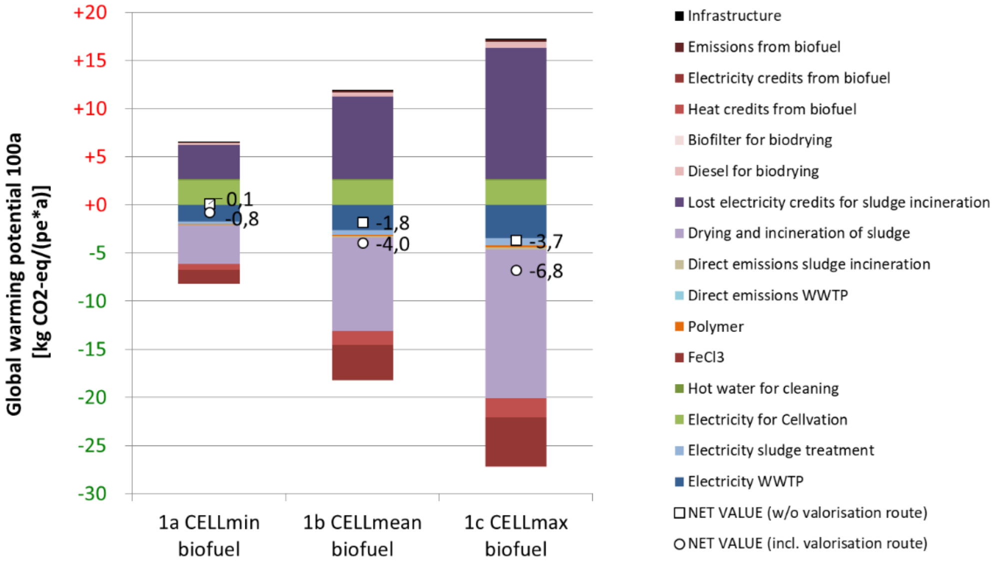

Figure 2-6: Change in global warming potential for cellulose recovery scenarios at WWTP Geestmerambacht compared to baseline. Valorisation route is bio-drying and use as biofuel

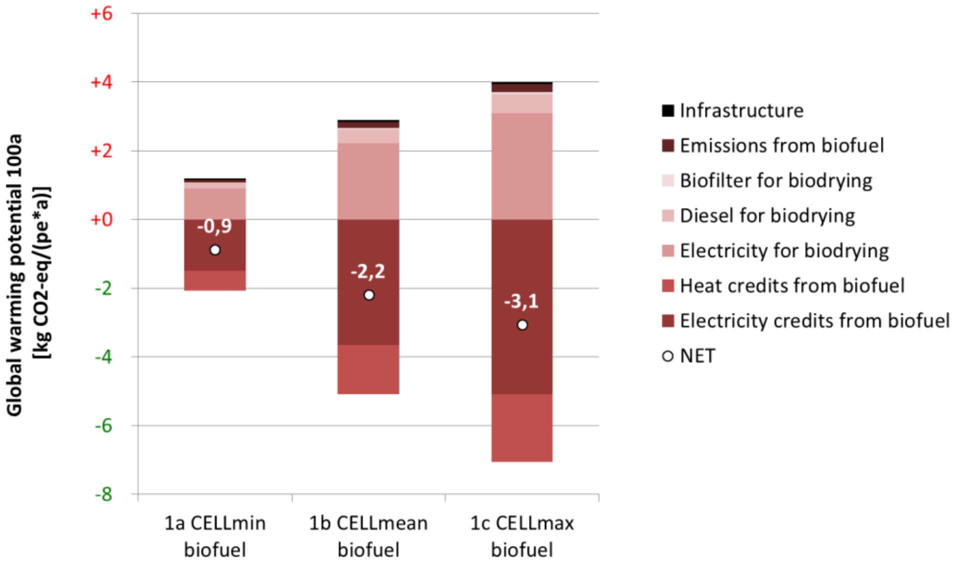

Figure 2-7: Balance of global warming potential for valorisation route of cellulosic sludge (30% DM) in bio-drying and use as biofuel

Terrestrial acidification potential (TAP)

The baseline net TAP accounts to 96 g SO_2-eq/(pe*a), which is caused by a gross TAP of 180 g SO_2-eq/(pe*a) and credits of -85 g SO_2-eq/(pe*a) (**Figure 2-8**). In contrast to GWP, direct emissions of the WWTP process play a major role in this indicator, which is mainly caused by NH_3 emissions from aeration of raw wastewater and partial stripping of NH_4-N. In addition, the sludge treatment route has an overall negative TAP footprint, saving -32 g SO_2-eq/(pe*a) in sludge disposal.

Hence, the introduction of a cellulose recovery process slightly increases the net TAP of the entire system by 3-5% or 3-5 g SO_2-eq/(pe*a), mainly due to the lower sludge production which decreases the TAP credits from sludge disposal. The processing of cellulosic material in bio-drying and its valorisation as biofuel does not have a negative impact on TAP, saving -0.1 to -0.8 g SO2-eq/(pe*a) in total (**Figure 2-9**). Here, the bio-filter reduces potentially harmful emissions of NH_3 by 90%, illustrating that this emission reduction measure is important to mitigate potentially negative effects of cellulose valorisation on the overall environmental footprint.

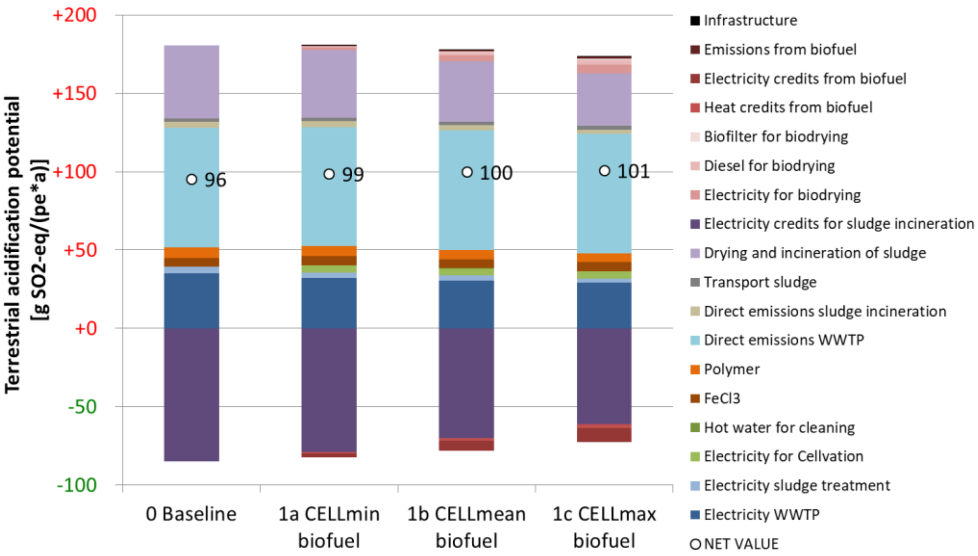

Figure 2-8: Total terrestrial acidification potential for baseline and cellulose recovery scenarios at WWTP Geestmerambacht. Valorisation route is bio-drying and use as biofuel

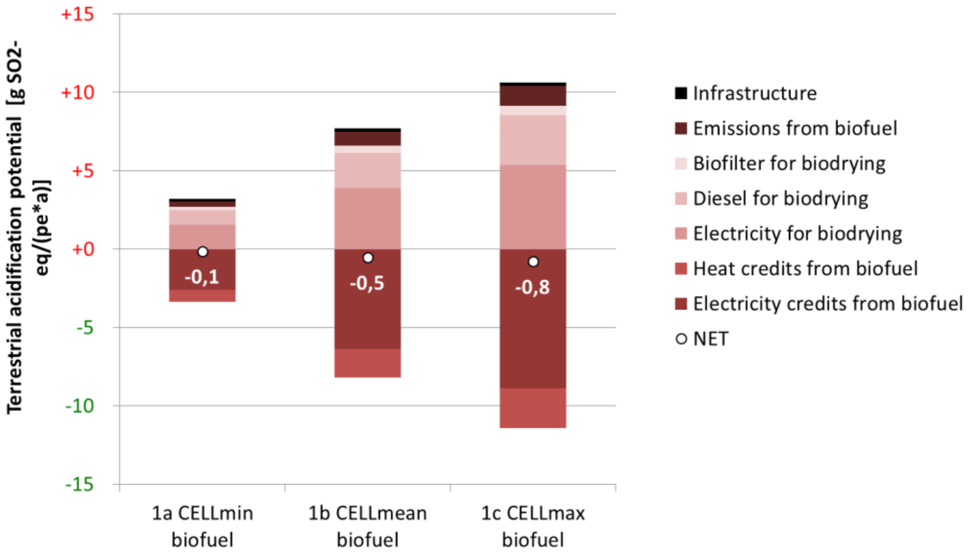

Figure 2-9: Balance of terrestrial acidification potential for valorisation route of cellulosic sludge (30% DM) in bio-drying and use as biofuel

Finally, the TAP indicator reveals that cellulose recovery can also have a potentially negative impact on the environmental footprint of WWTP Geestmerambacht. However, the detected effect is rather small, affects an environmental impact that is most likely not seen as a priority environmental problem in the region, and is directly linked to the specific situation of sludge disposal at this plant.

2.3.2 Cellulose valorisation in bio-composite production

Cumulative energy demand (CED)

For the valorisation of cellulose pellets in bio-composite production, the total net CED of the WWTP Geestmerambacht (623 MJ/(pe*a)) is reduced by 2-18% in scenarios 2a-2c, depending on the efficiency of the cellulose recovery unit (**Figure 2-10**). Overall, the energetic benefits of bio-composite production are not as high as for the valorisation as biofuel. This is mainly due to the fact that cellulose replaces another renewable natural material (wood flour), which is also produced with low energy and GHG footprint.

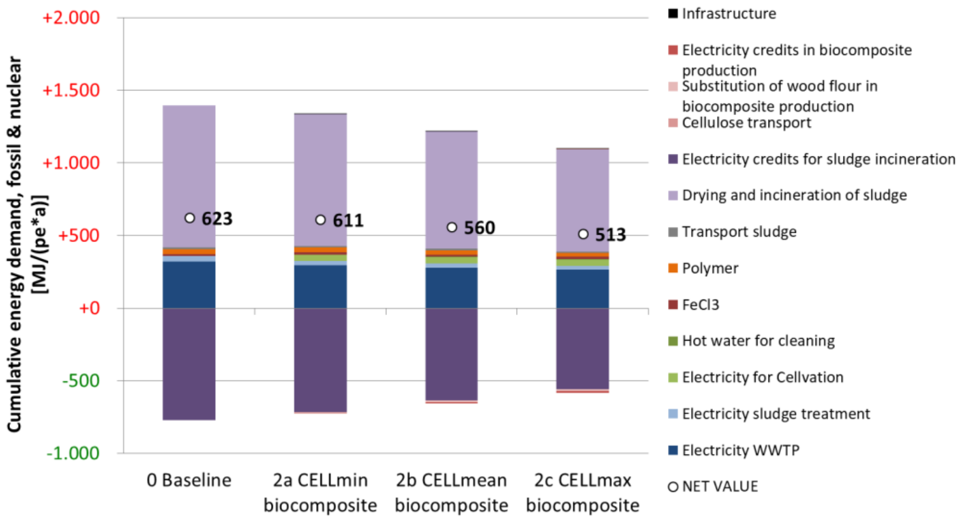

Figure 2-10: Total cumulative energy demand for baseline and cellulose recovery scenarios at WWTP Geestmerambacht. Valorisation route is drying and bio-composite production

Again, the detailed analysis of the relative changes in CED reveals that the effects of cellulose extraction at the WWTP (lower electricity demand, less polymer) and in the sludge disposal route (less sludge to dry and incinerate) are decisive for the overall effect, whereas the valorisation as bio-composite plays only a minor role (**Figure 2-11**). The benefits of using cellulose in bio-composite production (i.e. replacing wood flour, plus some energy savings in the process) account for -7 to -25 MJ/(pe*a), improving the CED balance only marginally.

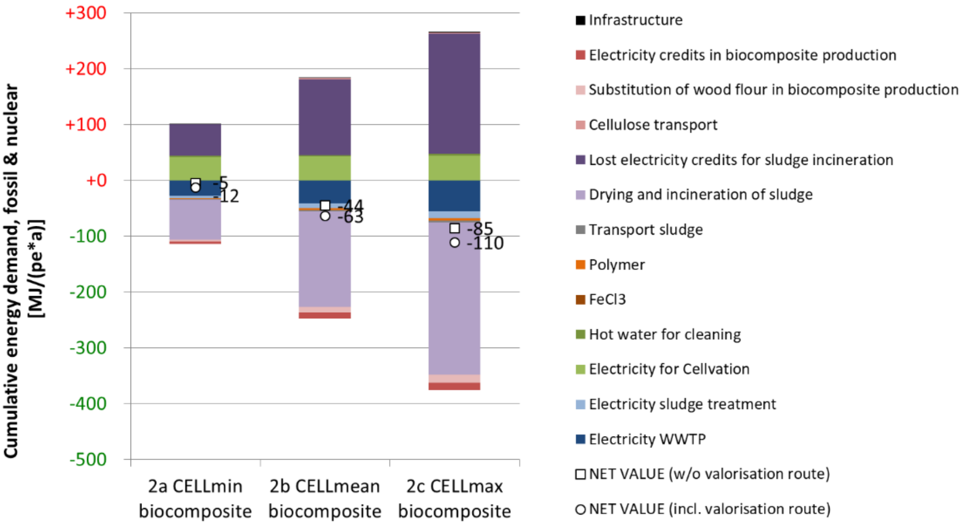

Figure 2-11: Change in cumulative energy demand for cellulose recovery scenarios at WWTP Geestmerambacht compared to baseline. Valorisation route is drying and bio-composite production

In relation to the total amount of recovered cellulose pellets (462, 1134, and 1576 tons of DM per year for scenarios 2a, 2b, and 2c), the net CED footprint of cellulose recovery is calculated to -5.2, -11.1, and -14.0 GJ per ton of cellulose DM at the WWTP Geestmerambacht depending on the efficiency of the cellulose recovery process when using cellulose pellets for bio-composite production.

On-site drying of the cellulosic sludge is assumed with available excess heat and does not contribute to energy demand of this valorisation route. Besides the energy needed for transport of cellulose pellets (100 km by truck), the bio-composite route yields credits for substituting wood flour, and also for saving some electricity in the production process. Overall, this route accounts for -7.5 to -25.5 MJ/(pe*a) for the different scenarios

(**Figure 2-12**), or -3.2 GJ per ton of DM in cellulose pellets. In total, the valorisation of cellulose as structural material is less positive for the overall energy balance compared to the biofuel route, which yielded -7.5 GJ/ton as shown in chapter 2.3.1. Again, this is due to the fact that cellulose replaces a low-energy primary material (wood flour) in this route.

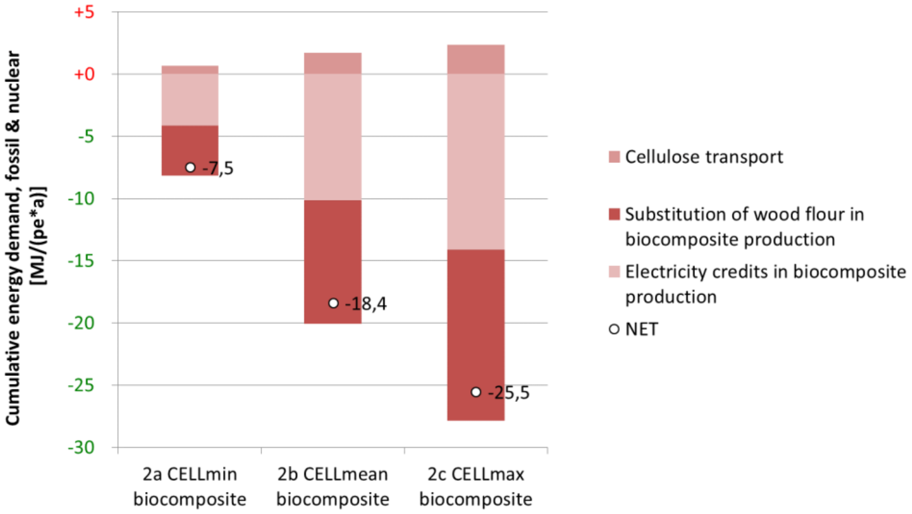

Figure 2-12: Balance of cumulative energy demand for valorisation route of cellulosic sludge (30% DM) via on-site drying and bio-composite production

Global warming potential (GWP)

For the bio-composite route, cellulose recovery reduces the net GWP of the baseline scenario (36.7 kg CO_2-eq/(pe*a)) by 1-15% depending on the efficiency of cellulose extraction (**Figure 2-13**). These benefits are lower than for the biofuel route, which is equivalent to the results of CED above.

The detailed analysis of the GWP impacts of cellulose recovery shows that major benefits are due to savings at the WWTP and in the sludge line (+0.1 to -3.7 kg CO_2-eq/(pe*a)), whereas the valorisation of cellulose as bio-composite material puts -0.5 to -1.8 kg CO2-eq/(pe*a) on top (**Figure 2-14**). Related to the total amount of recovered cellulose, the net GWP footprint is calculated to -0.2, -0.5 and -0.7 ton CO_2-eq per ton of DM in cellulose pellets for scenarios 2a, 2b, and 2c using the bio-composite route.

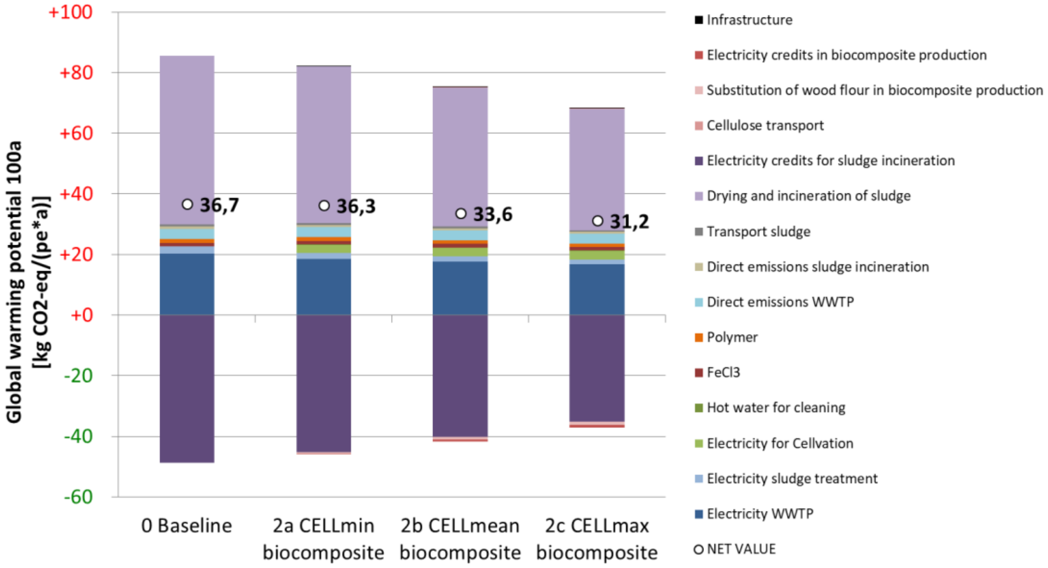

Figure 2-13: Total global warming potential for baseline and cellulose recovery scenarios at WWTP Geestmerambacht. Valorisation route is on-site drying and bio-composite production

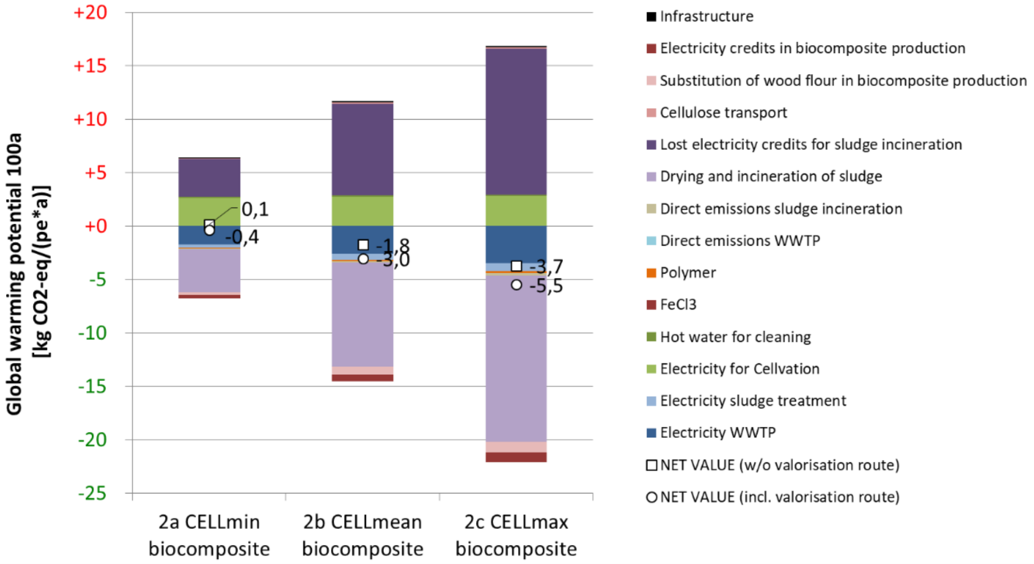

Figure 2-14: Change in global warming potential for cellulose recovery scenarios at WWTP Geestmerambacht compared to baseline. Valorisation route is on-site drying and bio-composite production

The valorisation as bio-composite yields GWP credits of -0.5 to -1.8 kg CO_2-eq/(pe*a) depending on the different extraction efficiency (**Figure 2-15**). This positive impact is contributed to ca. 50% by the substitution of wood flour as structural material, and to 50% from electricity savings in the production process. This route leads to GWP credits of -230 kg of CO_2-eq per ton DM in cellulose pellets, which are lower than for the bio-fuel route mainly due to the substitution of a carbon-neutral primary material (wood flour) in this case.

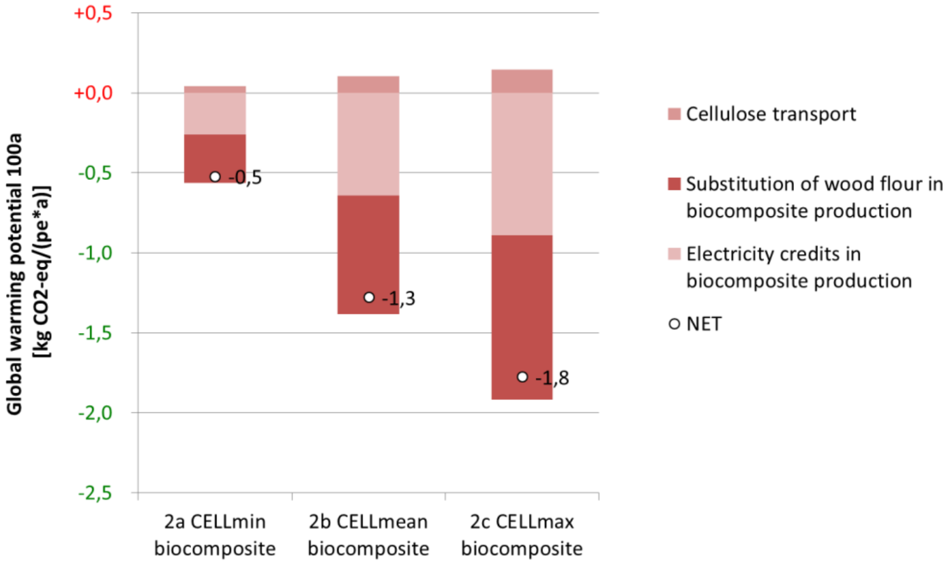

Figure 2-15: Balance of global warming potential for valorisation route of cellulosic sludge (30% DM) via on-site drying and bio-composite production

2.4 Interpretation and conclusions

This LCA case study analyses the potential environmental impacts of implementing a system for cellulose recovery at the WWTP Geestmerambacht (NL), taking into account all direct and indirect effects on the WWTP, in the sludge disposal route, and also from the valorisation of the recovered cellulose material. Depending on the actual efficiency of the fine sieve for cellulose extraction, between 2.3 and 7.9 kg cellulose DM can be extracted per person and year. For the WWTP Geestmerambacht with a mean influent concentration of 290 g total SS per m^3, this amounts to 29-100 g cellulose DM per m^3 influent (**Table 2-9**).
For valorisation of the extracted cellulose, two different routes have been analysed: a) bio-drying and incineration as biofuel and b) thermal drying and use as structural material in the production of bio-composites.

Valorisation of cellulose as biofuel
The main outcomes of the LCA for this valorisation route can be summarized as follows (**Table 2-9**):

- The implementation of a cellulose recovery process reduces the net environmental impact of the WWTP significantly. Overall, the **net energy demand of the system decreases by 4-23%** depending on the efficiency of cellulose removal in the process, while the **net GHG emissions are reduced by 2-19%**.
- Additional efforts for cellulose extraction and processing (electricity, hot water for cleaning the belt filter, and infrastructure) are fully compensated by the positive effects of cellulose extraction on the downstream WWTP process. In particular, savings in aeration energy (-5 to -15%) and reduced sludge amount to disposal (-10 to -30%) have a positive impact on the environmental balance.
- In addition, valorisation of cellulosic sludge via bio-drying and use as biofuel generates additional credits in avoided energy demand and related GHG emissions. **Per ton DM of wet cellulosic sludge at 70% water content, this route gives a credit of -7.5 GJ and -390 kg CO_2-eq**.
- In total, the implementation of a full-scale system for cellulose recovery at WWTP Geestmerambacht (200.000 pe) and its valorisation as a biofuel is expected to **save 4,400 – 28,800 GJ per year of non-renewable fuels and to avoid 153-1,351 t CO_2-eq of GHG emissions (= 0.3-0.9 t CO_2-eq/t cellulose dry matter ion product)**.
- For emission of acidifying gases, cellulose recovery has a slightly negative net impact, enhancing terrestrial acidification potential of the entire system by 3-5%. This is mainly due to the lower amount of sludge to be disposed, as the sludge disposal route of WWTP Geestmerambacht (200.000 pe).

Valorisation of cellulose in bio-composite production
The main outcomes of the LCA for this valorisation route can be summarized as follows (**Table 2-9**):

- Again, cellulose recovery improves the environmental footprint of the WWTP significantly. Cellulose recovery for bio-composite production **decreases net energy demand of the system by 2-18% and GWP emissions by 1-15%** depending on the efficiency of cellulose removal in the process.
- Efforts for cellulose extraction and drying are fully compensated by savings at the WWTP and in the sludge disposal route. It should be noted here that drying of cellulose pellets is assumed to use available excess heat, i.e. operates without external energy input.
- Valorisation of dry cellulose pellets as structural material in bio-composite production generates additional credits for substituting primary material (i.e. wood flour) and by reducing energy demand in bio-composite production. **Per ton DM of dry cellulosic pellets at 10% water content, this route gives a credit of -3.2 GJ and -230 kg CO_2-eq.** The credits of this route are ca. 50% lower than for the bio-fuel route, mainly because cellulose replaces another renewable material (wood flour) with low environmental footprint.
- In total, the implementation of a full-scale system for cellulose recovery at WWTP Geestmerambacht (200.000 pe) and its valorisation in bio-composite production is expected to **save 2,400 – 22,000 GJ per year of non-renewable fuels and to avoid 77-1,094 t CO_2-eq of GHG emissions (= 0.2-0.7 t CO_2-eq/t cellulose dry matter in product)**.

Table 2-9: Summary of LCA results for cellulose recovery scenarios at WWTP Geestmerambacht (200.000 pe): impact on energy demand and global warming potential for minimum, mean, and maximum efficiency of cellulose extraction

Parameter	*Unit*	Baseline system	Valorisation as biofuel			Valorisation in bio-composite production		
			MIN	MEAN	MAX	MIN	MEAN	MAX
Cellulose recovered	*g DM/m³ influent*	-	29	72	100	29	72	100
	t DM/a	-	462	1134	1576	462	1134	1576
	*kg DM/(pe*a)*	-	2.3	5.7	7.9	2.3	5.7	7.9
Cumulative energy demand	*MJ/(pe*a)*	**623**	**-22**	**-87**	**-144**	**-12**	**-67**	**-110**
		100%	**-4%**	**-14%**	**-23%**	**-2%**	**-11%**	**-18%**
Global warming potential	*kg* CO_2*-eq/(pe*a)*	**36.7**	**-0.8**	**-4.0**	**-6.8**	**-0.4**	**-3.0**	**-5.5**
		100%	**-2%**	**-11%**	**-19%**	**-1%**	**-8%**	**-15%**

Limitations and transferability of the case study results to other WWTPs

Overall, the implementation of cellulose recovery has a positive impact on the environmental footprint of WWTP Geestmerambacht. Additional efforts for cellulose extraction and processing are more than off-set by savings in aeration energy, polymer consumption, and amount of sludge to be disposed. Further credits in energy demand and GHG emissions are generated in the valorisation of cellulosic material due to substitution of primary materials or non-renewable energy carriers.

However, the following aspects have to be considered when transferring these LCA results to other WWTPs and boundary conditions:

- The sludge disposal route at WWTP Geestmerambacht (i.e. dewatering of raw sludge, drying on natural gas, and co-incineration) needs an external input of energy and produces related GHG emissions. Hence, **reducing the excess sludge amount by cellulose extraction leads to a positive impact in this LCA for this specific WWTP.** However, WWTPs with an energetically optimised sludge disposal route (e.g. anaerobic digestion and mono-incineration with on-site pre-drying) **can also have a net energy and GHG benefit from sludge disposal.** In these cases, a reduction in sludge amount by cellulose extraction will lead to lower energy and GHG credits from sludge disposal (e.g. less biogas). This could **affect the overall net environmental footprint of cellulose recovery significantly.**
- Currently, WWTP Geestmerambacht has no primary treatment such as a sedimentation tank, i.e. no generation of primary sludge. In other WWTPs with existing primary treatment, the implementation of a fine sieve for cellulose extraction upstream will have less positive effects on the downstream WWTP, as >50% of the TSS are already removed with primary treatment. Hence, the **results of this LCA are only transferable to WWTP upgrades without any existing primary treatment.**
- Downstream impacts of cellulose recovery on the WWTP and sludge line are estimated from other full-scale installations based on experiences of the supplier (CirTec). As these **downstream impacts are decisive for the overall environmental balance, the related assumptions should be checked and validated for each case separately** to support the conclusions drawn in this LCA.
- Energetic valorisation of cellulose as bio-fuel is more beneficial in this LCA than material-related valorisation in bio-composite production, because the latter route substitutes a low-impact primary material (i.e. wood flour). If cellulose could **replace another primary material with higher environmental footprint** (e.g. virgin cellulose fibres with > 5x higher GWP than wood flour), **the material valorisation route will have higher environmental benefits**.

3. LCA OF ANAEROBIC PRIMARY TREATMENT (SMARTECH 2A)

A standard wastewater treatment plant (WWTP) removes around 35% of the influent COD load in primary and over 60% in secondary treatment. The COD removal in aerobic biological treatment requires aeration of the activated sludge, and is therefore energy intensive. An anaerobic primary treatment to remove more COD upfront can help to reduce the COD load of the biological stage and minimise the overall energy consumption of the WWTP significantly.

The “mainstream polyurethane-based anaerobic biofilter“ tested in SMART-Plant replaces the conventional primary settler with an anaerobic pre-treatment of the raw wastewater, removing up to 55% of the influent COD load by converting it to either biogas and primary sludge. Around 33% of the removed COD load is converted into biogas, and 67% is extracted as primary sludge. Consequently, energy for aeration in secondary treatment is saved and additional biogas is produced, which improves the electrical self-sufficiency of the WWTP. In the SMART-Plant project, a pilot-scale anaerobic biofilter with a capacity of 100 m^3 raw sewage/d is tested at the WWTP of Karmiel (Israel). The biofilter is operated as an up-flow reactor which is filled with a polymer-based matrix to reach a large surface area and with impregnated anaerobic microorganisms to prevent wash-out of the bacteria.

As the system has been tested in pilot-scale, the following assessment is based on careful up-scaling of the pilot data to reflect a full-scale mainstream anaerobic biofilter. In particular, the downstream effects of implementing the biofilter on the biological treatment, sludge treatment and biogas yield of the digester could not be quantified in practice. Those effects were carefully estimated in close cooperation with the technology provider AgRobics and the WWTP operator Mekorot, based on a reference layout with a conventional primary settler as pre-treatment.

The goal of this LCA is to illustrate all direct and indirect impact of implementing an anaerobic biofilter at WWTP Karmiel and show its environmental effects on primary energy demand and greenhouse gas (GHG) emissions. Results will illustrate a net overall impact of replacing a standard primary settler by an anaerobic biofilter. The upgrade of an additional treatment step in the WWTP mainline can have effects on the effluent quality and capacity of the WWTP, which is not addressed in this LCA.

3.1 Goal and scope definition

3.1.1 Goal of the study

The goal of this LCA is to analyse and compare the potential environmental impacts of the Karmiel (Israel) wastewater treatment plant (WWTP) with a conventional primary settler or an innovative anaerobic primary treatment, by taking into account all indirect and direct downstream effects for the sludge and water line.
The focus of this study is on primary energy demand and greenhouse gas emissions (GHG emissions), as the anaerobic primary treatment aims to increase the biogas production and to decrease the energy demand of the WWTP. The target group of this LCA consist of WWTP experts, planners and practitioners, which want to be informed about the holistic environmental impacts of an anaerobic primary treatment step in a WWTP.

3.1.2 Function and functional unit

The primary function of Karmiel WWTP relates to wastewater treatment with defined regional standards, including the valorisation and disposal of generated sludge. Consequently, the system function can be formulated as "municipal wastewater treatment to reach a defined effluent quality per population equivalent (pe) and year". Energy efficient wastewater treatment and energy recovery are secondary functions of the system. Based on these system functions, the functional unit is defined as the impacts of a wastewater treatment process per capita loading and year [1/(pe*a)]. All direct and indirect impacts are related to this functional unit.
The system perspective enables a comparison of different processes and pathways (in this case different primary treatment technologies) of wastewater treatment, showing all related total environmental impact of the system.

3.1.3 Scenarios

For this LCA three scenarios have been defined and are shown in **Table 3-1**. All three scenarios reach the same WWTP effluent quality for the parameters total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP). The effluent quality is defined to be 3 mg TSS/ L, 45 mg COD/L, 19 mg TN/ L and 2.5 mg TP/L.

0 Reference WWTP: This scenario represents a standard layout of Karmiel WWTP (215,000 pe), which consist of a grit removal, a primary treatment, a biological stage with a secondary clarifier, a sand filter and final dosing of a chemical disinfectant. The effluent is used for unrestricted irrigation and the sewage sludge is applied in agriculture after further composting process. To reflect a wider range of WWTPs and conventional layout of treatment schemes, two modifications were made for the reference scenario compared to the actual plant in Karmiel. First modification: Instead of the existing aerated reservoir with 60% COD removal, a standard primary treatment with 35% of COD removal is taken into account. Second modification: the existing CHP of Karmiel WWTP with low efficiency is planned to be exchanged in the near future, therefore higher efficiency rates of a modern CHP are assumed to better reflect the full benefits of enhanced biogas production on the energy balance.

1 Anaerobic biofilter: The biofilter is an anaerobic primary treatment and is fed with screened wastewater. In the lower part of the reactor sedimentation takes place, and in the upper part a polyfoam matrix immobilize the biomass. The biofilter replaces the conventional primary treatment of the WWTP and removes 55% of the total COD. Around 30% of the produced biogas is dissolved in the effluent and uncontrolled stripped in the biological stage.

2 Anaerobic biofilter + degasser: The second scenario is identical to the first scenario for the anaerobic biofilter implementation. To prevent loss of dissolved biogas with the effluent, a vacuum cascade stripper is integrated downstream of the biofilter. With this stripping unit, so that 85% of the dissolved biogas is removed and can be used in the CHP for energy recovery. Consequently, only 5% of the methane produced in the biofilter is lost.

Table 3-1: Scenarios for anaerobic primary treatment at WWTP Karmiel

Scenarios	Description	Remarks
0. Reference WWTP	Modified Karmiel WWTP	Primary settler: 35% COD removal, new CHP with higher efficiency
1. Anaerobic biofilter	Karmiel WWTP with anaerobic primary treatment	Primary treatment: 55% COD removal
2. Anaerobic biofilter + degasser	Karmiel WWTP with anaerobic primary treatment and degasser to remove dissolved biogas	Primary treatment: 55% COD removal

3.1.4 System boundaries

The system boundaries of this LCA are drafted in **Figure 3-1** and include all relevant processes at the WWTP for water and sludge treatment. The water treatment covers primary treatment (incl. grid), secondary treatment and a post-treatment with a sand filter and hypochlorite dosing. The treated effluent is directly used for unrestricted irrigation and the sand filter backwash water for restricted irrigation. Sludge treatment includes dewatering aggregates, anaerobic sludge treatment (digester + CHP), sludge transportation and agricultural sludge application and the avoided mineral fertilizer production. The production of electricity and the agricultural use of nutrients in the sludge are reflected by crediting the avoided impacts of conventional production routes. Additionally, system boundaries include background processes for production of electricity, additional chemicals, fuels, materials and infrastructure.

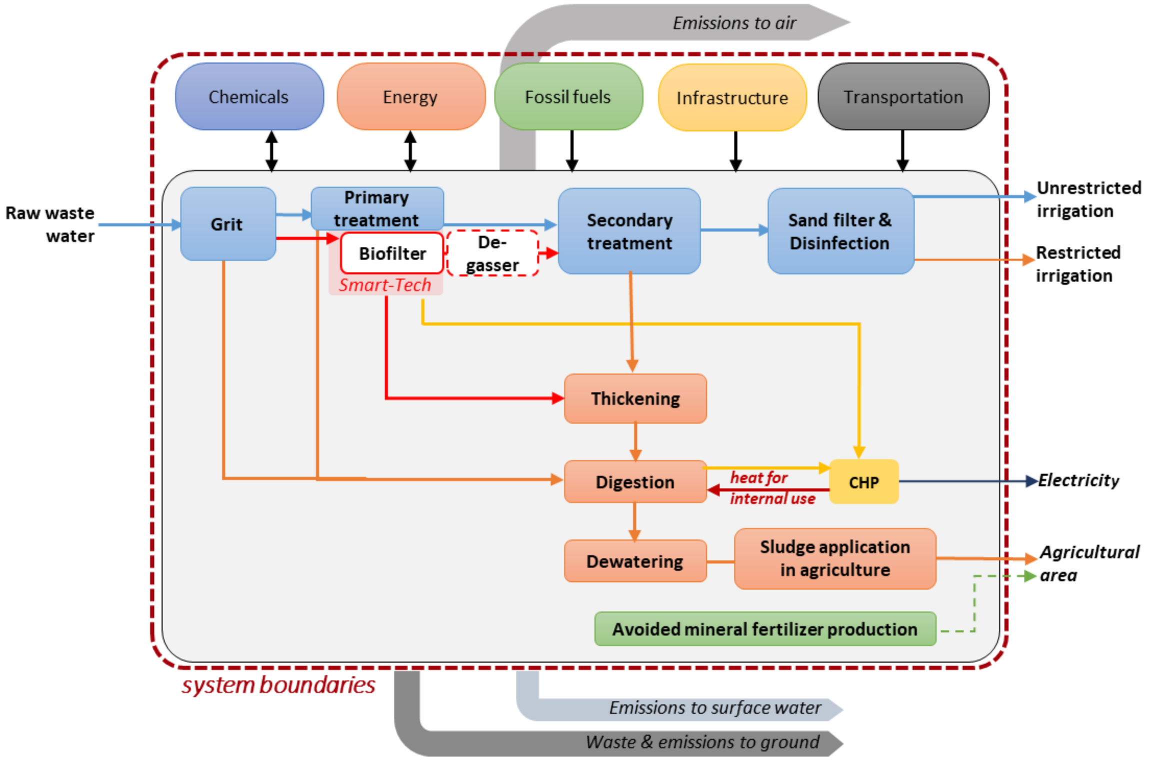

Figure 3-1: System boundaries of the LCA for anaerobic primary treatment

3.1.5 Data source and quality

Table 3-2 gives an overview of the data quality. The collection of input data for the anaerobic biofilter relies mainly on primary data collected from the pilot system operated in 2018. The data quality is assumed to be medium to high because the anaerobic filter has not been realized in full-scale yet, and the operation of the pilot plant was not always stable during the investigated period. Hence, up-scaling of process data from pilot installations to full-scale plants was required for the biofilter, which was done in close contact with the associated partners. The reference system was defined together with the National Water Company Mekorot. Transfer from site-specific process data to the defined conditions in the reference model was required to reflect the process performance in a “standard WWTP” (i.e. assuming only primary settler without existing aerated reservoir upstream). The data quality can be described as high for the reference WWTP because Mekorot has many years of experience in operating WWTPs. Downstream effects (biological treatment, sludge quantity, different biogas yields of primary sludge, biofilter sludge and secondary sludge) are estimated in close consultation with Mekorot and AgRobics. Nevertheless, for the downstream effects no primary or secondary data are available. Therefore, the data quality is assumed to be medium. Efficiency and energy demand of the degasser is estimated by KWB; therefore, the data quality is low.

Table 3-2: Data quality for LCA of anaerobic primary treatment

Process	Data source	Responsible partner	Data quality
WWTP Karmiel; influent, effluent, sludge, energy and chemical demand	Modified full-scale data of operator	Mekorot	High
Anaerobic biofilter	Pilot data (WP 3)	AgRobics	Medium to high
Downstream effects of anaerobic primary treatment	Estimations, experiments	Mekorot, AgRobics, KWB	Medium
Degasser	Estimations	KWB	Low

3.1.6 Indicators for impact assessment

The focus of this LCA study is on two specific environmental indicators: **primary non-renewable energy demand** and **greenhouse gas emissions**, because in the scenarios mainly the energy consumption/ production is modified. For primary energy demand, the indicator of cumulative energy demand (CED) for non-renewable fuels as defined in VDI 4600 (VDI 2012) is used. This indicator sums up fossil and nuclear fuels to a single score. For greenhouse gas emissions, factors of IPCC are used to calculate the global warming potential (GWP) for a time horizon of 100 years (IPCC 2014). Long-term emissions > 100 years are neglected.

Toxicity and eutrophication indicators are not seen as relevant for this study due to the focus on biogas production and energy-related issues. In addition, boundary conditions like WWTP effluent quality and emissions to air (other than greenhouse gas emissions) are defined as equal for all three scenarios.

3.2 Input data (Life Cycle Inventory)

This chapter serves to present and discuss the used input data, which is reference system, background processes, biogas quantity and their crediting for the LCA-model.

3.2.1 Input data for WWTP Karmiel

Data for the reference scenario has been collected and adapted from Mekorot and is given in **Table 3-3.**
The Karmiel WWTP has a capacity of 215,000 pe. Effluent quality shows a high removal of TSS (>99%) and COD (>95%) at the WWTP. The very high removal rate is due to the post-treatment (sand filter). The effluent is directly used for unrestricted irrigation, the sand filter backwash water (< 4% of influent) for restricted irrigation, and the dewatered sludge for agricultural application.

Direct gaseous emissions of the WWTP process are estimated to 0.19% of N input as N_2O based on a linear correlation between total N removal and N_2O emission factors (Parravicini et al., 2016).

Table 3-3: Relevant influent, return load and effluent quality parameters of WWTP Karmiel

Parameter	Unit	Influent of WWTP	Influent primary treatment (incl. return load)	Effluent of WWTP (tertiary treatment)	Return load	Sand filter backwash water[+]
Volume	m^3/d	10,137,128	10,768,127	9,725,740	578,616	405,000
TSS	g/m^3	490	580	4	2,000	520
Total COD	g/m^3	1,090	1,130*	47	3,300	242
Total N	g/m^3	83	86[#]	19	281	64
Total P	g/m^3	14	15[#]	2.5	64	32

**thereof 380 g/m³ dissolved COD,* [#] *data modelled,* [+]*for restricted irrigation*

3.2.2 Input data

Input material, electrical power requirements, heat, chemicals, changes in sludge quantity (estimated) and biogas yields (mainly estimated) are summarised in **Table 3-4**. Unless otherwise specified, the values refer to the input volume of the respective treatment step. The essential differences between the scenarios with biofilter and the reference scenario are briefly described below.

The biofilter produces 500 Nm^3 biogas/t metabolized COD. During the project it was monitored that on average 17 mg CH_4/ L (80% of the methane saturation concentration) are dissolved in the biofilter effluent and are assumed to be stripped to the atmosphere in the biological treatment step (see deliverable D4.1). Consequently, only 70% of the produced biogas from the biofilter can be used for energy production and 30% are lost to air, if no degasser after the biofilter is applied. According to the assumptions of degasser efficiency (85% recovery of dissolved gas), the degasser reduces the biogas loss from 30 to 5%.

The primary treatment with the biofilter removes 55% of COD and TSS. The primary sludge (PS) has a TSS content of 1.5%, so it has to be thickened to achieve a TSS content of 4% before being fed to the digester (see **Figure 3-1**). In addition, the anaerobic primary treatment with biofilter has some effects on the downstream biological stage and sludge treatment processes. Due to a reduced COD load, electricity savings of around 12% in the secondary treatment and an excess sludge volume reduction of 25% is assumed. In total, the sludge volume for thickening (more primary sludge, less excess sludge) and therefore the total electricity demand for dewatering and polymer demand is increased by 20%. The specific biogas yield per ton volatile solids (VS) of primary and secondary sludge is different. Therefore, in the LCA model, the total amount of biogas is calculated related to the proportion of primary and secondary sludge and the total amount of raw sludge. The specific biogas yield of the anaerobic primary sludge from biofilter is assumed as slightly lower than the referring biogas yield of the settled primary sludge in the reference case. The different biogas yields and the corresponding methane content are shown in **Table 3-4**.

Due to the reduced electricity demand of the scenarios with an anaerobic filter and a higher biogas recovery, the self-sufficiency increases from around 50 to 80%. Heat produced in CHP is used on-site for digester heating, but excess heat is not credited.
As a rough estimation for the additional infrastructure for a full-scale biofilter was made and includes 30 tons of stainless steel; 1 ton of reinforcing steel, 19 tons of concrete and 3 tons of PE. The corresponding lifetimes of the equipment are estimated to 25 years for concrete, 20 years for steel and 5 years for PE.

Table 3-4: Inventory for all scenarios of WWTP Karmiel

Parameter	Unit	0. Reference WWTP	1. Anaerobic biofilter	2. Anaerobic biofilter + degasser
Primary treatment		Grid& Primary settler	Grid&biofilter	Grid&biofilter
Electricity grid	kWh/m^3	0.02	0.02	0.02
Electricity PT	kWh/m^3	0.004	0.01	0.01
Biogas yield	Nm^3/t $COD_{metabolized}$	-	500 (72% CH4)	500 (72% CH4)
TS removal	%	50	55	55
COD removal	%	35	55*	55*
TN removal	%	12	12	12
TP removal	%	21	21	21
TS content of PS	%	4	1.5	1.5
Degasser				
Electricity	kWh/m^3	-	-	0.01
Efficiency of biogas recovery	%	-	-	85
Secondary treatment				
Electricity	kWh/m^3 WW	0.62 (Base)	- 0.55 (-12%)	- 0.55 (-12%)
TS of excess sludge	kg TSS/(pe*a)	17	13 (- 25%)	13 (- 25%)
COD removal	%	93	93	93
Sand filter				
Electricity	kWh/m^3 WW	0.05	0.05	0.05
Backwash water	% of inflow	4	4	4
Disinfection				
Electricity	kWh/m^3 WW	0.01	0.01	0.01
NaOCl (100%)	mg/ L	5	5	5
Thickening of excess and biofilter sludge				
Electricity	kWh/m^3 sludge	1	1	1
Polymer	g/kg TSS	5.5	5.5	5.5
Digestion				
TS of raw sludge (PS+SS)	kg TSS/(pe*a)	31	27 (- 12%)	27 (- 12%)
Electricity	kWh/m^3 sludge	4.8	4.8	4.8
Heat	MJ/m^3 sludge	0	0	0
Biogas yield PS/ biofilter	Nm^3/t VS_{in}	571 (70% CH_4)	500 (70% CH_4)	500 (70% CH_4)
Biogas yield SS	Nm^3/t VS_{in}	333 (60% CH_4)	333 (60% CH_4)	333 (60% CH_4)
Dewatering DS				
Electricity	kWh/m^3 sludge	3	3	3
Polymer	g/kg TSS	9	9	9
Cogeneration (CHP)				
Electrical efficiency	%	38	38	38
Electrical self-sufficiency	%	54	81	80
Heat credit	MJ/Nm^3 biogas	0	0	0
Transportation				
Transportation of sludge to agriculture	km	50	50	50

** thereof 20% are converted to biogas*

3.2.3 COD balance and related methane production

Biogas production takes place in the digester and in the biofilter. With the implementation of the biofilter the primary and excess sludge amount, the related COD load and the corresponding biogas yields in the digester is decreased. Overall, this leads to a lower biogas/methane production in the digester. **Table 3-5** gives an overview of the modelled COD loads to digester and biofilter and the corresponding methane production. For methane production in the **digester**, specific methane yields are assumed and are given in **Table 3-4**.

Overall, implementation of the biofilter leads to a reduction of 16% of biogas production in the digester, mainly due to the lower specific yield of the primary sludge from this system. In the **biofilter,** a methane yield of 350 Nm^3/t COD metabolized is estimated. The biofilter produces the biogas to around 50% from dissolved COD and 50% from particulate COD. The COD load is modelled on basis of sludge data presented in **Table 3-5**. Over the whole system the anaerobic primary treatment leads to an additional methane production of +18% (scenario 1) and +23% if a degasser is applied to recover the dissolved biogas (scenario 2).

Table 3-5: COD load and methane production in digester and biofilter

Input	**0. Reference WWTP**		**1. Anaerobic biofilter** **2. Anaerobic biofilter + degasser**		**Change to reference**	
	COD_{in} (t/a)	Methane (Nm^3/a)	COD_{in} (t/a)	Methane (Nm^3/a)	COD (%)	Methane (%)
Digester						
Grit + Primary Sludge*	4,272	1,220,000	4,336	1,072,000	+1.5%	- 11.5%
Excess Sludge	2,680	382,000	1,950	278,000	- 27%	- 27%
Total	6,950	1,602,000	6,286	1,350,000	- 10%	-16%
Anaerobic biofilter						
Raw wastewater	-	-	12,110[#]	780,000°	-	+100%
Atmospheric losses of methane				1. 234,000 2. 35,100		
Total methane to CHP	**-**	**1,602,000**	**-**	1.**1,897,000** 2. **2,093,000**	**-**	**+ 18%** **+ 23%**

**Note: Primary sludge of primary settler and anaerobic reactor has different methane yields (see Table 3-4)*

[#] *2,230 t COD are metabolized in biofilter, thereof 1,100 t dissolved COD*

° *Thereof, 30% of the methane is dissolved in the effluent*

3.2.4 Background data

Background processes are modelled with datasets from ecoinvent database v3.4 (Ecoinvent, 2017). The related datasets are shown in **Table 3-6**. The market mixes refer to the global market [GLO] or European market [RER]. For electricity, the market mix of Israel is applied.

Table 3-6: Datasets for background data

Process	**Dataset from ecoinvent v3.4**	**Remarks**
Electricity	market for electricity, medium voltage [IL]	For all operational electricity demand and credits from biogas
Hypochlorite	market for sodium hypochlorite, without water, in 15% solution state [GLO]	Disinfection of effluent
Polymer	market for acrylonitrile [GLO]	746 g acrylonitrile + water = 1kg of polymer active substance

Truck transport	transport, freight, lorry 16-32 metric ton, EURO5 [RER]	50 km for sludge to application in agriculture
Nitrogen	diammonium phosphate, as N, at regional storehouse [RER]	Fertilizer credit for N in sludge in agriculture
Phosphate	market for phosphate fertiliser, as P2O5 [GLO]	Fertilizer credit for P in sludge in agriculture
Concrete	market for concrete [RoW]	Infrastructure material for biofilter foundation
Stainless steel	steel production, electric, chromium steel 18/8 [RoW]	Infrastructure material for biofilter
PE	polyethylene production, low density, granulate [RER]	Infrastructure material for growth bodies in biofilter

3.3 Results of environmental indicators (Life Cycle Impact Assessment)

The total results of this LCA are presented below, reflecting the selected LCA indicators CED and GWP. In addition, the environmental impacts of biofilter implementation are quantified in relation to the reference scenario "Reference WWTP", showing only the changes in environmental impact due to the new system configuration.

Cumulative energy demand of non-renewable resources (CED)

As seen in **Figure 3-2**, the electricity consumption of the WWTP and the CHP credit for biogas production determine the results of this indicator. Chemical consumption, transportation and credits for nutrients play a minor role. The reference net CED accounts for nearly 250 MJ/(pe*a), which results from a gross CED of 600 MJ/(pe*a) and credits of 350 MJ/(pe*a). The implementation of a biofilter (Scenario 1) reduces the total electricity consumption of the WWTP by around 21% and increases the biogas production and related electricity credits by 18%. This leads to a net CED of 64 MJ/(pe*a), reducing the net impact of the WWTP by 74%.

By installing a degasser after the biofilter (scenario 2), the electricity production can be increased by+23%or +38 MJ/(pe*a) compared to the reference scenario. At the same time the CED is increased by 54 MJ/(pe*a) to operate the degasser, which leads to a net CED of 80 MJ/(pe*a). Overall, for this indicator, the increased CHP credit due to higher biogas recovery after the biofilter does not off-set the additional electricity needed for the degasser.

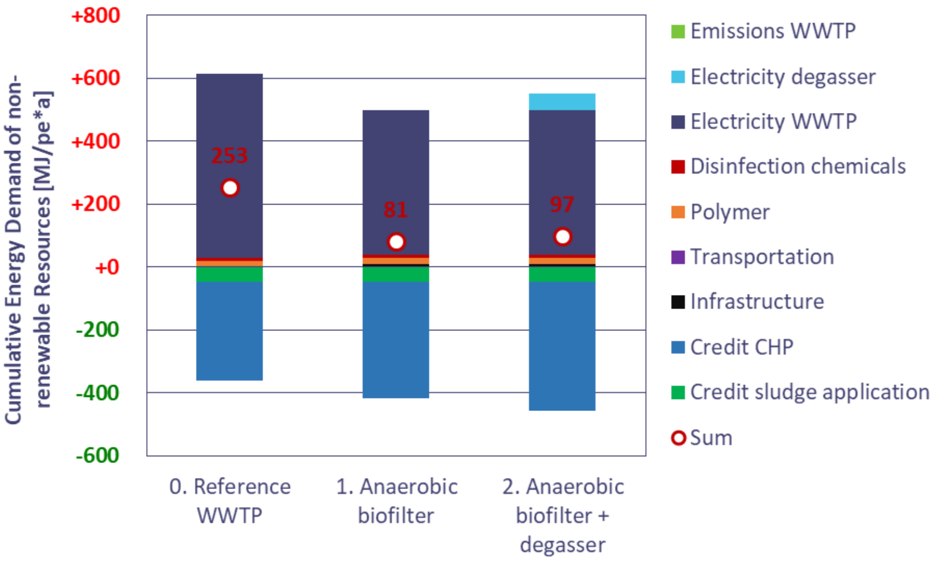

Figure 3-2: Cumulative energy demand for WWTP Karmiel for reference and biofilter scenarios

Relative changes of – 172 MJ/(pe*a) and -156 MJ/(pe*a) can be observed if a biofilter is applied (see **Figure 3-3**). The benefit in CED is determined by the additional amount of biogas, but also to a substantial part by energy savings at the wastewater treatment plant. The electricity demand of the degasser (scenario 2) is higher than the total credits for energy savings in the WWTP and due to additional produced biogas.
All other consumer goods (for example chemicals, polymer) hardly change with biofilter implementation. The anaerobic reactor generates a very small additional credit for sludge application (+5%), which can be explained by the slightly higher N load in the sewage sludge. This is because more N is drawn off via the sludge in the primary treatment and thus bypasses nitrification/denitrification. The polymer demand for thickening and dewatering decreases by around 6%, but this has no relevant impact on the overall CED (- 1%).

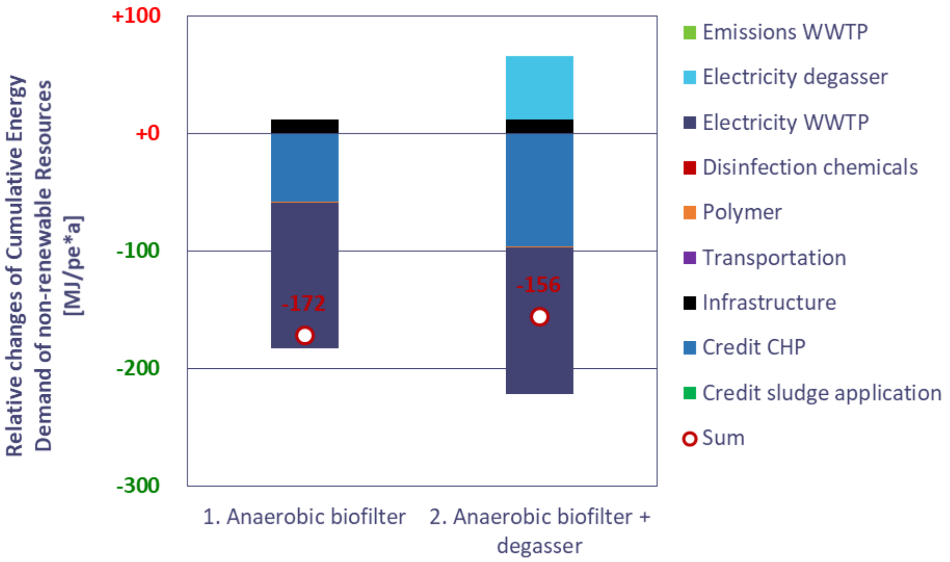

Figure 3-3: Relative changes of total cumulative energy demand due to the implementation of a biofilter

Global warming potential (GWP)
The results of the indicator GWP of the LCA differ from the results of the CED (see **Figure 3-4**).
The total net GWP of the reference WWTP amounts to 32 kg CO_2-eq/(pe*a), which results of 58 kg CO_2-eq/(pe*a) gross impacts and -26 kg CO_2-eq/(pe*a) gross savings. The main drivers of the impacts are direct emissions of WWTP (14 kg CO_2-eq/(pe*a)) and the electricity demand of the WWTP (43kg CO_2-eq/(pe*a)). The direct emissions consist to over 90% of N_2O emissions and originate from the biological stage (>12 kg CO_2-eq/(pe*a)).

The implementation of a biofilter (scenario 1) increases the total net GWP by 34% despite. the higher credits for biogas production (+18%) and the lower electricity demand of the WWTP (-20%) compared to the reference scenario. This is due to the higher direct emissions of methane at the WWTP, which have a share of 52% (37 kg CO_2-eq/(pe*a) of the total GWP impacts. The increase of the direct emissions is due to the dissolved methane in the biofilter effluent, which strips uncontrolled in the biological stage during aeration. The dissolved methane can be reduced by installing a degasser in scenario 2, removing 85% of the methane from the biofilter effluent and supplying it to the CHP. Consequently, a degasser reduces the net GWP of direct WWTP emissions by 54% to 17 kg CO_2-eq/(pe*a) and increases the CHP credits by 9%. These positive effects are slightly diminished by the additional electricity demand of a degasser (+ 4 kg CO_2-eq/(pe*a), but overall the degasser has a highly beneficial impact on the GWP of the process.

Overall, the implementation of an anaerobic biofilter increases the GWP from 32 kg CO_2-eq/(pe*a) to 44 kg CO_2-eq/(pe*a) (+37%) and the implementation of a biofilter with a degasser reduces the GWP to 25kg CO_2-eq/(pe*a) (- 22%). This underlines the importance of installing a recovery unit for the high amount of dissolved methane that leaves the biofilter with the effluent, which is not only lost for energy production, but will also be emitted as highly potent greenhouse gas in the downstream WWTP.

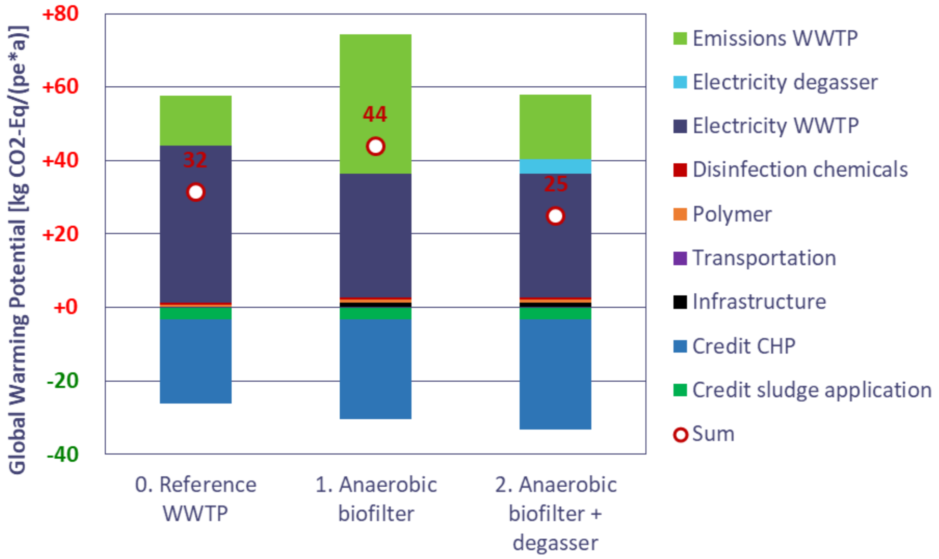

Figure 3-4: Global Warming Potential for WWTP Karmiel with and without anaerobic primary treatment

Figure 3-5 shows again the main effect on the GWP. If a biofilter is installed without a degasser, the increased CHP credits and energy savings at the WWTP do not off-set the impacts due to dissolved methane in the biofilter effluent and lead to additional +12 kg CO_2-eq/(pe*a). If a degasser is applied, the CHP credit increases again (+9%) and the WWTP emission are reduced by 85% compared to the scenario without degasser. Thus, the net GWP can be reduced by -7 kg CO_2-eq/(pe*a) compared to the reference WWTP.

Similar to the CED and valid for all scenarios, chemicals for disinfection, polymer demand, transportation and infrastructure have no relevant effect on the total gross GWP (< 7%).

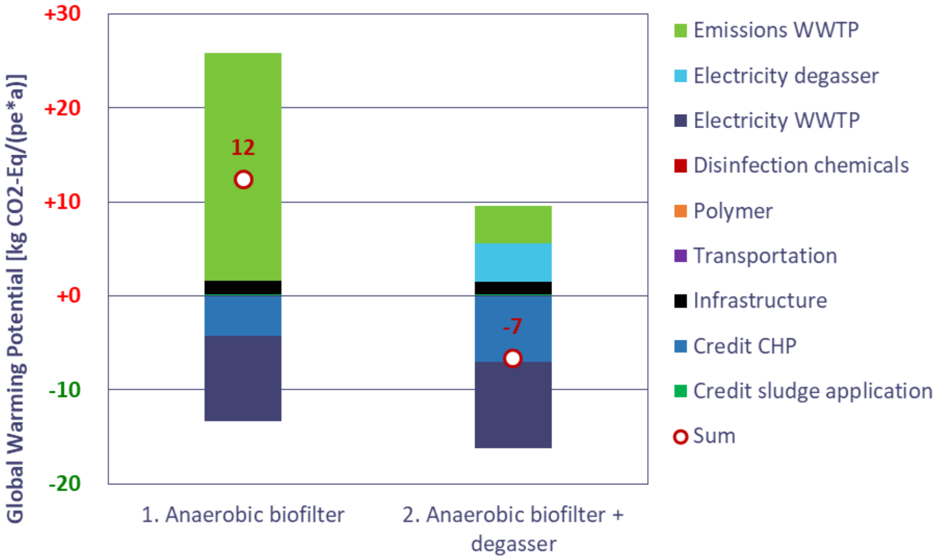

Figure 3-5: Relative changes of Global Warming Potential due to the implementation of a biofilter

3.4 Interpretation and conclusions

The LCA illustrates all direct and indirect impact of implementing an anaerobic biofilter at WWTP Karmiel and show its environmental effects on energy demand and GHG emissions. The replacement of a standard preliminary treatment by an anaerobic primary treatment is associated with environmental benefits, but also with drawbacks if a biofilter is implemented without degasser.

The outcomes of the two main energy demand and GHG emissions are shown in **Table 3-7** and can be summarized as follows:

- A biofilter without degasser (scenario 1) reduces the electricity consumption of the WWTP by -21% (mainly savings in aeration energy) and increases the biogas production by +18% (stand-alone biofilter). This leads to an overall CED reduction of -68%.
- On the other hand, a biofilter without degasser increases the net GWP by +37%, mainly because 30% of the produced methane remains dissolved in the biofilter effluent and is stripped uncontrolled in the secondary treatment.
- Implementing a degasser, the CED decreases by -62% compared to the reference WWTP and increases the CED by +6% compared to a stand-alone biofilter due to the electricity consumption of the degasser.
- The combination of a degasser + biofilter decreases the GWP by -22% compared to a standard WWTP.

Table 3-7: Summary of methane production and LCA results for anaerobic biofilter at WWTP Karmiel (215,000 pe)

Parameter	Unit	0. Reference WWTP	1. Anaerobic biofilter	2. Anaerobic biofilter + degasser
Methane production	Nm^3/a	1,602,000	2,131,000 **(+25%)**	
Methane to CHP	Nm^3/a		1,897,000 **(+18%)**	2,093,000**(+23%)**
Methane losses	Nm^3/a	-	252,000	38,000
Energy demand	MJ/(pe*a)	253	81 **(-68%)**	97 **(-62%)**
GHG emissions	kg CO_2-eq./(pe*a)	32	44 **(+37%)**	25 **(-22%)**

It can be summarized that a biofilter improves the energetic self-sufficiency of a WWTP. However, the total GHG emissions are increased by an anaerobic pre-treatment due to additional methane emissions. A degasser capturing the dissolved methane reduces the total GHG emissions compared to a conventional WWTP and should thus be an obligatory part of this system.

Limitations and transferability of the case study results to other WWTPs

Summarizing the LCA results, an anaerobic biofilter as primary treatment has a positive environmental impact at WWTP Karmiel, if an additional degasser is installed. However, an anaerobic primary treatment has downstream effects on the biogas yields of primary and excess sludge, as well as on the biological stage (energy consumption, sludge volume etc.). These relevant downstream effects have been estimated in this LCA carefully but could not be proved. Therefore, there are high uncertainties for the estimated downstream effects on the Karmiel WWTP.

For transferring the technology and the LCA to other WWTPs and boundary conditions, the following aspects should be considered:

- The anaerobic biofilter was tested in Israel, which has an annual average air temperature of around 20 °C. A stable operation in a country with lower temperatures cannot be ensured, as kinetics of anaerobic processes are known to be negatively affected by temperature.
- The efficiency and electricity consumption of the degasser is based on estimations. Therefore, the results for scenario 3 can vary widely and should be updated with full-scale data from practise.
- Biogas produced in the biofilter from dissolved COD adds-up as “additional biogas” for the new concept and saves aeration energy in the activated sludge stage due to a reduced dissolved COD load. In the Karmiel biofilter ca. 50% of the COD converted to biogas in the biofilter is dissolved. If the biogas is produced from settled particulate COD, this COD is missing in the primary sludge, which would be converted to biogas in the conventional digester. In this study, 50% of biogas potential in the biofilter is from settled particulate COD and is consequently shifted from primary sludge/digestor to the biofilter. Biogas from particulate settled COD does not add up as “additional biogas” for the whole system.
- The WWTP influent in Karmiel has an above average COD concentration of 1,090 g COD/m^3, corresponding to a high COD/N ratio of 13. If the technology is transferred to a WWTP with lower COD inflow concentration and lower COD/N ratio, a lack of COD for denitrification can occur when an anaerobic pre-treatment is installed.

4. LCA OF MAINSTREAM BIOPOLYMER AND STRUVITE RECOVERY (SMARTECH 2B + DOWNSTREAM SMARTECH A)

In conventional wastewater treatment plants, the incoming organic load is to a large extent converted into CO_2 by biological activity, often using the activated sludge process for removal of dissolved organic matter. Apart from primary and excess sludge which can be used for biogas production, the chemical and energetic potential of the incoming organic matter is basically destroyed at the expense of considerable energy input, mainly for aeration of the activated sludge. Finally, this concept for wastewater treatment is following the linear approach of “waste disposal” by eliminating pollutants from the water and minimising any residuals for final disposal.

However, new concepts and processes for wastewater treatment have been developed in recent years which try to exploit the chemical and/or energetic potential of the organic matter in a better way, moving towards a “circular economy” concept for the wastewater treatment plants of the future. One of these concepts is based on the microbial conversion of influent organic matter into valuable organic products such as poly-hydroxy-alkanoate (PHA), a family of biodegradable bioplastic compounds which can be used for a variety of applications. This can be realized with a process configuration called SCEPPHAR (“Short-Cut Enhanced Phosphorus and PHA Recovery”) which was originally developed to treat high-strength streams such as sludge liquor from dewatering, using a carbon source to maximize PHA production (Frison et al., 2015). Meanwhile, it has been tested and applied also for the treatment of raw municipal wastewater in the mainline (Basset et al., 2016; Larriba et al., 2020).

Within the SMART-PLANT project, the application of the SCEPPHAR process for mainstream wastewater treatment is further optimized and demonstrated in pilot-scale (SMARTech 2b). The process includes two sequencing batch reactors (SBR), an interchange vessel and a chemical system for P precipitation as struvite. In the first SBR, heterotrophic biomass is operated under an anaerobic/anoxic/aerobic sequence, while the second SBR is devoted to autotrophic nitritation. At the end of the anaerobic cycle of the heterotrophic SBR, P-rich wastewater is extracted to precipitate P as struvite for P recovery. Anaerobic excess sludge wasted from the heterotrophic SBR contains a high fraction of PHA, which can then be processed further as a source material for bioplastic production (Larriba et al., 2020).

This LCA investigates the potential of the SCEPPHAR process for mainline treatment of municipal wastewater after primary settling. Besides the removal of organic matter and nutrients from wastewater, the process produces both struvite as a P fertilizer and a PHA-rich sludge for further processing into bioplastic applications. As a downstream treatment for this sludge, the extraction and purification of PHA from the excess sludge into a powder is also demonstrated within SMART-PLANT in lab scale (Downstream SMARTech A), and this extraction step is integrated into the LCA of the system. The case study is based on the data of WWTP Manresa (ES) where the demonstration unit of SCEPPHAR has been operated. In its current configuration serving as a reference for the LCA, the WWTP Manresa is equipped with primary settling and conventional biological treatment to remove BOD, N and P. Primary and excess sludge is anaerobically digested with on-site valorisation of biogas in a CHP unit, and the dewatered sludge is sent to agriculture for final disposal.

During the demonstration phase of SCEPPHAR, the low strength of influent wastewater after primary treatment with regard to soluble COD posed significant challenges for a successful operation of the process, especially concerning the enrichment of PHA in the excess sludge of the system. In addition, conclusive monitoring of N_2O emissions during the nitritation phase has been affected by operational difficulties and process disturbance. Finally, this LCA analyses a projected full-scale design and performance of the SCEPPHAR process based on pilot results and complemented by best estimates for some process parameters. For PHA valorisation, different routes are analysed, namely a) the use of PHA-rich sludge for biogas production, b) the direct use of dried PHA-rich sludge as an input material for bioplastics, and c) the extraction of PHA from sludge and its use as a powder ingredient for bioplastic formulations. For the latter scenario, inventory data for the LCA is based on lab and small pilot trials for PHA extraction with actual PHA-rich sludge carried out within SMART-PLANT.

4.1 Goal and scope definition

4.1.1 Goal of the study

The goal of this LCA is to calculate the potential environmental impacts of the annual operation of WWTP Manresa (ES), comparing the current operation using conventional treatment with different configurations of the SCEPPHAR system. All direct and indirect effects of changing the WWTP design into a SCEPPHAR system will be quantified in the life cycle, focussing on primary energy demand and GHG emissions as major environmental impacts, but also assessing water quality impacts on freshwater and marine eutrophication. The LCA includes the valorisation of PHA-rich sludge in different routes.

The target group of this LCA are mainly WWTP experts, planners and practitioners which should be informed about the holistic environmental impacts of a mainstream SCEPPHAR system compared to a conventional WWTP.

4.1.2 Function and functional unit

The primary function of the system under study is the treatment of municipal wastewater to defined local standards, including the final disposal of sewage sludge. Consequently, the functional unit is defined as "treatment of municipal wastewater per population equivalent (pe) and year" or $[pe*a]^{-1}$. WWTP Manresa currently treats raw wastewater with a load of 109.000 pe based on a daily COD load of 120 g/pe. All direct and indirect impacts of the system are related to this functional unit. As a secondary function, some scenarios recover struvite and/or PHA-rich sludge as a valuable material which is further processed and valorised downstream. This function is accounted by crediting the avoided primary products to the system.

4.1.3 Scenarios

Four scenarios have been defined for this LCA, as listed in **Table 4-1** below. In detail, the scenarios can be described as follows:

0 Baseline: this scenario reflects the current situation at WWTP Manresa, using operational data of 2016. After mechanical pre-treatment, the plant consists of primary settlers, activated sludge tanks with anoxic and aerobic zones (Modified Ludzack-Ettinger configuration), and final clarifiers. Nitrogen is removed by conventional nitrification/denitrification, while phosphorus is removed mainly by chemical precipitation with Fe/Al salts. Raw sludge is thickened by gravity (primary sludge) or with flotation (waste activated sludge), before it is digested in mesophilic reactors. Digested sludge is dewatered in belt filters before final disposal in agriculture. Biogas is valorised on-site in CHP plants to produce electricity and heat for internal use. Excess heat beyond the internal demand is not further valorised and thus not accounted in this LCA.

1 SCEPPHAR + PHA for biogas: this scenario represents the implementation of a SCEPPHAR system for mainstream wastewater treatment after primary settling. It includes the production of struvite for P recovery and the use of PHA-rich excess sludge in digestion for biogas production together with primary sludge.

2 SCEPPHAR + dried PHA sludge: comparable to scenario 1, SCEPPHAR is implemented after primary settling for mainstream wastewater treatment, and struvite is recovered. PHA-rich excess sludge from the system is dewatered, dried and directly applied as a bioplastic raw material (e.g. for the production of bio-composites). Primary sludge is digested on-site for biogas production and valorisation in the CHP plant.

3 SCEPPHAR + PHA extraction: this scenario also includes the SCEPPHAR system for mainstream treatment after primary settling and struvite recovery. Here, the PHA-rich sludge is dewatered and then sent to chemical PHA extraction to produce a purified PHA powder. This product can then substitute alternative bioplastics in different grades depending on the final purity of the PHA product.

Table 4-1: Scenarios for SCEPPHAR implementation at WWTP Manresa (see text for details)

Scenario	Description	Remarks
0 Baseline	WWTP Manresa	Data of 2016
1 SCEPPHAR + PHA for biogas	SCEPPHAR for mainstream treatment after primary settling, production of struvite and PHA-rich sludge, use of PHA-rich sludge for biogas production	PHA-rich sludge is digested on-site together with primary sludge
2 SCEPPHAR + dried PHA sludge	SCEPPHAR for mainstream treatment after primary settling, production of struvite and PHA-rich sludge, direct use of dried PHA sludge	Assumption: dried PHA sludge is suitable for direct use (e.g. in bio-composite production)
3 SCEPPHAR + PHA extraction	SCEPPHAR for mainstream treatment after primary settling, production of struvite and PHA-rich sludge, chemical extraction of PHA from sludge	PHA powder can substitute PHA from pure culture

4.1.4 System boundaries

The system boundaries of this LCA cover all relevant processes for water and sludge treatment at WWTP Manresa, including sludge treatment with digestion, dewatering and final disposal, and the different valorisation routes for PHA-rich sludge (**Figure 4-1**). For drying of PHA-rich sludge, available off-gas heat from CHP plant is used and complemented with natural gas. For PHA extraction, chemical treatment of PHA-rich sludge, drying, and waste disposal of residual sludge is accounted. Basic infrastructure material is included for SCEPPHAR reactors, while all other infrastructure is neglected (i.e. existing WWTP, PHA valorisation). Products such as electricity from CHP plants, nutrients in disposed sludge, struvite, and PHA are credited by avoided impacts of primary products ("avoided-burden approach") such as grid electricity, mineral N and P fertilizer, and pure-culture PHA from refined sugars.

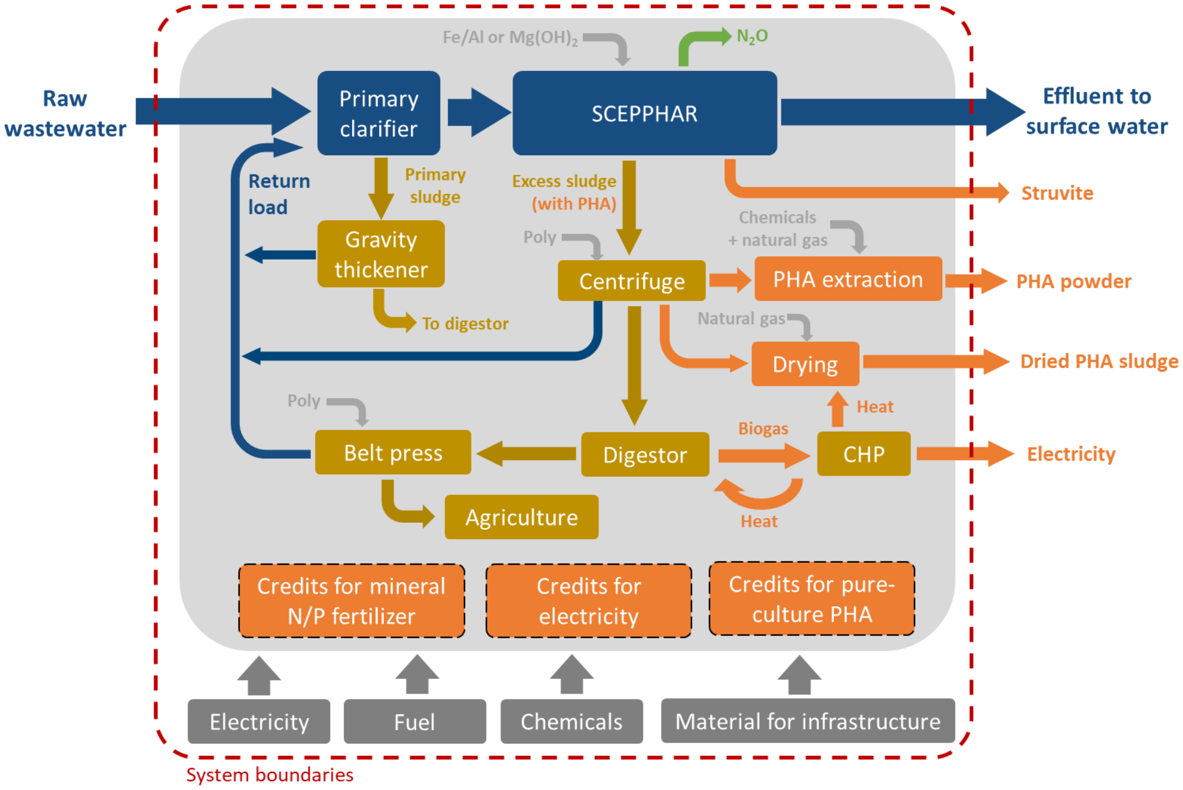

Figure 4-1: System boundaries of LCA study for mainstream SCEPPHAR and PHA valorisation at WWTP Manresa

4.1.5 Data sources and quality

Input data for the baseline operation of WWTP Manresa is collected from operator Aigües de Manresa based on a full dataset collected for an energy audit in the EU-H2020 project POWERSTEP. This dataset represents full-scale operational data of the year 2016 for electricity and chemicals demand, closed mass balances of water and sludge treatment, and related influent and effluent quality. For sludge disposal in agriculture, data for nutrient credits has been estimated based on available literature.
For the performance of the SCEPPHAR system in terms of effluent quality, electricity and chemicals demand, and product yield, data has been provided by UAB based on experience from the SCEPPHAR pilot plant and estimated mass balances in relation to the baseline scenario. N_2O emission factors for conventional and SCEPPHAR treatment are based on results of monitoring campaigns at the site (see D4.1) and other SMART case studies of short-cut N removal processes. Data for PHA extraction has been provided by Biotrend and is based on extrapolation of lab-scale trials into full-scale design.

Overall, data quality of this LCA can be described as high for the baseline data, and medium for the SCEPPHAR system and the PHA extraction (**Table 4-2**). Reference data for the baseline scenario is collected and checked by operators and fully represents the mean situation at the plant. SCEPPHAR performance is based on pilot trials, although difficulties during pilot operation required some extrapolation and estimate of UAB for projecting full-scale data (e.g. PHA yield, electricity demand). Some uncertainty is also related to the N_2O emission factors both for the baseline and for SCEPPHAR and how these compare to each other, which has to be taken into account during interpretation of results. Drying of PHA sludge is estimated based on commercial data of large-scale dryers. Data for PHA extraction is taken from lab-scale and small-scale pilot trials extrapolated to full-scale with the experience of Biotrend. Overall, data quality is quite sufficient for a prospective LCA to show the potential environmental impacts of SCEPPHAR implementation at WWTP Manresa, but underlying assumptions and their impact on the validity of the outcomes should be clearly communicated with the LCA results.

Table 4-2: Data quality for LCA of SCEPPHAR mainstream treatment and PHA valorisation at WWTP Manresa

Process	Data source	Responsible partner	Data quality
WWTP Manresa: influent + effluent, sludge treatment, energy and chemicals demand, biogas production, CHP plants	Full-scale data of operator	AdM + KWB	High
Sludge disposal in agriculture	Literature	KWB	Medium - high
SCEPPHAR performance, electricity and chemical demand, product yield	Pilot data (WP3) with extrapolation	UAB	Medium - high
N_2O emission factors	Mainline: estimate SCEPPHAR: monitoring results + expert judgement	UAB + KWB	Medium
Drying of PHA-rich sludge	Estimate based on commercial dryer data	UAB	High
PHA extraction	Extrapolation from lab and small pilot trials	Biotrend	Medium

4.1.6 Indicators for impact assessment

This study focusses on four specific environmental impacts: primary energy demand, greenhouse gas emissions, and freshwater and marine eutrophication.

- For primary energy demand, the indicator of cumulative energy demand (CED) for non-renewable fuels as defined in VDI 4600 (VDI, 2012) is used, adding up fossil and nuclear fuels to a single score.
- For greenhouse gas emissions, factors of IPCC are used to calculate the global warming potential (GWP) for a time horizon of 100 years (IPCC, 2014). Long-term emissions > 100a are neglected.

- For water quality impacts, the indicators of freshwater eutrophication potential (FEP) and marine eutrophication potential (MEP) are applied at midpoint level (Hierarchist perspective) as defined in the ReCiPe method (Huijbregts et al., 2017). These indicators account for phosphorus (FEP) and nitrogen (MEP) emissions into the aquatic environment, reflecting the impact of effluent quality from WWTP Manresa on receiving waters.

4.2 Input data (Life Cycle Inventory)

4.2.1 Data of WWTP Manresa

Detailed data for influent and effluent volume and quality, full mass balances for each stage, and demand of electricity, heat, and chemicals for WWTP operation was adopted from a previous EU H2020 project POWERSTEP. This project carried out a full energy audit using the commercial software OCEAN (Veolia), and the collected data was transferred to SMART-PLANT upon confirmation by the operator Aigues de Manresa. The data relates to operational data of WWTP Manresa for the year 2016. For the sludge disposal route (application to farmland), data has been compiled from available literature.

Mass flow data for water and sludge line of WWTP Manresa

Relevant annual mean data for volume, TSS, COD, and total nitrogen for WWTP influent and effluent is reported in **Table 4-3** below. The annual COD influent load amounts to 4,785 t/a, which corresponds to around 109,000 pe when assuming a daily COD load of 120 g/pe (ATV, 2000), confirming the number defined for the functional unit. Effluent quality shows a high removal of TSS (>97%), COD (>94%), TN (78%), and TP (>87%) at the WWTP. Return load from sludge thickening and dewatering adds around 10% of TN load and 19% of TP load to the influent WWTP per year.

Direct gaseous emissions of the activated sludge tank are estimated to 0.75% of N eliminated as N_2O based on literature (Vasilaki et al., 2019), as no monitoring data for the plant is available .

Table 4-3: Input data for WWTP Manresa: influent and effluent quality and return load with sludge liquor

Parameter	*Unit*	Influent of WWTP	Effluent of WWTP	Sludge liquor from thickening		Sludge liquor from dewatering
				Primary sludge	*Excess sludge*	
Volume	*m^3/d*	22,587	22,576	589	421	177
Susp. solids	*g/m^3*	276	8	348*	150*	2,795*
COD	*g/m^3*	580	33	675	143	3,077
Total N	*g/m^3*	53	11.7	56.8	16	427
Total P	*g/m^3*	6.5	0.8	7.8	6	119

**calculated*

Raw primary sludge is thickened by gravity to 4.1% DM, while excess sludge is thickened with flotation to 3.3% DM. Final mixed sludge to digestion has around 3.7% DM (**Table 4-4**). Biogas production amounts to 328 NL/kg VS_{in} or a total of 579,000 Nm^3 per year, assuming a VS reduction of 40% and a methane content of 60.2 Vol-%. 79% of the biogas is fed to the CHP unit to produce electricity (642 MWh/a) and heat, while the remaining biogas is used in a heater to cover the relatively high heat demand of the digestor (not insulated).

After digestion, digested sludge is dewatered to 17.6% DM in centrifuges.

Sludge disposal in agriculture

Dewatered sludge is transported to agriculture for final disposal (estimate: 20 km via truck), accounting for some substitution of nitrogen and phosphorus mineral fertilizer with 25% of N and 60% of P content in sludge.

Table 4-4: Input data for WWTP Manresa: primary and excess sludge, mixed sludge to digestion, and dewatered sludge for disposal

Parameter	*Unit*	Primary sludge to thickening	Excess sludge to thickening	Mixed sludge to digestor	Dewatered sludge to disposal
Mass	*t/d*	684	514	189	26
Dry matter	*% DM*	0.6	0.62	3.7	17.6
Volatile solids	*% of DM*	76	56	69	57
Total nitrogen	*% of DM*	3.9	3.2	3.2	2.9
Total phosphorus	*% of DM*	0.9	3.8	2.2	2.8

Electricity and chemicals demand
Total electricity demand for WWTP operation amounts to 3,573 MWh/a or 0.43 kWh/m³ influent. This gross electricity demand is attributed to the different stages of water and sludge treatment according to energy data from the audit software to be able to track any changes related to implementation of the SCEPPHAR process. In particular, 73% of total electricity demand (0.31 kWh/m³) is attributed to the activated sludge process, mainly for aeration. The remaining electricity demand is distributed in the model to other aggregates (primary treatment, thickening, digestion, dewatering) based on typical specific values of medium-sized WWTPs.

For chemical demand, the LCA takes into account polyelectrolyte used for thickening and dewatering, and also metal salts for precipitating of phosphorus ($FeCl_3$, polyaluminium chloride (PACl)). Based on available data, polymer demand as active matter is determined to 0.28 kg/t DM for excess sludge thickening and 4.7 kg/t DM for dewatering of digested sludge. Fe salt is dosed with 0.76 mol Fe/mol P in the inlet of the activated sludge tank, while PACl is dosed seasonally with a mean dose of 0.39 mol Al/mol P. Overall, the annual demand of chemicals add up to 8.3 t polyelectrolyte (as active matter), 503 t $FeCl_3$ solution (13% Fe), and 353 t PACl solution (5% Al). Any other chemicals for WWTP operation are not considered in this study.

4.2.2 Data for SCEPPHAR system

Data for the SCEPPHAR system is delivered by UAB based on long-term pilot trials at WWTP Manresa and related modelling. As the pilot trials posed some difficulties for valid assessment of full-scale mass balances and energy data of the process, SCEPPHAR data has to be interpreted with care. In particular, COD content of primary settled wastewater was too low during most of the pilot trials to enrich PHA in the excess sludge as planned. Hence, some estimates are taken by UAB to reflect projected conditions of the process for a full-scale installation at WWTP Manresa.

Performance and energy/chemicals demand of SCEPPHAR system
SCEPPHAR pilot trials at WWTP Manresa demonstrated a good removal for COD, TN, and TP removal, which is fully comparable with the existing WWTP process (**Table 4-5**). Hence, effluent quality is assumed to be equal to the baseline scenario for all three parameters. N_2O emissions are set to 1.0% N_2O of N eliminated for all SCEPPHAR scenarios based on data of UAB from N_2O monitoring (see D4.1) and expert judgement, predicting an increase of 33% compared to the N_2O emission factor for the baseline. Electricity demand of the entire SCEPPHAR process is assumed to increase by 24% to 0.39 kWh/m³ compared to the existing activated sludge process (0.31 kWh/m³). For struvite precipitation, 1.07 mol Mg is dosed per mol P eliminated in struvite, amounting to 40 t per year of $Mg(OH)_2$.

Products of SCEPPHAR system: struvite and PHA-rich excess sludge
Based on pilot trials, 45% of eliminated phosphorus can be extracted as struvite, amounting to 157 t pure struvite (MAP) per year (**Table 4-5**). For PHA-rich excess sludge, it is assumed that the total amount of excess sludge as dry matter will not change compared to the baseline. However, due to the higher amount of organics in the sludge, the VS content increases from 56% VS (baseline) to 80% VS (SCEPPHAR). Based on the projected enrichment of PHA in the excess sludge, it is assumed that the PHA concentration in the excess sludge is 16%

of DM (or 20% of VS). In total, this amounts to a PHA content of 173t per year in the excess sludge of the SCEPPHAR system, originating from an input of 2854 t COD per year in the inflow of SCEPPHAR.

Table 4-5: Input data for SCEPPHAR for COD/TN/TP removal, N_2O emissions, electricity and chemicals demand, and yield of struvite and PHA in excess sludge

Parameter	*Unit*	1 SCEPPHAR + PHA for biogas	2 SCEPPHAR + dried PHA sludge	3 SCEPPHAR + PHA extraction	Remarks
COD removal	*%*	94	94	94	UAB data
N removal	*%*	78	78	78	UAB data
P removal	*%*	87	87	87	UAB data
N_2O	*% N_2O/N elim.*	1.0*	1.0*	1.0*	UAB estimate
Electricity for SCEPPHAR process	*kWh/m³ influent*	0.39*	0.39*	0.39*	UAB estimate: +24% compared to existing WWTP (0.31 kWh/m³)
Mg dosing for struvite	*Mol Mg/mol P*	1.07	1.07	1.07	40 t/a $Mg(OH)_2$ (100%) in total
Struvite yield	*t/a*	157	157	157	45% of removed P can be extracted as struvite
Excess sludge	*t TS/a*	1177 (thickened)	1070 (dried)	1081 (dewatered)	Estimate: same amount of dry matter, 80% VS
PHA content	*g PHA/g TS*	0.16	0.16	0.16	20% PHA in VS
Final PHA yield	*t/a*	188 (for biogas)	171 (in dried sludge)	156 (after extraction)	PHA accounted to replace pure-culture PHA

** estimate*

4.2.3 Data for product valorisation: PHA and struvite

For struvite, the product is valorised as fertilizer in agriculture. Both P and N content of struvite are accounted for 100% to replace mineral fertilizer due to the slow-release characteristics of struvite. From the total amount of struvite produced (157 t/a), the related amounts of mineral P (20 t/a) and N (9 t/a) fertilizer are avoided.

PHA for biogas production

In scenario “1 SCEPPHAR + PHA for biogas”, PHA-rich excess sludge is valorised on-site for biogas production. After thickening of PHA-rich excess sludge to 3.3% DM using 0.42 kg polyelectrolyte per ton DM (assumption: +50% compared to baseline), thickened excess sludge is sent to digestion. Return liquor from thickening is assumed to 515 g/m³ COD, 20 g/m³ TN, 11 g/m³ TP. In digestion, biogas yield from PHA-rich sludge (80% VS) is estimated with 643 NL/kg VS removed, assuming a VS degradation of 73%. Based on this estimate, total biogas production amounts to 976,000 Nm³/a, which is a +68% increase compared to the baseline. Electricity production from CHP plant also increases by +68%, yielding a total electricity production of 1,082 MWh/a. Digested excess sludge is dewatered and contributes to the return load with same liquor quality as mixed sludge in baseline (**Table 4-3**). Dewatered excess sludge is sent to agriculture and yields some additional credits for its N and P content, although less than the baseline scenario because struvite has been extracted before.

Direct use of PHA-rich sludge after drying

In scenario “2 SCEPPHAR + dried PHA sludge”, PHA-rich excess sludge is dewatered and dried on-site. According to pilot trials, the dried sludge can be directly applied in bio-composite production, although problems of odour have not been fully resolved yet.

PHA-rich excess sludge is dewatered to 40% DM (assumption, feasibility to be tested) using a centrifuge with 90% TS separation efficiency and 6.5 kg polyelectrolyte per ton DM. Return liquor from thickening is assumed to 515 g/m³ COD, 20 g/m³ TN, and 11 g/m³ TP. Drying of dewatered PHA sludge to 90% DM requires 700 kWh of heat (estimate for state-of-the art energy efficient drier) and 35 kWh of electricity per m³ H_2O evaporated (1515 m³ H_2O/a). Around 45% of heat demand can be covered by available excess heat of the CHP plant, while 55% of heat is provided using natural gas. Condensate from drying (5,700 g/m³ COD, 2,421 g/m³ TN, 123 g/m³ TP) is recycled to the WWTP as return load. Dried PHA sludge amounts to 1190 t per year, containing 1070 t DM and 171 t PHA (1.57 kg PHA/(pe*a)). This product is credited with the substitution of an equal amount of PHA from other substrates (here: pure-culture PHA from sucrose). The functional equivalency of dried PHA sludge and pure-culture PHA is not proven here, but it is assumed that both products fulfil the same function in the production of bio-composites such as the Ecodek product.

Chemical extraction of PHA and drying to PHA powder

In scenario “3 SCEPPPHAR + PHA extraction”, PHA-rich excess sludge is dewatered and chemically digested to extract and purify the PHA. The resulting slurry is dried into a powder to be used as input for bio-composite production, replacing PHA from pure-culture production.

As in scenario 2, PHA-rich excess sludge is dewatered to 40% DM (assumption, feasibility to be tested) using a centrifuge with 90% TS separation efficiency and 6.5 kg polyelectrolyte per ton DM. Return liquor from thickening is assumed to 515 g/m³ COD, 20 g/m³ TN, 11 g/m³ TP. Dewatered PHA sludge is then chemically digested using two chemicals in dedicated dosing (confidential data), a procedure which was tested and optimised during the project. Extraction efficiency is 90%, and 10% of PHA are lost with the residual liquor from extraction. For intermediate washing, 23 L of water per kg TS are assumed. Electricity for PHA extraction amounts to 1.8 kWh/m³ PHA sludge, while heat for spray drying is estimated to 0.88 kWh/kg TS. Residual waste liquor from PHA extraction (29730 m^3/a) contains remaining TS (31 kg/m³), COD (33 kg/m³), TN (1.1 kg/m³) and TP (0.75 kg/m³) from biomass. This highly loaded wastewater stream is supposed to be again treated in another wastewater treatment process before discharge, requiring 6.38 kWh of electricity per m³ for treatment (conservative estimate).

Extracted PHA powder (156 t/a or 1.43 kg/(pe*a)) is credited with substituting the equivalent amount of pure-culture PHA from refined sugars. As in scenario 2, the functional equivalency of PHA powder from SCEPPHAR and pure-culture PHA is not proven here, and the HV contents of the SMART-PLANT polymer is much higher (> 30%) than that of the commercially available PHA from pure cultures (< 3%) which will convey different mechanical and thermal properties. However, for this LCA it is assumed that both products fulfil the same function in the production of bio-composites.

Infrastructure

Material demand for building a mainstream SCEPPHAR system is roughly estimated by the design of the pilot system. With three SBR tanks with 3 m³ each, the pilot treats 10 m³ per day. Using the same ratio, the full-scale system needs 21.600 m³ of SBR volume to treat 24.000 m³ of wastewater per day (including return load). With an estimated material demand of 0.25 m³ concrete and 30 kg reinforcing steel per m³ tank volume for SBR tanks, the total material demand for SCEPPHAR amounts to 5,400 m³ concrete and 648 t reinforcing steel. For the complex piping between reactors, a lump amount of 50 t PE pipes is estimated. Excavation for the tanks is estimated to 18,500 t of soil material. The corresponding lifetime of the installation is estimated to 50 years.

4.2.4 Background data

Background processes are modelled with datasets from ecoinvent database v3.4 (Ecoinvent, 2017). The related datasets are listed below (**Table 4-6**), mainly relating to European or global markets. For electricity, the market mix of Spain is applied. For transport of chemicals to the WWTP, a distance of 300km has been estimated.

Table 4-6: Datasets for background data

Process	Dataset from ecoinvent v3.4	Remarks
Energy		
Electricity	market for electricity, medium voltage [ES]	For all operational electricity demand and credits from CHP plant
Heat	heat production, natural gas, at boiler condensing modulating <100kW [Europe without Switzerland]	Heat for drying of sludge and PHA powder
Transport and fuels		
Truck transport	transport, freight, lorry 16-32 metric ton, EURO5 [RER]	300 km for chemicals, 20 km for sludge disposal to agriculture
Chemicals		
Polyelectrolyte	market for acrylonitrile [GLO]	746 g acrylonitrile + water = 1kg of polymer active substance
FeCl3	market for iron (III) chloride, without water, in 40% solution state [GLO]	40% FeCl3
PACl	polyaluminium chloride production [GLO]	18% PACl, 5% Al
Mg(OH)2	market for magnesium oxide [GLO]	MgO modelled as Mg(OH)2
Chemical 1	market [GLO]	For PHA extraction (confidential)
Chemical 2	market [GLO]	For PHA extraction (confidential)
Tap water	market for tap water [Europe without Switzerland]	Water for PHA extraction
Mineral N fertilizer	market for nitrogen fertiliser, as N [GLO]	Credits for sludge application in agriculture and struvite
Mineral P fertilizer	market for phosphate fertiliser, as P2O5 [GLO]	Credits for sludge application in agriculture and struvite
Materials		
Concrete	market for concrete, for de-icing salt contact [RoW]	Infrastructure material for SCEPPHAR
Reinforced steel	reinforcing steel production [RoW]	Infrastructure material for SCEPPHAR
HDPE	polyethylene production, low density, granulate [RER]	Infrastructure material for SCEPPHAR
Excavation	excavation, hydraulic digger [RER]	Excavated material for tanks

4.3 Results of environmental indicators (Life Cycle Impact Assessment)

Cumulative energy demand (CED)

The total net CED of WWTP Manresa including sludge disposal amounts to 223 MJ/(pe*a) (**Figure 4-2**), accounting for electricity and chemicals demand at the WWTP, electricity recovered in sludge treatment, and nutrient credits for sludge disposal. The gross CED of 298 MJ/(pe*a) for WWTP operation and sludge treatment is mainly due to electricity demand (83%) for operation, plus chemicals for P removal and sludge dewatering (15%). This gross energy demand is partially compensated (15%) by electricity produced from biogas in CHP plants (-45 MJ/(pe*a)) and nutrient credits for sludge disposal in agriculture (-30 MJ/(pe*a)). Overall, the plant supplies only 18% of its electricity demand by biogas valorisation in the CHP plant, which is mainly due to two issues: a) the existing CHP operates at low electrical efficiency (21-23%) as it runs mostly at <50% of its capacity, and b) 20% of the biogas is used directly in a heating boiler to heat the digestor, which is not isolated. These issues reflect the situation at the plant in 2016, and may have been improved meanwhile.

Introducing a SCEPPHAR system for mainstream wastewater treatment and recovery of PHA and struvite can either decrease of increase the net CED of the system depending on the valorisation route of the PHA-rich sludge (**Figure 4-2**). Use of PHA for biogas production in scenario 1 decreases net CED by -15%, while drying of PHA sludge and direct use for production of bio-composites yields -18% decrease. In contrast, downstream extraction of PHA and use as a powder will slightly increase net energy demand by +6%. These results underline the importance of the valorisation route for the overall energy profile of the SCEPPHAR process.

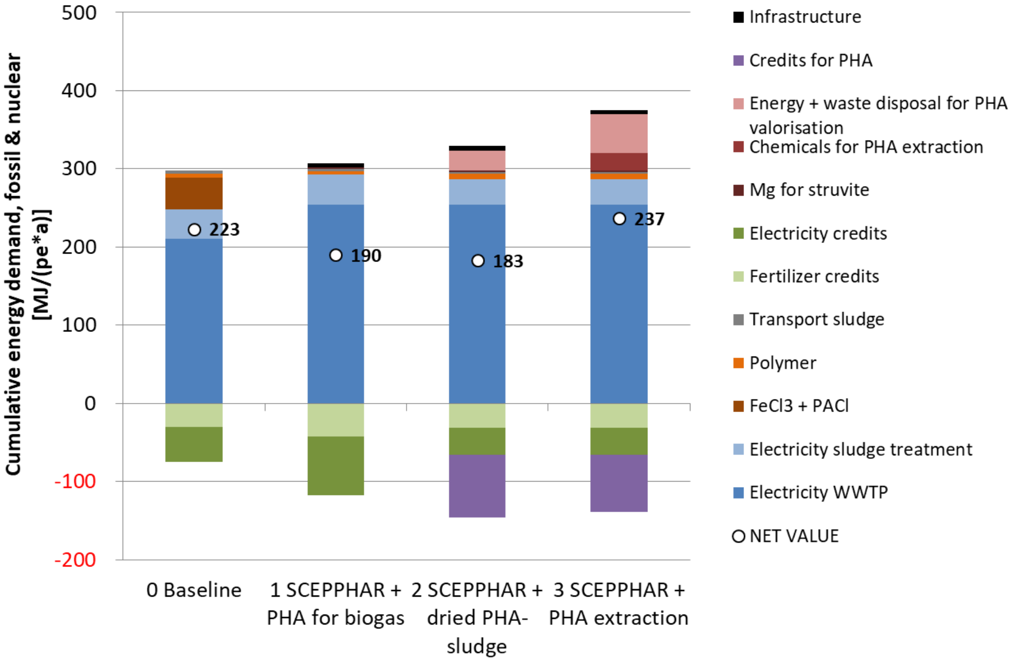

Figure 4-2: Total cumulative energy demand for baseline and SCEPPHAR scenarios at WWTP Manresa

For a detailed analysis of the SCEPPHAR scenarios, the relative changes of CED due to SCEPPHAR implementation are shown below for the different valorisation routes (**Figure 4-3**). Overall, the implementation of SCEPPHAR leads to a change in net CED between +14 and -40 MJ/(pe*a) depending on the downstream use of the PHA sludge. The contribution analysis shows several effects of SCEPPHAR on the total energy demand of the system:

- From the electricity balance, it becomes evident that mainstream SCEPPHAR treatment requires 15-18% more electricity for WWTP operation. Basically, the SCEPPHAR process with its three reactor configuration needs more electricity for pumping and mixing compared to the activated sludge process (**Table 4-5**), whereas electricity for sludge treatment is comparable or slightly lower than in the baseline.
- The additional electricity demand for SCEPPHAR is almost completely off-set (92%) by savings in chemical usage, mainly because metal coagulants for P removal are not required any more.
- Valorisation of PHA sludge for biogas production yields additional credits for electricity and nutrients contained in this sludge, which finally end up in agriculture. Both impacts contribute substantially to the energy benefits of this scenario.
- Valorisation of PHA as bioplastic yields substantial credits for substituting pure-culture PHA in scenarios 2 and 3. However, additional efforts for drying (scenario 2) or PHA extraction (scenarios 3) are off-setting some of these credits. Overall, drying of PHA sludge and direct use is energy-positive and further decreases overall CED compared to PHA valorisation for biogas. In contrast, PHA extraction needs a substantial amount of chemicals and also much energy for PHA drying and waste treatment (dissolved excess sludge), which leads to an overall energy input required for this valorisation route.
- Chemicals for struvite precipitation (Mg) and additional polyelectrolyte for dewatering of SCEPPHAR sludge play only a minor role for the overall energy balance of the SCEPPHAR scenarios. Likewise,

infrastructure required for the SCEPPHAR system does only marginally add additional energy demand for the SMART scenarios.

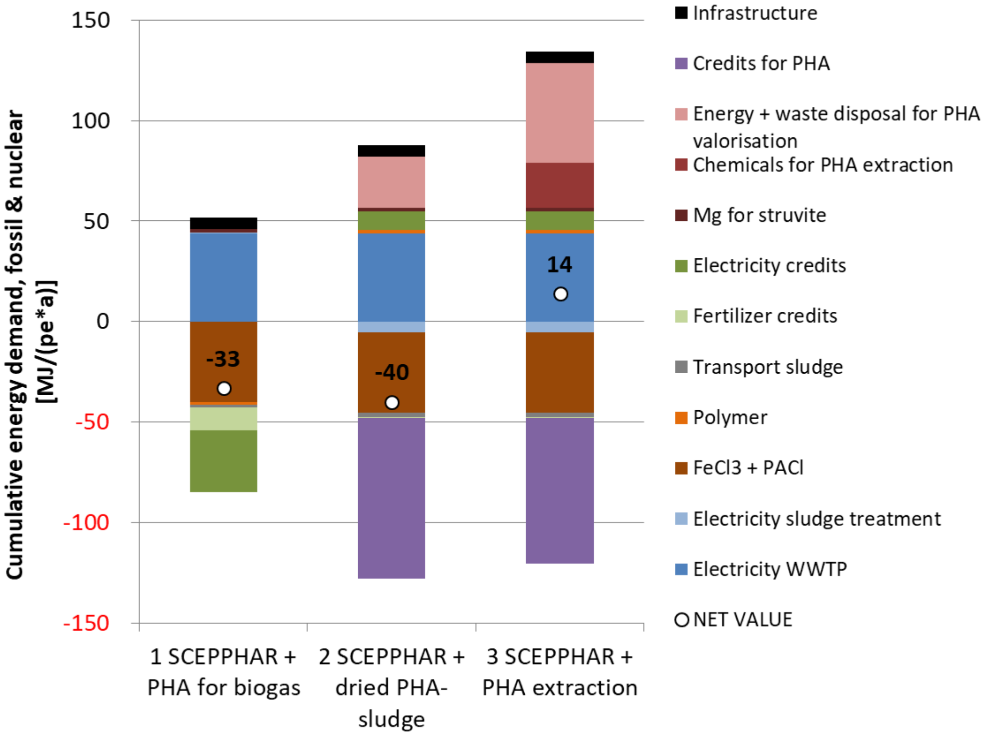

Figure 4-3: Change in cumulative energy demand for SCEPPHAR scenarios at WWTP Manresa compared to baseline

The analysis above revealed that the valorisation route for PHA-rich excess sludge is decisive for the overall energy balance of SCEPPHAR. For a more detailed view of these effects, CED of the different routes is explicitly shown in **Figure 4-5**, excluding all other impacts from the WWTP and starting from raw PHA-rich excess sludge as produced by the SCEPPHAR process.

Again, it becomes evident that the use of PHA-rich sludge for biogas production on-site is beneficial for the energy balance, as scenario 1 yields -27 MJ/(pe*a) in total. For drying of PHA sludge and direct use for bio-composite production, the energy balance is also beneficial, giving credits of -33 MJ/(pe*a). Drying of the PHA sludge does not require too much energy input, as 45% of heat for drying can be supplied by excess heat from the CHP. This depends very much on the final extent of dewatering that can be reached with raw PHA sludge, which is assumed to 40% DM in this study by UAB. The feasibility of this dewatering step and the actual DM that can be realized should be validated, as this has a substantial impact on heat required for drying and could consequently affect the energy balance of this route significantly.

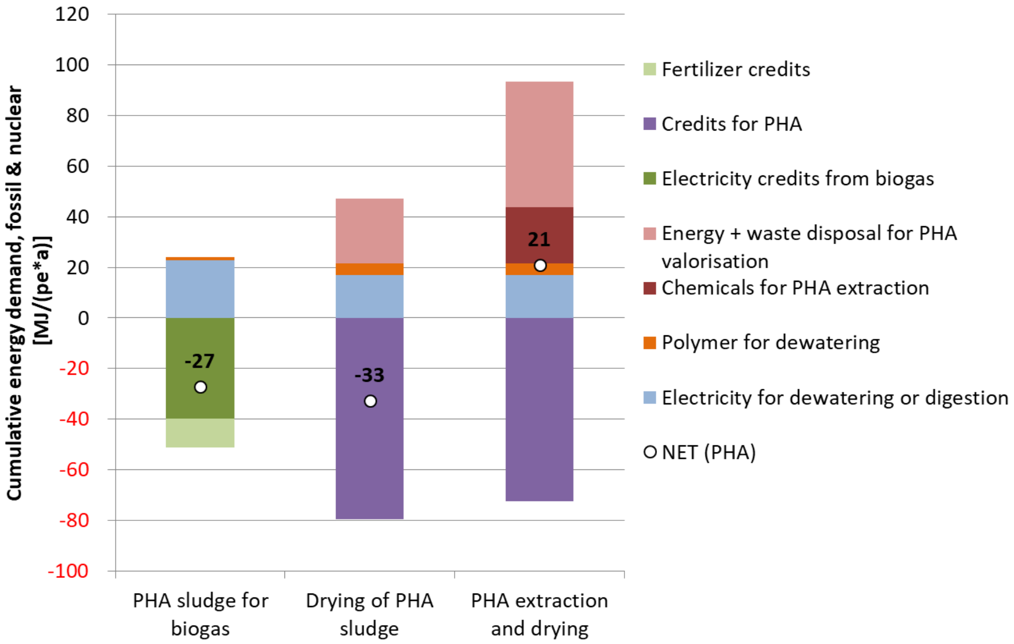

Figure 4-4: Balance of cumulative energy demand for valorisation route of PHA-rich excess sludge (0.64% DM) for biogas, as dried PHA sludge, or with PHA extraction and drying of powder

For PHA extraction, the CED balance shows that the energy input required for chemicals, electricity for PHA extraction, heat for drying of the powder, and treatment of liquid waste adds up to a high demand. In total, energy needs for this route are higher than potential energy credits for substituting pure-culture PHA, resulting in a +21 MJ/(pe*a)) increase of total CED (**Figure 4-4**). The extraction of PHA from excess sludge leads to a high effort for chemical digestion, but also comes at the expense of considerable energy required for treating the re-dissolved sludge. Finally, chemical extraction of PHA leads to the full solubilisation of the excess sludge organics again, which need additional wastewater treatment again. A decisive figure for the overall energy profile of this route seems to be the PHA content in the sludge, as both chemical needs and treatment of residual waste are related to the dry matter directly: the more PHA can be extracted from a specific amount of DM, the lower are the related energy needs per kg of recovered and purified PHA. Hence, it should be a goal to maximize the PHA content in the sludge for this valorisation route (here: 16% PHA in TS) to end up with a beneficial energy balance for the entire system. PHA contents of up to 60% in TS can be achieved in optimised mixed culture systems, comparable to performances attained in pure culture systems, which would allow a significant reduction of chemical and energy consumption and of residual waste treatment requirements per kg of recovered and purified PHA.

Global warming potential (GWP)

The total net GWP of the baseline scenario amounts to 23.2 kg CO_2-eq/(pe*a) (**Figure 4-5**). Thereof, the system has a gross GWP impact of 28 kg CO_2-eq/(pe*a) and receives credits for energy and nutrients recovery of -4.8 kg CO_2-eq/(pe*a), compensating 17% of its GWP. In analogy to the CED, the operation of the WWTP contributes to gross GWP mainly with electricity demand (41%) and less with chemicals (12%). On top, the direct emissions of N_2O from the activated sludge tank are a significant factor for gross GWP (43%), while other greenhouse gases (e.g. CH_4 at centrifuges or off-gas from CHP) play only a minor role (3%).
Implementing a SCEPPHAR system changes net GWP between +8% and -12% depending on the valorisation route of the PHA sludge. Interestingly, scenario 1 (“PHA for biogas”) increases net GWP, although its energy balance was favourable (see CED results), indicating a difference between energy and GHG impacts for this system. Scenario 2 with direct used of dried PHA sludge decreases overall GWP, while PHA extraction adds to the net GWP in analogy to its impact on the energy balance. A detailed analysis of the changes in GWP due to SCENA implementation is provided below.

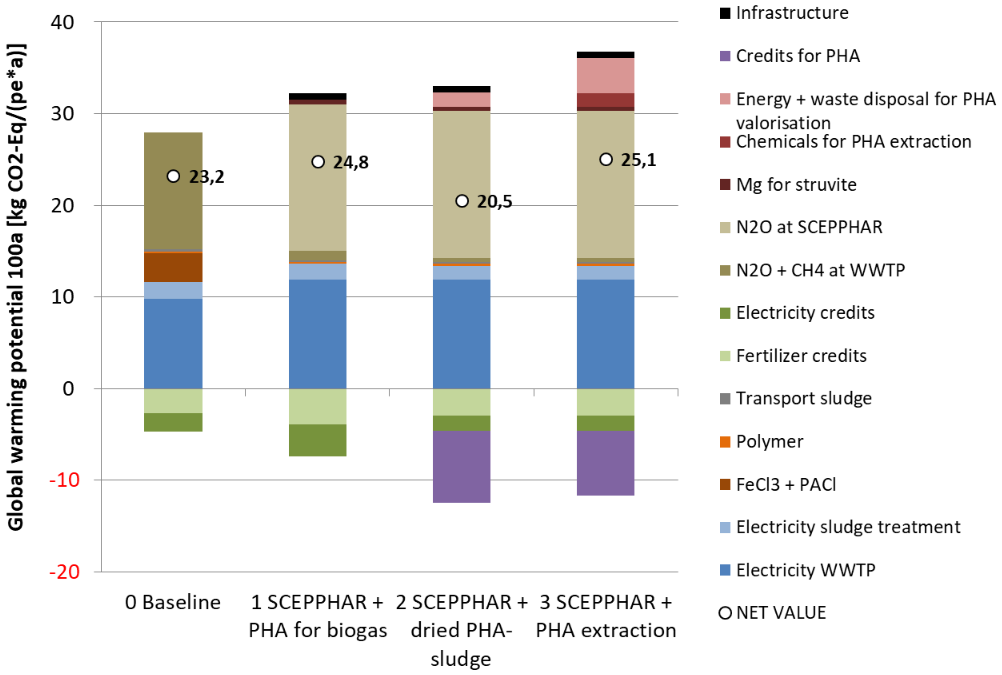

Figure 4-5: Total global warming potential for baseline and SCEPPHAR scenarios at WWTP Manresa

In scenarios 1-3, net GWP of the system changes between +1.9 to -2.7 kg CO_2-eq/(pe*a) depending on the valorisation route (**Figure 4-6**). While some factors are in analogy to the energetic balance, others are particularly associated with specific greenhouse gases:

- For the operation of the WWTP, GHG benefits for chemical savings exceed additional GWP from enhanced electricity required for the SCEPPHAR system.
- However, this positive impact is fully off-set by the emissions of N_2O, which are higher for SCEPPHAR (+33%) than for the conventional process. Overall, the operation of the water line has an inferior GWP balance with SCEPPHAR, meaning that SCEPPHAR will increase net GWP for the WWTP.
- GWP credits for use of PHA for biogas production are rather small. In fact, nutrient credits from sludge and struvite are now in the same range, indicating that the positive impact of producing more biogas is not as pronounced for GHG emissions as it is for the energy balance. In total, the credits for this route are not able to compensate the higher GWP from the water line due to N2O, leading to an overall increase of GHG emissions for scenario 1 (+1.6 kg CO_2-eq/(pe*a)).
- For scenario 2, the net GWP impact is still positive, decreasing overall emissions by -2.7 kg CO_2-eq/(pe*a). In analogy to the energy balance, efforts for drying the sludge are lower than credits for PHA, so that the valorisation route is able to compensate the higher GWP from the water line.
- For scenario 3, net GWP is increased by +1.9 kg CO_2-eq/(pe*a). PHA extraction and related demand of chemicals and energy off-sets most of the credits for PHA, so that this route is not able to fully compensate the higher GWP from the water line.

Overall, it is clear that the N_2O emissions from the SCEPPHAR process are one of the major factors leading to an inferior GWP balance for this process. They are calculated to +33% compared to the conventional process, a factor which should be validated by further monitoring of the full-scale process in realistic operating conditions.

As for CED, the valorisation route is also decisive for the overall impact of SCEPPHAR on the GHG emission profile. Hence, a detailed GWP analysis of these routes is provided below, starting from the raw PHA-rich excess sludge coming out of the SCEPPHAR process.

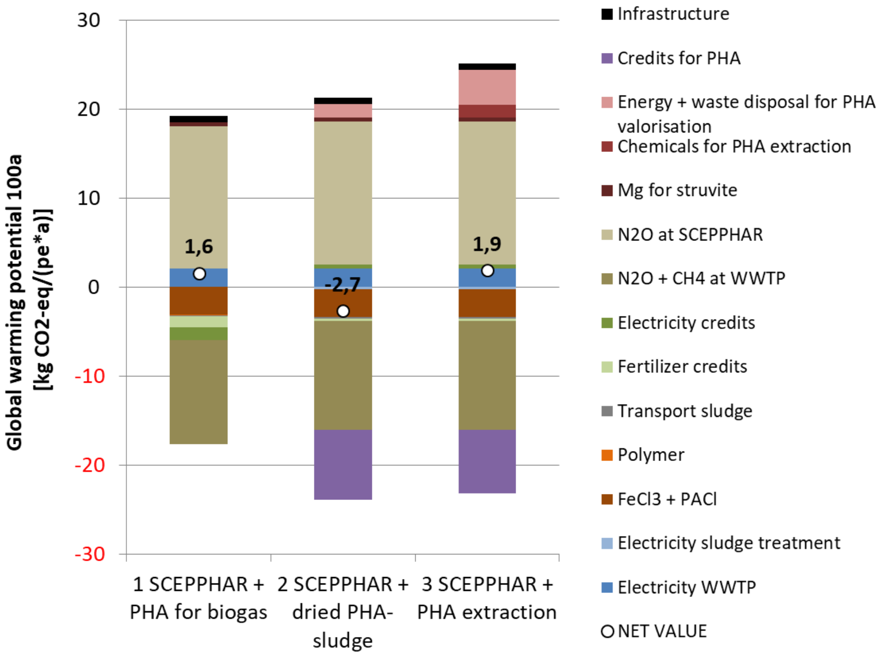

Figure 4-6: Change in global warming potential for SCEPPHAR scenarios at WWTP Manresa compared to baseline

Analysing the GWP profile of the valorisation routes only, it is evident that all routes have a potential to reduce GHG emissions between -0.8 and -5.4 kg CO2-eq/(pe*a) (**Figure 4-7**). Electricity-related effects are comparable to CED, while credits for fertilizer and PHA have a higher contribution in GWP compared to the energy balance. Overall, PHA for biogas yields some GWP credits with -1.4 kg CO_2-eq/(pe*a) or -0.8 kg CO_2-eq/kg PHA, while direct use of dried PHA sludge generates -5.4 kg CO_2-eq/(pe*a) or -3 kg CO_2-eq/kg PHA. Extraction of PHA and drying of powder still has some credits (-0.8 kg CO2-eq/(pe*a) or -0.5 kg CO2-eq/kg PHA), but the majority of the PHA credits are off-set by the substantial needs of energy and chemicals for the extraction process and related waste streams. Again, higher PHA content in the sludge would gain more benefits for the latter route.

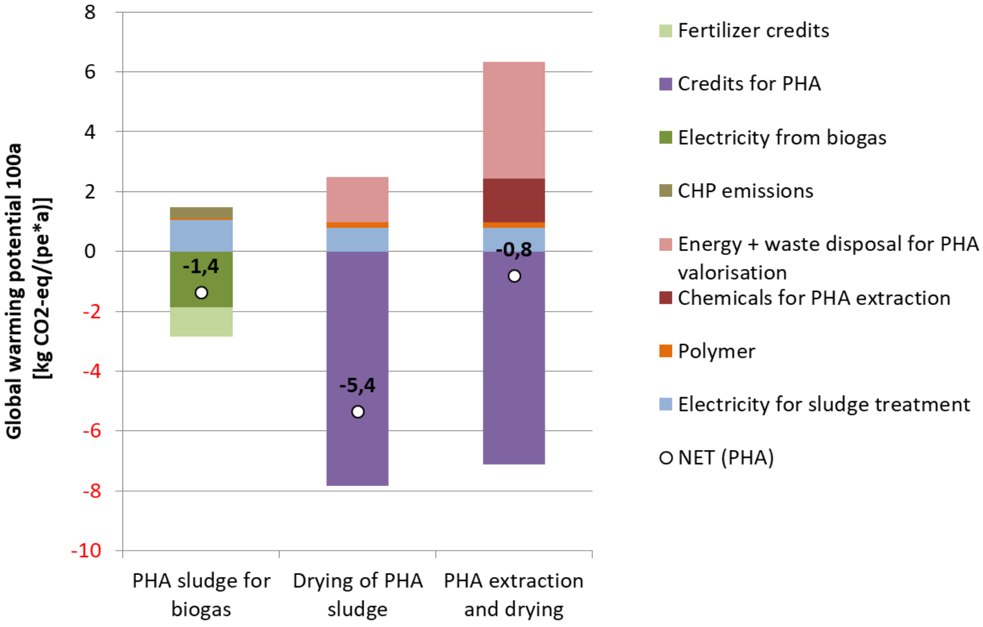

Figure 4-7: Balance of global warming potential for valorisation route of PHA-rich excess sludge (0.64% DM) for biogas, as dried PHA sludge, or with PHA extraction and drying of powder

Freshwater eutrophication (FEP)

This indicator predominantly reflects the effluent quality of the WWTP in terms of phosphorus load to freshwater. As defined by the inventory, the SCEPPHAR scenarios deliver the same effluent quality for TP than the existing WWTP (**Figure 4-8**). The small reduction of FEP in the SCEPPHAR scenarios (-6 to -14%) originates from life-cycle impacts of fertilizer application: struvite is a more effective P fertilizer than digested sludge, meaning that P losses to groundwater during its application are lower which leads to a lower FEP. In addition, the substitution of pure-culture PHA from refined sugars in scenarios 2 and 3 avoids some P fertilizer use during growing of sugar crops, further improving the life-cycle FEP balance.

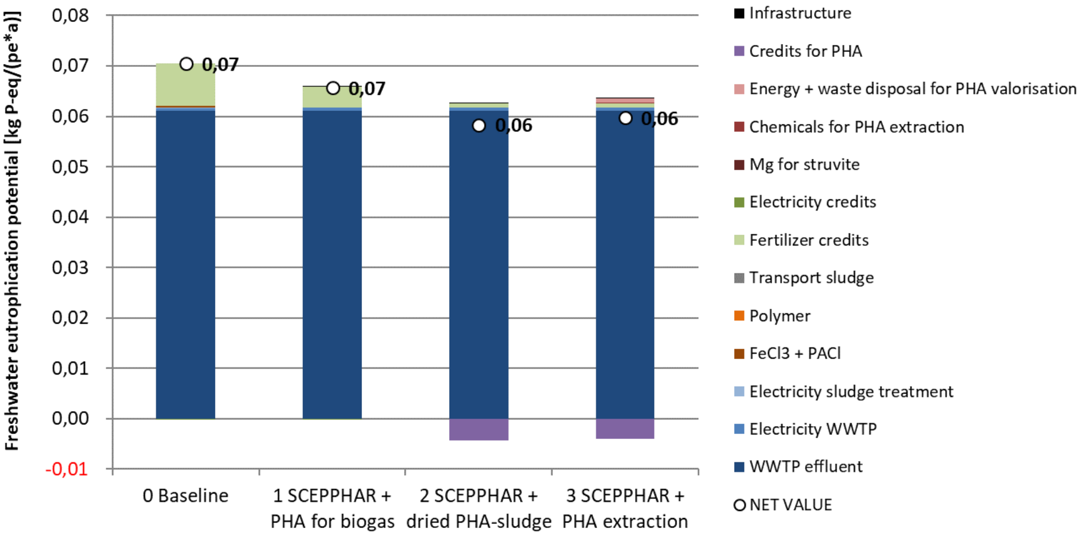

Figure 4-8: Total freshwater eutrophication potential for baseline and SCEPPHAR scenarios at WWTP Manresa

Marine eutrophication (MEP)

This indicator mainly reflects the effluent quality of the WWTP in terms of nitrogen load to marine waters. As defined in the inventory, the SCEPPHAR scenarios deliver the same TN effluent quality than the existing plant (**Figure 4-9**). In addition, MEP can be decreased in scenarios 2 and 3 by avoiding pure-culture production of PHA from refined sugars. The latter process involves N fertilizer production and related emissions during the growing of the substrate, and these nitrogen emissions can be avoided when using PHA from the SCEPPHAR process. For information, N_2O does not account for MEP.

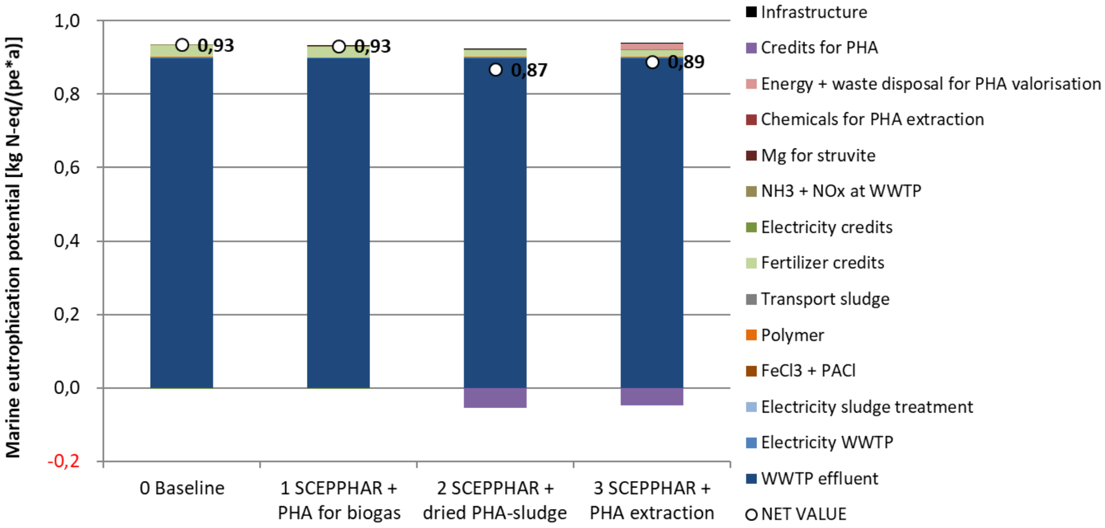

Figure 4-9: Total marine eutrophication potential for baseline and SCEPPHAR scenarios at WWTP Manresa

4.4 Interpretation and conclusions

This LCA case study analyses the potential environmental impacts of implementing a SCEPPHAR system for mainstream wastewater treatment with recovery of PHA and struvite at the WWTP Manresa (ES), taking into account all direct and indirect effects on the WWTP and in the sludge disposal route. Products of the SCEPPHAR are struvite as P/N fertilizer and PHA-rich excess sludge. The latter can be valorised in different routes, namely for biogas production on-site, for direct use in bio-composite production in dried form, or for chemical extraction of PHA and production of a PHA powder.

The main outcomes of the LCA for this case study can be summarized as follows (**Table 4-7**):

- All scenarios of SCEPPHAR deliver **comparable WWTP effluent quality to the existing system** with activated sludge. Small benefits in related indicators for marine and freshwater eutrophication mainly originate from life-cycle impacts of recovered struvite (higher efficiency than P recycling with digested sludge) or fertilizer savings in avoided PHA production from sucrose.
- Implementing a SCEPPHAR system for mainstream wastewater treatment can have a positive impact on the net energy balance and related GHG emissions of the entire system. However, this **depends on the valorisation route for the PHA-rich sludge** containing 1.8 kg PHA/(pe*a).
- For the WWTP, SCEPPHAR has a neutral effect on the energy balance. Additional electricity required for the process (+15-18%) is mostly compensated by savings in coagulation chemicals, which are not required with the bio-P removal of SCEPPHAR. For global warming, the SCEPPHAR process will **increase net GHG emissions**, mainly due to the predicted **higher N_2O** emissions (+33%) compared to the conventional activated sludge process. However, N_2O emission factors should be validated with further monitoring in full-scale plants under realistic operational conditions.
- **PHA valorisation for biogas** production on-site will **reduce net energy demand by -15%**, mainly by generating additional electricity from the biogas. For GHG emissions, this route leads to a **slight increase in net GWP of +7%**, as higher N_2O emissions from the SCEPPHAR off-set all credits coming from the biogas. Overall, this valorisation route has a positive environmental impact, but is not seen as attractive as the use of PHA as a bio-plastic raw material. It can be an **option if no other use of PHA-rich sludge is feasible** from an economic or logistic perspective.
- Drying of dewatered PHA sludge and **direct use of dried PHA sludge in bio-composite** production **reduces net energy demand by -18% and net GHG emissions by -12%**. If dewatering of PHA sludge to 40% DM is feasible and drying can be realized partially using excess heat from the CHP (45%), this route is favourable in terms of its environmental benefits. However, it is **to be validated if this type of material can be applied in bio-composite** production from a legal, economic, and consumer-acceptance point of view. In fact, the organic matter of the excess sludge is “recycled” here as a valuable product and ends up in a consumer product, thus avoiding any further efforts for sludge disposal. Pilot trials in the project indicated that residual odour of the bio-composite produced with dried PHA sludge could be a barrier for successful marketing. Use of these bio-composites in areas where odour is not a problem (e.g. in outdoor applications at WWTP!) can be a potential solution to this problem. If this issue and related legal regulations (“end-of-waste criteria”) have been solved, this route seems attractive as it yields a valuable product without too much efforts in PHA processing.
- **Chemical extraction of PHA and production of a purified PHA powder** is not beneficial for energy balance and GHG emissions in this study, **increasing net energy demand by +6% and net GWP by +8%**. For this route, chemical demand for PHA extraction and especially energy required for treatment of liquid waste (basically dissolved excess sludge) are substantial and off-set all credits for PHA use downstream. As both factors are depending on the dry matter content of the PHA sludge, a **higher concentration of PHA** in this material towards the levels attainted in pure cultures (> 60%) will greatly improve the environmental profile of this route. Compared to the direct use of dried PHA sludge, the acceptance of the produced PHA powder in the market is estimated to be higher, potentially leading to a higher value in environmental and economic terms (substituting a higher grade of PHA from other substrates). Finally, this valorisation route is still to be optimised, but could be promising for PHA.

- Additional infrastructure as well as chemicals required for SCEPPHAR (Mg for struvite, polymer for dewatering) have only a minor impact on energy and GHG balance.

Table 4-7: Summary of LCA results for mainstream wastewater treatment with SCEPPHAR at WWTP Manresa (109,000 pe): impact on energy demand, global warming potential, freshwater eutrophication, and marine eutrophication

Parameter	*Unit*	Baseline system	SCEPPHAR + PHA for biogas	SCEPPHAR + dried PHA sludge for direct use	SCEPPHAR + PHA extraction and drying
PHA in excess sludge	*t/a*	-	192	192	192
	*kg/(pe*a)*	-	1.8	1.8	1.8
Struvite production	*t/a*	-	157	157	157
	*kg/(pe*a)*	-	1.4	1.4	1.4
Cumulative energy demand	*MJ/(pe*a)*	**223**	**-33**	**-40**	**+14**
		100%	**-15%**	**-18%**	**+6%**
Global warming potential	*kg CO_2-eq/(pe*a)*	**23.2**	**+1.6**	**-2.7**	**+1.9**
		100%	**+7%**	**-12%**	**+8%**
Freshwater eutrophication potential	*g P-eq/(pe*a)*	**70**	**-4**	**-12**	**-10**
		100%	**-6%**	**-17%**	**-14%**
Marine eutrophication potential	*kg N-eq/(pe*a)*	**0.93**	**0**	**-0.06**	**-0.04**
		100%	**0%**	**-6%**	**-4%**

Overall, it can be concluded that SCEPPHAR is a suitable process to treat wastewater to the standards required at WWTP Manresa and recover valuable products at the same time. SCEPPHAR itself is neutral in its energy balance at the WWTP, but has a clear drawback in its potentially higher N_2O emissions which should be a focus of future studies. Overall, its net environmental profile in terms of energy demand and GHG emissions depends on the valorisation route of the PHA-rich sludge. While energetic valorisation in the digestor for biogas production is a simple and beneficial solution, the use of PHA for bio-composite production is more attractive from an environmental point of view. If PHA sludge can be dewatered and dried as predicted in this study and the resulting product finds an application in the market, this route can generate a valuable product with lower environmental footprint than PHA from other sources. Required efforts for PHA extraction and production of a powder are still quite high, and chemical demand and also energy for treatment of residual liquid waste should be minimised to justify this processing step. Maximising the PHA concentration in the sludge would help to enable this route with a positive environmental footprint. For all routes, struvite is a beneficial product from the process and helps to improve the situation of nutrient recycling compared to the application of digested sludge on farmland.

Limitations and transferability of the case study results to other WWTPs

Overall, the implementation of a SCEPPHAR process for mainstream wastewater treatment has mixed impacts on the environmental footprint of WWTP Manresa in this LCA study, depending on the valorisation of PHA. Its simple and effective use for biogas production or as dried raw material are positive for the energy and GHG profile, while substantial efforts required for chemical extraction are not clearly justified with the actual PHA concentration in the sludge. Increased N_2O emissions are a potential drawback of the SCEPPHAR and should be a focus of future optimisation studies.

When transferring the results of this LCA to other WWTPs and boundary conditions, the following aspects have to be considered:

- Effluent quality, energy demand and sludge production/PHA yield of the SCEPPHAR system depend on **influent composition and relation between COD, TN and TP in raw wastewater**. Pilot tests should be used to validate its performance and confirm the estimates for effluent quality of this study (comparable effluent quality to existing WWTP).
- The LCA inventory further depends on some assumptions which have been taken by UAB based on the results of pilot trials and monitoring. These factors should be further validated, in particular the **N_2O emission factor** (1% of N eliminated = +33% in relation to baseline N_2O emission factor which is estimated based in literature), the **amount of excess sludge** (same as existing WWTP), and the **final PHA concentration** in excess sludge (16% PHA in DM). All factors can have a substantial impact on the results and final energy and GHG balances.
- **Dewatering of PHA-rich excess sludge** has not been tested in this project. Related assumptions for final DM content to be reached (e.g. 40% DM before drying) should be validated, as this can have a major impact on the energy and GHG profile of the respective valorisation routes.
- Energy recovery from biogas at WWTP Manresa can be optimised, as the current CHP system yields only 23% electrical efficiency due to various operational reasons. Other WWTPs with better CHP systems will have **higher benefits from the biogas route** for PHA valorisation.
- PHA use for bio-composite production is credited with avoiding the production of pure-culture PHA from refined sugars. However, the product quality of the latter is supposed to be superior to the mixed-culture PHA produced in SCEPPHAR. The **equivalency of both PHA grades** should be further investigated to fully justify the crediting of sugar-based PHA for the SCEPPHAR scenarios.

5. LCA OF MAINSTREAM ION EXCHANGE FOR N AND P RECOVERY (SMARTECH 3)

Nutrient removal in waste water treatment plants (WWTPs) requires a significant amount of energy and chemicals to eliminate nitrogen and phosphorus from municipal wastewater with biological and/or chemical processes. In addition, stricter regulations on nutrient discharge limits to surface and marine waters are expected in the near future such as 0.5 mg NH_4^+-N/L and 0.3 mg TP/L. These discharge limits will lead to the need for additional treatment steps such as tertiary filtration, microfiltration etc.

A competing innovative technology to biological and/or chemical processes for nutrient removal is ion exchange (IEX). IEX can be implemented downstream of a biological stage to enable the specific removal of inorganic ions such as ammonia (NH_4) and phosphate (PO_4) depending on the type of IEX media used. Benefits of IEX processes include their potential to remove these nutrients to very low limits, and also to recover them as valuable products from the regenerant brines, in the form of nitrogen or phosphorus intermediates, which can then be directly used as fertiliser or as input material in the chemical industry.

The IEX process for mainstream nutrient removal demonstrated in SMART-PLANT consists of a micro screen to remove residual solids followed by two sequentially connected ion exchange stages. The first IEX stage removes ammonium (N-IEX) using a specific zeolite resin (MesoLite), and the second IEX stage eliminates phosphate (P-IEX) with a hybrid anionic ion exchange resin (HAIX). Upon saturation of the IEX media, the IEX is regenerated by backwashing with a 10% KCl or NaCl solution for the MesoLite (N-IEX) or with a 2% NaOH solution for the HAIX (P-IEX). Subsequently, the nutrients can be recovered from the regenerant brines by stripping of gaseous ammonia (e.g. by vacuum or membrane stripping) and precipitating phosphorus as a mineral salt (i.e. by lime dosing).

In this study, IEX treatment schemes were compared for their environmental impacts in relation to reference WWTP schemes, with conventional technologies to show the benefits of this innovative technology against the current state. For this comparison, two different scenarios for the IEX configuration have been defined: a) polishing of effluent to very low nutrient limits and b) maximum nutrient recovery with the IEX technology. The first scenario assumes high nutrient removal in the secondary biological stage with conventional technology, and the downstream IEX will then only remove the residual nutrients to reach effluent limits of 0.3 mg TP/L and 0.5 NH_4-N mg/L. For the second scenario, the secondary biological treatment should remove only a limited amount of nutrients, so that the following IEX stage can remove and recover the maximum amount of nutrients.

As the IEX system has been tested at demonstration scale, the following assessment is based on up-scaling of the demo data to reflect full-scale mainstream IEX including the regenerant treatment and recovery of nutrient intermediates. Effects of implementing the IEX after the biological treatment and the WWTP performance, as well as changes in WWTP operation could not be quantified in practice. Those effects were carefully estimated in close cooperation with Cranfield University and Severn Trent Water based on two conventional reference layouts of WWTPs in the UK. The analysis we completed for two different sizes of WWTP, 10,000 population equivalent (pe) and 100,000 pe, which used different conventional technology and thus represent different types of existing WWTPs.

The goal of this LCA was to illustrate all direct and indirect impacts of implementing an IEX at a WWTP in order to show its environmental effects on primary energy demand, greenhouse gas (GHG) emissions and eutrophication potential. Results showed environmental impacts of shifting from conventional nutrient removal to nutrient removal and recovery with IEX. Upgrading the WWTP mainline with an IEX also impacted the effluent quality, which was also addressed in this LCA.

5.1 Goal and scope definition

5.1.1 Goal of the study

The goal of this LCA is to assess the potential environmental impacts of implementing an ion exchange process for nutrient removal and recovery at a municipal WWTP, considering all relevant effects on the upstream wastewater treatment process. The new WWTP schemes combined with IEX are compared to a reference system, which reflects a typical existing WWTP in the United Kingdom (UK). The comparison allows a quantification of environmental benefits and drawbacks of the IEX treatment compared to conventional processes for nutrient removal. The target group of this study are WWTP operators, engineers, scientists and companies working in the wastewater sector who are involved in ensuring low WWTP effluent nutrient concentrations in combination with nutrient recovery.

5.1.2 Function and functional unit

The function of the system studied relates to the treatment of municipal wastewater for compliance with defined limit values for ammonium and phosphorus in the WWTP effluent. Furthermore, the treatment of sewage sludge resulting from wastewater treatment is taken into account. This includes dewatering units, biogas production and sludge disposal in agriculture. Consequently, the primary system function can be formulated as “municipal wastewater treatment to reach a minimum defined effluent quality”. Nutrient recovery from WWTP effluent is a secondary function of the system, which is introduced by the implementation of dedicated processes for recovering P and N products. This secondary function is reflected by crediting the avoided production of equivalent products to the respective scenario.

Based on the primary system function, the functional unit is defined as the impacts of a wastewater treatment process “per capita loading (pe) and annum” [impacts/(pe*a)].

This system perspective enables a comparison of different processes and pathways of wastewater treatment with a system view, showing the related total environmental impact of the system.

5.1.3 System boundaries

The system boundaries of the LCA include all processes of a WWTP related to wastewater treatment, sludge treatment and disposal (**Figure 5-1**). In particular:

- Wastewater treatment processes to reach a defined effluent quality
- Sludge thickening, digestion, dewatering, transport and disposal in agriculture
- Biogas valorisation in combined heat and power (CHP) plant
- All major background processes required for production of electricity, chemicals, and fuels
- Additional infrastructure of the IEX system (excluding infrastructure of reference system)
- Nutrients (N and P) delivered to agriculture via sludge application or via products from IEX are credited with avoided mineral fertiliser production, following an “avoided burden” approach. Field emissions and plant availability of applied nutrients are taken into account.

The geographical and temporal scope of the LCA is defined for the UK. Background data is related to UK conditions (electricity mix) or EU/world averages (chemicals, transport, infrastructure, mineral fertiliser production). Data for the reference system is assumed to represent mean operating conditions for WWTPs in the UK.

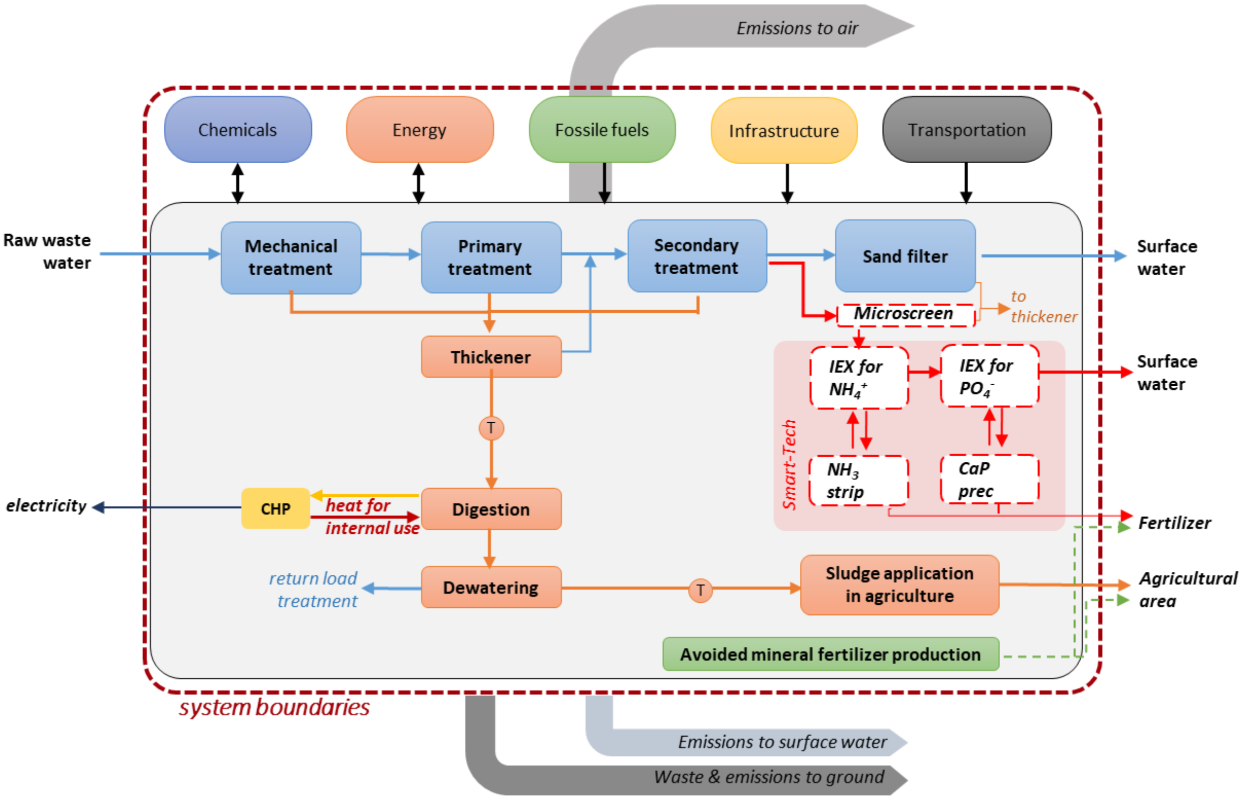

Figure 5-1: System boundaries of the LCA for conventional and IEX configurations

5.1.4 Scenarios

For the LCA, two different sizes of WWTP are analysed: a 10,000 pe WWTP representing small sites and 100,000 representing large sites. Both sizes of WWTP were compared against a reference scenario defined in cooperation with Severn Trent Water and Cranfield University which represents a typical WWTP design and operation in the UK.

Case study "small WWTP" (10,000 pe)

A short overview of the case study "small WWTP" is given in **Table 5-1** and in the descriptions below. In this case study the IEX configuration has the target to remove residual nutrients N and P after a conventional treatment process to very low concentrations ("polishing" of the WWTP effluent). Two technical alternatives for the IEX resin regeneration and ammonium stripping are analysed with different scenarios:

- Comparison of ammonium recovery from the regeneration solution with a vacuum stripper or a membrane stripping process
- Comparison of potassium chloride or sodium chloride for the N-IEX regeneration solution

0. S-REF: The reference scenario (S-REF) removes biochemical oxygen demand (BOD) and ammonia by using a trickling filter with integrated nitrification. Ferric sulphate is dosed upstream of the trickling filter and upstream of the final sand filter for chemical phosphorus removal.

Sludge treatment of this system takes place through collection and transport to a centralized larger WWTP, and thickened excess sludge is transported there via truck. Data for sludge treatment (e.g. efficiencies and energy consumption of digestion, dewatering and return load treatment) are similar to the reference scenario of the case study "large WWTP" (see below). The nutrient effluent limit values for S-REF "small WWTP" are 3 mg NH_4^+-N/ L and 0.5 mg TP/ L.

1. – 4. S-IEX: The IEX scenarios (S-IEX) also consist of trickling filters, which are operated mainly for BOD removal and remove nutrients only via biomass growth, i.e. without full nitrification or iron dosing for P

removal. The sludge treatment is similar to the scenario S-REF. Nutrients are removed by operating a two-stage IEX system downstream of the trickling filter.

The different IEX scenarios represent two different regeneration solutions for the N-IEX (KCl or NaCl) and different ammonium recovery processes (vacuum stripper or membrane stripper).
Two scenarios use a vacuum stripper for ammonium recovery as aqueous ammonia solution and can be identified by “VAC” in the scenario name: S-IEX-KCl-VAC and S-IEX-NaCl-VAC. These two scenarios differ in the regeneration solution for the N-IEX, which consists of a 2% KCl- or 2% NaCl regeneration solution. The scenarios S-IEX-KCl-MEM and S-IEX-NaCl-MEM have the same regenerant alternatives (KCl and NaCl) and recover ammonium in the form of ammonium sulphate using modules of a hollow fibre membrane contactor with sulphuric acid.

All IEX scenarios recover P in the form of calcium phosphate (CaP) by adding hydrated lime to the spent NaOH regenerant. The precipitation product can be separated from the liquid by filtration.

Table 5-1: LCA scenarios of the case study “small WWTP” (10,000 pe) with different processes for N and P removal and recovery

Scenarios	BOD removal	N removal/ recovery	P removal/ recovery
0. S-REF	trickling filter (with nitrification)	nitrification	Fe dosing and sand filter
1. S-IEX-KCl-VAC	trickling filter (without nitrification)	IEX (KCl*) + vacuum stripping	IEX (NaOH*) + CaP precipitation
2. S-IEX-NaCl-VAC		IEX (NaCl*) + vacuum stripping	
3. S-IEX-KCl-MEM		IEX (KCl*) + membrane stripping	
4. S-IEX-NaCl-MEM		IEX (NaCl*) + membrane stripping	

** additive of regeneration solution*

Case study “large WWTP” (100,000 pe)
For this WWTP size, two different targets for IEX operation are analysed (**Table 5-2**). While the “recovery” IEX configuration aims for maximum nutrient recovery and consequently limited nutrient removal in the biological stage, the “polishing” IEX configuration represents the removal of residual nutrients to very low limits after a biological nutrient removal (BNR) plant upstream.

0. L-REF: This scenario describes the reference scenario (L-REF) and represents a typical 100,000 pe biological nutrient removal (BNR) plant of Severn Trent Water. After a primary clarifier, the secondary treatment consists of biological P and N removal combined with a small supplementary iron dose. For tertiary treatment to remove P to very low limits, a second stage of iron dosing in combination with a sand filter is applied. Sludge treatment (thickening, digestion, dewatering) takes place on-site at the WWTP. The effluent limit values for the case study “large WWTP” are defined as 0.5 mg/ L NH_4-N and 0.3 mg/ L TP.

1. L-IEX-POL (“polishing target”): This scenario (L-IEX-POL) has a “polishing target” and secondary treatment consists of a BNR plant like in the reference scenario but without Fe dosing in this stage. Tertiary treatment consists of a micro screen and a two-stage IEX system for NH_4^+ and PO_4^{3-} removal to reach the defined low effluent standards. Compared to the reference scenario and recovery scenario, concentrations of NH_4^+-N/ L

and P before the IEX systems are comparatively low due to biological nutrient removal in the secondary treatment step (**Table 5-7**). The sludge treatment is similar to the L-REF scenario. Additional sludge produced in the micro screen upstream of the IEX is considered in the downstream sludge treatment.

2. L-IEX-REC ("recovery target"): This scenario (L-IEX-REC) has a "recovery target" and secondary treatment consists of an activated sludge plant for BOD removal but without targeted nutrient removal, i.e. without nitrification/denitrification and without Fe dosing. Tertiary treatment consists of a micro screen and a two-stage IEX system for NH_4^+ and PO_4^{3-} removal. Although a small proportion of nutrients is still removed in primary/secondary treatment and in the micro screen, this leaves a larger share of nutrients that can be recovered in the IEX. The setup of the sludge line is similar to the other scenarios.
For this scenario, nutrient content in the biological sludge is lower than in the other scenarios, which has consequences in sludge treatment, return load, and credits for nutrient content in agricultural disposal. Due to the lower sludge age of the biological process, the amount of excess sludge is higher.

Table 5-2: LCA scenarios of the case study "large WWTP" (100,000 pe) with different processes for N and P removal and recovery

Scenarios	BOD removal	N removal/ recovery	P removal/ recovery
0. L-REF	Activated sludge	Nitrification and denitrification	Biological P removal and tertiary sand filter with Fe dosing
1. L-IEX-POL	Activated sludge	Nitrification and denitrification and N-IEX for polishing*	Biological P removal and P-IEX for polishing
2. L-IEX-REC	Activated sludge	N-IEX for removal and maximum recovery*	P-IEX for removal and maximum recovery

**Regeneration liquid KCl for N-IEX and NaOH for P-IEX and ammonium recovery with a vacuum stripper*

5.1.5 Data source and quality

Table 5-3 shows an overview of the data quality of the used data. The input data for the sub-studies "small WWTP" and "large WWTP" (reference and in combination with IEX) are based on experiences of Severn Trent Water. The data quality is estimated as high, because Severn Trent Water operates several WWTP in different design sizes. Data regarding the IEX is mainly based on primary data collected from the demonstration plant operated from 2017 to 2019. The data quality regarding the effluent quality, energy and chemical demand is assumed to be only medium to high, because the IEX systems have not yet been realized at full-scale. However, the data relies on a long-term operating phase of two years (2017 to 2019). Nevertheless, upscaling of process data from demonstration plant installations to full-scale plants was required and was done in close cooperation with the associated partners.

The implementation of an IEX system affects the entire WWTP scheme and influences WWTP effluent quality, energy demand for treatment, but also sludge quantity and composition. These effects were estimated in close consultation with Severn Trent Water and Cranfield University, therefore the data quality is assumed to be medium to high. Efficiency, energy demand and product quality of the vacuum degasser and membrane stripper bases on laboratory experiments and estimations, therefore the data quality is low to medium. Data for precipitation of calcium phosphate from laboratory experiments were supplemented with literature data; consequently, the data quality is seen as medium.

Table 5-3: Data quality for the LCA of nutrient recovery with IEX

Process	Data source	Responsible partner	Data quality
Small and large WWTP reference system: influent, effluent, sludge, energy and chemical demand	Full-scale data of operator	Severn Trent Water	High
Operational data of upstream WWTP in IEX scenarios	Estimations	Severn Trent Water	Medium to high
N-IEX and P-IEX layout and operation, including regenerant management	Demonstration plant data (WP 3)	Cranfield University	Medium to high
Ammonium recovery from regeneration solution (vacuum degasser and membrane stripper)	Estimations, laboratory experiments	Cranfield University	Low to medium
Calcium phosphate recovery from regeneration solution	Laboratory experiments, literature	Cranfield University, KWB	Medium

5.1.6 Indicators for impact assessment

The results of this LCA study are reflected by different environmental indicators, which are calculated based on the following models:

- Cumulative energy demand (CED) for non-renewable fuels, sums up fossil and nuclear fuels to a single score and is defined in VDI 4600 (VDI 2012).
- Global warming potential (GWP), sum of all greenhouse gases. Converting factors of IPCC are used to calculate the total GWP for a time horizon of 100 years (IPCC 2014). Long-term emissions > 100 years are neglected.
- Freshwater and marine eutrophication potential (FEP and MEP), enrichment of freshwater or marine ecosystem with nitrogen or phosphor containing compounds.
- Terrestrial acidification potential (TAP), acidification of soils due to the release of gases such as nitrogen oxides and sulphur oxides.

FEP, MEP and TAP are defined in the ReCiPe method (Huijbregts *et al.* 2017). For this LCA, long-term emissions > 100a were neglected.

5.2 Input data (Life Cycle Inventory)

This chapter presents and discusses the used input data for reference WWTP, IEX configurations and background processes.

The data for WWTP and post treatment influent, for WWTP effluent and return load for the reference scenarios was defined in cooperation with Severn Trent Water and Cranfield University. Return load quantity and composition for the IEX-scenarios were modelled based on previous LCA studies.

5.2.1 Input data for case study "small WWTP" (10,000 pe)

Water quality

Relevant data for wastewater quality for total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), ammonium (NH_4-N) and total phosphorus (TP) in the influent and effluent of the different stages is given in **Table 5-4**. Effluent quality shows removal rates of TSS (> 95%), COD (> 92%), TP (> 94%) and NH_4-N (92% for S-REF and 95% for S-IEX). The high removal rates of COD and TSS are due to the post-treatment (sand filter or micro screen). The effluent is directly discharged into surface water. In the small WWTP case study, the thickened sludge is treated in a centralised treatment plant, therefore the dewatering liquor is also treated there. Therefore, the return load treated on-site at the small WWTP only consists of supernatant from gravity thickening and sand filter backwash water (4% of influent). For the centralised WWTP energy and chemical consumptions are calculated according to the WWTP of the large reference (see electricity consumption of case study "large WWTP"). From the defined effluent quality follows a removal rate for NH_4^+ and P of 93% in the IEX modules.

Table 5-4: Input data for water line of case study „small WWTP": Influent and effluent quality and return load

Parameter	Unit	Influent of WWTP	Effluent of biological stage	Final effluent of WWTP	Return load
0. S-REF					
Volume	m^3/a	911,040	943,811	906,059	44,893*
TSS	mg/L	260	20	10	2,973
COD	mg/L	480	44	35	2,322
NH_4-N	mg/L	30	3	2	-
TN	mg/L	40	20	20	28
TP	mg/L	8.4	2	0.5	332
1.- 4. S-IEX					
Volume	m^3/a	911,040	906,858	906,858	7,677°
TSS	mg/L	260	10	1	554°
COD	mg/L	480	40	25	600°
NH_4-N	mg/L	30	30	3	-
TN	mg/L	40	38	8	30°
TP	mg/L	8.4	7	0.5	24°

** Return load includes supernatant from gravity thickening and for reference scenario sand filter backwash water, ° Data modelled*

Energy

Compared to the S-REF trickling filter, the S-IEX trickling filter has a smaller filter bed volume because of no nitrification required. The energy consumption for the different trickling filters is assumed to be equal. The temperature of the regenerant is at 40°C for the vacuum stripping process therefore, it is heated (with natural gas). The membrane stripper is assumed to be operated at ambient temperature (no heat necessary). All relevant data for the energy balance of the WWTP is given in **Table 5-5**.

Table 5-5: Energy inventory of case study "small WWTP". The values refer to the input volume of the respective treatment step

Wastewater line	Unit	S-REF	S-IEX
Primary treatment (PT)			
Electricity rake	kWh/m^3	0.05	0.05
Electricity PT	kWh/m^3	0.05	0.05
Secondary treatment (Trickling filter)			
Electricity	kWh/m^3	0.19	0.19
Tertiary treatment (Sand filter/ IEX columns)			
Sand filter	kWh/m^3	0.08	-
Electricity micro screen	kWh/m^3	-	0.01
Electricity IEX	kWh/m^3	-	0.02
Nutrient recovery			
Electricity	kWh/m^3 regenerant	-	N: 0.25 (VAC), 0.53 (MEM) P: 0.37
Natural gas (Heat)	MJ/m^3 regenerant	-	44.76 (VAC)$^{(1)}$
Thickening			
Electricity	kWh/m^3 sludge	0.06	0.06

(1) Only needed for vacuum stripper (VAC). (2) Heat produced in BHKW and heat demand of digester is assumed to be equal (no heat demand and credits)

Chemical consumption

The specific chemical consumption of the small case study is summarised in **Table 5-6**. In the reference scenario mainly, ferric sulphate for chemical P removal and polymer for sludge treatment are used. For tertiary treatment iron dosing in combination with a sand filter is applied.

IEX scenarios need resin, chemicals for regeneration of the IEX resin and chemicals for product recovery. The amount of cationic and anionic resin is based on data from the demonstration plant in Cranfield with a flow rate of 10 m^3/d. At a flow rate of 10 m^3/d, for the cationic bed a volume of 100 L resin (density 0.78 kg/L) is assumed. The bed volume of the anionic resin is estimated to be 28 L (density 0.85 kg/L). Life time of the resins is assumed to be 5 years, accounting also for mechanical abrasion with 4% loss per year. Disposal expenditures for the spent anionic resin are included. The spent cationic resin consists of zeolite which is enriched with ammonium and can theoretically be used as fertiliser. Therefore, for the cost of disposal for the cationic resin is assumed to be zero, but related nutrient credits for ammonium and zeolite are not given because its application is not approved.

The amount of sodium and potassium chloride required for N-IEX regeneration is calculated by molar ion balancing: each NH_4^+ ion replaces one K^+ or Na^+ ion, which is lost in the effluent and has to be replaced with fresh salt solution. In addition, 2% losses of the regeneration solution are accounted per year. The anionic ion exchanger adsorbs PO_4^{3+}-ions and releases them into the regeneration solution at a high pH value, exchanging with OH^- ions. These ions are “recharged” to the regeneration solution by using caustic lime for P precipitation. Consequently, the sodium hydroxide consumption is comparatively low and covers only the regular losses (2% per regeneration cycle).

Sulphuric acid is used to produce ammonium sulphate (21% N) in the IEX-scenarios with membrane stripping (S-IEX-MEM). The required amount is calculated stoichiometrically. In addition, sulphuric acid consumption is calculated stoichiometrically for the P-IEX system in order to convert the recovered CaP into a plant-available form, so that a conventional plant-available P-fertiliser can be credited for this product.

Table 5-6: Chemical demand for case study "small WWTP". Unless otherwise specified, the values refer to the input volume of the respective treatment step.

Wastewater line	Unit	S-REF	S-IEX
Secondary treatment (trickling filter)			
Ferric sulphate (100% Fe)	g/m^3	17.00	-
Tertiary treatment (Sand filter/ IEX columns)			
Ferric sulphate (100% Fe)	g/m^3	8.00	-
Potassium chloride (100%) (Sodium chloride)(1)	kg KCl (NaCl)/kg N removed	-	3.42 (2.02)
Sodium hydroxide (100%)*(2)*	kg NaOH/a	-	3.70
Cationic resin*(3)*	t/a	-	4.04
Anionic resin*(3)*	t/a	-	1.23
Nutrient recovery			
Sulphuric acid (98%) for N recovery *(4)*	kg/kg N in product	-	3.57*(4)*
Sulphuric acid (98%) for conversion of CaP	kg/kg P in product	-	3.22
Hydrated lime ($Ca(OH)_2$, 100%*(5)*	kg/kg P	-	2.64
Thickening			
Polymer (100% active substance)	kg/t DS	3.00	3.00
Credit for nutrients in product			
Recovered N (100% N)	t/a	-	25
Recovered P (100% P)	t/a	-	6

(1) *Nutrient recovery from regeneration solution takes place if 800 mg N/ L are reached in regenerant.*

(2)*Adsorption process, consequently ions are not spent. Regeneration takes place if 600 mg P/L are reached in regenerant. 100 regeneration cycles are possible with the same solution.* (3) *Cationic and anionic resin has an assumed life time of 5 years. The mechanical abrasion is estimated to be 4% per year.* (4) *Only needed for S-IEX-MEM scenarios.* (5) *Beta factor for calcium dosing 1.8 mol Ca/mol P.*

Direct emissions of WWTP

For the reference, direct N_2O emissions to the air of the WWTP process are estimated be 1% of influent TN to the biological stage. This assumption is based on a linear correlation between total N removal and N_2O emission factors (Parravicini et al., 2016). For the IEX scenarios no targeted N removal takes place in the biological stage of the WWTP. Consequently, no N_2O emissions of the biological stage are assumed in this LCA study. Direct ammonia emissions of biological treatment are assumed to be 0.6% of NH_4-N load in the influent (Bardtke et al., 1994).

Sludge treatment

The biological stage of the case study “small WWTP” consists of trickling filters, which remove mainly BOD and eliminate nutrients by biomass growth only (- 5% for TN and TP into the sludge). Due to the lower sludge age, an increase of 10% in organic sludge yield is assumed for the trickling filter in IEX scenarios.

The thickened sludge is transported to and treated in a centralised WWTP at a distance of 15 km. The efficiencies, energy and chemical consumptions for digestion and dewatering are the same as for the case study “large WWTP”.

For the treatment of liquor from sludge dewatering, electricity factors as defined in the case study “large WWTP” are assumed (ATV, 2000). Removal efficiencies for the centralised dewatering liquor treatment are 90% for COD, 99% for NH_4-N, 80% for total N via denitrification and 96% for TP.

Sludge and product application in agriculture

Dewatered sludge is used for agricultural application. For the crediting of nitrogen and phosphate in the sewage sludge, nutrient equivalency factors of the Lower Saxony Chamber of Agriculture (Landwirtschaftskammer Niedersachsen, LWK NS) and results of the P-REX project (Remy and Jossa, 2015)are used to calculate the substitution potential of nutrients in sludge and products in relation to mineral fertilizer. For nitrogen, an accounting rate of 25% for sewage sludge (LWK NS, 2018) and 100% for ammonium sulphate or ammonia solution represent the average of literature values. For phosphate in sludge, higher accounting rates e of 60% can be assumed due to its accumulation in soil. For conventional P-fertiliser (in this case CaP treated with sulfuric acid) the application rate is assumed to be 80%.

The direct emissions into groundwater and air due to product and sludge application in agriculture were estimated for the non-utilized fraction on the basis of literature references.

Direct emissions from nutrient application are assumed for ammonia to be 10.7% of TN in sludge and 6.2% of TN in conventional fertiliser, for nitrous oxide 1.0% of TN in sludge or product and for nitrogen dioxide 1.2% of TN in sludge or product N (EEA, 2016; Eionet, 2017). Emissions to groundwater are calculated for nitrogen 7.9% of TN and 5.0% of P_2O_5 applied (Ecoinvent, 2017).

Infrastructure

Material demand for additional infrastructure is accounted only for the IEX stage. A rough estimation of the additional infrastructure for the IEX was made and includes 0.5 tons of stainless steel, 0.5 of reinforcing steel, 10 m^3 of concrete and 5 tons of PE. The corresponding lifetimes of the equipment are estimated to 25 years for concrete, 20 years for steel and 5 years for polyethylene.

5.2.2 Input data for case study “large WWTP” (100,000 pe)

Water quality

Table 5-7 presents an overview of the wastewater quality parameters. Removal rates of TSS (> 98%), COD (> 94%), TP (> 94%) and TN (> 96%) are estimated.

For the reference scenario, backwash water from the sand filter of the reference scenarios adds to the return load to the WWTP (< 4% of influent). In the case study “large WWTP” the return load consists of sludge thickening, sludge dewatering and sand filter backwashing, which is estimated differently for all scenarios. The IEX system results in a nutrient removal rate of 98% for NH_4^+ and 96% for P for the recovery IEX and a removal rate of IEX 95% for NH_4^+ and 83% for P for the polishing IEX.

Table 5-7: Input data for waterline of case study “large WWTP”: Influent and effluent quality, concentrations of nutrients and return load

Parameter	Unit	Influent of WWTP	Influent post treatment[#]	Effluent (quality) of WWTP	Return load
0. L-REF					
Volume	m^3/a	9,110,400	9,481,400	9,102,200	687,200*
TSS	mg/L	260	10	5	592
COD	mg/L	480	40	30	511
NH_4-N	mg/L	30	0.5	0.5	
Total N	mg/L	40	15.5	15.5	28
Total P	mg/L	8.4	0.75	0.3	21
1. L-IEX-POL					
Volume	m^3/a	9,110,400	9,103,100		305,000°
TSS	mg/L	260	10	1	590°
COD	mg/L	480	40	30	638°
NH_4-N	mg/L	30	10	0.5	

TN	mg/L	40	15.5	5	146°
TP	mg/L	8.4	2	0.3	25
2. L-IEX-REC					
Volume	m^3/a	9,110,400	9,103,100		305,000°
TSS	mg/L	260	10	1	590°
COD	mg/L	480	40	30	638°
NH$_4$-N	mg/L	30	30	0.5	
TN	mg/L	40	38	6	146°
TP	mg/L	8.4	7	0.3	90°

** Including sand filter backwash water, # For IEX-scenarios: downstream micro screen, before N-IEX, ° Data modelled*

Energy demand

The energy demand for the scenarios of the case study “large WWTP” is shown in **Table 5-8**. For all scenarios the specific electricity demand for primary treatment and sludge treatment (thickening and dewatering) is estimated to be equal. Electricity demand for the biological stage varies between 0.14 and 0.25 kWh/m^3, depending on the nutrient removal targets of this stage. The electricity consumption of secondary treatment is calculated according to (ATV, 2000) using the following electricity factors: 1 kg O_2 requirement per kg degraded COD (aerobic degradation), 4.57 kg O_2 requirement per kg degraded NH_4 (nitrification) and 2.86 kg O_2 recovery per kg degraded NO_3 (denitrification). The total energy consumption for oxygen transfer into the aeration tank via aeration is assumed to be 0.5 kWh/kg O_2. For the recirculating of wastewater from the aerobic to the anoxic zone (for upstream denitrification) an electricity consumption of 1 kWh/kg degraded N is assumed for pumping (MUNLV, 1999).

For the reference an electricity consumption of 0.08 kWh/m^3 is estimated for the final sand filter. For the IEX scenarios, 0.03 kWh/m^3 is assumed for the micro screen and the pumps for the IEX modules. For the digester, the electricity demand amounts to 16 kWh/m^3 sludge and the methane yield 350 Nm^3/t COD removed. Heat demand of the digester and heat production of the CHP is estimated to be balanced.

Table 5-8: Energy inventory of case study “large WWTP”. The values refer to the input volume of the respective treatment step.

Wastewater line	Unit	L-REF	L-IEX-POL	L-IEX-REC
Primary treatment (PT)				
Electricity rake	kWh/m^3	0.05	0.05	0.05
Electricity PT	kWh/m^3	0.05	0.05	0.05
Secondary treatment (BNR plant)				
Electricity	kWh/m^3	0.25	0.24	0.14(1)
Tertiary treatment (Sand filter/ IEX columns)				
Electricity sand filter	kWh/m^3	0.08	-	-
Electricity micro screen	kWh/m^3	-	0.01	0.01
Electricity IEX	kWh/m^3	-	0.02	0.02
Nutrient recovery				
Electricity	kWh/m^3 regenerant	-	N: 0.25 P: 0.37	N: 0.25 P: 0.37
Natural gas (Heat)	MJ/m^3 regenerant	-	44.76	44.76
Thickening				
Electricity	kWh/m^3 sludge	0.06	0.06	0.06
Digestion				
Electricity demand(2)	kWh/m^3 sludge	16.64	16.64	16.64

Wastewater line	Unit	L-REF	L-IEX-POL	L-IEX-REC
Methane yield	Nm^3/t COD removed	350	350	350
COD degradation ratio	%	48	48	48
Electrical efficiency of CHP	%	41.70	41.70	41.70
Dewatering				
Electricity	kWh/m^3 sludge	2.00	2.00	2.00

(1) Pumping for internal sludge recirculation is not included, pumping for return sludge is included. (2) Heat produced in BHKW and heat demand of digester is assumed to be equal (no heat demand and credits)

Chemical consumption

An overview of the specific chemical consumption is given in **Table 5-9**. Ferric sulphate dosing for chemical P removal is only applied in the reference. The specific chemical consumption for the IEX systems is calculated in analogy to the case study "small WWTP".

Table 5-9: Chemical demand of case study "large WWTP". Unless otherwise specified, the values refer to the input volume of the respective treatment step.

Wastewater line	Unit	L-REF	L-IEX-POL	L-IEX-REC
Secondary treatment (BNR plant)				
Ferric sulphate (100% Fe)	g/m^3	2.00	-	-
Tertiary treatment (Sand filter/ IEX columns)				
Ferric sulphate (100% Fe)	g/m^3	4.00	-	-
Potassium chloride (100%)(1)	kg KCl/kg N removed	-	3.42	3.42
Sodium hydroxide (100%)*(2)*	kg NaOH/a	-	8.97	36.36
Cationic resin*(3)*	t/a	-	40.57	40.57
Anionic resin*(3)*	t/a	-	12.31	12.31
Nutrient recovery				
Sulphuric acid (98%) for conversation of CaP	kg/kg P in product	-	3.22	3.22
Hydrated lime ($Ca(OH)_2$, 100%)*(4)*	kg/kg P	-	2.64	2.64
Thickening				
Polymer (100% active substance)	kg/t DS	3.00	3.00	3.00
Dewatering				
Polymer (100% active substance)	kg/t DS	7.00	7.00	7.00
Credit for nutrients in products				
Recovered N (100% N)	t/a	-	86	268
Recovered P (100% P)	t/a	-	91	400

(1) Nutrient recovery from regeneration solution takes place if 800 mg N/ L are reached in regenerant. (2) Adsorption process, consequently ions are not spent. Regeneration takes place if 600 mg P/L are reached in regenerant. 100 regeneration cycles are possible with the same solution. (3) Cationic and anionic resin has an assumed life time of 5 years. The mechanical abrasion is estimated to be 4% per year. (4) Beta factor for calcium dosing 1.8 mol Ca/mol P.

Direct emissions of WWTP

For the reference, direct N_2O emissions to the air of the WWTP process are estimated to be 0.85% of influent TN and for the polishing IEX configuration 0.9% of influent TN to the biological stage. This assumption is based on a linear correlation between total N removal and N_2O emission factors (Parravicini *et al.* 2016). For the recovery IEX configuration no targeted N removal takes place in the biological stage of the WWTP. Consequently, no N_2O emissions of the biological stage are assumed in this LCA study. Analogue to the case study “small WWTP”, direct ammonia emissions from biological treatment are assumed to be 0.6% of influent NH_4-N (Bardtke et al., 1994).

Sludge treatment and disposal

The setup of the sludge line is similar for each scenario, but the side-stream water line configurations suffer changes depending on the downstream sludge treatment processes. The amount of sludge and therefore the absolute biogas production increases in the IEX setups. This results from two effects: i) no targeted nutrient removal in the biological stage leads to lower sludge ages and higher sludge amounts (+10% in organic matter) and ii) additional sludge from the micro screen upstream of the IEX stage.

Sludge treatment takes place on-site of the large WWTP. Requirements for electricity and polymer for sludge dewatering and thickening are shown in **Table 5-8** and **Table 5-9**. The dewatered sludge is transported 15 km for agricultural application. Nutrient credits for sewage sludge and products and direct emissions of nutrient application are estimated according to the case study “small WWTP”.

Infrastructure

A rough estimation of the additional infrastructure for the two sub-studies was made and includes 5 tons of stainless steel, 5 ton of reinforcing steel, 100 m^3 of concrete and 50 tons. The corresponding lifetimes of the equipment are estimated to 25 years for concrete, 20 years for steel and 5 years for polyethylene.

5.2.3 Background data

Background processes are modelled with datasets from ecoinvent database v3.4 (Ecoinvent, 2017). The related datasets are shown in **Table 5-10**. The market mixes refer to the global market [GLO] or European market [RER]. For electricity, the market mix of the UK is applied.

Table 5-10: Datasets for background data

Process	Dataset from ecoinvent v3.4	Remarks
Electricity	market for electricity, medium voltage [GB]	For all operational electricity demand and credits from biogas
Heat	Heat production, natural gas, at boiler modulating <100kW [RER]	Heat for ammonium stripping
Polymer	market for acrylonitrile [GLO]	746 g acrylonitrile + water = 1kg of polymer active substance
Ferric sulphate	iron sulphate production [RER]	Precipitation agent
Sulfuric acid	market for sulfuric acid [GLO]	Acid to produce ammonium sulphate
Potassium chloride	market for potassium chloride, as K2O [GLO]	For regeneration solution for N-IEX
Sodium chloride	market for sodium chloride, brine solution [GLO]	For regeneration solution for N-IEX
Sodium hydroxide	market for sodium hydroxide, without water, in 50% solution state [GLO]	For regeneration solution for P-IEX
Hydrated lime	market for lime, hydrated, lose weight [RoW]	For precipitating CaP
Cationic resin	market for cationic resin [GLO]	Resin of N-IEX
Anionic resin	market for anionic resin [GLO]	Resin of P-IEX

Process	Dataset from ecoinvent v3.4	Remarks
Disposal of anionic resin	market for spent anion exchange resin from potable water production [GLO]	Disposal of spent resin
Ammonia solution (100% N)	diammonium phosphate, as N, at regional storehouse [RER]	Credit for recovered ammonium
Calcium phosphate	market for phosphate fertiliser, as P2O5 [GLO]	Credit for recovered CaP
Truck transport	transport, freight, lorry 16-32 metric ton, EURO5 [RER]	Sludge transports
Nitrogen	diammonium phosphate, as N, at regional storehouse [RER]	Fertiliser credit for N in sludge in agriculture
Phosphate	market for phosphate fertiliser, as P2O5 [GLO]	Fertiliser credit for P in sludge in agriculture
Concrete	market for concrete [RoW]	Infrastructure material for IEX foundation
Stainless steel	steel production, electric, chromium steel 18/8 [RoW]	Infrastructure material for IEX
Reinforced steel	reinforcing steel production [RoW]	Infrastructure material for IEX
Polyethylene	polyethylene production, low density, granulate [RER]	Infrastructure material for IEX

5.3 Results of environmental indicators (Life Cycle Impact Assessment)

The total results of this LCA are presented below for each indicator, reflecting the selected LCA indicators CED, GWP, FEP and MEP. In addition, for CED and GWP the environmental impacts of IEX implementation are quantified in relation to the corresponding reference scenarios "S-REF" and “L-REF”, showing only the changes in environmental impact to enable a clear tracking of the main contributions.

5.3.1 Results for case study “small WWTP”

Cumulative energy demand of non-renewable resources (CED)
As seen in Figure 5-2 the electricity consumption of the WWTP and the CHP credit for biogas production have a big influence on the results of this indicator. The reference net CED accounts for nearly +201 MJ/(pe*a), which results from a gross CED of +430 MJ/(pe*a) and credits for biogas and nutrients of -230 MJ/(pe*a). The implementation of an ion exchanger with KCl as regeneration solution and a vacuum stripping process to recover ammonium (scenario 1) increases the net CED by 32% to +265 MJ/(pe*a). Although the net credits increase by more than 100% due to a higher nutrient recovery, expenditures for the IEX system such as chemicals of +122 MJ/(pe*a), heat of +182 MJ/(pe*a) and electricity of +55 MJ/(pe*a) completely off-set these benefits of the IEX system. Compared to the reference scenario, there are additional savings of -102 MJ/(pe*a) in the WWTP electricity consumption and -28 MJ/(pe*a) for the substituted precipitation agent (ferric sulphate). Overall, the increased nutrient credits, savings in WWTP electricity and savings in precipitation agent do not off-set the additional efforts needed for the IEX process. The results show a different picture, if excess heat for the vacuum stripping process is available. In this case, the net CED of the first scenario is reduced by nearly 40% to +83 MJ/(pe*a) compared to the reference scenario (NET VALUE with excess heat).
Using NaCl instead of KCl for the N-IEX regeneration reduces the cumulative energy demand by -57 MJ/(pe*a) and results in a net CED of +208 MJ/(pe*a) and +26 MJ/(pe*a) if excess heat is available, see scenario 2.

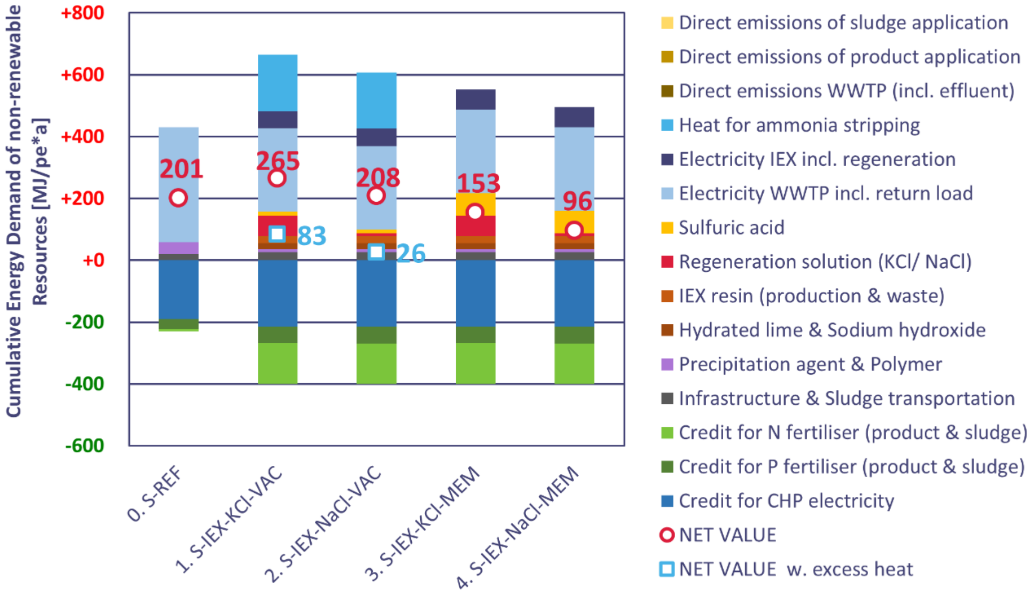

Figure 5-2: Cumulative energy demand for reference and IEX scenarios of a small WWTP (10,000 pe)

Regenerating the ammonium with a membrane stripper instead of the vacuum stripper results in energy savings of -172 MJ/(pe*a) for the IEX process, see scenarios S-IEX-KCl-MEM and S-IEX-NaCl-MEM. This results in a net CED of +153 MJ/(pe*a) with KCl and +96 MJ/(pe*a) with NaCl as N-IEX regeneration liquid. Sulfuric acid for collecting ammonium in the membrane stripping process (+60 MJ/(pe*a)) is energetically cheaper than the heat demand for the vacuum stripping process (+182 MJ/(pe*a)). For the energy indicator, infrastructure and sludge transportation play a minor role.

Overall, the implementation of an IEX system increases the net CED in the range of 3-32% if ammonium is recovered with a vacuum stripper, and decreases in the range of 24-52% if it is recovered with a membrane stripper. In the lower percent range NaCl and in the higher range KCl is used for the regeneration of the N-IEX resin.

Relative changes between +65 MJ/(pe*a) and -105 MJ/(pe*a) can be observed if an IEX for tertiary treatment is applied and no excess heat is available, see Figure 5-3. The main benefits of the implementation of an IEX system are the reduced WWTP energy demand (-100 MJ/(pe*a)) and production of N-fertiliser (-123 MJ/(pe*a)). Smaller benefits are a slightly higher biogas production due to additional sludge from the micro screen (-15 MJ/(pe*a)), omission of precipitation agent (-28 MJ/(pe*a)) and production of P-fertiliser (-22 MJ/(pe*a)). If only the energy and chemical demand of the IEX process are compared with the given nutrient credits, i.e. if the side-effects on the WWTP are ignored, the CED results differ significantly. The total additional nutrient credits are -145 MJ/(pe*a). In contrast, the energetic efforts for chemicals and energy quantify between +191 and +360 MJ((pe*a), which is between 32% and 1.5-fold higher than the nutrient credits. It is concluded, therefore that the IEX is only energetic beneficial if positive side-effects on the WWTP occur such as savings in energy or chemical demand.

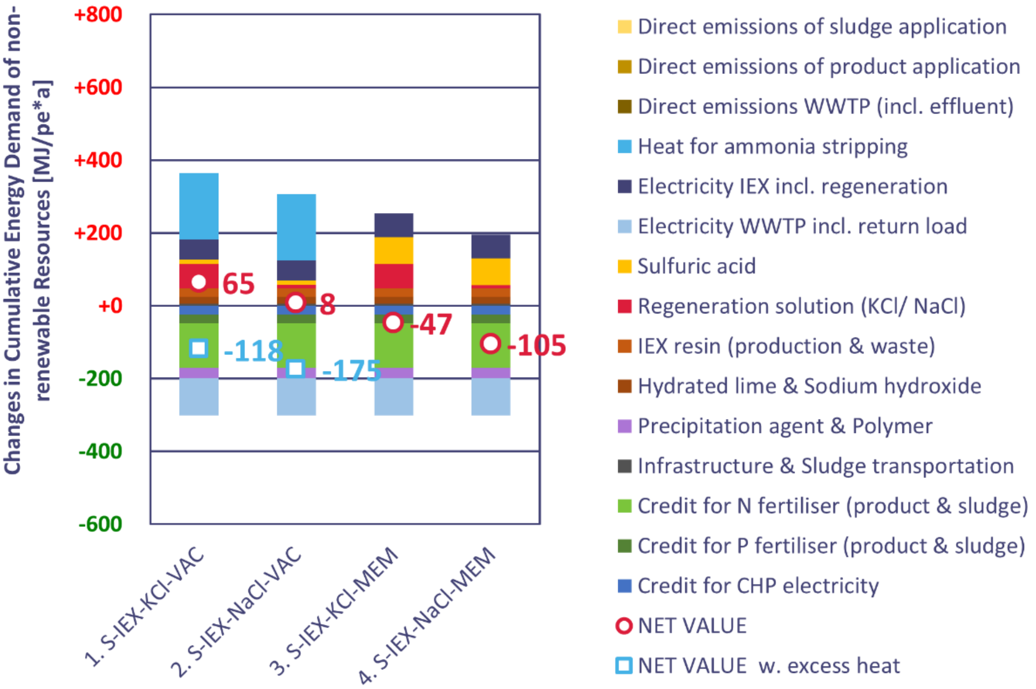

Figure 5-3: Relative changes of total cumulative energy demand due to the implementation of an IEX process in a small WWTP (10,000 pe)

Global warming potential (GWP)
The results of the indicator GWP of the LCA differ slightly from the results of the CED (**Figure 5-4**). The net GWP of the reference WWTP amounts to +35 kg CO_2-eq/(pe*a), which results from +51 kg CO_2-eq/(pe*a) gross impacts and -16 kg CO_2-eq/(pe*a) gross savings. The main drivers of the impacts are direct emissions of WWTP (+18 kg CO_2-eq/(pe*a)) and the electricity demand of the WWTP (+28 kg CO_2-eq/(pe*a)). The direct greenhouse gas emissions consist to over 90% of N_2O emissions originating from the biological stage.
The total net GWP for the IEX scenarios is between +10 and +23 kg CO_2-eq/(pe*a), depending on the regeneration and recovery processes of the N-IEX.

For scenario 1, the implementation of an IEX decreases the total net GWP by 34% to +71 kg CO_2-eq/(pe*a). Compared to the reference scenario, higher credits for nutrient recovery (+500%), lower electricity demand of the WWTP (-29%) and a reduction in N_2O-emissions from biological stage (-95%) contribute mainly to the reduction in greenhouse gases. The remaining direct emission of the IEX scenarios result from methane degassing in the centrifuge after the digester. These positive effects are partly diminished by the additional electricity (+4 to +5 kg CO_2-eq/(pe*a)), heat (+11 kg CO_2-eq/(pe*a)) and chemical demand (+6 to +9 kg CO_2-eq/(pe*a)) of the IEX processes.

Corresponding to the CED indicator, using NaCl instead of KCl for N-IEX resin regeneration is beneficial and saves -3 kg CO_2-eq/(pe*a). Recovering ammonium with a membrane stripper instead of a vacuum degasser reduces the GWP by additional -10 kg CO_2-eq/(pe*a). Direct emissions of sludge application reduce the total GWP by another -2 kg CO_2-eq/(pe*a) due to a reduced nitrogen content in sludge applied in agriculture and related N_2O emissions.
Overall, the implementation on an IEX has a beneficial impact on the GWP of the WWTP.

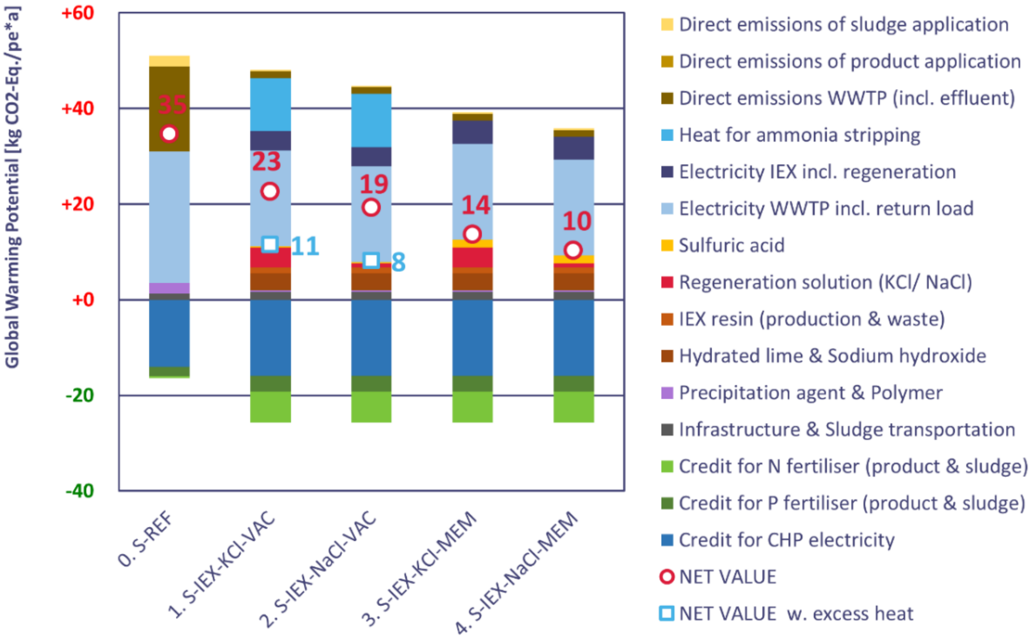

Figure 5-4: Global warming potential for reference and IEX scenarios of a small WWTP (10,000 pe)

Figure 5-5 shows the effects on the GWP in relation to the reference. If an IEX system is installed, the increased nutrient credits, direct emission and energy savings at the WWTP off-set the impacts due to additionally required chemical and energy (-12 to -24 kg CO_2-eq/(pe*a)). If excess heat is available, the net GWP can be reduced up to -27 kg CO_2-eq/(pe*a) compared to the reference WWTP. For this indicator the most beneficial operation mode of an IEX is reflected by scenario 2. That means N-IEX resin is regenerated with NaCl and the vacuum stripper for ammonium recovery is operated with excess heat (-27 kg CO_2-eq/(pe*a)). If no excess heat is available, it is beneficial to strip ammonium with a membrane stripper (-24 kg CO_2-eq/(pe*a)).

Similar to the CED and valid for all scenarios, transportation and infrastructure have no relevant effect on the total gross GWP (<6%).

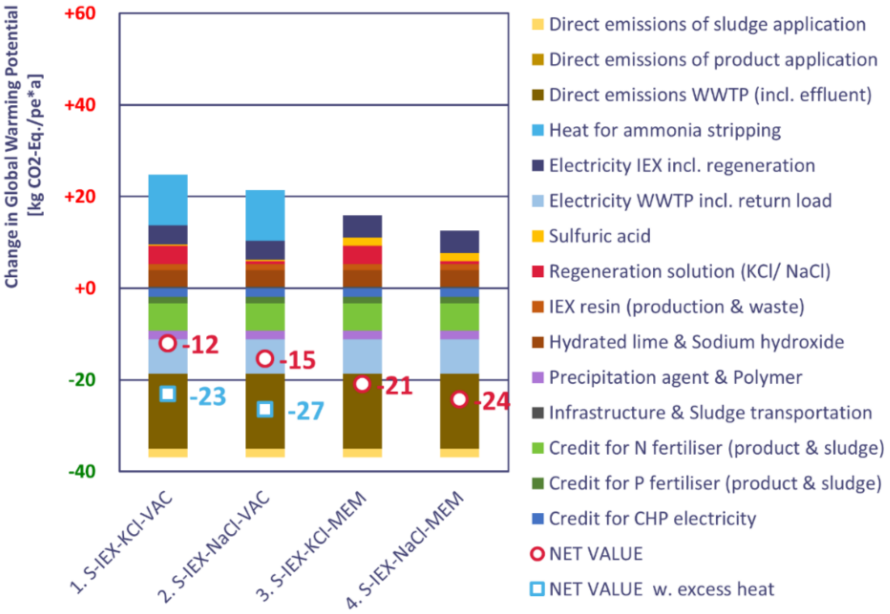

Figure 5-5: Relative changes of total global warming potential for reference and IEX scenarios of a small WWTP (10,000 pe)

Freshwater Eutrophication Potential (FEP)

The net FEP of the reference WWTP amounts to +62 g P-eq/(pe*a) and around +57 g P-eq/(pe*a) for the IEX scenarios. The gross efforts of the FEP is determined to over 80% by the direct WWTP emissions, which reflect in this case the residual phosphorus content in the WWTP effluent. The WWTP effluent quality for P is defined as 0.5 mg P/L for all scenarios of the small case study, consequently **Figure 5-6** shows the same direct WWTP emissions (+49 g P-Eq./(pe*a)) for all scenarios.

The FEP for the reference scenario shows higher direct emissions for sludge application due to a higher P-load in the sludge. In the IEX scenarios, direct emissions of P-product application occur at the same time. The higher fertilizing efficiency of the P product from IEX leads to lower field emissions during application, which is a real benefit of nutrient recovery into a concentrated form of fertilizer compared to the direct application of nutrients with sludge. Energy and chemical consumption, as well as fertiliser credits are not relevant for the results of FEP.

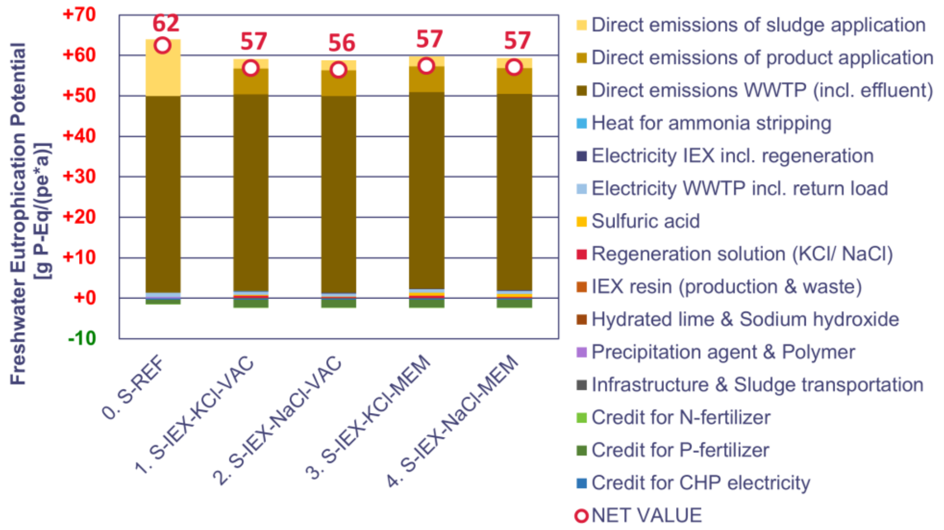

Figure 5-6: Freshwater Eutrophication Potential for reference and IEX scenarios of a small WWTP (10,000 pe)

Marine Eutrophication Potential (MEP)

In analogy to the FEP indicator, the MEP indicator is determined by the WWTP effluent quality. For MEP, the total nitrogen content in the WWTP effluent is decisive.

The net MEP of the reference WWTP amounts to +2.1 kg N-eq/(pe*a) and +0.8 kg N-eq/(pe*a) for the IEX scenarios (**Figure 5-7**). These differences result from different defined TN values in the WWTP effluent. For the reference scenario TN equals 20 mg TN/ L (full nitrification, but no denitrification) and for the IEX scenarios only 8 mg TN/ L (direct removal of NH_4). The ammonium concentration for all scenarios is less or equal to 3 mg NH_4-N/ L. This shows that WWP effluent quality of treatment plants without denitrification can be significantly improved if an IEX process is used to directly remove NH_4 to a larger extent.

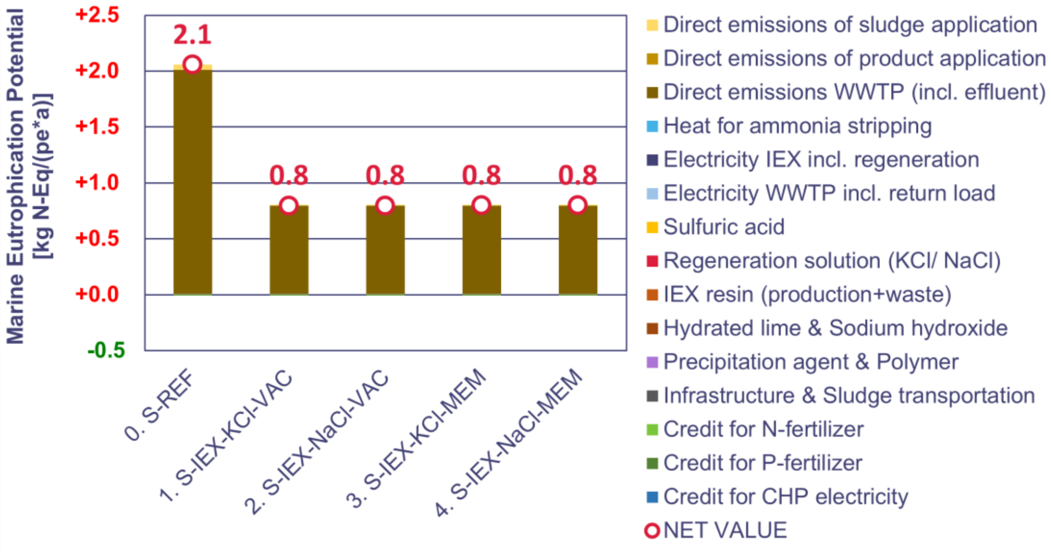

Figure 5-7: Marine Eutrophication Potential for reference and IEX scenarios of a small WWTP (10,000 pe)

Terrestrial Eutrophication Potential (TAP)

The reference net TAP accounts to +0.29 kg SO_2-eq/(pe*a), which is caused by a gross TAP of +0.38 kg SO_2-eq/(pe*a) and credits of -0.08 kg SO_2-eq/(pe*a), (**Figure 5-8**). Direct emissions of the WWTP process result from ammonia emissions, which are mainly caused by aeration of raw wastewater in the biological stage and partial stripping of ammonium. The estimated ammonia emission factor is the same for all scenarios. In the reference another big TAP contribution is caused by the N compounds in the sludge, if it is applied in agriculture (+0.16 kg SO_2-eq/(pe*a). The direct emissions of sludge application reflect the net additional field emissions of sludge application. The high non-utilized fraction of N in sludge (75%) leads to high field emissions of NH_3, whereas the recovered N product from IEX can be fully utilized, i.e. generates no additional emissions compared to the use of mineral N fertilizer. For the scenarios with a membrane stripper, the production of sulfuric acid demand has also a big share on TAP (+0.07 kg SO_2-eq/(pe*a)).

Overall, for the IEX scenarios the TAP is reduced by 34 to 59%, mainly by transferring nitrogen from the sewage sludge with low availability into a conventional fertiliser with high availability.

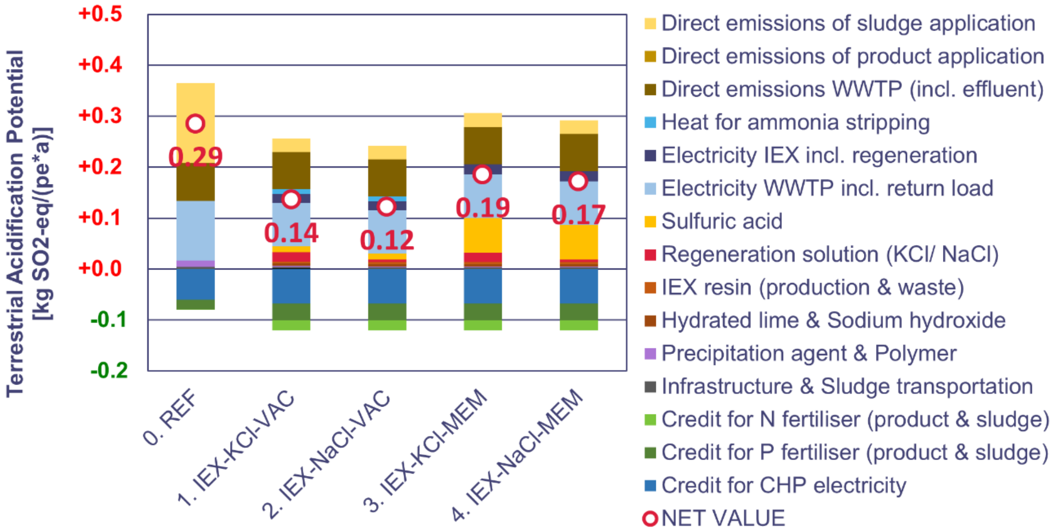

Figure 5-8: Terrestrial Acidification Potential for reference and IEX scenarios of a small WWTP (10,000 pe)

5.3.2 Results for case study “large WWTP”

Cumulative energy demand of non-renewable resources (CED)

Figure 5-9a shows the CED of the large reference and the large IEX scenarios. For the reference WWTP the net CED amounts to +246 MJ/(pe*a) which results from +508 MJ/(pe*a) gross impacts and -261 MJ/(pe*a) gross savings. The main drivers of the impacts are the electricity demand of WWTP (+487 MJ/(pe*a) and the main credit is the energy production (-217 MJ/(pe*a)). Consequently, the energy self-sufficiency is at 45%.

IEX implementation at a large WWTP increases the CED by 2-9% compared to the reference, mainly due to chemical use and heat for the vacuum stripper. The net CED is reduced by 17 (NET VALUE) and 72% if on-site excess heat is available (NET VALUE with excess heat). The IEX reduces the energy demand of the biological stage by 18 and 38%, depending on the nutrient target of the biological treatment.

The amount of recovered nutrients increases by factor 2 for the polishing scenario and nearly a factor 4 for the recovery scenario. But for the CED indicator, the credit for the nutrients does not off-set the energy and chemical demand for the nutrient recovery, if no excess heat is available. However, the additional effort can be mitigated by positive side-effects on the WWTP such as energy and chemical savings.

Figure 5-9b shows the relative changes, which are +22 MJ/(pe*a) or -40 MJ/(pe*a) with available excess heat for the polishing scenario and +6 MJ/(pe*a) or -178 MJ/(pe*a) with available excess heat (with heat) for the recovery scenario. Furthermore **Figure 5-9**b shows that the chemical and energy demand of the IEX system correlates linearly to the amount of recovered nutrients, as chemicals are used stoichiometrically for IEX regeneration and nutrient recovery.

It is noticeable that the credit for the P-fertiliser changes only slightly in the scenarios. This is due to the fact that phosphorus removed with the IEX is missing from the sewage sludge and the accounting factor for P in the sludge and in the IEX product is similar (60% for sewage sludge and 80% for IEX product). The higher CHP credit of scenario 2 results from a higher sludge amount due to a lower sludge age in the biological stage as no nitrogen removal is required in this stage.

Overall, the implementation of an IEX has only a beneficial impact on the CED of the large WWTP if excess heat is available and energy savings in the biological stage can be realized.

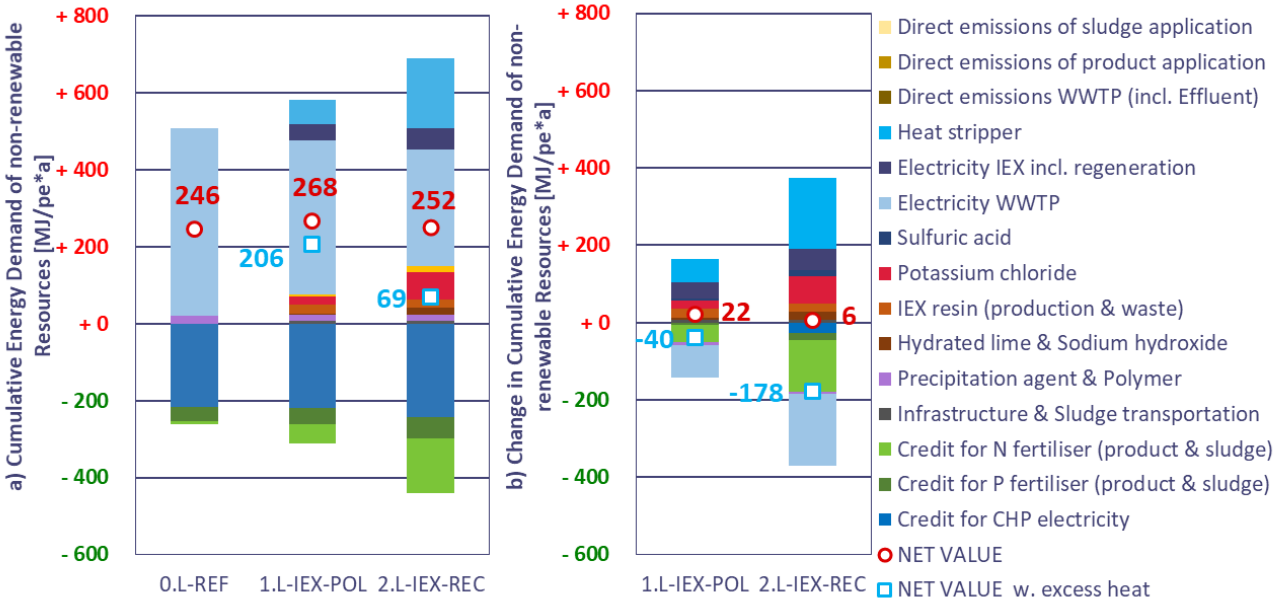

Figure 5-9: Cumulative energy demand for reference and IEX scenarios of a large WWTP (100,000 pe): a) total CED and b) CED changes in relation to the reference

Global warming potential (GWP)

The total net GWP of the baseline scenario amounts to +39 kg CO_2-eq/(pe*a), see **Figure 5-10a**. Thereof, the system has a gross GWP impact of +58 kg CO_2-eq/(pe*a) and receives credits for energy recovery and sludge application of -18 kg CO_2-eq/(pe*a). Hence, one third of the system's GWP is compensated. Similar to the CED, the main driver of the gross GWP is the electricity consumption for the WWTP operation. In addition, the reference scenario in Figure 5-10a shows direct emissions (mainly N_2O from biological stage) of +18 kg CO_2-eq/(pe*a).

If an IEX system is installed for effluent polishing purposes, savings regarding the WWTP electricity consumption are made. Those savings result mainly due to the avoided energy for the sand filter, but they are directly off-set by the electricity demand of the IEX modules and of the micro screen. Overall, the GWP for the polishing scenario is nearly equal to the reference scenario (+ 1 to - 3 kg CO_2-eq/(pe*a)), depending on the impacts of ammonium recovery.

The IEX recovery scenario shows a GWP reduction of 46% compared to the reference scenario. This is due mainly to the avoided direct N_2O emissions because there is no targeted nitrogen removal in the biological stage. Furthermore, there are higher nutrient credits by factor of 5, which account in total -10 kg CO_2-eq/(pe*a). The savings in GWP are slightly mitigated by the heat demand of the vacuum stripper with +11 kg CO_2-eq/(pe*a) and electricity and chemical consumption of the IEX (+15 kg CO_2-eq/(pe*a)). Infrastructure and transportation account for less than 3% of the total GWP for all scenarios.

Figure 5-10b shows the change in GWP due to implementing for the two IEX scenarios. For the polishing scenario, the electricity savings and nutrient credit and additional efforts for the IEX operation are balanced. The recovery scenario has savings in GWP due to positive side-effects (mainly energy and N2O savings in biological stage) which are higher than the efforts for IEX operation.

Overall, the implementation of an IEX reduces the net GWP significantly if positive side-effects like mitigation of direct N_2O emissions to air (from the biological stage and from sludge application in agriculture) and reduction of the electricity demand for the biological stage occur. If there are no beneficial side-effects on the wastewater treatment plant due to IEX implementation, the GWP increases slightly. This is due to the fact that the credit from the recovered nutrients is lower than the additional chemicals and energy required for the IEX process.

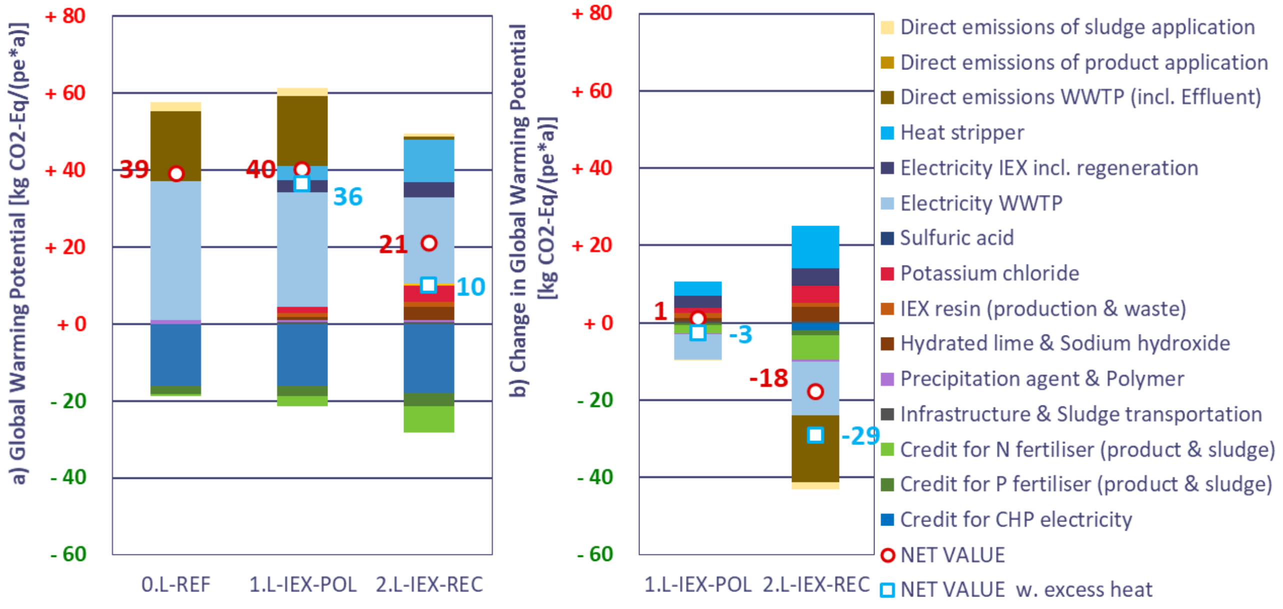

Figure 5-10: Global Warming Potential for reference and IEX scenarios of a large WWTP (100,000 pe): a) total GWP and b) GWP in relation to the reference

Freshwater Eutrophication Potential (FEP)

The net FEP of the reference WWTP amounts to +43 g P-eq/(pe*a) and +42 and +36 g P-eq/(pe*a) for the IEX scenarios. In analogy to the case study "small WWTP", the gross efforts of the FEP is mainly determined by the direct WWTP emissions (62%) and in this case also by sludge application (36%). Compared to the FEP of the case study "small WWTP", the concentration of P in the WWTP effluent is lower (0.3 mg P/L) for this set of scenarios, which is reflected by smaller direct emissions of the WWTP effluent. Comparing the polishing and recovery scenario in **Table 5-12** shows that the transfer of nutrients from the sludge to a conventional fertiliser reduces the FEP by 14%.

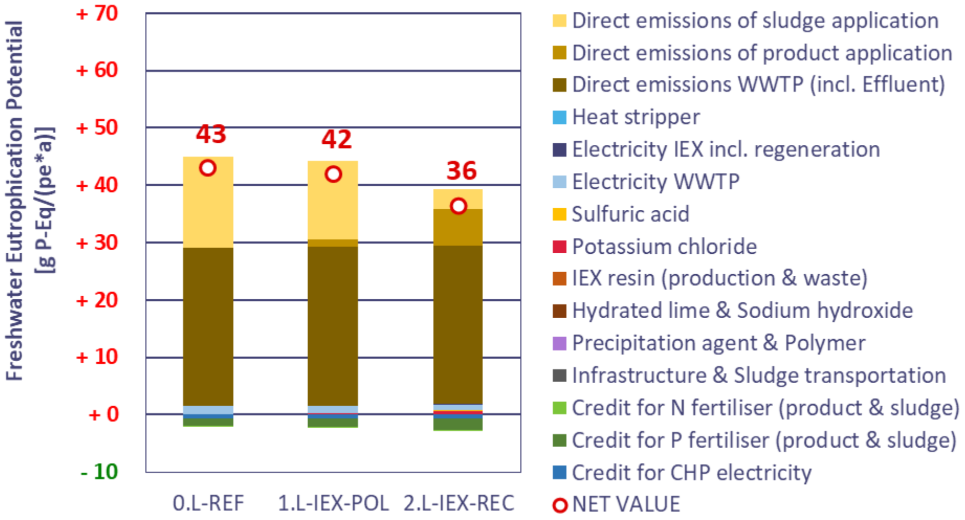

Figure 5-11: Freshwater Eutrophication Potential for reference and IEX scenarios of a large WWTP (100,000 pe)

Marine Eutrophication Potential (MEP)

The reference net MEP accounts to +1.5 kg N-eq/(pe*a), (Figure 5-12). Direct emissions of the WWTP process play a major role for this indicator, which is caused by nitrogen in the effluent. In addition, the sludge application has an impact of +0.1 kg N-eq/(pe*a) for the reference and polishing scenario.

Due to lower total nitrogen concentration in the WWTP effluent for the IEX scenarios, the MEP is reduced by 60 to 53% to a net MEP of +0.6 and +0.7 kg N-eq/(pe*a). Hence, the implementation of an IEX is beneficial for the MEP, as the WWTP effluent quality is thereby improved due to the direct removal of NH_4.

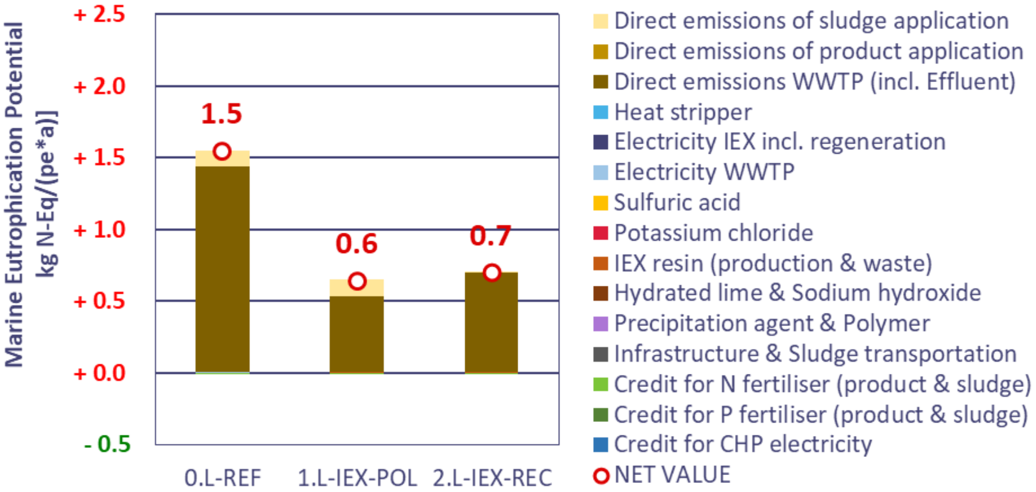

Figure 5-12: Marine Eutrophication Potential for reference and IEX scenarios of a large WWTP (100,000 pe)

Terrestrial Eutrophication Potential (TAP)

The reference net TAP accounts to +0.31 kg SO_2-eq/(pe*a) (Figure 5-13). Again, the direct emissions of the WWTP process and of sludge application play a major role in this indicator, which is caused mainly by ammonia emissions. The reference and polishing scenario have nearly the same TAP footprint, because the same nitrogen content in sludge is modelled. Major savings of around 50% occur for the recovery scenario. According to the "small WWTP", these savings are caused by transferring the nitrogen from the sludge into a conventional fertiliser.

Generally, IEX systems can decrease the total TAP footprint of a WWTP if the nitrogen content in sludge is reduced and consequently, the ammonia emissions resulting from sludge application.

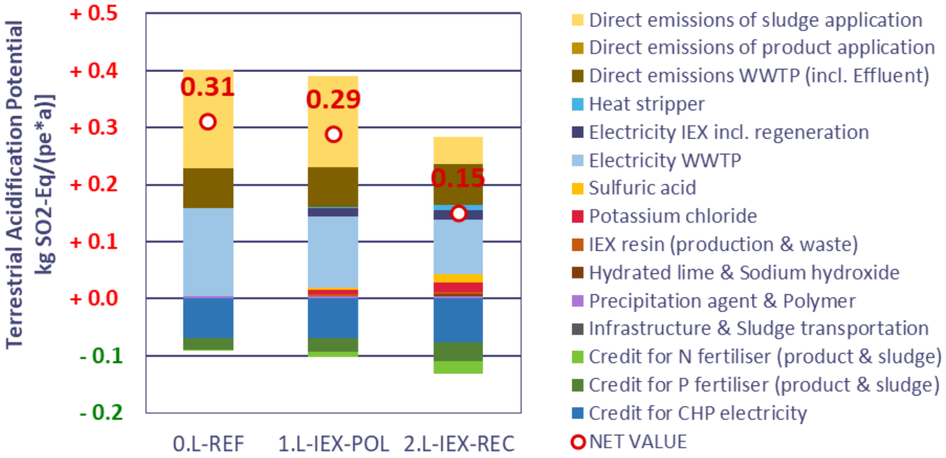

Figure 5-13: Terrestrial Acidification Potential for reference and IEX scenarios of a large WWTP (100,000 pe)

5.4 Interpretation and Conclusions

The LCA illustrates all direct and indirect impacts of implementing an IEX system at a typical small or large WWTP in UK and shows its environmental effects on energy demand, GHG emissions, marine and freshwater eutrophication and terrestrial acidification. The implementation of an ion exchanger system is associated with a number of environmental benefits, but can also be associated with some drawbacks depending mainly on the technical realization of the ammonium stripping technology.

Case study "small WWTP"

The outcomes of the LCA are illustrated in **Table 5-11** and can be summarized as follows:

- In terms of energy demand, the implementation of a two-stage IEX system for N and P removal requires a high amount of chemicals and heat, which cannot fully off-set the energy credits gained by the recovered nutrients. This is especially true for the N-IEX process, where the regeneration requires high amounts of salt and also heat for NH_3 stripping. Overall, the IEX process can only be energetically attractive, when compared with the reference scenario using conventional technologies, when accounting for energy and chemical savings in the upstream biological stage of the WWTP, and with an optimized energy and chemical demand for the N-IEX. Energy demand of the N-IEX can be optimized by using available excess heat or avoiding heat demand with membrane stripping. Changing to low-energy chemicals such as NaCl for regeneration also gives a substantially lower energy demand for the N-IEX.
- For the small WWTP, the maximum energy savings of the IEX configuration amounts to -52% in this LCA with the optimized N-IEX process, indicating the high potential of the process to reduce overall energy demand.
- The emission of greenhouse gases can be substantially reduced by the IEX configuration (-34 to -71%), mostly because direct N_2O emissions during nitrogen removal in the biological stage can potentially

be fully mitigated. This effect can substantially reduce the greenhouse gas footprint of WWTPs, but has to be validated with on-site monitoring of N_2O emissions.

- In terms of effluent quality, the IEX configuration can reach similar targets for phosphorus as conventional WWTPs with tertiary treatment. For nitrogen, the IEX process enables small WWTPs to reach a lower nitrogen target without requiring efforts for denitrification in the biological stage.
- Compared to nutrient recycling via sludge application in agriculture, the targeted recovery of nutrients into efficient fertilizer products also leads to lower N or P losses into groundwater and atmosphere.
- The production of sulfuric acid has a high impact on the terrestrial acidification, which can increase the TAP of an IEX system significantly.

Table 5-11: Summary of LCA results per indicator for ion exchange in case study "small WWTP" (10,000 pe)

Indicator	Unit	0. S-REF	1. S-IEX-KCl-VAC	2. S-IEX-NaCl-VAC	3. S-IEX-KCl-MEM	4. S-IEX-NaCl-MEM
Recovered N	t/a	-	25			
	% of total N load	-	69			
Recovered P	t/a	-	6			
	% of total P load	-	78			
Cumulative energy demand	MJ/(pe*a)	201	265 (+32%)	208 (+3%)	153 (-24%)	96 (-52%)
Global Warming Potential	kg CO_2-eq./(pe*a)	35	23 (-34%)	19 (-46%)	14 (-60%)	10 (-71%)
Freshwater Eutrophication Potential	g P eq./(pe*a)	62	56 (-10%)	56 (-10%)	57 (-8%)	56 (-10%)
Marine Eutrophication Potential	kg N eq./(pe*a)	2.1	0.8 (-62%)	0.8 (-62%)	0.8 (-62%)	0.8 (-62%)
Terrestrial Eutrophication Potential	kg SO_2-eq/(pe*a))	0.29	0.14 (-52%)	0.12 (-59%)	0.19 (-34%)	0.17 (-41%)

Case study "large WWTP"

The results of the case study "large WWTP" are shown in **Table 5-12** and can be summarized as follows:

- Compared to an activated sludge plant with tertiary treatment, the IEX process can only be energetically beneficial when accounting for major energy and chemical savings in the upstream biological stage of the WWTP. If IEX is used only for polishing after enhanced biological nutrient removal, energy demand and greenhouse gas emissions of IEX operation are higher than the reference system with a tertiary sand filter. Only if the IEX is implemented as the main step for nutrient removal (maximum "recovery"), can the related efforts for biological nutrient removal be avoided and thus an overall beneficial environmental profile achieved.
- The amount of nutrients recovered with IEX plays only a subordinate role in the footprint of this process, since the consumption of chemicals and energy in IEX operation is almost a linear correlation to the amount of nutrients recovered. Thus, the credit for P and N products increases when maximum recovery is enforced, but the associated expenses also increase in the same range. Major differences between scenarios mainly occur when the upstream biological stage can be operated with lower footprint due to high nutrient removal in the IEX, e.g. saving in greenhouse gases by a reduction in N_2O emissions and savings in electricity consumption for aeration by operating the biological stage without nitrification.

- It has to be noted here that the configuration of the N-IEX process in this case study (KCl as regenerant, vacuum stripping for NH_3 recovery) is related to the highest energy and GHG impact as shown above. Consequently, the results for the large WWTP can also be improved by optimising the N-IEX operation as in indicated in Table 5-11.
- Again, the load of nitrogen and phosphorus in the WWTP effluent is decisive for the eutrophication indicators. Here, the IEX system can reach comparable P levels to a conventional tertiary treatment (sand filter with Fe dosing) and lower levels of total nitrogen compared to a biological system without dosing of an external carbon source. Some additional benefits for the freshwater eutrophication occur, if the agricultural P-fertilisation (e. g. with the IEX product) is conducted with conventional fertiliser instead of sewage sludge.
- IEX systems decrease the total TAP footprint of a WWTP if the nitrogen content in sludge is reduced and consequently, the ammonia emissions resulting from sludge application. This is rather the case for the IEX scenario with a recovery target than for the IEX scenario with a polishing target.
- From the results of the small case study, it can be expected that the environmental performance could be improved even more if the N-IEX is regenerated with a NaCl regeneration solution and the ammonia recovery is conducted with a membrane stripper instead of a vacuum stripper.

Table 5-12: Summary of LCA results per indicator for ion exchange in case study "large WWTP" (100,000 pe)

Indicator	Unit	0. L-REF	1. L-IEX-POL	2. L-IEX-REC
Recovered N	t/a	-	87	268
	% of total N load	-	24	74
Recovered P	t/a	-	13	58
	% of total P load	-	17	76
Cumulative energy demand	MJ/(pe*a)	236	268 **(+9%)**	252 **(+2%)**
Global Warming Potential	kg CO_2- eq. /(pe*a)	39	40 **(+3%)**	21 **(-46%)**
Freshwater Eutrophication Potential	g P eq./(pe*a)	43	42 **(-2%)**	36 **(-15%)**
Marine Eutrophication Potential	kg N eq./(pe*a)	1.5	0.6 **(-61%)**	0.7 **(-53%)**
Terrestrial Eutrophication Potential	kg SO_2-eq/(pe*a))	0.31	0.29 **(-6%)**	0.15 **(-52%)**

Limitations and transferability of the case study results to other WWTPs:

- For the global warming potential and cumulative energy demand indicators, savings and side-effects of the IEX on the WWTP play a major role in the results and will determine whether IEX systems are beneficial (or not). Since these side-effects have been estimated in the present study and have not been verified in full-scale plants, the results should be treated with caution. As soon as an ion exchanger is put into operation on an industrial scale, the assumptions should be verified.
- In this study, the large reference WWTP is defined with a high energy consumption compared to average treatment plants. Therefore, the energy saving in the mainline of the WWTP are higher than if an IEX system is used in an energetically optimised WWTP.

- If excess heat is available on-site of the WWTP, the heat consumption of the vacuum stripper for ammonium recovery is accounted in this study without environmental impact. It is important that the respective excess heat is not missing for other applications.
- For the eutrophication indicators the nutrient load in the WWTP effluent is decisive. Beneficial results for these indicators cannot necessarily be attributed to ion exchangers, but to the definition of the effluent quality. In theory, the same effluent quality can also be achieved with other technologies.
- The assumed life time of the IEX resin (5 years for both HAIX and MesoLite) must be proven in praxis. If the life time of the resins decreases to around one year, the production of the resin will cause a more significant environmental impact. Furthermore, it would be advisable to model the production process of IEX resin more precisely for a future LCA in this area, since it is unclear whether the used LCA data sets adequately reflect the medium used.
- In this LCA study, N_2O emission factors of the biological stage are only assumptions and should be validated with on-site monitoring. Changing N removal from a biological to a chemical (IEX) leads to full mitigation of N_2O emissions from the biological stage and gives high benefits to the GWP for IEX scenarios. Also, this effect has to be checked in future studies.

6. LCA OF SIDESTREAM N REMOVAL AND P RECOVERY (SMARTECH 4A + DOWNSTREAM SMARTECH B) OR SIDESTREAM BIOPOLYMER AND STRUVITE RECOVERY (SMARTECH 5 + DOWNSTREAM SMARTECH A)

Sludge liquor from dewatering of anaerobically digested sewage sludge contains a high amount of nutrients, particularly nitrogen (N) and phosphorus (P). This process water is usually recycled back to the influent of the wastewater treatment plant (WWTP) for treatment, significantly contributing to the total load of the system via this “return load”. Typically, N and P return load can account for up to 20% of the total nutrient load to a WWTP depending on the sludge characteristics, efficiency of anaerobic digestion, and actual raw wastewater concentration and load. This effect puts operational restrictions on the WWTP mainline in terms of treatment capacity and/or effluent quality.

This LCA investigates two different process alternatives to remove N and P from sludge liquor of dewatering and thus reduce the total load to the WWTP mainline: the SCENA and the SCEPPHAR process.
The first process called SCENA (“short-cut enhanced nutrients abatement”) removes N and P efficiently with a comparably low demand of electricity and carbon source. Due to the low COD/N ratio in sludge liquor, conventional nitrification/denitrification treatment is often limited by carbon availability. This problem is overcome with SCENA using a short-cut metabolic pathway via nitrite to save on carbon source, combined with process conditions to allow for enhanced biological phosphorus removal (EBPR). The process operates as a Sequencing Batch Reactor (SBR) with dedicated control strategies to achieve both short-cut N removal and EBPR. Different sources for readily biodegradable organic carbon (e.g. measured as volatile fatty acids (VFA)) can be utilized with SCENA, such as fermentation liquor of sewage sludge or acetate as an external carbon source. Apart from the nutrient removal, the excess sludge of SCENA has a high content of bioavailable P, and this valuable P-rich sludge can be used as biofertilizer after suitable post-treatment (e.g. composting).
The second process called SCEPPHAR (“short-cut enhanced phosphorus and PHA recovery”) also removes N and P from the sludge liquor in a three-stage SBR process, but in addition generates high-value products such as struvite and a sludge enriched with poly-hydroxy-alkanoates (PHA). Whereas struvite is precipitated from the liquor and can be used directly as fertilizer, the biological production of PHA requires a high amount of VFA to enable the enrichment of PHA in the sludge. This VFA can be produced on-site at the WWTP by fermentation of sludge such as cellulosic sludge from sieving of raw wastewater (cf. chapter 2) or excess sludge from the biological stage. The PHA-rich excess sludge of SCEPPHAR can then be used to extract pure PHA powder in a chemical process, and the final PHA can be used for multiple purposes, e.g. the production of bio-composites.

Both SCENA and SCEPPHAR have been demonstrated at the WWTP of Carbonera (Italy) during the project. Whereas SCENA has been implemented at full-scale (SMARTech 4a), the SCEPPHAR system has been tested in pilot-scale together with a finescreen to product cellulosic sludge from raw wastewater and an acidogenic fermentation reactor to produce VFA from this stream (SMARTech 5). Post-processing of products has been demonstrated for the P-rich sludge of SCENA in pilot-scale (Downstream SMARTech B), whereas extraction of PHA was realized in lab-scale (Downstream SMARTech A).
The present LCA study analyses the environmental implications of installing a SCENA or SCEPPHAR system for sidestream treatment at the WWTP of Carbonera. Different scenarios are investigated in relation to the choice of carbon source for SCENA and SCEPPHAR to reveal the impact of these alternatives on the environmental profile. The focus of this study is on the life-cycle impacts of these processes on total energy demand and greenhouse gas emissions of the WWTP operation, including the processing and valorisation or products. Potential improvements in WWTP capacity or effluent quality from the reduced return load are not accounted in this LCA as defined together with the project partners ATS and UNIVR. However, positive impacts from sidestream treatment or primary sieving of wastewater on the operational efforts of the biological stage (i.e. savings in aeration energy) are considered based on estimates of the operator or process supplier.

6.1 Goal and scope definition

6.1.1 Goal of the study

The goal of this LCA is to calculate the potential environmental impacts of the annual operation of WWTP Carbonera (IT), comparing the current operation with different configurations of the SCENA or SCEPPHAR system for sidestream treatment. All direct and indirect effects of upgrading the WWTP design with a sidestream treatment will be quantified in the life cycle, focussing on primary energy demand and GHG emissions as major environmental impacts. The LCA includes the processing and valorisation of recovered products such as P-rich sludge (SCENA) or PHA-rich sludge and struvite (SCEPPHAR).
The target group of this LCA are mainly WWTP experts, planners and practitioners which should be informed about the holistic environmental impacts of sidestream treatment with SCENA or SCEPPHAR at a municipal WWTP.

6.1.2 Function and functional unit

The primary function of the system under study is the treatment of municipal wastewater to defined local standards, including the final disposal of sewage sludge. Consequently, the functional unit is defined as "treatment of municipal wastewater per population equivalent (pe) and year" or $[pe*a]^{-1}$. WWTP Carbonera is designed to treat raw wastewater with a load of 40.000 pe based on a daily COD load of 120 g/pe. All direct and indirect impacts of the system are related to this functional unit. As a secondary function, some scenarios recover P-rich sludge or struvite and PHA-rich sludge as valuable materials, which are further processed and valorised downstream. This secondary function is accounted by crediting the avoided primary products to the system.

6.1.3 Scenarios

As two different systems for sidestream treatment have been demonstrated at WWTP Carbonera in this project, the LCA scenarios are also divided into two groups: one group of scenarios analyses the SCENA system in different configurations, and one group of scenarios relates to the SCEPPHAR system.

SCENA scenarios

Four scenarios have been defined for this process, as listed in **Table 6-1** below. In detail, the scenarios can be described as follows:

0a Baseline: this scenario reflects the situation at WWTP Carbonera before upgrading, using operational data of the operator. After mechanical pre-treatment, the plant consists of primary settlers, activated sludge tanks with anoxic and aerobic zones (Schreiber reactor), and final clarifiers. Nitrogen is removed by conventional nitrification/denitrification, while phosphorus is removed mainly by chemical precipitation with Al salts. Tertiary treatment of WWTP effluent is realized by chemical disinfection with peracetic acid and filtration with disc filters. Excess sludge from the biological stage is returned from clarifiers into the primary settler, so that a mixed sludge is extracted from this stage. Mixed sludge is thickened by gravity before it is anaerobically digested in mesophilic conditions. Digested sludge is thickened again by gravity and then dewatered in centrifuges before final processing in composting and disposal in agriculture. Biogas is valorised on-site in a heater to produce heat for digestor and other internal use. Excess heat beyond the internal demand is not further valorised and thus not accounted in this LCA.

0b Baseline dynThick: this scenario represents the configuration of WWTP Carbonera after an upgrade of the sludge treatment line with a dynamic thickener. Mixed sludge from primary settler is thickened with polymer to improve the digestion process and achieve a more concentrated sludge liquor from final dewatering, which is beneficial for the efficiency of the sidestream treatment.

1a SCENA 100% Ac: this scenario represents the implementation of a SCENA system for sidestream nutrient removal using an external carbon source (acetic acid). This system was implemented before the WWTP upgrade with a dynamic thickener, and is therefore compared only to scenario “0a Baseline” as reference. P-rich sludge from the SCENA is dewatered and further treated in a dynamic composting process to produce a valuable biofertilizer with high P content.

1b SCENA 100% VFA: this scenario relates to the implementation of SCENA after the WWTP upgrade with a dynamic thickener, using fermentation liquor of excess sludge as an internal carbon source for SCENA. The scenario includes the SBR process of SCENA and the production line for the carbon source (mesophilic fermenter, screw press, and storage of bio-available carbon source (BACS)). As this configuration was implemented after the WWTP upgrade, this scenario is compared to the scenario “0b Baseline dynThick” as reference. As in the former scenario, P-rich sludge from SCENA is treated by dynamic composting and valorised as biofertilizer with high P content.

Table 6-1: Scenarios for SCENA implementation at WWTP Carbonera (see text for details)

Scenario	Description	Remarks
0a Baseline	WWTP Carbonera (before upgrade)	Operational data
0b Baseline dynThick	WWTP Carbonera (upgraded with dynamic thickener)	Operational data
1a SCENA 100% Ac	SCENA for sidestream treatment before upgrading with dynamic thickener, using acetic acid as carbon source	Full-scale data of SCENA system in 2016
1b SCENA 100% VFA	SCENA for sidestream treatment after upgrading with dynamic thickener, using volatile fatty acids from excess sludge fermentation	Full-scale data of SCENA system in 2018-2019

SCEPPHAR scenarios

Four scenarios have been defined for this process, as listed in **Table 6-2** below. In detail, the scenarios can be described as follows:

0b Baseline dynThick: this scenario reflects the situation at WWTP Carbonera as described above. It relates to the upgraded configuration of the plant with a dynamic thickener in 2018.

2a SCEPPHAR 0% WAS: this scenario represents the implementation of a SCEPPHAR system for sidestream treatment. The carbon source for PHA production is produced internally by fermentation of cellulosic sievings which are extracted from raw wastewater by implementing a fine screen. The scenario consists of fine screens for primary sieving, mesophilic fermentation of cellulosic sludge, solid-liquid separation, storage of BACS liquor, and the three-stage SBR process of SCEPPHAR for struvite precipitation and PHA enrichment. After the PHA accumulation, a part of the exhausted BACS solution (70%) is returned to the digestor to reach a suitable water content in the mixed sludge for digestion. The PHA-rich sludge from SCEPPHAR is dewatered, and the PHA is chemically extracted and dried to produce a PHA powder.

2b SCEPPHAR 62% WAS: this scenario resembles the former scenario 2a, but increases the amount of VFA fed to the PHA production by also fermenting 62% of the waste activated sludge (WAS) of the plant together with the cellulosic sievings. This fraction was selected based on the PHA production target of 1 kg PHA per pe and year. Fermentation of WAS was not demonstrated in pilot scale in the project, so the data is based on lab and pilot trials of WAS fermentation from UNIVR. Valorisation of PHA-rich sludge is comparable to scenario 2a.

2c SCEPPHAR 100% WAS: this scenario is fully comparable in its configuration with scenario 2b, but uses the maximum amount of WAS for PHA production. Hence, it demonstrates the maximum production of PHA from internal carbon sources in this configuration.

Table 6-2: Scenarios for SCEPPHAR implementation at WWTP Carbonera (see text for details)

Scenario	Description	Remarks
0b Baseline dynThick	WWTP Carbonera (upgraded with dynamic thickener)	Operational data of 2018
2a SCEPPHAR 0% WAS	SCEPPHAR for sidestream treatment, incl. fine screen in mainstream for cellulose extraction and fermentation of cellulosic sludge for VFA production	Pilot-scale data of SCEPPHAR system in 2018-2019
2b SCEPPHAR 62% WAS	SCEPPHAR for sidestream treatment, incl. fine screen in mainstream for cellulose extraction and fermentation of cellulosic sludge plus 62% of waste activated sludge for VFA production	Pilot-scale data of SCEPPHAR system in 2018-2019 + lab data of WAS fermentation
2c SCEPPHAR 100% WAS	SCEPPHAR for sidestream treatment, incl. fine screen in mainstream for cellulose extraction and fermentation of cellulosic sludge plus 100% of waste activated sludge for VFA production	Pilot-scale data of SCEPPHAR system in 2018-2019 + lab data of WAS fermentation

6.1.4 System boundaries

SCENA scenarios

The system boundaries for this group of scenarios cover all relevant processes for water and sludge treatment at WWTP Carbonera, including sludge treatment with digestion, dewatering and final disposal, and the valorisation of P-rich sludge from SCENA via dynamic composting (**Figure 6-1**). For the SCENA process, production of the internal carbon source is included with fermentation, screw press, and BACS storage. Basic infrastructure material is included for the SCENA system (fermenter, screw press, storage, SBR) and the composting, while all other infrastructure is neglected (i.e. existing WWTP). Products such as nutrients in disposed sludge or biofertilizer are credited by avoided impacts of primary products ("avoided-burden approach") such as mineral N and P fertilizer.

SCEPPHAR scenarios

The system boundaries for this group of scenarios cover all relevant processes for water and sludge treatment at WWTP Carbonera, including sludge treatment with digestion, dewatering and final disposal, and the valorisation of struvite and PHA-rich sludge from SCEPPHAR (**Figure 6-2**). For the SCEPPHAR process, production of the internal carbon source is included with fine sieving of raw wastewater (rotating belt filter) to produce cellulosic sludge, fermentation of this sludge and eventually a fraction of WAS, solid-liquid separation, and storage of BACS. The SCEPPHAR system consists of SBR reactors for struvite precipitation, nitritation of sludge liquor from dewatering, and selection/PHA enrichment. A fraction of the exhausted BACS liquid is recycled to the digestor to maintain a suitable water content for digestion. PHA-rich sludge from SCEPPHAR is dewatered, and PHA is chemically extracted and dried to produce a PHA powder.

Basic infrastructure material is included for the SCEPPHAR system (fermenter, solid-liquid, storage, SBR), while all other infrastructure is neglected (i.e. existing WWTP, PHA extraction). Products such as nutrients in disposed sludge or struvite and PHA powder are credited by avoided impacts of primary products ("avoided-burden approach") such as mineral N and P fertilizer or pure-culture PHA.

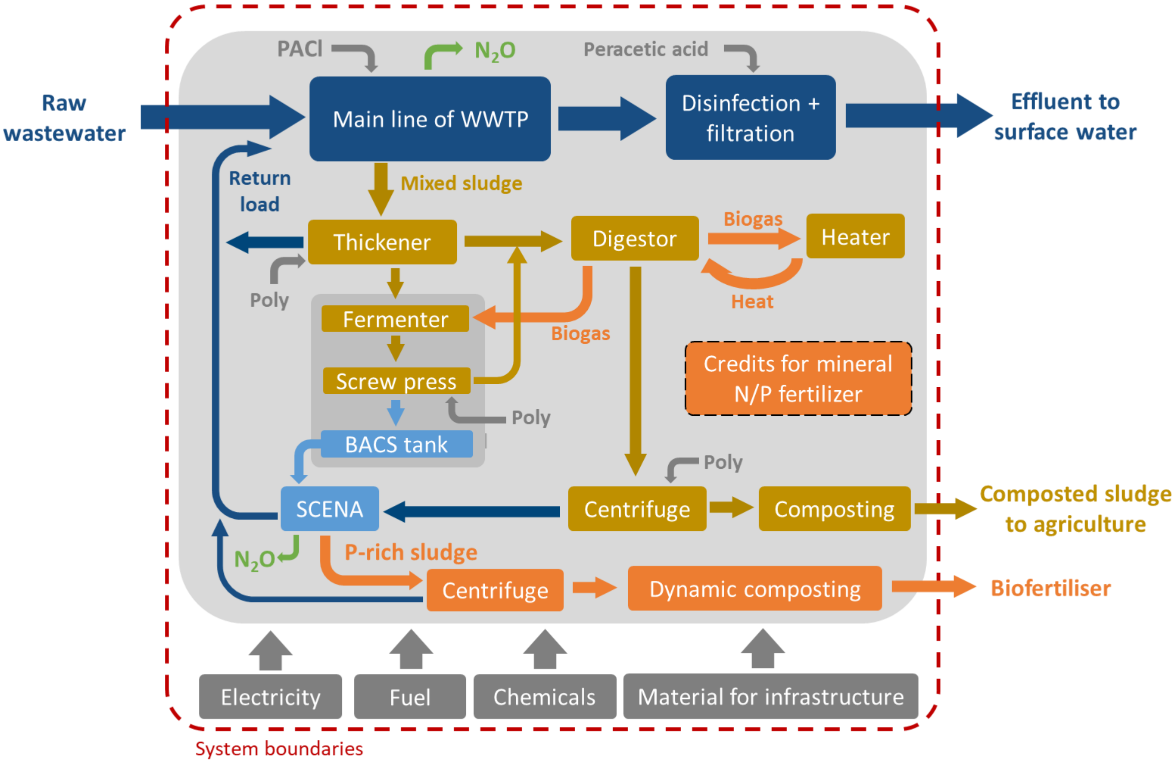

Figure 6-1: System boundaries of LCA study for sidestream SCENA and valorisation of P-rich sludge at WWTP Carbonera

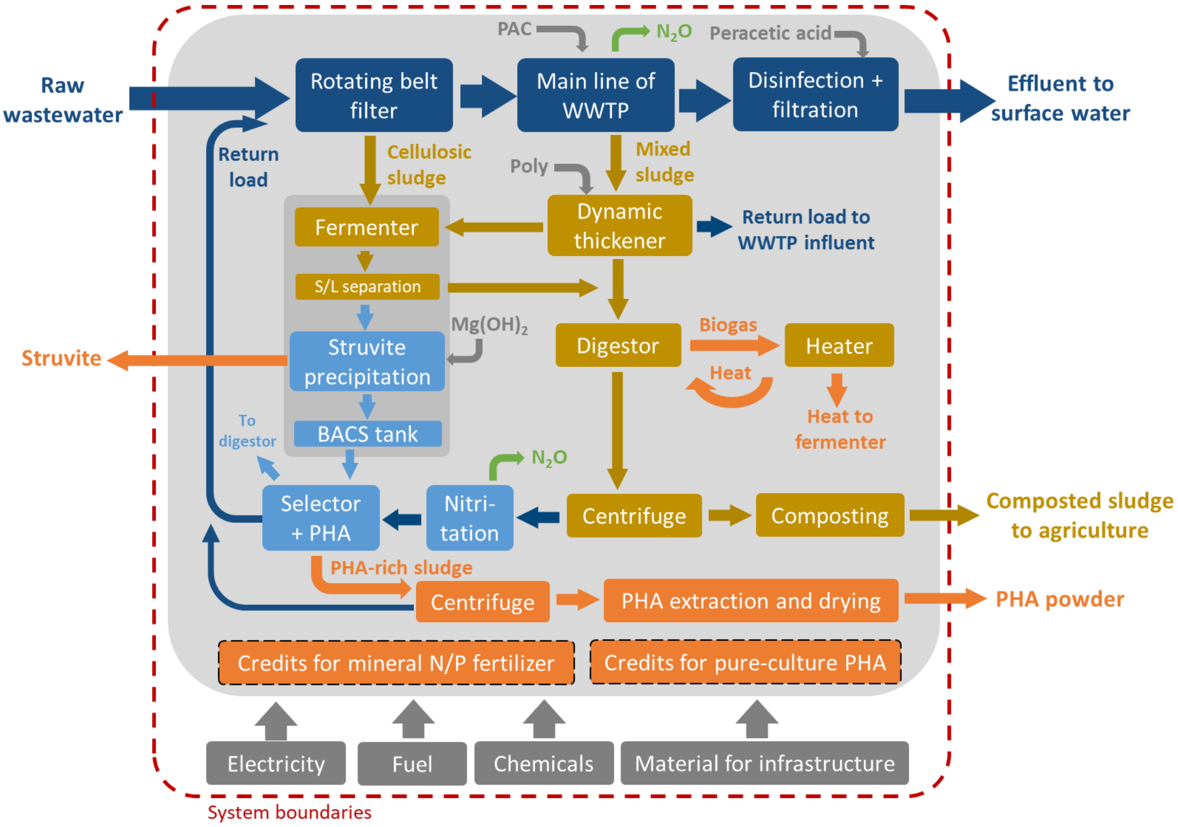

Figure 6-2: System boundaries of LCA study for sidestream SCEPPHAR and valorisation of struvite and PHA-rich sludge at WWTP Carbonera

6.1.5 Data sources and quality

Input data for the baseline operation of WWTP Carbonera has been collected from operator ATS and project partner UNIVR based on operational data of the plant (**Table 6-3**). The data represents full-scale operational data of the year 2014 and 2018 for electricity and chemicals demand, mass balances of water and sludge treatment, and related influent and effluent quality. For sludge composting and disposal in agriculture, data has been estimated based on available literature.

For the SCENA system, full-scale data of 2018-2019 has been collected by ATS and UNIVR. Effects of sidestream treatment on operation of the biological stage (i.e. savings in aeration energy) could only be estimated by ATS, as the existing control system did not allow to realize the full potential to decrease aeration energy based on the reduced N load of the biological stage. N_2O monitoring of the biological stage and the SCENA system allowed to quantify N_2O emission factors for both systems. For dynamic composting, pilot data was collected by UVIC based on pilot trials with P-rich sludge samples from Carbonera.

For the SCEPPHAR system, pilot data was collected by UNIVR for the fine sieving of raw wastewater, the fermentation of cellulosic sludge, and the operation of the SCEPPHAR reactors for struvite precipitation, short-cut N removal, and PHA production. Electricity and chemical demand of the process has been extrapolated from pilot plant results, and mainline effects of primary fine sieving is estimated based on data of Cirtec (cf. chapter 2). N_2O emission factors for the nitritation stage have been monitored by UNIVR in pilot size and extrapolated to full-scale operation. Data for PHA extraction has been provided by Biotrend and is based on extrapolation of lab-scale trials into full-scale design.

Overall, data quality of this LCA can be described as high for the baseline and SCENA data, medium for the mainline effects, and medium-high for the N_2O emission factors, the SCEPPHAR system and the PHA extraction (**Table 6-3**). Data quality is sufficient for a prospective LCA to show the potential environmental impacts of SCENA or SCEPPHAR implementation at WWTP Carbonera, but underlying assumptions and their impact on the validity of the outcomes should be clearly communicated with the results.

Table 6-3: Data quality for LCA of SCENA or SCEPPHAR sidestream treatment and product valorisation at WWTP Carbonera

Process	Data source	Responsible partner	Data quality
WWTP Carbonera: influent + effluent, sludge treatment, energy and chemicals demand, biogas production, heater	Full-scale data of operator	ATS + UNIVR	High
N_2O emission factor	Monitoring data	UNIVR	High
Sludge disposal in agriculture	Literature	KWB	Medium - high
SCENA system			
SCENA performance, electricity and chemical demand, product yield	Full-scale data	ATS + UNIVR	High
Mainstream effects (aeration savings)	Estimates	ATS	Medium
N_2O emission factor	Monitoring data	UNIVR	Medium-High
Dynamic composting	Pilot plant data with P-rich sludge from Carbonera	UVIC	High
SCEPPHAR system			
Fine-sieving of raw wastewater	Pilot plant data	UNIVR	High
SCEPPHAR performance, electricity and chemical demand, product yield	Pilot plant data	UNIVR	Medium - high
Mainstream effects (aeration savings)	Estimates	ATS + CirTec	Medium
N_2O emission factor	Monitoring data + extrapolation	UNIVR	Medium - high
PHA extraction	Extrapolation from lab trials with sludge from Carbonera	Biotrend	Medium-High

6.1.6 Indicators for impact assessment

This study focusses on two specific environmental impacts: primary energy demand, and greenhouse gas emissions.

- For primary energy demand, the indicator of cumulative energy demand (CED) for non-renewable fuels as defined in VDI 4600 (VDI, 2012) is used, adding up fossil and nuclear fuels to a single score.
- For greenhouse gas emissions, factors of IPCC are used to calculate the global warming potential (GWP) for a time horizon of 100 years (IPCC, 2014). Long-term emissions > 100a are neglected ("without LT").

6.2 Input data (Life Cycle Inventory)

6.2.1 Data of WWTP Carbonera

Detailed data for influent and effluent volume and quality, mass balances for each stage, and demand of electricity, heat, and chemicals for WWTP operation was collected by the operator ATS in cooperation with UNIVR. The data relates to full-scale operational data of WWTP Carbonera. Due to inconsistencies and different data quality between the different time periods of operation, a representative state of the plant was defined for all scenarios based on the same influent quality and volume. For the sludge disposal route (composting and application to agriculture), data has been compiled from available literature.

Mass flow data for water and sludge line of WWTP Carbonera

Relevant annual mean data for volume, TSS, COD, and total nitrogen for WWTP influent and effluent is reported in **Table 6-4** below. The annual COD influent load amounts to 2,218 t/a, which corresponds to around 50,628 pe when assuming a daily COD load of 120 g/pe (ATV, 2000). In relation to the design load which is also used to define the functional unit (40,000 pe), the data shows that the plant is slightly overloaded. Effluent quality shows a high removal of TSS (95%), COD (93%), TN (68%), and TP (76%) at the WWTP. Return load from sludge thickening and dewatering adds around 8% of TN load and 3% of TP load to the influent WWTP per year. In the baseline scenario with dynamic thickening, the concentration of sludge liquor from thickening and especially from dewatering is increased, but the total return load is comparable (+8.5% TN, +3.6% TP).
Direct gaseous emissions of the activated sludge tank are calculated as 1.5% of N eliminated as N_2O-N based on monitoring data for the plant (see D4.1).

Table 6-4: Input data for WWTP Carbonera: influent and effluent quality and return load with sludge liquor for baseline scenarios

Parameter	*Unit*	Influent of WWTP	Effluent of WWTP	Sludge liquor from thickening	Sludge liquor from dewatering
Scenario 0a Baseline					
Volume	*m^3/d*	15,538	15,635	38*	91
Suspended solids	*g/m^3*	200	10.1	5,050*	309*
COD	*g/m^3*	391	26.8	150	550
Total N	*g/m^3*	38	12	77	500
Total P	*g/m^3*	5.8	1.4	13	20
Scenario 0b Baseline dynThick					
Volume	*m^3/d*	15,538	15,635	53*	46
Suspended solids	*g/m^3*	200	10.1	906*	1,700*
COD	*g/m^3*	391	26.8	500	789
Total N	*g/m^3*	38	12	80	1,000
Total P	*g/m^3*	5.8	1.4	40	23.6

**calculated*

Raw mixed sludge is thickened by gravity to 2.5% DM, while dynamic thickening increases this parameter to 5.0% DM (**Table 6-5**). This upgrade has a major effect on digestor performance: in the baseline 0a, biogas production amounts to 280 NL/kg VS_{in} (VS degradation: 29%) or a total of 172,600 Nm^3 per year. The implementation of dynamic thickening enables a longer hydraulic retention time and a higher VS reduction (41%), increasing biogas production to 500 NL/kg VS_{in} (355,000 Nm^3/a). For both scenarios, methane content in the biogas is assumed to 64 Vol-%. The entire amount of biogas is fed to the central heater to produce heat for the digestor and on-site facilities. No excess heat is valorised outside of the plant, so the biogas use yields no energy credits in this LCA apart from covering the heat demand of the WWTP. An upgrade of the plant with combined heat and power units is planned for the future and would significantly improve the energy recovery from the biogas. After digestion, digested sludge is dewatered to 23% DM in centrifuges.

Sludge disposal in agriculture

Dewatered sludge is transported to agriculture for final disposal (172 km via truck), accounting for some substitution of nitrogen and phosphorus mineral fertilizer with 20% of N and 20% of P content in sludge.

Table 6-5: Input data for WWTP Carbonera: mixed raw sludge, thickened sludge to digestion, digested sludge to dewatering, and dewatered sludge to disposal

Parameter	*Unit*	Mixed sludge to thickening	Thickened sludge to digestor	Digested sludge to dewatering	Dewatered sludge to disposal
Scenario 0a Baseline					
Mass	*t/d*	127	89	89	7
Dry matter	*% DM*	1.9	2.5	1.9	23
Volatile solids	*% of DM*	81	81	74	74
Total nitrogen	*% of DM*	5.3	5.7*	7.6*	4.9*
Total phosphorus	*% of DM*	2.9	3.2*	4.3*	4.2*
Scenario 0b Baseline dynThick					
Mass	*t/d*	100	47	47	6.5
Dry matter	*% DM*	2.4	5.0	3.3	23
Volatile solids	*% of DM*	81	81	68	68
Total nitrogen	*% of DM*	5.3	5.3*	7.9*	5.2*
Total phosphorus	*% of DM*	2.9	2.9*	4.4*	4.6*

**calculated*

Electricity and chemicals demand

Total electricity demand for WWTP operation amounts to 2,200 MWh/a or 0.39 kWh/m^3 influent in the baseline 0a, and is reduced to 2,065 MWh/a with dynamic thickening (0.36 kWh/m^3) mainly due to savings in digestor and centrifuge operation. This gross electricity demand is attributed to the different stages of water and sludge treatment according to operator data to be able to track any changes related to implementation of the SCENA or SCEPPHAR process. In particular, 1,568 MWh/a or 71% of total electricity demand (0.28 kWh/m^3) is attributed to the water treatment line, mainly for aeration in the activated sludge process.

For chemical demand, the LCA takes into account polyelectrolyte used for thickening and dewatering, poly-aluminium chloride (PACl) for precipitating of phosphorus, and peracetic acid (PAA) as final disinfectant. Based on available data, polymer demand as active matter is determined to 6.1 kg/t DM for dynamic sludge thickening (no polymer for gravity thickening) and 16.5 kg/t DM for dewatering of digested sludge. Al salt is dosed with 0.59 mol Al/mol P in the activated sludge tank for P removal, and peracetic acid (40%) is dosed after final filtration with 3 g/m^3. Overall, the annual demand of chemicals adds up to 10 t polyelectrolyte (as active matter, 14.8 t with dynamic thickener), 97 t PACl solution (18% Al), and 17 t PAA solution (40%). Any other chemicals for WWTP operation are not considered in this study.

6.2.2 Data for SCENA system

Data for the SCENA system is delivered by ATS and UNIVR based on long-term full-scale implementation of the process at WWTP Carbonera. The system is described based on energy demand and mass balances of the installation, which were closely monitored during the project. Mainline effects of sidestream treatment, especially savings in aeration energy due to reduced N return load, could only be estimated by the operator ATS as the actual aeration control system of the plant did not allow to realize the full potential due to limited options for aeration adjustment.

Performance and energy/chemicals demand of SCENA system

SCENA operation at WWTP Carbonera demonstrated a good removal for TN (77%) and TP (70%) in long-term operation, which is independent of the carbon source used (**Table 6-6**). N_2O emissions of short-cut nitrogen removal have been projected to 2.27% of N removed based on intensive monitoring campaigns (see D4.1) and process mass balances, including suitable mitigation measures in process control. However, N_2O emissions of SCENA are still +50% compared to the N_2O emission factor in the mainline. Electricity demand of the SCENA process amounts to 5.1 kWh/kg N removed (65 MWh/a) if an external carbon source is used, and 5.4 kWh/kg N removed (70 MWh/a) including the internal production of VFA via fermentation of mixed sludge. If acetic acid is used as carbon source (scenario 1a), the COD demand amounts to 2.2 kg COD/kg N (= 34.4 t/a acetic acid). For the production of an internal carbon source in scenario 1b, 24% of the thickened mixed sludge (~ 11 m^3/d) are fermented with 14 kWh/m^3 heat demand supplied by the heater operated on biogas and dewatered in a screw press to 18% DM by using 14 kg polyelectrolyte (active substance) per t dry matter. The resulting VFA-rich liquor (8.4 m^3/d, 13.5 g/L COD) is stored and dosed to the SCENA process as internal carbon source (~ 2.5 kg COD_{VFA}/kg N). No other chemicals are accounted here for the SCENA operation.

Effects on mainstream WWTP

SCENA sidestream treatment reduces N return load to the mainline by around 13 t TN/a. The related potential savings in aeration energy in the mainline are estimated to 9 kWh/kg N by the operator, amounting to a total reduction of 117 MWh/a or -8% in electricity demand for the mainline. Potential savings in coagulant dosing for P removal have been neglected here. WWTP effluent quality was comparable to the baseline situation, so no changes for TN or TP discharge concentration are accounted with SCENA implementation. Due to the reduced TN load to the mainline, related N_2O emissions for this fraction can be avoided with SCENA based on the emission factor for the mainline (1.5% of N_2O-N per kg N removed).

Table 6-6: Input data for SCENA for TN/TP removal, N_2O emissions, electricity and chemicals demand, and yield of P-rich sludge

Parameter	*Unit*	1a SCENA 100% Ac	1b SCENA 100% VFA	Remarks
N removal	*%*	77	77	Data of ATS + UNIV
P removal	*%*	70	70	Data of ATS + UNIV
N_2O	*% N_2O-N/N removed*	2.27	2.27	Monitoring data of UNIV
Dosing of acetic acid (100%)	*kg COD/kg N influent*	2.2	-	UNIV data for acetic acid
Dosing of VFA (100%)	*kg COD/kg N influent*	-	2.53	UNIV data for BACS
Electricity for SCENA	*kWh/kg N removed*	5.1	5.4	Full-scale data (incl. production of BACS)
Electricity savings in mainline	*kWh/kg N*	9	9	Estimate of ATS
Excess sludge yield	*g TS/g N influent*	0.4*	0.4*	UNIV data
Total amount of sludge	*t DM/a*	6.67	6.74	Calculated
N content in excess sludge	*% of DM*	6.0	6.0	Estimate
P content in excess sludge	*% of DM*	7.0	6.1	Calculated with P removal

** estimate*

Products of SCENA system: P-rich sludge

Based on full-scale mass balances, excess sludge of SCENA amounts to 0.4 g TS/g N influent or around 6.7 t DM/a with and a P content of 6-7% (**Table 6-8**) . This sludge (5% DM) is dewatered on-site to 17% DM using 10 kg polyelectrolyte (active matter) per ton dry matter and processed in dynamic composting to produce a valuable biofertilizer.

Infrastructure for SCENA

Material demand for building a mainstream SCENA system is roughly estimated by the operator based on the existing design. Dynamic thickener is estimated to need 5 t stainless steel. BACS production with fermenter and screw press requires 60 t concrete and 10 t stainless steel, while SBR tanks for SCENA require 310 t concrete. The corresponding lifetime of the installation is estimated to 12 years for machinery (stainless steel) and 50 years for concrete.

6.2.3 Data for product valorisation: dynamic composting of P-rich sludge

Data for dynamic composting is delivered by project partner UVIC based on pilot trials of composting of P-rich sludge and experience from other projects on composting (**Table 6-7**).

P-rich sludge at 17% DM is mixed with bulk material to enable good aeration of the mixture, and bulk material is recovered after dynamic composting with a sieving stage and recycled to the input. Although a part of the bulk material remains in the product, this LCA does not account for the footprint of bulk material production as it is assumed that it will be mostly waste biomass with negligible impact.

DM of the output is 54% after dynamic composting, and the final product is a stable biofertilizer with high P content. Gaseous emission factors for NH_3, N_2O, CH_4, and VOCs from composting are estimated based on mass balances and results of pilot trials. No bio-filter for emission control is planned for the full-scale system at WWTP Carbonera due to the small size of the system (~ 10 t/a of biofertilizer production). In case of a larger system, gaseous emissions could be substantially reduced by a covered operation with a biofilter.

Electricity demand for final sieving is calculated to 22 kWh per ton of input material. Mechanical turning during the process is done by machinery using 0.44 L diesel/t.

Table 6-7: Input data for dynamic composting

Parameter	Unit	Value	Remark
DM after composting	*%*	54	Data from pilot trials
Mass balance to final product	*%*	-72	Partial degradation of organic matter, data represents net balance after bulking material is extracted
TS balance to final product	*%*	-10	
VS balance to final product	*%*	-17	
NH_3 emission factor	*mg/kg TS*	18,000	No biofilter, 24% of TN load emitted as NH_3
N_2O emission factor	*mg/kg TS*	34	No biofilter, 0.04% of TN load emitted as N_2O
CH_4 emission factor	*mg/kg TS*	272	No biofilter, 0.05% of TOC emitted as CH_4
VOC emission factor	*mg/kg TS*	3,100	No biofilter
Electricity for composting	*kWh/t*	22	Related to input sludge, mainly for sieving
Diesel for composting	*l/t*	0.44	Related to input sludge, mainly for turning

Infrastructure

Material demand for building a composting system is estimated based on a related LCA dataset of ecoinvent ("composting facility construction, open (CH)") and scaled down to the production volume of the site. Overall, the composting unit requires 1.5 m^3 concrete, 85 kg reinforcing steel, 200 kg iron, and 150 kg low-alloyed steel for construction. The corresponding lifetime of the installation is estimated to 50 years.

6.2.4 Data for SCEPPHAR system

Data for the SCEPPHAR system is delivered by UNIV based on long-term pilot trials at WWTP Carbonera. Pilot trials covered the fine-sieving of raw wastewater with a rotating belt filter, the fermentation of cellulosic sludge, and the operation of a SCEPPHAR pilot unit. All scenarios are related to the baseline scenario 0b of WWTP Carbonera with dynamic thickening as reference (for data cf. chapter 6.2.1).

Performance and energy demand of rotating belt filter

Fine-sieving of raw wastewater after mechanical treatment (350 µm mesh) removes 50% of total solids and 35% of COD. Generated cellulosic sludge amounts to 34 m^3/d with a DM content of 4.6%, 1.8% N and 0.4% P. Electricity demand of the rotating belt filter is estimated to 0.04 kWh/m^3.

Downstream effects of extraction of cellulosic sludge on biological treatment

Based on experience from other case studies of primary fine-sieving (cf. chapter 2.2.1), the savings in aeration energy in the downstream biological process are estimated to 20% or -314 MWh/a due to the reduced load of solids and COD. In addition, the extraction of cellulosic sludge also removes 5% of the TN load to the biological stage, reducing related emissions of N_2O (1.5% of N_2O-N per kg N removed). Effluent quality of the WWTP is not affected by primary treatment as defined by the operator. Total amount of excess sludge from the system is reduced by -30% in dry matter to an annual amount of 616 t DM/a, with related impacts on downstream sludge treatment such as biogas production, sludge dewatering and disposal.

Performance and energy/chemicals demand of SCEPPHAR system

The first stage of the SCEPPHAR process is the internal production of carbon source from cellulosic sludge plus a certain amount of excess sludge depending on the scenario (**Table 6-8**). The respective amount of sludge is fermented in mesophilic conditions for five days, assuming 15 kWh/m^3 heat demand covered by the internal heater operated on biogas. Fermentation yield is assumed to 0.3 kg COD_{VFA} per kg VS input as mean value for a mixture of cellulosic and waste activated sludge. Fermentation of cellulosic sludge only (scenario 2a) requires chemical addition of NaOH to keep the fermenter in alkaline conditions (5 g NaOH (100%)/kg TS), while co-fermentation of WAS fractions in scenarios 2b and 2c results in an alkaline pH without chemical needs. Fermented sludge is dewatered in solid-liquid separation to produce a VFA-rich liquor as carbon source for the SCEPPHAR system, assuming 0.9 kWh/m^3 electricity demand and a polyelectrolyte dosing of 14 kg active matter per ton DM. Concentration in the VFA-rich liquor is assumed to 13 g/L COD_{VFA}, 0.28 g/L TN, and 0.068 g/L TP. Dewatered solids are returned to the digestor of the WWTP.

From the VFA-rich liquor, struvite is precipitated by dosing $Mg(OH)_2$ at a molar ratio of 1.5 mol Mg per mol P. With this precipitation step, 88% of phosphorus in the liquor can be recovered in crystallized form and be directly used as fertilizer. Electricity demand of this step is included in the total electricity demand of the SCEPPHAR process, and potential heat demand for drying of wet struvite recovered from the process is neglected here. After struvite precipitation, the carbon source is stored before being fed to the SCEPPHAR process.

From the BACS, the carbon source is fed either to the selection or accumulation reactor of the SCEPPHAR process. The combination of nitritation and selection stage removes 85% of TN and 80% of TP from the supernatant of dewatering, while nutrient removal from the carbon source is limited only to biomass growth (-5% of TN and TP). COD from supernatant and carbon source is removed to 88% and is mostly used for nitrogen removal via-nitrite and PHA accumulation. Part of the exhausted carbon source (70%) is recycled back to the digestor to dilute the fermented solids to a suitable dry matter content for digestion.

N_2O emissions from the SCEPPHAR relate only to the nitritation stage and are accounted with a comparable N_2O emission factor than SCENA based on pilot monitoring results of SCEPPHAR and projection to full-scale operation, which is 2.27% of N_2O-N related to the N removed from the supernatant.

Overall, the entire SCEPPHAR process with struvite precipitation, nitritation, selection, and accumulation stage requires an electricity demand of 3 kWh per kg N removed from the supernatant. For stabilisation of pH in nitritation, dosing of alkalinity is required with 3 kg $CaCO_3$ (100%) per kg TN in supernatant.

Table 6-8: Input data for SCEPPHAR for COD/TN/TP removal, N_2O emissions, electricity and chemicals demand, and yield of struvite and PHA in excess sludge

Parameter	*Unit*	2a SCEPPHAR 0 % WAS	2b SCEPPHAR 62% WAS	2c SCEPPHAR 100 % WAS	Remarks
Fermenter					
Input sludge	*m^3/d*	34 -	34 + 20	34 + 33	Cellulosic sludge + waste activated sludge
Heat demand for fermenter	*kWh/m^3*	15	15	15	UNIV data
NaOH (100%)	*g NaOH/kg TS*	5	-	-	For pH control
Fermentation efficiency	*g COD_{VFA}/g VS*	0.3	0.3	0.3	VS from cellulosic sludge and WAS
Solid-liquid separation					
Electricity demand	*kWh/m^3*	0.9	0.9	0.9	Estimate
Polymer demand	*g/kg TS*	14	14	14	Estimate
Final TS	*%*	18	18	18	95% TS separation
Volume of BACS	*m^3/d*	28	45	55	
COD_{VFA} in BACS	*mg/L*	13,000	13,000	13,000	
TN in BACS	*mg/L*	280	280	280	
TP in BACS	*mg/L*	68	68	68	
Struvite precipitation					
Dosing of Mg	*Mol Mg/mol P*	1.5	1.5	1.5	Dosing as $Mg(OH)_2$
Yield	*% of input P*	88	88	88	
Struvite mass	*t/a*	4.9	7.7	9.4	Pure $MgNH_4PO_4 \cdot 6H_2O$
Nitritation, selection and accumulation SBR					
COD removal	*%*	88	88	88	UNIV data
N removal	*%*	85*	85*	85*	UNIV data
P removal	*%*	80*	80*	80*	UNIV data
N_2O	*% N_2O/N removed*	2.27*	2.27*	2.27*	UNIV data: monitoring and full-scale projection
Electricity demand	*kWh/kg N removed*	3.0	3.0	3.0	UNIV data for entire SCEPPHAR
Electricity savings in mainline aeration	*kWh/kg N*	9	9	9	Estimate of ATS
Dosing of $CaCO_3$ (100%)	*kg/kg TN in*	3.0	3.0	3.0	For alkalinity
PHA yield	*g PHA/g COD_{VFA}*	0.2	0.2	0.2	Related to COD_{VFA} in BACS
PHA amount	*t/a*	27	42.5	52	Calculated from COD_{VFA}
PHA content in sludge	*g PHA/g VS*	0.35	0.35	0.35	90% VS in DM
PHA sludge	*t DM/a*	86	135	165	Calculated via PHA yield and PHA content

** only for supernatant of dewatering that undergoes nitritation and selection stage*

Effects of SCEPPHAR on mainstream WWTP

SCEPPHAR sidestream treatment reduces N return load to the mainline by around 13-14 t TN/a depending on the scenario. The related potential savings in aeration energy in the mainline are estimated to 9 kWh/kg N by the operator in analogy to SCENA, amounting to a total reduction of 117-126 MWh/a or -8% in electricity demand for the mainline. These electricity savings come on top of the aeration savings induced by the fine-sieving of raw wastewater (-20%). Overall, WWTP effluent quality is assumed to be comparable to the baseline situation, so no changes for TN or TP discharge concentration are accounted with SCEPPHAR implementation. Due to the reduced TN load to the mainline, related N_2O emissions for this fraction can be avoided with SCEPPHAR based on the emission factor for the mainline (1.5% of N_2O-N per kg N removed).

Products of SCEPPHAR system: struvite and PHA-rich excess sludge

Based on pilot trials, 88% of phosphorus in fermentation liquor can be extracted as struvite, amounting to 4.9-9.4 t pure struvite ($MgNH_4PO4*6H_2O$) per year depending on the scenario (**Table 6-8**). The amount of PHA-rich excess sludge from accumulation stage is calculated based on the PHA yield of the accumulation stage (0.2 g PHA per g COD_{VFA}), the PHA content of the excess sludge (35% of VS is PHA), and its VS content (90% of DM). Finally, a total amount of 27-52 t PHA can be produced with the SCEPPHAR system, which relates to a total mass of 86-165 t dry matter of excess sludge with a dry matter content of 2%. This PHA-rich sludge is further processed for PHA extraction (see below).

Infrastructure for SCEPPHAR

Material demand for building a sidestream SCEPPHAR system is roughly estimated by the design of the pilot system, scaling up from the SCENA design values based on the higher volume processed in the fermenter and the higher volume treated in SBR tanks. The rotating belt filter is neglected here.

For scenarios 2a/b/c, the required material amounts add up to 771/959/1074 m³ of concrete and 35/53/65 t of stainless steel. The corresponding lifetime of the installation is estimated to 50 years for concrete (tanks) and 12 years for stainless steel.

6.2.5 Data for product valorisation: struvite and PHA sludge

Struvite

For struvite, the product is valorised as fertilizer in agriculture. Both P (12.7%) and N (5.6%) content of struvite are fully accounted to replace mineral fertilizer due to the slow-release characteristics of struvite. From the total amount of struvite produced (**Table 6-8**), the related mass of mineral P and N fertilizer are avoided.

Chemical extraction of PHA and drying to PHA powder

PHA-rich excess sludge is dewatered and chemically digested to extract the PHA. The resulting powder is dried to be used as input for bio-composite production, replacing PHA from pure-culture production.

PHA-rich excess sludge is dewatered to 20% DM (assumption, feasibility to be tested) using a centrifuge with 95% TS separation efficiency, 1 kWh/m³ electricity demand and 5 kg polyelectrolyte per ton DM. Liquor from dewatering is assumed to 480 mg/L COD, 77 mg/L TN, and 13 mg/L TP and is returned to the WWTP inlet. Dewatered PHA sludge is chemically digested using two chemicals in dedicated dosing (confidential data), a procedure which was tested and optimised during the project. Extraction efficiency is 90%, and 10% of PHA are lost with the residual liquor from extraction. For intermediate washing, 23 L of water per kg TS are assumed. Electricity for PHA extraction amounts to 1.8 kWh/m³ PHA sludge, while heat for spray drying is estimated to 0.88 kWh/kg TS. Residual liquor from PHA extraction (2,240-4,310 m^3/a) contains remaining TS, COD (30 g/L), TN (1.8 g/L) and TP (0.16 g/L) from biomass. This highly loaded wastewater stream is supposed to be treated requiring 9.5 kWh of electricity per m³ for treatment (conservative estimate). Infrastructure for PHA extraction is neglected in this LCA study.

Extracted PHA powder (23-44 t/a or 0.58-1.11 kg/(pe*a)) is credited with substituting the equivalent amount of pure-culture PHA from sucrose. The functional equivalency of PHA powder from SCEPPHAR and pure-culture PHA is not proven here, but it is assumed that both products fulfil the same function in the production of bio-composites.

6.2.6 Background data

Background processes are modelled with datasets from ecoinvent database v3.4 (Ecoinvent, 2017). The related datasets are listed below (**Table 6-9**), mainly relating to European or global markets. For electricity, the market mix of Italy is applied. For transport of chemicals to the WWTP, a distance of 300km has been estimated.

Table 6-9: Datasets for background data

Process	Dataset from ecoinvent v3.4	Remarks
Energy		
Electricity	market for electricity, medium voltage [IT]	For all electricity demand
Heat	heat production, natural gas, at boiler condensing modulating <100kW [Europe without Switzerland]	Heat for drying of PHA powder
Transport and fuels		
Truck transport	transport, freight, lorry 16-32 metric ton, EURO5 [RER]	300 km for chemicals, 172 km for sludge to agriculture
Diesel	diesel, burned in agricultural machinery [GLO]	Diesel for composting
Chemicals		
Polyelectrolyte	market for acrylonitrile [GLO]	746 g acrylonitrile + water = 1kg of polymer active substance
PACl	market for aluminium hydroxide [GLO], market for hydrochloric acid, w/o water, in 30% solution state [RER]	1 kg PACl (18% Al) requires 0.19 kg Al(OH)3, 0.22 kg HCl, and 0.04 kWh electricity
Peracetic acid	market for acetic acid, w/o water, in 98% solution state [GLO], market for hydrogen peroxide, w/o water, in 50% solution state [GLO], market for sulfuric acid [GLO], market group for tap water [RER]	1 kg PAA (40%) requires 0.72 kg acetic acid, 0.24 kg H_2O_2, 0.01 kg H_2SO_4, 0.03 kg tap water, and 0.5 kWh electricity
Acetic acid	market for acetic acid, without water, in 98% solution state [GLO]	Carbon source for SCENA
$Mg(OH)_2$	market for magnesium oxide [GLO]	MgO modelled as Mg(OH)2
NaOH	market for sodium hydroxide, without water, in 50% solution state [GLO]	For pH control of SCEPPHAR fermenter
$CaCO_3$	market for limestone, crushed, washed [RoW]	For alkalinity control in SCEPPHAR
Chemical 1	market [GLO]	For PHA extraction (confidential)
Chemical 2	market [GLO]	For PHA extraction (confidential)
Tap water	market for tap water [Europe without Switzerland]	Water for PHA extraction
Mineral N fertilizer	market for nitrogen fertiliser, as N [GLO]	Credits for sludge application in agriculture and struvite
Mineral P fertilizer	market for phosphate fertiliser, as P2O5 [GLO]	Credits for sludge application in agriculture and struvite
Materials		
Concrete	market for concrete, for de-icing salt contact [RoW]	Infrastructure for SCENA, composting, and SCEPPHAR
Reinforced steel	reinforcing steel production [RoW]	Infrastructure for composting
Low-alloyed steel	steel production, low-alloyed, hot rolled [RoW]	Infrastructure for composting
Stainless steel	steel production, electric, chromium steel 18/8 [RoW]	Infrastructure for thickener, fermenter and screw press
Cast iron	cast iron production [RoW]	Infrastructure for composting

6.3 Results of environmental indicators (Life Cycle Impact Assessment)

Results of this LCA are separately discussed for the SCENA and SCEPPHAR scenarios below.

6.3.1 SCENA system

Cumulative energy demand (CED)

The total net CED of WWTP Carbonera including sludge disposal amounts to 433 MJ/(pe*a) in the baseline scenario 0a, and 417 MJ/(pe*a) in the baseline 0b with dynamic thickening (**Figure 6-3**), accounting for electricity and chemicals demand at the WWTP, transport of sludge, and nutrient credits for sludge disposal. The CED for WWTP operation and sludge treatment is mainly due to electricity demand for operation (82%), chemicals for P removal, disinfection, and sludge dewatering (12%) and sludge transport (6%). This gross energy demand is only marginally compensated (5%) by nutrient credits for sludge disposal in agriculture (-21 MJ/(pe*a)). Overall, the plant uses its entire biogas produced in digestion only to cover the internal heat demand of the WWTP. Therefore, the increase in biogas production due to dynamic thickening (+78%) is not reflected in the energy balance, as the internal heat demand is already covered in the baseline scenario. If the biogas would be utilized in a CHP unit to produce electricity and heat, the energy balance of the WWTP could be greatly improved, especially after the dynamic thickening was installed. A first estimate of potential electricity production amounts to 800 MWh/a for the latter scenario 0b, covering 39% of the electricity demand of the WWTP.

Introducing a SCENA system for sidestream nutrients removal can either decrease of increase the net CED of the system depending on the carbon source used (**Figure 6-3**). Using acetate as an external carbon source for SCENA, the CED of the baseline scenario 0a is increased by +8% in scenario 1a. In contrast, the production of an internal carbon source by fermentation of mixed sludge into VFA in scenario 1b leads to a decrease of -2% in net CED compared to the related baseline scenario 0b. These results underline the importance of the choice of carbon source for the overall energy balance of the SCENA process.

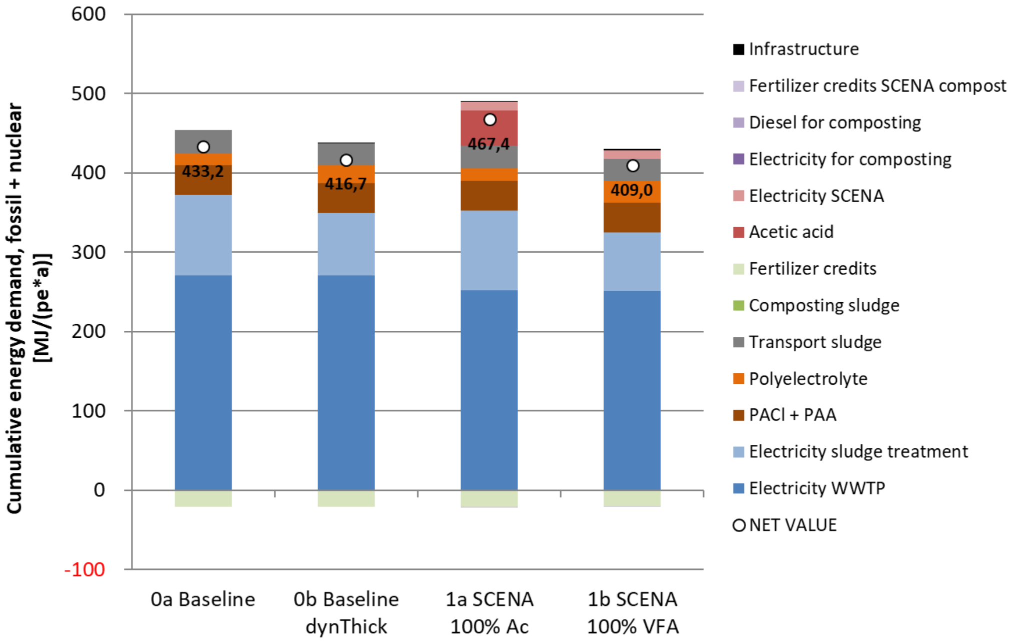

Figure 6-3: Total cumulative energy demand for baseline and SCENA scenarios at WWTP Carbonera

For a detailed analysis of the SCENA scenarios, the relative changes of CED due to SCENA implementation are shown below in relation to the respective baseline (**Figure 6-4**). Overall, the implementation of SCENA leads to a change in net CED between +34 and -8 MJ/(pe*a) depending on the carbon source used. The contribution analysis shows several effects of SCENA on the total energy demand of the system:

- From the electricity balance, it is evident that the sidestream SCENA treatment requires less electricity for nitrogen removal than its treatment in the mainline process. Indeed, the SCENA process requires 5.1-5.4 kWh/kg N removed, whereas the mainline treatment is accounted with 9 kWh/kg N.
- However, the significant energy required to produce the external carbon source (acetic acid) completely off-sets this benefit in electricity needs in scenario 1b and leads to an overall increase in energy demand compared to the respective baseline (+34 MJ/(pe*a)).
- If the carbon source is produced by fermentation of mixed sludge on-site, it comes at lower energetic costs, mainly associated with some electricity demand for fermentation and solid-liquid separation, and additional polymer demand for dewatering after fermentation. On top, this additional energy demand of BACS production is partially off-set by related electricity savings in the sludge treatment line, as the volume of sludge to be digested and dewatered is reduced by around 18%. Overall, this configuration leads to a slight reduction in total energy demand of the system (-8 MJ/(pe*a)).
- Valorisation of P-rich sludge from SCENA via dynamic composting into a biofertilizer has only negligible impact on the total energy balance. Overall, energy demand for composting is low compared to the SCENA process, but energy credits from nutrients in biofertilizer are also relatively small due to the low total amount of recovered nutrients. In addition, SCENA only leads to a transfer of nutrients from digested sludge into biofertilizer, although leading to a higher plant availability of P in biofertilizer (100%) compared to digested sludge (20%) and thus to higher nutrient credits. This underlines the primary goal of SCENA, which is seen in the nutrient removal from sidestream liquor, while the recovery of nutrients is only a minor aspect in the environmental balance.
- Infrastructure for the SCENA and composting processes plays only a negligible role for the overall energy balance of the scenarios.

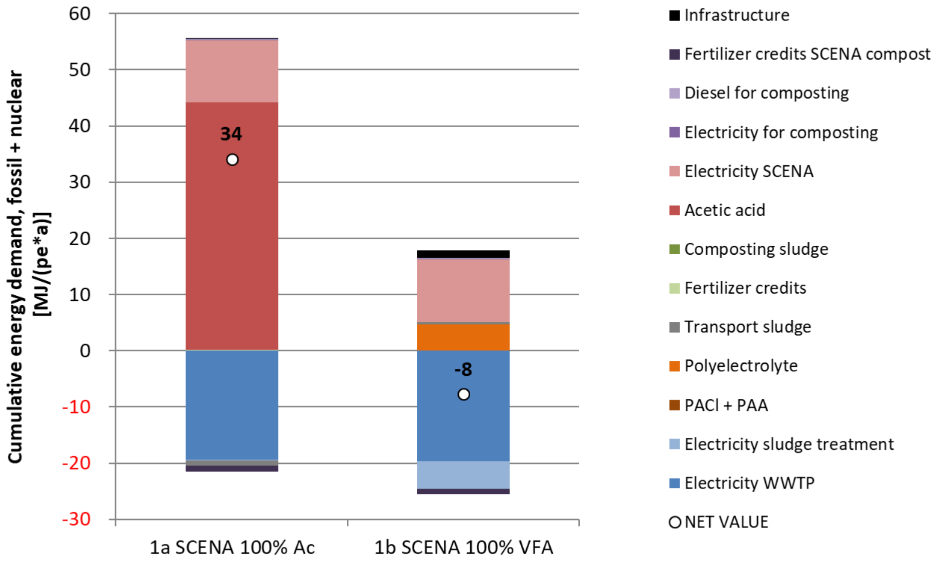

Figure 6-4: Change in cumulative energy demand for SCENA scenarios at Carbonera Manresa compared to respective baseline (0a for 1a, 0b for 1b)

The analysis above revealed that the valorisation of the P-rich sludge plays only a minor role for the overall energy balance. Focussing only on the process of dynamic composting of the dewatered P-rich sludge, a small energy credit can be generated from this route (**Figure 6-5**). Composting is a low-energy process and enables the recovery of valuable nutrients in the SCENA sludge with low energetic efforts.

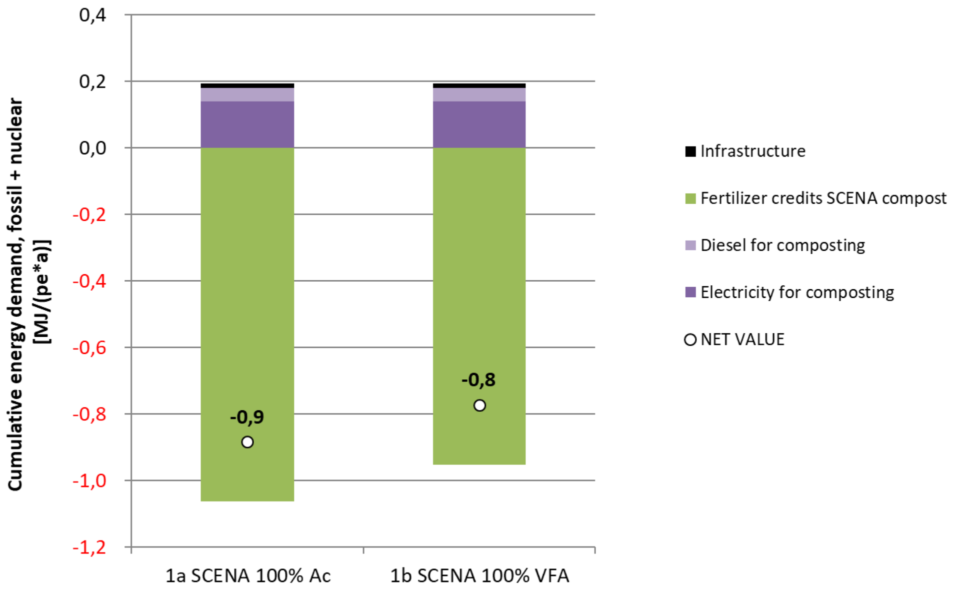

Figure 6-5: Balance of cumulative energy demand for valorisation route of P-rich excess sludge (20% DM) with dynamic composting into biofertiliser

Global warming potential (GWP)

The total net GWP of the baseline scenarios amounts to 53-54.5 kg CO_2-eq/(pe*a) depending on the implementation of the dynamic thickening (**Figure 6-6**). In analogy to the CED, the operation of the WWTP contributes to the GWP mainly with electricity demand (42%) and less with chemicals (4%) and sludge disposal (7%). On top, the direct emissions of N_2O from the activated sludge tank are a significant factor for the GWP (46%), while other greenhouse gases (e.g. CH_4 at centrifuges or off-gas from heater) are negligible (1%).

Implementing a SCENA system increases net GWP between +1% and +4% depending on the carbon source used. Apart from the energy-related aspects discussed above, the higher direct N_2O emissions of the SCENA process also play a decisive role here. A detailed analysis of the changes in GWP due to SCENA implementation is provided below.

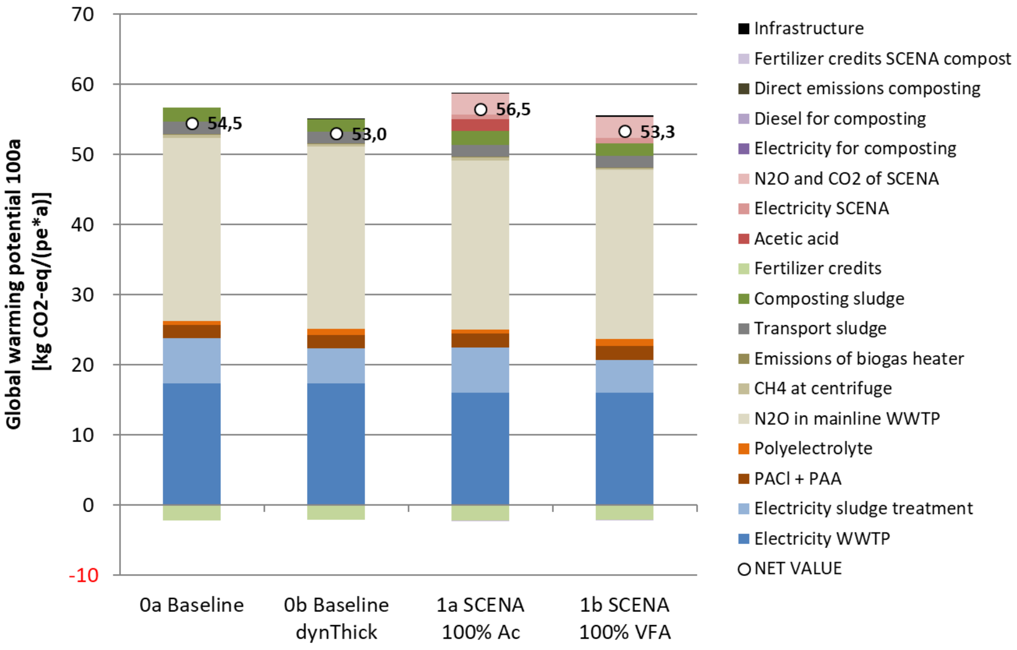

Figure 6-6: Total global warming potential for baseline and SCENA scenarios at WWTP Carbonera

In scenarios 1a and 1b, net GWP of the system changes between +0.4 to +2.0 kg CO_2-eq/(pe*a) depending on the carbon source used (**Figure 6-7**). While some factors are in analogy to the energetic balance, others are particularly associated with specific greenhouse gases:

- For electricity demand, the benefits of SCENA are also reflected in the GWP indicator. However, using an external carbon source in scenario 1a also leads to a higher GWP than the respective baseline due to the related greenhouse gas emissions during the production of acetic acid.
- On top of the energetic profile, the higher N_2O emissions of SCENA compared to the mainline N removal also affect the GWP balance. N_2O emissions are projected to be 50% higher in SCENA (2.27% of N removed) than in the mainline (1.5% of N removed) due to the short-cut N removal via nitrite. This aspect has a major impact on the GWP balance, and off-sets the benefits of SCENA also for the scenario 1b with internal carbon source. In the end, both SCENA setups lead to a higher GWP balance of the system. However, further optimisation of process control to mitigate N_2O emissions from SCENA (e.g. improving the oxygen transfer efficiency) could help to reduce this drawback.
- As for the energy balance, the processing and valorisation of P-rich sludge from SCENA plays only a minor role for the overall GWP balance.

Overall, it is evident that the higher N_2O emissions from the SCENA process are one of the major factors leading to an inferior GWP balance for this process. Indeed, this factor could be critical in the GWP balance of any short-cut N removal process via nitrite, as nitrite accumulation could be intrinsically associated with high N_2O emissions off-setting the energy benefits of this process. Future optimisation of the SCENA process should target the minimisation of N_2O emissions to avoid or minimise this potential drawback (e.g. improving the oxygen transfer efficiency to reduce zones of low oxygen).

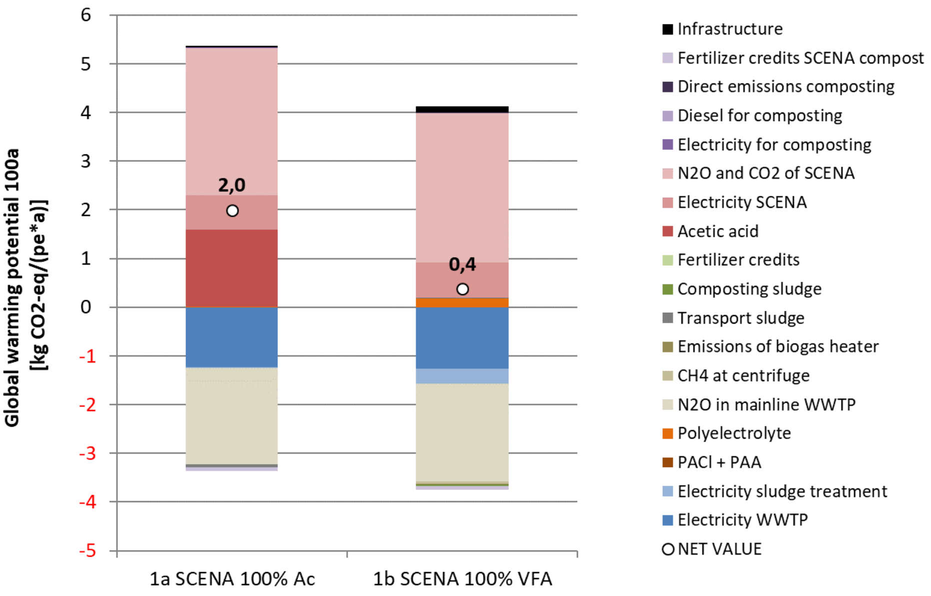

Figure 6-7: Change in global warming potential for SCENA scenarios at WWTP Carbonera compared to respective baseline (0a for 1a, 0b for 1b)

Analysing the GWP profile of the valorisation route for P-rich sludge only, it is evident that composting and use as biofertilizer has the potential to reduce GHG emissions between -0.05 and -0.06 kg CO2-eq/(pe*a) (**Figure 6-8**). The process is energetically beneficial due to the low energy use and the nutrient credits, and direct greenhouse gas emissions from aerobic composting (N_2O, CH_4) are low and could even be further reduced by a biofilter (not implemented here). Overall, the GWP balance of this route shows that composting is a suitable process to valorise the SCENA sludge with environmental benefits, although the low total amount of recovered nutrients does not help much to improve the total greenhouse gas balance of the process.

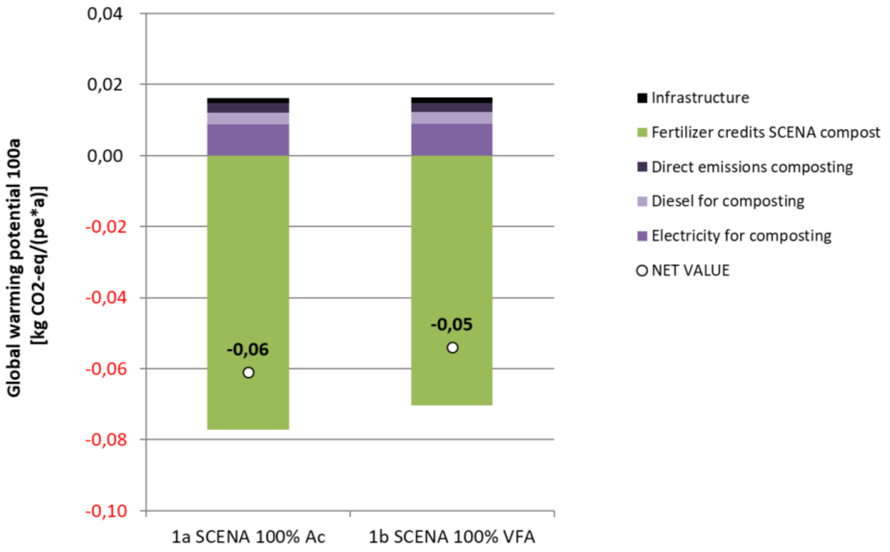

Figure 6-8: Balance of global warming potential for valorisation route of P-rich excess sludge (20% DM) with dynamic composting into biofertiliser

6.3.2 SCEPPHAR system

Cumulative energy demand (CED)

The total net CED of WWTP Carbonera with dynamic thickening amounts to 417 MJ/(pe*a), accounting for electricity and chemicals demand at the WWTP and nutrient credits for sludge disposal (**Figure 6-9**). The specific contributions of the different factors to the energy balance have been discussed in detail above (cf. chapter 6.3.1).

Introducing a SCEPPHAR system for sidestream treatment and recovery of PHA and struvite decreases the net CED of the system by -5 to -8% depending on the amount of PHA produced. The more sludge is converted to VFA and used for PHA production, the more energy can be saved in the system.

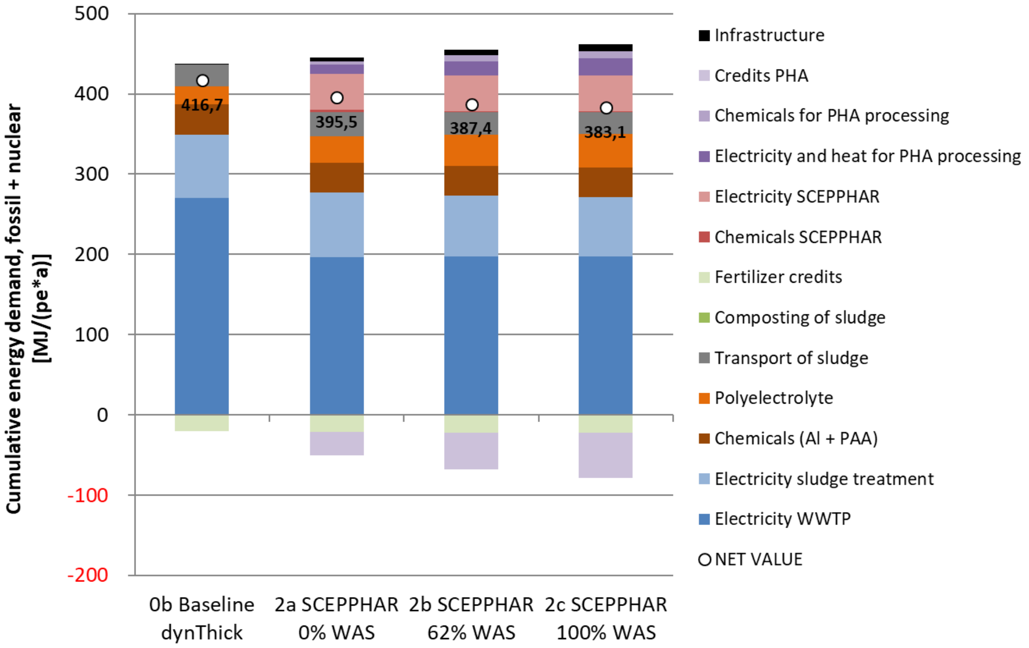

Figure 6-9: Total cumulative energy demand for baseline and SCEPPHAR scenarios at WWTP Carbonera

For a detailed analysis of the SCEPPHAR scenarios, the relative changes of CED due to SCEPPHAR implementation are shown below for the different scenarios (**Figure 6-10**). Overall, the implementation of

SCEPPHAR leads to a change in net CED between -21 and -34 MJ/(pe*a) depending on the amount of WAS that is used for PHA production. The contribution analysis shows several effects of SCEPPHAR on the total energy demand of the system:

- From the electricity balance, it becomes evident that sidestream SCEPPHAR treatment requires less electricity than can be saved in the mainline. Electricity needs for the SCEPPHAR is mostly for sieving of wastewater (230 MWh/a), and less for VFA production and sidestream treatment (52-65 MWh/a). Similarly, electricity savings in the mainline aeration are mostly due to effects of primary sieving and lower COD/TS load (-314 MWh/a) and less due to reduced N load by sidestream treatment (-117 to -126 MWh/a). In total, net electricity savings on the plant amount to around -145 MWh/a.
- Additional polyelectrolyte for dewatering of fermented carbon source and PHA sludge amounts to 7-14 t/a active matter, which adds some energy demand to the SCEPPHAR scenarios (+10-19 MJ/(pe*a)). Other chemicals for SCEPPHAR such as NaOH for fermentation or $CaCO_3$ for alkalinity control do not play a major role in the overall energy balance.
- Valorisation of PHA-rich sludge as bioplastic raw material yields high credits for substituting pure-culture PHA, which amount to 50.5 MJ/kg PHA or -29 and -56 MJ/(pe*a) depending on the scenario (**Figure 6-10**). However, a substantial part of the credits is off-set by chemicals and energy required for PHA extraction. The energy balance of this route for post-processing and product valorisation is analysed in detail below.
- Infrastructure required for the SCEPPHAR system does only marginally add additional energy demand for the SMART scenarios (+4-8 MJ/(pe*a)).

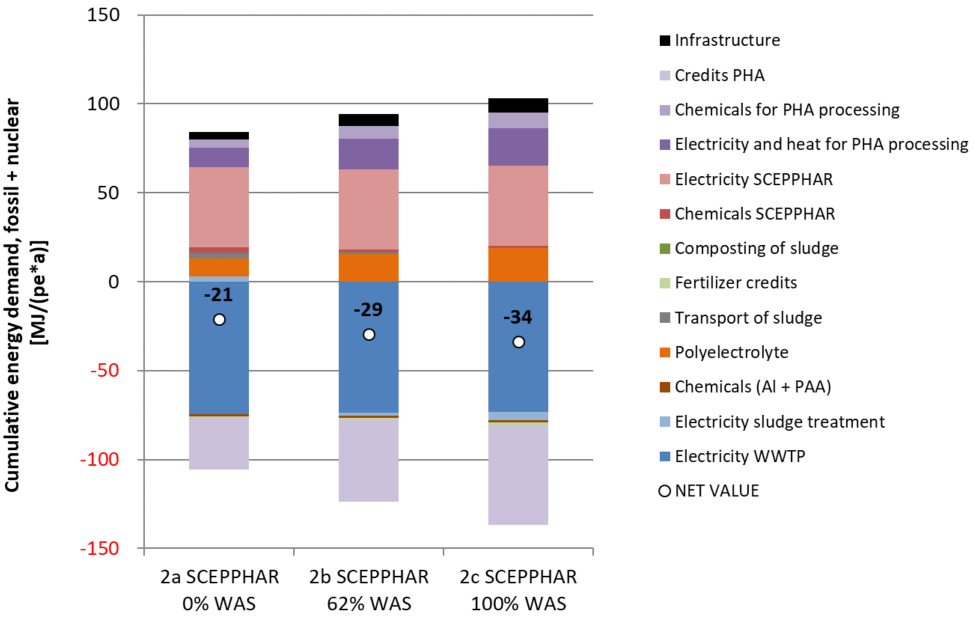

Figure 6-10: Change in cumulative energy demand for SCEPPHAR scenarios at WWTP Carbonera compared to baseline

The analysis above revealed that the valorisation of PHA-rich excess sludge contributes significantly to the overall positive energy balance of SCEPPHAR. For a more detailed view of these effects, CED of PHA valorisation is explicitly shown in **Figure 6-11**, excluding all other impacts from the WWTP and starting from dewatered PHA-rich excess sludge.

Credits from substitution of pure-culture PHA clearly exceed the efforts for PHA extraction from the sludge. However, chemicals for PHA processing and especially energy required for drying of PHA and treatment of waste liquor off-set around 45-50% of the energy credits for the PHA product. From the total energy required for PHA extraction, heat for drying has the highest share (66%) followed by electricity for waste liquor treatment (33%) and electricity for the PHA extraction process itself (1%).

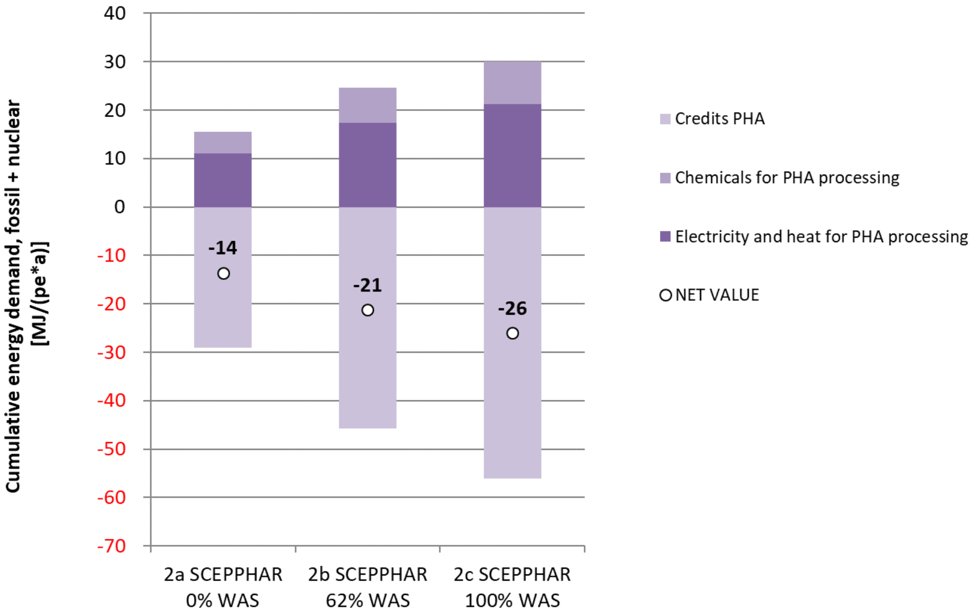

Figure 6-11: Balance of cumulative energy demand for valorisation route of dewatered PHA-rich excess sludge (20% DM) with PHA extraction and drying of powder

Overall, it can be concluded that the valorisation of PHA-rich sludge with reasonably high PHA content (here: 35% PHA in VS or 31.5% in DM) via chemical extraction yields net energetic benefits of around -24 MJ/kg PHA. This credit represents the major part of the energy benefits of SCEPPHAR (66-76% of total benefits), which underlines the importance of an effective valorisation of the product for the environmental benefit of this process. However, optimisation of heat demand for drying of PHA powder (e.g. use of excess heat) or a low-energy treatment of the generated waste liquor could still improve the energy benefits of this SMART product and make this recovery route even more attractive from an environmental point of view. Reaching a higher PHA content in the sludge would also benefit the energy balance, as chemical and energy efforts for extraction are mainly related to the dry matter content of the sludge: the more PHA concentration in the dry matter, the more credits can be gained.

Global warming potential (GWP)

The total net GWP of the baseline scenario with dynamic thickening amounts to 53.0 kg CO_2-eq/(pe*a) (**Figure 6-12**). As discussed in detail above, direct N_2O emissions from the biological treatment contribute much to this impact category apart from chemical and energy-related emissions (cf. chapter 6.3.1).

Implementing a SCEPPHAR system changes net GWP between -4% and -7% depending on the amount of sludge redirected to PHA production in the different scenarios. In contrast to SCENA, higher N_2O emissions of the short-cut N removal pathway do not neutralize the benefits of SCEPPHAR in this impact category. A detailed analysis of the changes in GWP due to SCEPPHAR implementation is provided below.

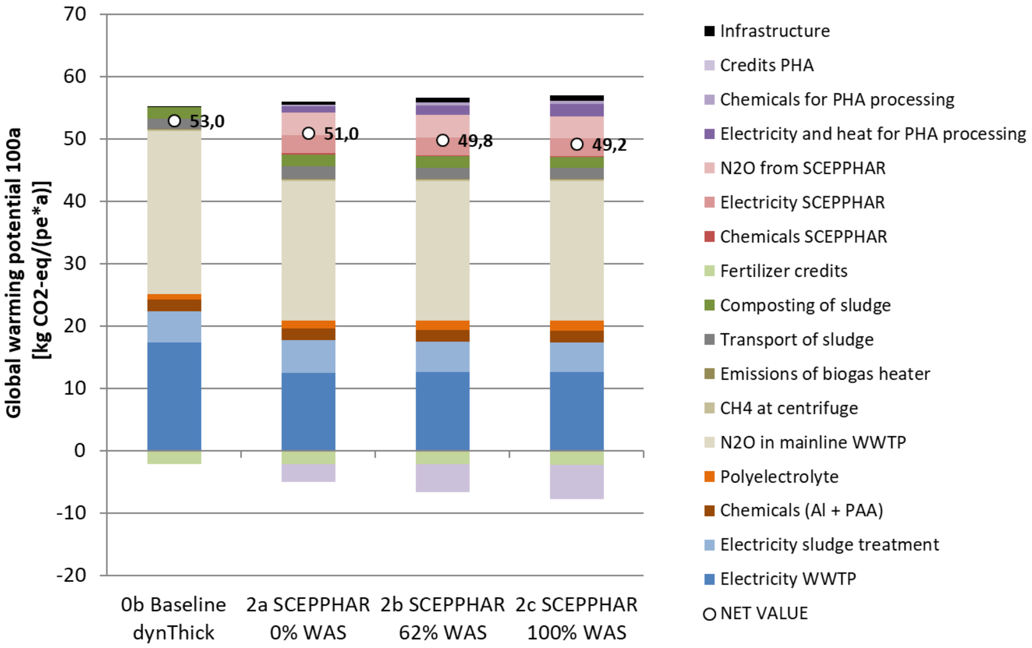

Figure 6-12: Total global warming potential for baseline and SCEPPHAR scenarios at WWTP Carbonera

In scenarios 2a-2c, net GWP of the system changes between -2.0 to -3.8 kg CO_2-eq/(pe*a) depending on the amount of PHA produced (**Figure 6-13**). While many factors for GWP are in analogy to the energetic balance, others are particularly associated with specific greenhouse gases:

- For the operation of the WWTP, energy benefits of SCEPPHAR also have a positive impact on the GWP balance. The highest benefits arise from the savings in electricity for WWTP operation.
- The balance of direct N_2O emissions on the WWTP is different to SCENA: although the short-cut N removal in SCEPPHAR still has higher N_2O emissions (+50% in emission factor) than the mainline N removal, this drawback is not effective in the net balance as the fine-sieving of wastewater also reduces the N load to the mainline, saving on total N_2O emissions from biological treatment by physically removing 5% of the TN from the mainline. This results overall in a neutral impact of SCEPPHAR implementation on the total N_2O emissions at the WWTP. However, this effect is only due to the data projected in this study, and should be validated by further N_2O monitoring of a full-scale SCEPPHAR system under realistic operational conditions.
- PHA extraction and valorisation also has a positive impact on the overall GWP balance, as credits for substitution of pure-culture PHA exceed the efforts for extraction. A more detailed analysis of this valorisation route is provided below.

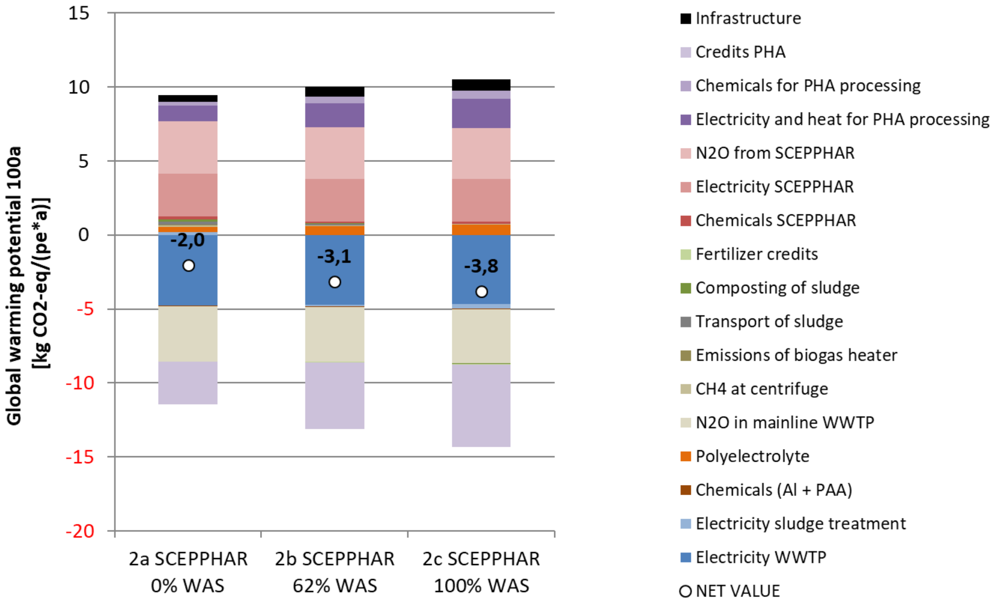

Figure 6-13: Change in global warming potential for SCEPPHAR scenarios at WWTP Carbonera compared to baseline

Analysing the GWP profile of the valorisation route for PHA-rich sludge only, it is evident that this route reduces GHG emissions between -1.6 and -3.0 kg CO2-eq/(pe*a) (**Figure 6-14**). Here, around 46% of GWP credits for the PHA product are off-set by chemical and energy-related GWP emissions for PHA extraction.

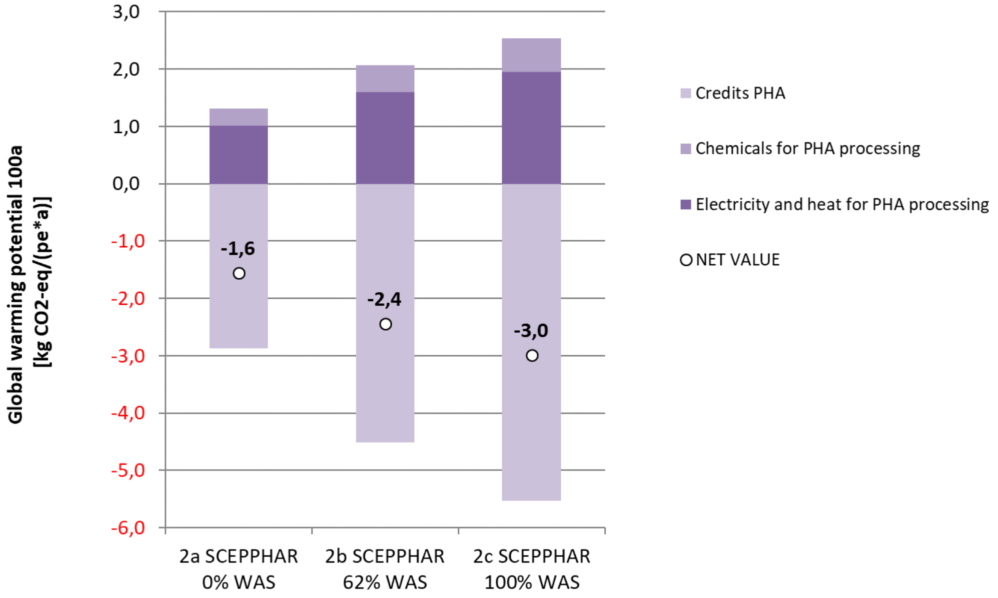

Figure 6-14: Balance of global warming potential for valorisation route of PHA-rich excess sludge (20% DM) with PHA extraction and drying of powder

In total, this valorisation route generates credits of -2.7 kg CO_2-eq per kg PHA. Comparable to the energy balance, the PHA valorisation route is also responsible for the major share of the GWP benefits of SCEPPHAR (~80%). This underlines again the importance of a downstream processing with lowest environmental impact to be able to realize a net environmental benefit in resource recovery.

6.4 Interpretation and conclusions

This LCA case study analyses the potential environmental impacts of implementing a SCENA or SCEPPHAR system for sidestream treatment with recovery of valuable products at the WWTP Carbonera (IT), taking into account all direct and indirect effects on the WWTP and in the sludge disposal route. Products of the systems are P-rich sludge for SCENA and struvite plus PHA-rich sludge for the SCEPPHAR process. Downstream processing of these intermediates into valuable products is included in this LCA with dynamic composting of P-rich sludge into biofertilizer and chemical extraction of PHA powder from PHA-rich sludge.

The main outcomes of the LCA for the SCENA system can be summarized as follows (**Table 6-10**):

- Implementation of a SCENA system for sidestream nutrient removal **did not have a positive energy balance when operated with an external carbon source**. Net energy demand is slightly higher than for the respective baseline scenario, because the energy benefits of the short-cut nutrient removal are fully off-set by the energy required to produce the external carbon source.
- **Using an internally produced carbon source, the SCENA process can reduce total energy demand** of the system, although only to a small extent.
- For GHG emissions, the environmental impact of the SCENA process is **negatively affected by the higher N_2O emissions** (+50%) detected for the short-cut N removal pathway compared to the mainline N removal. This leads to a **higher impact in net global warming potential with SCENA for both external and internal carbon source**. Altogether, this factor is an intrinsic drawback of this technology and should be closely monitored and minimised by suitable process control strategies to mitigate its environmental impact in this category.
- The recovery of **P-rich sludge and its downstream valorisation as biofertilizer after dynamic composting reduces overall energy demand and GHG emissions**. However, this positive environmental impact of resource recovery is only marginal compared to the other impacts of SCENA, and underlines the primary goal of this technology which is rather focussed on sidestream nutrient removal and not on resource recovery.

Table 6-10: Summary of LCA results for sidestream treatment with SCENA at WWTP Carbonera (40,000 pe): impact on energy demand and global warming potential

Parameter	*Unit*	Baseline system	SCENA with acetic acid as external carbon source	Baseline system with dynamic thickening	SCENA with VFA as carbon source
N return load	*t/a*	**17.7**	-12.8	**18.4**	-13.0
		100%	-72%	**100%**	-71%
Recovered N	*t/a*	**5.3**	5.3	**5.1**	5.1
Recovered P	*t/a*	**5.0**	5.4	**4.9**	5.3
Cumulative energy demand	*MJ/(pe*a)*	**433**	**+34**	**417**	**-8**
		100%	**+8%**	**100%**	**-2%**
Global warming potential	*kg CO_2-eq/(pe*a)*	**54.5**	**+2.0**	**53.0**	**+0.4**
		100%	**+4%**	**100%**	**+1%**

Overall, SCENA is seen as a promising process to achieve sidestream nutrient removal in an energy-efficient way if combined with the production of an internal carbon source from sludge. On top, its excess sludge can be valorised as a valuable biofertilizer with low efforts in treatment. However, the process should be optimised in terms of direct N_2O emissions to mitigate this potential environmental drawback of this technology.

The main outcomes of the LCA for the SCEPPHAR system are summarized below (**Table 6-11**):

- The SCEPPHAR sidestream treatment in the present configuration **combines the benefits of two SMARTechs** into a single scheme: a) **primary fine-sieving** and production of cellulosic sludge and b) **sidestream treatment of sludge liquor** to remove nutrients and produce a valuable product with the PHA-rich sludge. Both processes combined lead to **environmental benefits for the overall energy balance and also for GHG emissions**.
- Fine-sieving of raw wastewater is responsible for the major share of both electricity needs for the SCEPPHAR configuration and related savings in aeration at the WWTP mainline. This positive energy balance of the sieving is amplified by exploiting the VFA generated from cellulosic sludge into valuable PHA.
- The valorisation of PHA-rich sludge via chemical extraction and production of a PHA powder **generates a major share of the net environmental benefits** of the SCEPPHAR sidestream treatment. Consequently, the **additional use of VFA produced via fermentation of waste activated sludge** for PHA production increases this effect and has a positive impact on the environmental profile.
- **Higher N_2O emissions as potential drawback of the short-cut N removal pathway are partially mitigated here by the positive impact of fine-sieving** on the N load of the biological treatment. In total, overall N_2O emissions are not significantly increased when changing to the SCEPPHAR configuration. Consequently, energy benefits of SCEPPHAR and PHA valorisation directly translate into benefits also for the overall GHG balance.
- The recovery of struvite from the carbon source adds to the environmental benefits, but only with marginal benefits in energy and GHG emissions.

Table 6-11: Summary of LCA results for sidestream wastewater treatment with SCEPPHAR at WWTP Carbonera (40,000 pe): impact on energy demand and global warming potential

Parameter	*Unit*	Baseline system	SCEPPHAR with cellulosic sludge	SCEPPHAR with cellulosic and 62% WAS	SCEPPHAR with cellulosic and 100% WAS
N return load	*t/a*	**18.4**	-14	-13.4	-13
		100%	-76%	-73%	-73%
Recovered N	*t/a*	**5.1**	4.8	4.9	5.0
Recovered P	*t/a*	**4.9**	5.4	5.7	5.9
PHA in final product	*t/a*	**-**	23.0	36.3	44.4
	*kg/(pe*a)*	**-**	0.6	0.9	1.1
Cumulative energy demand	*MJ/(pe*a)*	**417**	**-21**	**-29**	**-34**
		100%	**-5%**	**-7%**	**-8%**
Global warming potential	*kg CO_2-eq/(pe*a)*	**53.0**	**-2.0**	**-3.1**	**-3.7**
		100%	**-4%**	**-6%**	**-7%**

Overall, it can be concluded that SCEPPHAR in its present configuration is a promising process to combine sidestream treatment and recovery of valuable resources into a single scheme. Important synergies between the sidestream treatment and the internal carbon source production are generated by the fine-sieving of raw wastewater to extract cellulosic sludge, which produces a suitable raw material for VFA production and has a substantial positive impact on the mainline operation. In addition, the good fermentation efficiency of this sludge generates a high amount of VFA which translates into a high concentration of PHA in the recovered sludge. This is a necessary condition for an efficient valorisation of this recovered material in chemical extraction, so that the recovered resource can be valorised with reasonable input of energy and chemicals into a valuable end product. Still, potential drawbacks of the short-cut nitrogen removal such as high N_2O emissions should also be closely monitored and minimised by suitable operational strategies, so that the overall environmental profile of the process is not deteriorated by this factor.

Limitations and transferability of the case study results to other WWTPs

Overall, the implementation of SCENA can have both positive and negative impacts on the environmental footprint of WWTP Carbonera, while the SCEPPHAR configuration showed the potential to reduce energy demand and GHG emissions of the plant. However, the underlying data and assumptions and the specific site conditions at WWTP Carbonera have a high impact on the results of this LCA, which should be carefully reflected in interpretation of this study.

When transferring the results of this LCA to other WWTPs and boundary conditions, the following aspects have to be considered:

- Potentially positive effects of SCENA or SCEPPHAR implementation on **WWTP effluent quality or WWTP capacity have not been evaluated** in this LCA, but should be taken into account for a holistic evaluation of this technology.
- Positive effects due to reduced return load such as **savings in aeration energy for the mainline have not been demonstrated in full-scale**, but are based on experience of the operator. These effects are site-specific and depend on the efficiency of the aeration system, on its control options, and on the configuration of the biological system. Hence, the underlying assumptions should be validated again for each WWTP.
- For fine-sieving of raw wastewater as part of the SCEPPHAR configuration, **downstream effects on the mainline aeration are estimated based on supplier data** from other sites (cf. chapter 2). However, this data relates to a WWTP without primary settler, whereas WWTP Carbonera is operated with a primary settler. Whether the implementation of a fine-sieve upfront a primary settler still has the same positive effects on the operation of the biological stage (-20% in aeration energy, -30% in excess sludge) could not be clarified in this study. If benefits of fine-sieving are less distinct, the overall environmental balance of SCEPPHAR could be negatively affected.
- WWTP Carbonera valorises its biogas only for internal heating purposes. **If biogas is valorised in a combined heat and power plant, effective energy recovery would be higher**, and losses in biogas potential could have negative effects. This could affect the overall balance for the **redirection of carbon from WAS into fermentation and PHA production rather than to biogas** production. For future studies, it would be interesting to compare the valorisation of carbon as biogas and CHP directly with the route of PHA production.
- PHA use for bio-composite production is credited with avoiding the production of pure-culture PHA from sucrose. However, the product quality of the latter is supposed to be superior to the mixed-culture PHA produced in SCEPPHAR. The **equivalency of both PHA grades should be further investigated** to fully justify the crediting of sucrose-based PHA for the SCEPPHAR scenarios.

7. LCA OF SIDESTREAM N REMOVAL (SMARTECH 4B)

Sludge liquor from dewatering of anaerobically digested sewage sludge contains a high amount of nutrients, particularly nitrogen (N) and phosphorus (P). This process water is usually recycled back to the influent of the wastewater treatment plant (WWTP) for treatment, significantly contributing to the total load of the system via this "return load". Typically, N and P return load can account for up to 20% of the total nutrient load to a WWTP depending on the sludge characteristics, efficiency of anaerobic digestion, and actual raw wastewater concentration and load. This effect puts operational restrictions on the WWTP mainline in terms of treatment capacity and/or effluent quality.

This LCA investigates a process for separate treatment of this sidestream to remove N and P and thus reduce the total load to the WWTP mainline. This process named SCENA ("short-cut enhanced nutrients abatement") removes N and P efficiently with a comparably low demand of electricity and carbon source. Due to the low COD/N ratio in sludge liquor, traditional nitrification/denitrification treatment is usually limited by carbon availability. This problem is overcome with SCENA using a short-cut metabolic pathway via nitrite to save on carbon source, combined with process conditions to allow for enhanced biological phosphorus removal (EBPR). The process operates as a Sequencing Batch Reactor (SBR) with dedicated control strategies to achieve both short-cut N removal and EBPR. Different sources for readily biodegradable organic carbon (e.g. measured as volatile fatty acids (VFA)) can be utilized with SCENA, such as thickened primary sludge supernatant, fermentation liquor of primary sludge or even acetate as an external carbon source.

In the present case, the SCENA process is tested and evaluated at the WWTP Psyttalia (SMARTech 4b), which is operated by project partners EYDAP and AKTOR and treats the wastewater of the city of Athens (Greece) with a design capacity of around 3.5 Mio pe. This WWTP is equipped with primary settlers, an activated sludge process with pre-denitrification, and final sedimentation. In the sludge line, 50% of the waste activated sludge (WAS) undergoes a thermal hydrolysis (TH) treatment (Cambi process) before combined digestion with primary sludge. Digested sludge is dewatered and thermally dried on-site, before it is transported to nearby cement plants as secondary fuel. Biogas is valorised in CHP plants to produce heat and electricity, and for operating the drying process.

Due to the enhanced anaerobic degradation after TH, the related sludge liquor from dewatering contains high amounts of both N and P and contributes significantly to the return load of the plant. To stabilize the effluent quality of the WWTP and enhance the treatment capacity of the site, a sidestream treatment for nitrogen removal will be beneficial in this setup. However, the sludge liquor after TH treatment is known to contain higher fractions of non-biodegradable COD, which results in a high demand for carbon source to treat the entire N load of this sidestream. Thus, the SCENA process with its low carbon demand can be a suitable technology to treat this difficult sidestream and allow the operators to enhance the total treatment capacity of Psyttalia WWTP.

Within SMART-PLANT, the SCENA process has been tested in pilot scale for the treatment of sludge liquor after TH treatment of WAS. During the trials, different types of carbon sources have been tested, ranging from an external carbon source (sodium acetate) to internal carbon sources with thickened primary sludge supernatant. Other carbon sources potentially produced on-site such as fermentation liquor from primary sludge could not be tested, but are in principle also suitable for supplying the SCENA process as tested in the Carbonera pilot site (see chapter 6).

During the trials, the SCENA process was successfully established and treated the sludge liquor after TH for nitrogen removal. However, a stable EBPR process could not be established at this site, potentially due to chemical inhibition of EBPR activity in the specific conditions of this sludge liquor. Finally, P removal at the SCENA pilot plant was limited to biomass uptake for growth requirements, and excess sludge from SCENA did not contain appreciable amounts of P from EBPR activity. Therefore, it was decided together with the local partners to disregard the aspect of resource recovery via P-rich sludge of SCENA at this site, as this potential benefit of the process could not be evidenced in the trials.

Nevertheless, the SCENA process can be an adequate sidestream treatment for N removal under this challenging conditions after TH treatment, which makes it worthwhile to analyse its environmental performance in an LCA. Consequently, this LCA focusses on the potential full-scale implementation of a SCENA process at Psyttalia WWTP for treating the sludge liquor after TH treatment. The major goal of this approach is the enhancement of treatment capacity at the WWTP, which would otherwise require an upgrading of the site. However, the latter solution is difficult to realize due to the island setting of the plant.

As no “product” is recovered from this process, the SCENA process is not coupled to any downstream treatment for product valorisation here. The reader is advised to refer to chapter 6 for this combination, which couples SCENA and dynamic composting to yield a P-rich compost as product.

7.1 Goal and scope definition

7.1.1 Goal of the study

The goal of this LCA is to calculate the potential environmental impacts of the annual operation of Psyttalia WWTP (GR) without and with a prospective full-scale SCENA system for sidestream treatment of sludge liquor after TH. All direct and indirect effects of implementing a SCENA system will be quantified in the life cycle of the WWTP, focussing on primary energy demand and GHG emissions as major environmental impacts, but also assessing changes in WWTP effluent quality via marine eutrophication. The positive effect of enhancing the plant capacity is not directly reflected in this LCA, whereas the projected improvement in WWTP effluent quality by decreasing the return load is included.

The target group of this LCA are mainly WWTP experts, planners and practitioners which should be informed about the holistic environmental impacts of sidestream nutrient removal with SCENA at a large WWTP.

7.1.2 Function and functional unit

The function of the system under study is the treatment of municipal wastewater to defined local standards, including the final disposal of sewage sludge. Consequently, the functional unit is defined as “treatment of municipal wastewater per population equivalent (pe) and year” or $[pe*a]^{-1}$. Psyttalia WWTP currently treats raw wastewater with a load of 3.800.000 pe based on a daily COD load of 120 g/pe. All direct and indirect impacts of the system are related to this functional unit.

7.1.3 Scenarios

Five scenarios have been defined for this LCA, as listed in **Table 7-1** below. In detail, the scenarios can be described as follows:

0 Baseline: this scenario reflects the situation before implementation of the SCENA system, using operational data of Psyttalia WWTP from 2017 and 2018. Mechanical pre-treatment on the mainland is not included within the study. Starting from pre-treated raw wastewater, the plant consists of primary settlers, activated sludge tanks, and final clarifiers. Raw sludge is thickened by gravity (primary sludge) or with belt thickeners (waste activated sludge). 50% of WAS is further dewatered and treated with TH (165°C) in a Cambi system, before it is mixed with thickened primary sludge for digestion. Digested sludge is dewatered separately for conventional and TH line, and dewatered sludge is further dried on-site in rotary drum dryers. Biogas is valorised on-site in CHP plants or used to supply the drying process. The existing on-site energy concept is rather complex (e.g. operating a CHP plant on natural gas to produce electricity), and this study accounts for a simplified energy system in which biogas from digestion covers the heat demand of the dryer, while the remaining biogas is utilized in CHP plants to supply heat and electricity to the plant. After covering heat demand for TH and anaerobic digestion, excess heat is not credited in this study. Finally, dried sludge is transported and used as secondary fuel in cement plants.

1 SCENA 100% Ac: this scenario represents the implementation of a SCENA system for sludge liquor treatment from the TH line of the plant. Sludge liquor from this line is treated in an SBR unit operating the SCENA process.

The carbon demand is met 100% by dosing of acetic acid as external carbon source. For pH control, sulfuric acid and/or caustic is dosed.

2a SCENA 65% Ac/35% PS: here, the carbon demand of SCENA is met with 65% acetic acid and 35% supernatant from the primary sludge (PS) thickeners. The latter stream contains around 2 kg/m^3 of biodegradable COD and can be directly fed into the SCENA system. No additional efforts for storage of this carbon source are accounted, and it is assumed that the availability of PS supernatant is not limited.

2b SCENA 30% Ac/70% PS: this scenario resembles scenario 2a, but with a higher ratio of PS supernatant. Here, 70% of carbon demand are met by PS supernatant, while only 30% are met using acetic acid.

3 SCENA 100% VFA: in this scenario, the carbon demand for SCENA is fully met by liquor from PS fermentation. This process was demonstrated in SMART-PLANT in full-scale at the WWTP Carbonera (see chapter 6). Assuming a similar configuration for Psyttalia WWTP, this implies a fermentation of primary sludge (38°C) for 5 days to produce a VFA-rich liquor. After fermentation, the mixture is thickened by gravity, and supernatant is fed into the SCENA process as carbon source. Thickened sludge is returned back to the sludge line and into the digestors. Process data is estimated in cooperation with local partners NTUA and based on results from WWTP Carbonera trials.

Table 7-1: Scenarios for SCENA implementation at Psyttalia WWTP (see text for details)

Scenario	Description	Remarks
0 Baseline	Psyttalia WWTP with TH treatment for 50% WAS	Data of 2017/18
1 SCENA 100% Ac	Baseline with SCENA for sludge liquor after TH treatment	Carbon source: 100% acetic acid
2a SCENA 65% Ac/35% PS	Baseline with SCENA for sludge liquor after TH treatment	Carbon source: 65% acetic acid, 35% primary sludge supernatant
2b SCENA 30% Ac/70% PS	Baseline with SCENA for sludge liquor after TH treatment	Carbon source: 30% acetic acid, 70% primary sludge supernatant
3 SCENA 100% VFA	Baseline with SCENA for sludge liquor after TH treatment	Carbon source: 100% VFA from liquor of primary sludge fermentation (not tested in pilot trials)

7.1.4 System boundaries

The system boundaries of this LCA cover all relevant processes for water and sludge treatment at Psyttalia WWTP, including the sludge treatment through digestion, on-site drying, transport, and use as secondary fuel (**Figure 7-1**). TH treatment for 50% of WAS amount includes pre-dewatering and TH of WAS before mixing with primary sludge and separate digestion and dewatering. For SCENA scenarios, the LCA includes the efforts for sidestream treatment (TH line only) in terms of electricity and chemicals demand. In case of on-site VFA production, fermentation and related heat requirements as well as thickening of fermented sludge is included. Basic infrastructure material is included for SCENA and fermentation unit, while all other infrastructure is neglected (i.e. existing WWTP). Products such as electricity from CHP plants or hard coal substituted at cement kilns are credited by avoided impacts of grid electricity production in Greece ("avoided-burden approach").

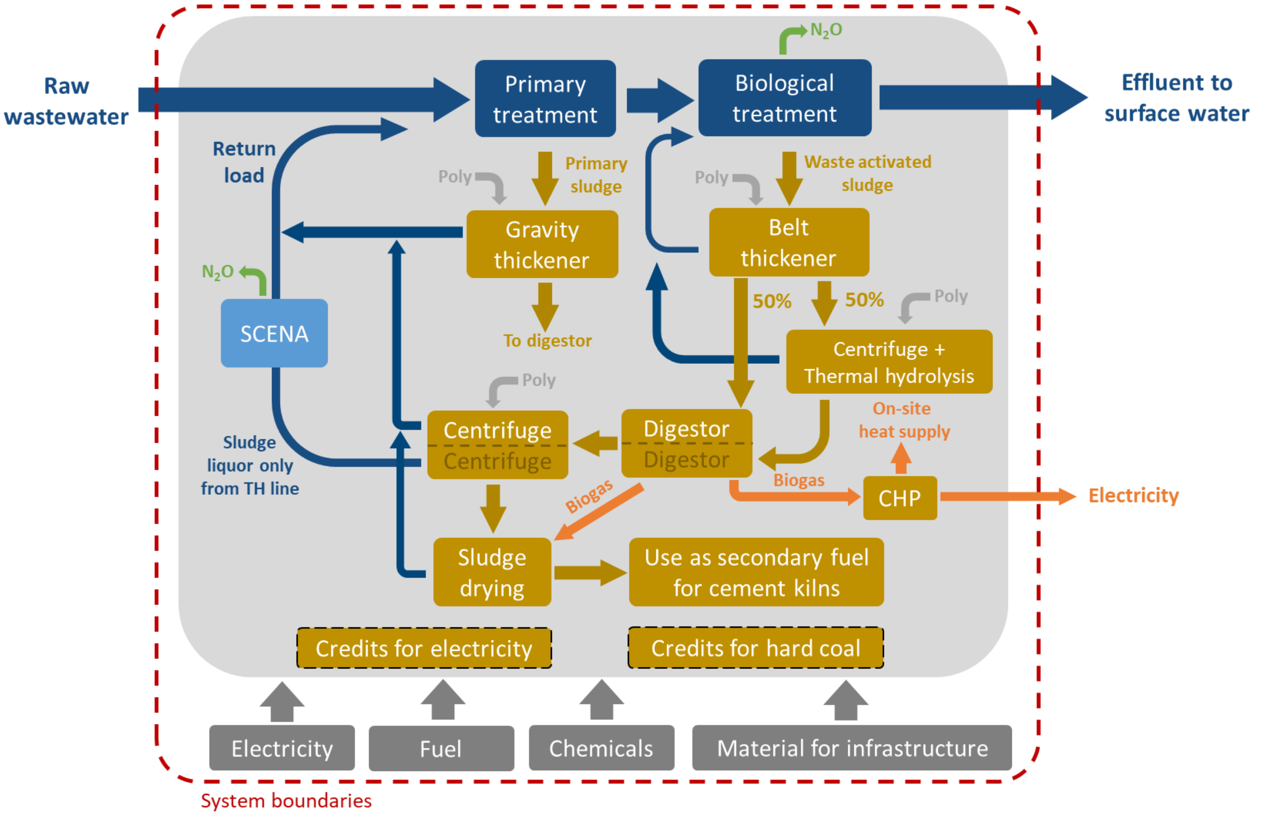

Figure 7-1: System boundaries of LCA study for sidestream nitrogen removal with SCENA at Psyttalia WWTP

7.1.5 Data sources and quality

Input data for the baseline operation of Psyttalia WWTP is collected from operators EYDAP and AKTOR via project partner NTUA and represents full-scale operational data of the years 2017/2018 for total electricity demand and influent/effluent quality. Detailed mass balances of both sludge lines and especially liquor quality and quantity has been extracted from available literature (Zikakis et al., 2017) and validated with NTUA. For sludge disposal as secondary fuel in cement kilns, data has been compiled from available literature.

For the performance of the SCENA system in terms of COD and nutrient removal, data from pilot trials has been compiled by NTUA after extensive validation and cross-checking for plausibility. Electricity demand for SCENA operation has been transferred from Carbonera case study, while chemical demand for carbon source or pH control is calculated based on pilot results and lab studies of NTUA. Process data for fermentation to produce VFA is taken from full-scale operational experience at WWTP Carbonera. N_2O emission factors for mainline and SCENA are projected from monitoring results at WWTP Carbonera (see D4.1).

Overall, data quality of this LCA can be described as high for most of the input data (**Table 7-2**). Reference data for the baseline scenario is collected and checked by operators and represents the mean situation at the plant. SCENA performance is based on pilot trials as well as carbon demand and chemicals for pH control, giving high confidence in this operational data. Electricity demand for SCENA is transferred from another site, but should be representative of a full-scale system with similar design here. Fermentation of primary sludge has not been demonstrated in this project, but lab-scale data of NTUA was used to cross-check the most important variables such as fermentation efficiency and VFA yield. Some uncertainty is related to the N_2O emission factors both for the mainline and for SCENA and how these compare to each other, which has to be taken into account during interpretation of results. Overall, data quality is sufficient for a prospective LCA to show the potential environmental impacts of SCENA implementation at Psyttalia WWTP.

Table 7-2: Data quality for LCA of sidestream nitrogen removal with SCENA at Psyttalia WWTP

Process	Data source	Responsible partner	Data quality
Psyttalia WWTP: influent + effluent, sludge treatment, energy demand, biogas production, CHP plants	Full-scale data of operator	EYDAP, AKTOR, NTUA	High
Sludge disposal in cement kilns	Literature	KWB	Medium - high
SCENA performance + chemical demand	Pilot data (WP3)	NTUA	High
SCENA electricity demand	Full-scale data from WWTP Carbonera (WP3)	UNIV + KWB	High
Fermentation of primary sludge to produce VFA	Full-scale data from WWTP Carbonera (WP3)	UNIV + KWB	High
N_2O emission factors	Mainline + SCENA: based on monitoring data from WWTP Carbonera	NTUA + KWB	Medium

7.1.6 Indicators for impact assessment

This study focusses on three specific environmental impacts: primary energy demand, greenhouse gas emissions, and marine eutrophication.

- For primary energy demand, the indicator of cumulative energy demand (CED) for non-renewable fuels as defined in VDI 4600 (VDI, 2012) is used, adding up fossil and nuclear fuels to a single score.
- For greenhouse gas emissions, factors of IPCC are used to calculate the global warming potential (GWP) for a time horizon of 100 years (IPCC, 2014). Long-term emissions > 100a are neglected ("without LT").
- For accounting better effluent quality of Psyttalia WWTP with sidestream N removal, the indicator of marine eutrophication potential (MEP) is applied at midpoint level (Hierarchist perspective) as defined in the ReCiPe method (Huijbregts et al., 2017). This indicator accounts for nitrogen emissions into marine environment, and reflects a reduction in nitrogen loads to the receiving waters of Psyttalia WWTP (Gulf of Saronic).

7.2 Input data (Life Cycle Inventory)

7.2.1 Data of Psyttalia WWTP

Basic data for influent and effluent volume and quality and gross electricity demand of Psyttalia WWTP was collected for the years 2018 from WWTP operators EYDAP and AKTOR via the project partner NTUA. More detailed data of sludge lines, gas production, sludge dewatering and drying and related energy balances was collected from available literature (Zikakis et al., 2017). Specific data of sludge liquors for quality and volume have been delivered by NTUA based on extensive sampling campaigns at the plant (Noutsopoulos et al., 2018). Data for sludge disposal route (transport, incineration) has been compiled from literature.

Mass flow data for water and sludge line of Psyttalia WWTP

Relevant annual mean data for flowrate, TSS, COD, and total nitrogen for WWTP influent and effluent is reported in **Table 7-3** below. The annual COD influent load amounts to 164,500 t/a, which corresponds to around 3,800,000 pe when assuming a daily COD load of 120 g/pe (ATV, 2000), confirming the number defined for the functional unit. Effluent quality shows a high removal of TSS (>95%), COD (>93%), and TN (> 84%) at the WWTP. Return load from sludge dewatering for both sludge lines adds around 11% of TN load to the influent WWTP, with thermally pre-treated sludge liquor responsible for 2160 t TN per year.

Direct gaseous emissions of the activated sludge tank are estimated to 1.5% of N eliminated as N_2O based on full-scale monitoring results of the mainline at WWTP Carbonera (see chapter 6.2.2).

Table 7-3: Input data for Psyttalia WWTP: influent and effluent quality and return load with sludge liquor

Parameter	*Unit*	Influent WWTP	Effluent WWTP	Sludge liquor from thickening		Sludge liquor from dewatering		
				Primary sludge	*Excess sludge*	*Conv. line*	*TH line pre-dewatering*	*TH line final dewatering*
Volume	*m^3/d*	702,000	702,000	3,560$^{\#}$	15,230	1,680$^{\#}$	620$^{\#}$	1,350$^{\#}$
Susp. solids	*g/m^3*	293	14	3,690*	1,480*	2,060*	7,246*	2,460*
COD	*g/m^3*	642	43	4,200*	43	2,000*	3,000*	4,500
Total N	*g/m^3*	58	8.4	60*	8	1,300*	430*	1,600

**estimated*

$^{\#}$ *calculated with model*

Raw primary and excess sludge is distributed to the "conventional" digestor line (w/o thermal hydrolysis) and to the TH line with thermal hydrolysis of excess sludge. According to plant data and liquor volume, 50% of excess sludge and 52% of primary sludge is fed to the TH line, whereas the remainder is digested in the normal line (**Table 7-4**). Excess sludge to TH is pre-dewatered to 14.5% DM before thermal treatment (Zikakis et al., 2017). Biogas production amounts to 400 NL/kg VS_{in} for normal line and 500 NL/kg VS_{in} for the TH line (+20%) with a methane content of 65 Vol-%. After digestion, digested sludge is dewatered to 22% and 31% for conventional and TH line before sludge is dried in rotary drum dryers. Drying requires a thermal input of 860 kWh/t H_2O evaporated, which is fully covered by biogas in this model (56% of total biogas production). The remaining biogas is used in CHP plants to produce electricity (21670 MWh/a) and heat to fully cover the internal heat demand for digestor heating and TH process. Dried sludge to disposal (92% DM) amounts up to 140 t/d and is disposed in cement kilns.

Table 7-4: Input data for Psyttalia WWTP: primary and excess sludge, mixed sludge to digestion for conventional and TH line, dewatered sludge, and dried sludge for disposal

Parameter	*Unit*	Primary sludge to thickening	Excess sludge to thickening	Mixed sludge to digestors		Dewatered sludge to drying		Dried sludge to disposal
				Conv. line	*TH line*	*Conv. line*	*TH line*	
Mass	*t/d*	5,716	16,847	1,850	1,420	300*	204*	140*
Dry matter	*% DM*	2.3	0.67	5.5	7.2	22	31	92
Volatile solids	*% of DM*	80*	75*	78*	78*	64*	56*	60*
Total nitrogen	*% of DM*	4.2*	3.6*	4.4*	4.4*	3.2*	3.3*	3.2*

**estimated by modelling*

Electricity and chemicals demand

Total electricity demand for WWTP operation amounts to 95642 MWh/a or 0.37 kWh/m^3 influent. This gross electricity demand is attributed to the different stages of wastewater and sludge treatment according to previous LCA models to be able to track any changes related to implementation of the SCENA process. In particular, 62% of total electricity demand is attributed to the activated sludge process, mainly for aeration. Aeration efficiency has been reported to 0.23 kWh/kg O_2 by operators, indicating a very efficient oxygen transfer due to the large depth of the aeration tanks (9.3m) and the fine bubble diffusion system. The remaining electricity demand is distributed in the model to other aggregates (primary treatment, thickening, digestion, TH, dewatering, and drying) based on typical specific values of large WWTP.

For chemical demand, the LCA model is limited to polyelectrolyte used for thickening and dewatering. Based on available data (Zikakis et al., 2017) and literature, polymer demand as active matter is estimated to 5 kg/t DM for excess sludge thickening, 15 kg/t DM for pre-dewatering of excess sludge prior to CAMBI, 17 kg/t DM for dewatering of digested sludge of conventional line, and 22 kg/t DM for dewatering of digested sludge of TH line. Overall, the annual demand of polyelectrolyte adds up to 1,900 t active matter. Any other chemicals for WWTP operation are not considered in this study.

Sludge disposal in cement kilns

Dried sludge is transported via truck (250 km) to nearby cement kilns, where it is used as secondary fuel due to its high heating value (13 MJ/kg), substituting an equivalent amount of hard coal (27 MJ/kg) in the process. While CO_2 emissions of dried sludge are not accounted for global warming (biogenic CO_2), N_2O emissions in cement kilns are assumed to 100 g N_2O/t DM. Avoided emissions of hard coal burning are estimated from power plants using hard coal. Sludge ash is integrated into the cement product and has no disposal burden.

7.2.2 Data for SCENA system

Data for the SCENA system is delivered by NTUA based on long-term pilot trials at Psyttalia WWTP with different carbon sources (acetic acid, primary sludge supernatant). For internal production of carbon source via fermentation of primary sludge, data of full-scale implementation of this process at WWTP Carbonera is used (see chapter 6).

Performance and energy/chemicals demand of SCENA system

SCENA pilot trials at Psyttalia WWTP demonstrated a TN removal of 80% on average, independent of the carbon source used (**Table 7-5**). N_2O emissions are projected to 2.27% N_2O of N eliminated for all scenarios based on monitoring data from full-scale implementation of SCENA at WWTP Carbonera. Electricity demand is projected to 3.9 kWh per kg N removed, equalling 4.5 kWh/m^3 centrate treated. For fermentation of primary sludge to VFA, 0.55 kWh per kg N removed is added for fermenter and screw press. In contrast to SCENA implementation at WWTP Carbonera, solid-liquid separation of fermented sludge is projected as gravity thickening by NTUA, thickening the fermented solids to 8.5% DM without the use of additional polyelectrolyte.

Table 7-5: Input data for SCENA for N removal, N_2O emissions, and demand of electricity, carbon source and chemicals for different carbon sources

Parameter		1 SCENA 100% Ac	2a SCENA 35% PS/ 65% Ac	2a SCENA 70% PS/ 30% Ac	3 SCENA 100% VFA	Remarks
N removal	*%*	80	80	80	80	NTUA data
N_2O	*% N_2O/N elim.*	2.27	2.27	2.27	2.27	UNIV data*
Electricity for SCENA	*kWh/kg N removed*	3.9	3.9	3.9	3.9	UNIV data* 4.5 kWh/m^3
Electricity for fermentation	*kWh/kg N removed*	-	-	-	0.55*	Fermenter, thickener, storage
Acetic acid (100%)	*kg COD/kg N removed*	2.5	1.63	0.75	-	NTUA data
bCOD from carbon source	*kg bCOD/kg N removed*	-	0.87	1.75	2.5	NTUA data
NaOH (30%)	*L/m^3*	0.5	0.5	0.5	0.5	pH control
H_2SO_4 (30%)	*L/m^3*	0.5	0.5	0.5	0.5	pH control

** data adapted from full-scale SCENA at WWTP Carbonera*

COD demand for SCENA operation (2.5 kg biodegradable COD per kg N removed) is met by either acetic acid, primary sludge supernatant, or VFA from fermentation as defined for each scenario (**Table 7-5**). Total N load in TH centrate is 2.15 t TN/d to be treated in SCENA, plus N load in carbon source from primary sludge supernatant (60 g/m³ TN or 0.04-0.08 t TN/d) or fermentation liquor (1070 g/m³ TN or 0.51 t TN/d). Finally, this results in the need to dose 765 and 1555 m³/d of primary sludge supernatant (at 2 kg bCOD/m³) in scenarios 2a and 2b, or 480 m³/d of fermentation liquid with 11 kg bCOD/m³ (NTUA data) in scenario 3.

For pH control, a fixed amount of caustic and acid is projected based on experience from pilot trials with TH centrate, independent on the type of carbon source used. Excess sludge of SCENA (1.31 kg TS per kg TN load from NTUA data, 72% VS) is fed back into the digestor to gain some additional biogas.

Mainline effects of SCENA implementation

Reducing TN return load with SCENA will lead to savings in aeration in the mainline of Psyttalia WWTP. Based on a theoretical oxygen balance of nitrification and denitrification, 2.13 kg O_2 demand will be avoided in the mainline for each kg of TN load reduction. Assuming an aeration efficiency of 0.23 kWh/kg O_2, this leads to electricity savings of 0.49 kWh/kg N removed in SCENA. In the model, TN load reduction with SCENA amounts to 583-690 t TN per year for scenarios 1-3, leading to mainline electricity savings for aeration of 285-337 MWh/a. Any positive effect on internal recirculation pump energy is estimated to be negligible by the operators. Similarly, excess sludge production is not affected by return load treatment per definition.

For WWTP effluent quality, a reduction of incoming TN load to the plant will most probably lead to an improvement of denitrification performance of the activated sludge process. Based on comprehensive modelling studies of Psyttalia WWTP by NTUA, it is estimated that WWTP effluent concentration of TN will decrease by 0.75 mg/L TN on average with SCENA, illustrating a positive effect of sidestream treatment. Simultaneously, the overall capacity of the WWTP is increased with sidestream treatment, while still complying with effluent quality standards. This positive effect of SCENA implementation cannot be exhibited in LCA, but is a major argument for the operators in favour of sidestream N removal.

Infrastructure

As a rough estimate for infrastructure material of the SCENA system (including storage of carbon source and SBR reactor for SCENA), 8370 m³ of concrete are assumed for the full-scale system. For scenario 3, 1620 m³ of concrete and 270 t of stainless steel is added for the fermentation and thickening units. The corresponding lifetime of the equipment is estimated to 50 years.

7.2.3 Background data

Background processes are modelled with datasets from ecoinvent database v3.4 (Ecoinvent, 2017). The related datasets are listed below (**Table 7-6**), mainly relating to European or global markets. For electricity, the market mix of Greece is applied. For transport of chemicals to the WWTP, a distance of 300km has been used.

Table 7-6: Datasets for background data

Process	Dataset from ecoinvent v3.4	Remarks
Energy		
Electricity	market for electricity, medium voltage [GR]	For all operational electricity demand and credits from CHP plant
Transport and fuels		
Truck transport	transport, freight, lorry 16-32 metric ton, EURO5 [RER]	300 km for chemicals, 250 km for sludge disposal
Chemicals		
Polymer	market for acrylonitrile [GLO]	746 g acrylonitrile + water = 1kg of polymer active substance

Acetic acid	market for acetic acid, without water, in 98% solution state [GLO]	Carbon source in scenarios1, 2a and 2b
NaOH	market for sodium hydroxide, without water, in 50% solution state [GLO]	For pH control
H2SO4	market for sulfuric acid [GLO]	For pH control
Materials		
Concrete	market for concrete, for de-icing salt contact [RoW]	Infrastructure material for SCENA
Stainless steel	steel production, electric, chromium steel 18/8 [RoW]	Infrastructure material for fermentation unit

7.3 Results of environmental indicators (Life Cycle Impact Assessment)

Cumulative energy demand (CED)

The total net CED of Psyttalia WWTP including sludge disposal amounts to 160 MJ/(pe*a) (**Figure 7-2**), accounting for electricity and chemicals demand at the WWTP and energy recovered in sludge treatment and disposal. The gross CED of 402 MJ/(pe*a) for WWTP operation and sludge treatment is mainly due to electricity demand (92%) for operation, plus chemicals for sludge dewatering (8%). This gross energy demand is partially compensated (62%) by electricity produced from biogas in CHP plants (-84 MJ/(pe*a)) and incineration credits for dried sludge in cement kilns (-158 MJ/(pe*a)). Overall, the plant supplies only 23% of its electricity demand by biogas valorisation in CHP plants in this LCA model, because the remaining biogas is used for drying the sludge. It has to be noted here that this energy balance does not reflect the actual situation at the plant, as natural gas could also be utilized for electricity and heat production in CHP plants in case it is needed.

Introducing a SCENA system for sidestream N removal from the sludge dewatering liquor of the TH line increases net CED of the system by 6-19% depending on the carbon source used (**Figure 7-2**). The highest increase in energy demand is associated with scenario 1 using an external carbon source (100% acetic acid). Substituting this external carbon source gradually with internal carbon sources can decrease the additional energy demand required for sidestream treatment substantially.

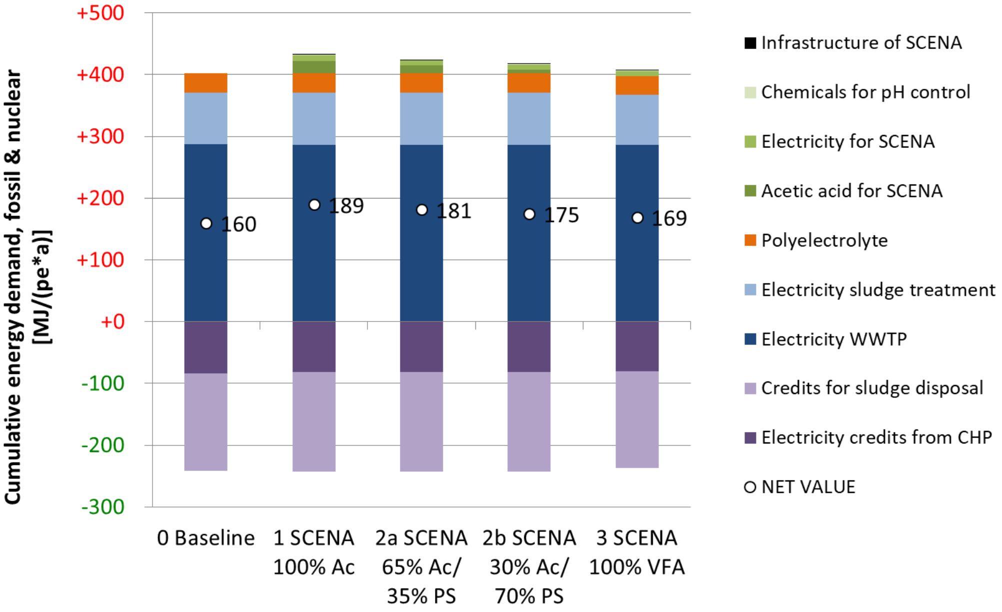

Figure 7-2: Total cumulative energy demand for baseline and SCENA scenarios at Psyttalia WWTP

For a detailed analysis of the SCENA scenarios, the relative changes of CED due to SCENA implementation are shown below (**Figure 7-3**). Overall, the implementation of SCENA leads to an increase of net CED between 9 and 30 MJ/(pe*a) depending on the carbon source used. The contribution analysis shows several effects of SCENA on the total energy demand of the system:

- From the electricity balance, it becomes evident that sidestream N treatment needs more electricity than what can be saved in the mainline aeration. Due to the very efficient aeration system at Psyttalia WWTP (9.3m depth of aeration tanks + fine bubble diffusors), the mainline electricity savings amount to only 0.49 kWh/kg TN, while SCENA requires between 3.9 and 4.5 kWh/kg TN removed depending on the carbon source (**Table 7-5**). The SCENA electricity data is taken from a retro-fit full-scale system at another WWTP, and may not reflect an optimised SCENA process design. However, it still seems difficult to operate any type of sidestream N removal with such an efficient aeration system to be competitive with the very efficient mainline aeration of Psyttalia WWTP.
- The additional excess sludge produced in SCENA needs some electricity in the drying unit, which further worsens the electricity balance for SCENA scenarios. It also consumes more biogas for the drying, leaving less biogas for electricity production at the CHP plants in SCENA scenarios. On the positive side, dried SCENA sludge generates some more energy credits during disposal in cement kilns, fully off-setting the energy required for additional drying. Overall, excess sludge of SCENA does not affect the net energy balance significantly.
- The carbon source is another significant factor for the net energy balance of SCENA. Acetic acid has a substantial energy demand in production, which is reflected by its high contribution in scenario 1 and although to a lesser extent, in scenarios 2a/b. Substituting this external carbon source with internally available COD decreases additional energy demand of sidestream N treatment considerably. Producing an internal carbon source via fermentation of primary sludge is the most attractive option in energetic terms if it can fully replace the use of acetic acid. Redirecting the carbon from digestion to fermentation leads to some inevitable losses in biogas production, but the positive effect of avoiding the use of acetic acid dominates the overall energy balance.
- Chemicals for pH control and dewatering of SCENA sludge play only a minor role for the energy balance of the SCENA scenarios. Likewise, infrastructure required for the SCENA system does only marginally add additional energy demand for the sidestream treatment scenarios.

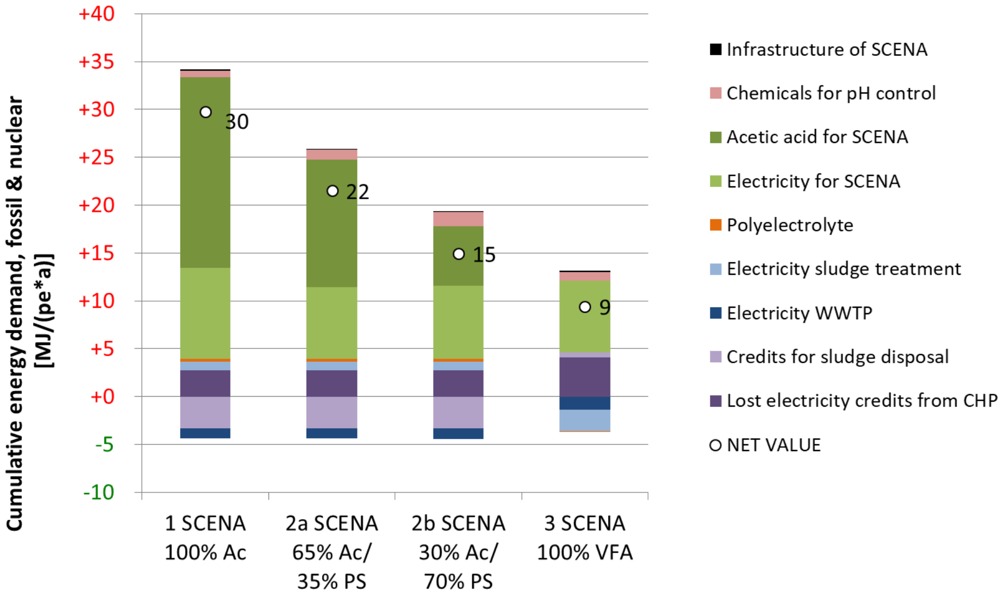

Figure 7-3: Change in cumulative energy demand for SCENA scenarios at Psyttalia WWTP compared to baseline

Global warming potential (GWP)

The total net GWP of the baseline scenario amounts to 23.6 kg CO_2-eq/(pe*a) (**Figure 7-4**). Thereof, the system has a gross GWP impact of 46.5 kg CO_2-eq/(pe*a) and receives credits for energy recovery of -22.9 kg CO_2-eq/(pe*a), compensating 49% of its GWP. In analogy to the CED, the operation of the WWTP contributes to gross GWP mainly with electricity demand (52%) and less with chemicals (2%). On top, the direct emissions of N_2O from the activated sludge tank are a significant factor for gross GWP (44%), while other greenhouse gases (e.g. CH_4 at centrifuges or off-gas from CHP) play only a minor role (2%).

Implementing a SCENA system adds between 6-9% to the net GWP in scenarios 1-3. Comparable to the energy profile, sidestream N treatment is not favourable in GWP due to different factors negatively affecting the greenhouse gas balance. A detailed analysis of the changes in GWP due to SCENA implementation is provided below.

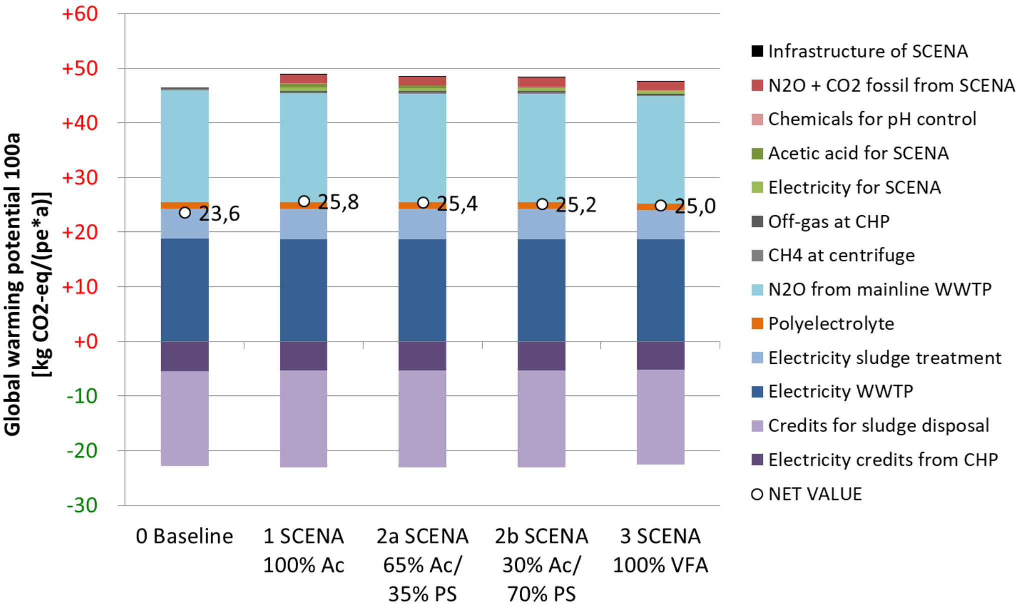

Figure 7-4: Total global warming potential for baseline and SCENA scenarios at Psyttalia WWTP

In scenarios 1-3, net GWP of the system is increased by +1.3 to +2.1 kg CO_2-eq/(pe*a) due to SCENA, indicating that the additional efforts for sidestream N treatment are not compensated by savings in the mainline (**Figure 7-5**). While some factors are well in analogy to the energetic balance, others are particularly associated with specific greenhouse gases:

- The unfavourable net electricity balance of SCENA and the need for an external carbon source affect the net GWP balance negatively. Both factors have been discussed above with the CED indicator.
- Direct emissions of N_2O are projected to be higher with SCENA (2.27% of N removed) than in the mainline (1.5% of N removed), leading to higher N_2O emissions in scenarios with SCENA. This effect is amplified in scenario 3, as fermentation liquor generates additional TN load to SCENA (+56 t TN/a) causing even more N_2O emissions. Mainline savings in N_2O emissions are also partially compensated by a higher total TN removal (= better TN effluent quality as predicted by dynamic modelling), as N_2O emission factors are related to TN removed in this LCA model. Hence, more TN removal leads to higher N_2O emissions.
- On top of N_2O, the use of acetic acid as carbon source generates fossil CO_2 emissions, as this chemical is produced from fossil carbon sources (natural gas). These fossil CO_2 emissions add to the GWP of SCENA in scenarios 1 and 2a/b and underline the benefit to use internal carbon sources based on biogenic materials (i.e. sewage sludge) rather than external carbon sources based on fossil resources.

In total, GWP results show that direct N_2O emissions are a significant factor for the environmental profile of sidestream N treatment, apart from the electricity balance and chemical needs of the process. Higher emissions of N_2O are a potential risk of biological N removal processes using the short-cut via nitrite route. It becomes evident in this analysis that a minimisation of N_2O emissions during SCENA operation should be targeted to prevent negative effects of this potent greenhouse gas on the environmental profile of the process.

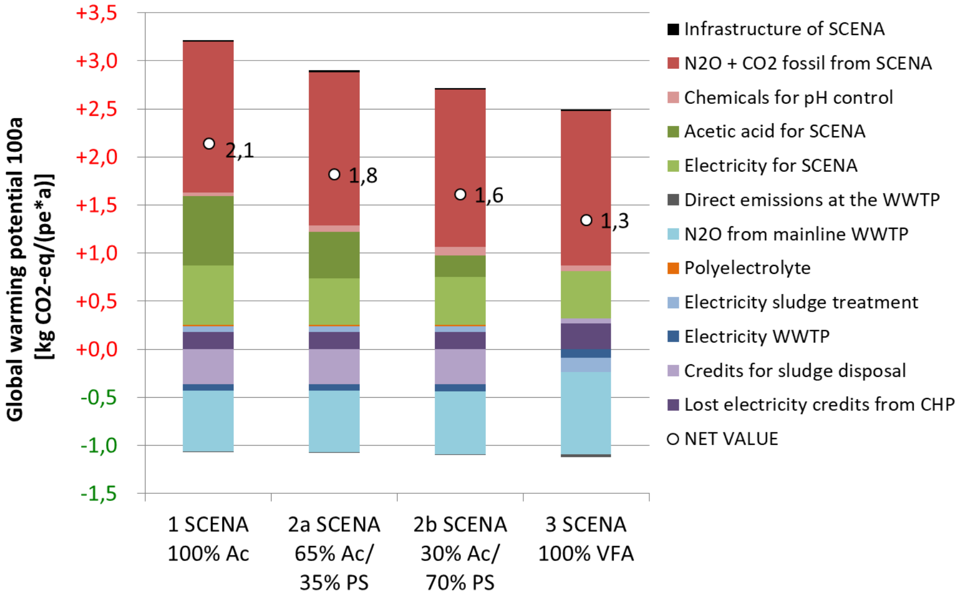

Figure 7-5: Change in global warming potential for SCENA scenarios at Psyttalia WWTP compared to baseline

Marine eutrophication (MEP)

This indicator reflects the effluent quality of the WWTP in terms of nitrogen load to marine waters. As predicted by a dynamic WWTP model, the implementation of SCENA leads to a reduction of N emissions into the Saronic gulf by around 10% (**Figure 7-6**). This positive effect of sidestream N removal is clearly a major benefit for the environment, as WWTP effluent loads contribute substantially to marine eutrophication. Reducing the total TN load to the mainline can either increase TN removal in the plant by improving the COD/N ratio in the influent, or it can help to increase the overall WWTP capacity while still complying with effluent discharge standards. As the latter effect of capacity increase cannot be reflected in this LCA model, the predicted decrease of TN effluent load can be seen as a proxy indicator for this effect.

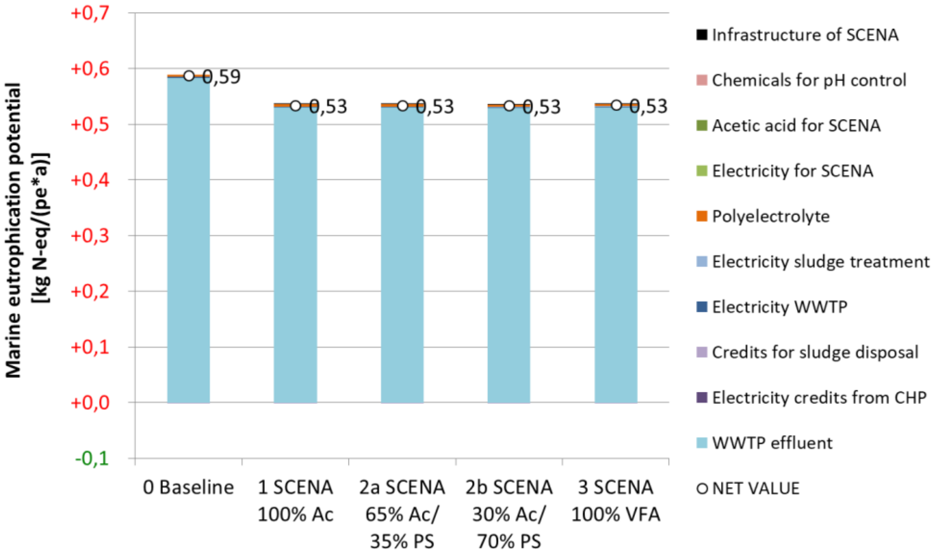

Figure 7-6: Total marine eutrophication potential for baseline and SCENA scenarios at WWTP Psyttalia

7.4 Interpretation and conclusions

This LCA case study analyses the potential environmental impacts of implementing a SCENA system for sidestream N removal from TH sludge liquors at the Psyttalia WWTP (GR), taking into account all direct and indirect effects on the WWTP and in the sludge disposal route. As no enhanced biological P removal could be efficiently established in pilot trials, no dedicated product such as P-rich sludge can be recovered, and SCENA sludge is sent to drying and incineration. Different scenarios reflect various options for adding a carbon source to the SCENA process, either as external carbon source (acetic acid) or internal carbon source such as primary sludge thickening supernatant or fermentation liquor of primary sludge.

The main outcomes of the LCA for this case study can be summarized as follows (**Table 7-7**):

- Implementing a SCENA system for sidestream N removal at Psyttalia WWTP will **improve the WWTP removal capacity for total nitrogen**. Based on dynamic modelling, a **10% decrease in TN effluent load** is predicted. Alternatively, the overall treatment capacity of the WWTP could be extended while still complying with the TN discharge standards.
- The implementation of a SCENA system for sidestream N removal increases the net environmental impacts of the WWTP in terms of energy demand and greenhouse gas emissions. Overall, the **net energy demand of the system increases by 6-18%** depending on the type of carbon source, while the **net GHG emissions increase by 6-9%**.
- Additional efforts for sidestream N removal with SCENA (electricity, chemicals, treatment of excess sludge, and direct emissions of N_2O and fossil CO_2) cannot be compensated by the positive effects of reduced TN return load in the mainline. In particular, **electricity savings in mainline aeration are much lower than electricity required for SCENA**, as the mainline aeration system at Psyttalia WWTP is highly efficient. However, it has to be noted here that electricity demand of the SCENA unit used in this LCA is transferred from a smaller plant size (WWTP Carbonera with 40.000 pe) to this study, which may represent a conservative estimate. A full-scale SCENA system at Psyttalia WWTP could be more energy-efficient if the design (e.g. depth of the SBR reactor for efficient aeration) is adjusted accordingly.

Table 7-7: Summary of LCA results for sidestream N removal with SCENA at Psyttalia WWTP (3.8 Mio pe): impact on energy demand, global warming potential, and marine eutrophication

Parameter	_Unit_	Baseline system	SCENA (100% Ac)	SCENA (65% Ac + 35% PS supernatant)	SCENA (30% Ac + 70% PS supernatant)	SCENA (100% VFA from fermented PS)
Nitrogen return load	_t TN/a_	**1850**	-663	-670	-685	-813
		100%	-36%	-36%	-37%	-44%
Cumulative energy demand	_MJ/(pe*a)_	**160**	**+30**	**+22**	**+15**	**+6**
		100%	**+19%**	**+13%**	**+9%**	**+6%**
Global warming potential	_kg CO_2-eq/(pe*a)_	**23.6**	**+2.1**	**+1.8**	**+1.6**	**+1.3**
		100%	**+9%**	**+8%**	**+7%**	**+6%**
Marine eutrophication potential	_kg N-eq/(pe*a)_	**0.59**	**-0.06**	**-0.06**	**-0.06**	**-0.06**
		100%	**-10%**	**-10%**	**-10%**	**-10%**

Ac: Acetic acid, PS: primary sludge

- **N_2O emissions are projected to be higher in the sidestream process based on short-cut N removal than in the mainline with conventional nitrification and denitrification**. However, the latter effect is based on monitoring data from another site (WWTP Carbonera), and should be validated further with on-site monitoring of N_2O emissions at full-scale.
- It becomes evident that **using an internal carbon source is beneficial for the environmental profile of the SCENA process**. It avoids fossil energy associated with the production of an external carbon source (e.g. acetic acid) and the related emissions of fossil CO_2 when this carbon source is consumed.

Overall, it can be concluded that SCENA is a suitable process for Psyttalia WWTP to treat sludge dewatering liquors from the sludge line operating with thermal hydrolysis. It will decrease the TN return load to the mainline by 36-42% and thus provide additional treatment capacity for TN removal. However, the process will increase total electricity demand at the WWTP, and also increase the amount of sludge to be dried and disposed. Direct greenhouse gas emissions will most probably increase with SCENA, although this effect still has to be validated with on-site monitoring. Finally, it will be interesting to compare the SCENA process with other low-energy options for sidestream N removal such as partial nitritation and deammonification. However, the refractory and potentially inhibitory organic content of the sludge liquors after thermal hydrolysis could pose additional risks to the stability and process performance of these processes (Zhang et al., 2016).

Limitations and transferability of the case study results to other WWTPs

Overall, the implementation of a SCENA process for sidestream N removal has mixed impacts on the environmental footprint of Psyttalia WWTP in this LCA study. Sidestream treatment will reduce TN return load and consequently improve effluent quality or increase the treatment capacity of the plant, but additional efforts for SCENA will probably lead to an increase in net energy demand and GHG emissions for the entire system. However, this negative effect can be minimised by using an internal carbon source for the process.

When transferring the results of this LCA to other WWTPs and boundary conditions, the following aspects have to be considered:

- The mainline aeration system of Psyttalia WWTP is highly efficient, making it very challenging to save electricity in a sidestream N removal process compared to N treatment in the mainline. **Optimising the SCENA system in terms of electricity demand could be one option to minimise this drawback**, e.g. by installing a more efficient aeration system. The data for electricity demand of SCENA in this study is adopted from a retro-fit full-scale system and may not reflect an energetically optimised design.
- Sludge liquor composition related to organic content and its availability as carbon source for biological processes is affected by thermal hydrolysis. **If SCENA is used for sidestream treatment without upstream thermal hydrolysis, effective demand for carbon addition to the process may be lower.** This will help to decrease the negative effects on energy demand and greenhouse gas emissions of the carbon source.
- N_2O emission factors in both SCENA and mainline N removal are based on monitoring data of another site. For validation of GWP results, **N_2O emissions should be quantified with on-site measurements for both the existing activated sludge process and also the SCENA process treating thermally pre-treated sludge liquors.**
- Data for production of VFA via fermentation of primary sludge is mostly adapted from another case study. **Fermentation efficiency and carbon availability of primary sludge fermentation liquor should be checked to validate results for this scenario.**

8. PRODUCT QUALITY AND RISK ASSESSMENT (UAB, UR)

Due to their origin from municipal wastewater and/or sludge, recovered materials from SMARTechs could be contaminated by potentially hazardous substances in organic or inorganic form. However, a safe use of these products is a prerequisite for their public acceptance and also legal conformity. Therefore, a check of product quality in terms of contamination and a following risk assessment to evaluate their safety is important to enable safe and sustainable use of these products for both human health and ecosystems. This is especially true for nutrient products and fertilizers which are directly applied into ecosystems and may affect the quality of produced food and thus human health through food consumption. However, other materials such as bioplastic or cellulose may also pose risks in their use due to direct contact with human skin or leaching of contaminants.

Within the project, it was decided to analyse selected samples of the different SMARTechs for a wide range of inorganic and organic contaminants to check if a potential contamination of SMART products could pose any unacceptable risks for human health or ecosystems. A focus was laid on these materials that are directly used in agriculture as fertilizer, as they may pose a direct risk to local ecosystems as well as human health via food consumption. In addition, materials such as cellulose, PHA, and produced bio-composites have also been analysed to check whether they contain any hazardous substances with potential risk during their use.

15 samples have been delivered by the partners in adequate form and have been analysed by UAB for heavy metals (7 substances), polycyclic aromatic compounds (16 substances), chloroalkanes, and pesticides (108 substances). In addition, a sub-set of 10 samples have been analysed by UR for contaminants of emerging concern, taking the EU watch list of 2018 as basis for substance selection.

For risk assessment, the resulting analytical results have been evaluated in relation to legal standards for the related products where available. For some products, uses or contaminants, no legal limits are set by national or European law yet (e.g. substances of the EU watch list). Here, a simplified risk assessment was done to relate these substances and their concentration level present to other studies or contaminants with similar toxicity or physico-chemical characteristics. Taking this approach, the safety of SMART products could be evaluated based on analytical results, legal benchmarks, and risk assessment approaches.

8.1 Methods

8.1.1 Type of samples and sample preparation

The samples received for analysis are listed below (**Table 8-1**). From the 15 samples, 7 are in the class of fertilizers or related products which are directly used in agriculture (calcium phosphate, struvite, and sludges or composts). 4 samples are related to raw materials for bio-composite production such as PHA-rich sludge, extracted PHA or cellulose. Another 4 samples are related to the final bio-composite product in different formulations, as well as a traditional bio-composite from wood as benchmark.

Table 8-1: Samples for analysis

Identifier	Description	Origin	Delivered by partner	Remarks
CaP.1 (UK)	Calcium phosphate from IEX (batch 1)	Cranfield, UK	CRAN	Different batches
CaP.2 (UK)	Calcium phosphate from IEX (batch 2)	Cranfield, UK	CRAN	
CaP.3 (UK)	Calcium phosphate from IEX (batch 3)	Cranfield, UK	CRAN	
Struvite (IT)	Struvite from SCEPPHAR sidestream	Carbonera, IT	UNIVR	Solid soft mineral
P-rich sludge (IT)	Surplus sludge from SCENA	Carbonera, IT	UNIVR	Excess sludge, 0.5-1% TS
P-rich compost (IT)	Compost from surplus sludge of SCENA	Carbonera, IT	UVIC	
Excess sludge (GR)	Surplus sludge from SCENA	Psyttalia, GR	NTUA	Excess sludge, 0.5-1% TS
PHA-rich sludge (IT)	PHA-rich sludge from SCEPPHAR sidestream	Carbonera, IT	UNIVR	
PHA-rich sludge (ES)	PHA-rich sludge from SCEPPHAR mainstream	Manresa, ES	UAB	Excess sludge, 0.5-1% TS
PHA	PHA powder	Carbonera, IT	Biotrend	Extracted PHA
Cellulose	Cellulose from Cellvation	Geestmerambacht, NL	Cirtec	Solid, dry, "cotton linter"
WPC	Wood plastic composite	UK	Ecodek	
SPC.50	Sludge plastic composite (50% cellulose)	UK	Ecodek	Edge-trim profile (ET500)
SPC.100	Sludge plastic composite (100% cellulose)	UK	Ecodek	Edge-trim profile (ET100)
SCC	Sludge cellulose composite	UK	UBRUN	

All samples were dried or lyophilized depending on their characteristics, and homogenized; the dried samples were stored refrigerated (4°C) until pre-treatment and analysis.

8.1.2 Analytical methods

Heavy metals analyses were conducted by the Servei d'Anàlisi Química of UAB. Polycyclic aromatic hydrocarbons (PAHs), chloroalkanes and pesticides were analysed externally in Soluciones Analíticas Instrumentales (Sailab) (Cerdanyola del Vallès, Catalonia). Contaminants of emerging concern were analysed at the lab of Uni Roma. The related analytical methods and substances are listed below.

Heavy metals

Cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb) and magnesium (Mg) were analysed by microwave digestion (MARS, CEM) followed by inductively coupled plasma mass (ICP-MS) spectrometry (Agilent Technologies). Mercury (Hg) was analysed by thermal decomposition followed by atomic absorption spectrophotometry (Perkin Elmer).

Polycyclic aromatic hydrocarbons

16 PAHs were analysed (**Table 8-2**) after using the same extraction performed for pesticides.

Table 8-2: Analysed polycyclic aromatic hydrocarbons

Acenaphthene	Benzo(a)pyrene	Chrysene	Indene(1,2,3-c,d)pyrene
Acenaphthylene	Benzo(b)fluoranthene	Dibenzo(a,h)anthracene	Naphthalene
Anthracene	Benzo(g,h,i)perylene	Fluoranthene	Phenanthrene
Benzo(a)anthracene	Benzo(k)fluoranthene	Fluorene	Pyrene

Chloroalkanes

The chloroalkanes between 10 and 13 carbons were analysed by solvent extraction.

Pesticides

108 pesticides were analysed (**Table 8-3**). A commercial extraction salt packet of QuEChERS (Quick, Easy, Cheap, Effective, Rugged and Safe) method was used for extraction. Then, a clean-up step was conducted with primary-secondary amine (PSA) and C18. Finally, the extract was diluted with water (1:2) before GC analysis.

Table 8-3: Analysed pesticides

Aclonifen	Dichlobenil	Mepanipyrim
Acrinathrin	Dichlofluanid	Metalaxyl
Alachlor	Dichlorvos	Methidathion
Aldrin	Dicofol	Methoxychlor
Ametryn	Dieldrin	Metolachlor
Atrazine	Difenoconazol	Metribuzin
Azinphos-methyl	Dimethoate	Mirex
Benalaxyl	Disulfoton	Nonachlor
Bifenox	Endosulfan I	Oxadixyl
Bifenthrin	Endosulfan II	Oxyfluorfen
Bromopropylate	Endosulfan Sulphate	Paclobutrazol
Captafol	Endrin	Parathion-ethyl
Captan	Epoxiconazole	Parathion-methyl
Carbaryl	Ethion	Penconazol
Chlordane-cis	Fenamiphos	Pendimethalin
Chlordane-trans	Fenarimol	Permethrin

Chlordecone	Fenhexamide	Phorate
Chlorothalonil	Fenitrothion	Piperonylbutoxide
Chlorphenvinfos	Fenvalerate + Esfenvalerate	Procymidone
Chlorpyrifos	Fipronil	Prometryn
Chlorpyrifos-methyl	Flusilazole	Propargite
Chlozolinate	Folpet	Propazine
Cyanazine	HCH-a	Propiconazole
Cypermethrin	HCH-b	Pyridaben
Cyphenothrin	HCH-d	Pyrimethanil
Cyproconazole	HCH-gamma (Lindane)	Pyrimiphos-methyl
Cyprodinil	Heptachlor	Quinalphos
DDD-2,4'	Heptachlor epoxide trans	Quinoxyfen
DDD-4,4'	Hexachlorobenzene	Sebutylazine
DDE-2,4'	Hexaconazole	Simazine
DDE-4,4'	Iprodione	Tebufenpyrad
DDT-2,4'	Irgarol1051 (Cibutryn)	Terbuthylazine
DDT-4,4'	Isodrin	Terbutryn
Deltamethrin	Kresoxim- methyl	Tetraconazole
Desethylatrazine	Lambda-Cyhalothrin	Trifluralin
Diazinon	Malathion	Vinclozolin

Contaminants of emerging concern (CEC) from EU watch list
The EC recently released a list of 15 substances which may pose a significant risk to the aquatic environment (EC, 2018), including antibiotics, pesticides, and estrogens (**Table 8-4**).

Table 8-4: Analysed contaminants of emerging concern (EU watch list 2018)

Analyte	Class
Erythromycin	Macrolides (Antibiotics)
Clarithromycin	Macrolides (Antibiotics)
Azithromycin	Macrolides (Antibiotics)
Ciprofloxacin	Fluoroquinolones (Antibiotics)
Thiacloprid	Neonicotinoids (insecticides)
Imidacloprid	Neonicotinoids (insecticides)
Thiametoxam	Neonicotinoids (insecticides)
Metaflumizone	Semicarbazone (insecticides)
Clothianidin	Neonicotinoids (insecticides)
Acetamiprid	Neonicotinoids (insecticides)
Methiocarb	Carbamates (pesticides)
Estrone	Hormones
17-β estradiol	Hormones
17-α ethinyl estradiol	Hormones

A method for the multi-class screening of the contaminants belonging to the 2018 EU watch-list was developed. A QuEChERS (Quick Easy Effective Rugged and Safe) procedure was optimized and applied for the extraction and purification of the analytes. Instrumental determination was accomplished by high performance liquid chromatography coupled to tandem mass spectrometry (HPLC-MS/MS) for high sensitivity and specificity. The QuEChERS method was optimized in terms of both recovery and matrix effect, and the method was validated by using a pool of the considered samples.

The final sample pre-treatment involved the following steps: one hundred mg of dried sludge was extracted with 10 mL of acetonitrile/H_2O (50/50, *v*/*v*), with 0.1% (*v*/*v*) of formic acid and 0.2% (*w*/*v*) Na_2EDTA; 4 g of $MgSO_4$ and 1 g of NaCl were added to obtain phase separation: the solution was immediately agitated and centrifuged. Afterwards, two aliquots of the acetonitrile (ACN) layer were collected: 1 mL was dried at ambient temperature, reconstituted in 300 µL of CH_3OH/H_2O (50/50, *v*/*v*), filtered through a 0.2 µm filter and analysed by HPLC-MS/MS for determination of ciprofloxacin (the clean-up step caused loss of this analyte). A second aliquot of 2 mL of the ACN extract was subjected to clean up with 300 mg of $MgSO_4$ and 100 mg of PSA (primary secondary amine) sorbent; the solution was shaken and centrifuged. One mL of the supernatant was evaporated to dryness and reconstituted with 200 µL of CH_3OH/H_2O (50/50, *v*/*v*). The sample was then filtered and analysed by HPLC-MS/MS.

All analyses were performed by ultra-high-performance liquid chromatography (UHPLC) coupled to tandem mass spectrometry. Chromatograhic separation was achieved by an elution gradient on a C18 column, the ion source was an electrospray ionization source (ESI) and mass spectrometric detection was performed by a triple quadrupole, in multiple reaction monitoring (MRM) mode. Several MS parameters were optimized to improve sensitivity. Triplicate injections were performed for all samples and calibration solutions.

The developed method was evaluated in terms of the following figures of merit: trueness (recovery and matrix effect), limit of detection (LOD), limit of quantitation (LOQ), linearity range and precision. The method demonstrated acceptable matrix effect (70-120%) and recovery (71-104%) for all analytes, except for amoxicillin, erythromycin and metaflumizone. These analytes showed problems of stability, therefore their reliable quantitation was not feasible. For the rest of the analytes, low detection and quantitation limits (**Table 8-5**), excellent linearity of the calibration curves (determination coefficient ≥ 0.99 in the range from LOQ to 125 ng mL^{-1}) and good precision (relative standard deviation always <20%) were obtained.

Table 8-5: Limit of detection (LOD) and limit of quantitation (LOQ) of CECs in matrix

Analyte	LOD	LOQ
	µg kg -1	
Clarythromycin	0.3	1.7
Azythromycin	1.4	4.6
Ciprofloxacin	7.9	26.5
Thiacloprid	0.5	1.8
Imidacloprid	1.9	6.5
Thiametoxam	1.6	5.5
Clothianidin	2.4	7.9
Acetamiprid	0.8	2.6
Methiocarb	0.6	2.1
Estrone	1.3	4.2
17-β estradiol	11.4	37.9
17-α ethinyl estradiol	21.4	71.4

When applying the final procedure to the SMART products, the matrix effects related to each sample were evaluated: some differences among the samples aroused. Therefore, for accurate quantitation, the standard addition method was used when the samples showed matrix effects substantially different from the values of the pooled extract.

8.2 Results

8.2.1 Heavy metals

Regulation (EU) 2019/1009 of the European Parliament and the Council of 5 June 2019 in Annex I design the product function categories of EU fertilising products (EC, 2019). The limit values for heavy metals depend on the type of fertiliser; therefore, a list with the samples analysed in this study and the corresponding product function category are presented in **Table 8-6**.

Annex I considered three categories of fertiliser: Organic, organo-mineral and inorganic. Within these categories, a fertiliser could be liquid or solid and finally, the inorganic fertilisers, besides the classification liquid or solid, had sub-classes depending on their content in macronutrients or micronutrients and also if they are composed by only one macro or micronutrient (straight fertiliser) or if they are composed by multiple macro or micronutrients (compound fertiliser).

Table 8-6: Classification of the samples for heavy metal limits

Product Function Category	Samples
Straight solid inorganic macronutrient fertiliser	CaP.1 (UK), CaP.2 (UK), CaP.3 (UK)
Compound solid inorganic macronutrient fertiliser	Struvite (IT), P-rich sludge (IT), P-rich compost (IT), Excess sludge (GR)

Table 8-7 shows the average values of the data obtained from the three determinations for each heavy metal. Moreover, the limit values for heavy metals in an inorganic macronutrient fertiliser are presented in **Table 8-8** (EC, 2019). It has to be noticed that this regulation only considered the hexavalent chromium; therefore, a specific analysis for this species should be performed to be fully comparable, as total Cr was reported in this analysis.

Table 8-7: Analytical results for heavy metals

Sample	Mg (mg/kg)	Cr (mg/kg)	Ni (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Cd (mg/kg)	Pb (mg/kg)	Hg (mg/kg)
CaP.1 (UK)	2822 ± 49	4.5 ± 0.3	2.25 ± 0.28	6.6 ± 0.5	70 ± 19	0.50 ± 0.01	1.17 ± 0.03	<0.01
CaP.2 (UK)	1683 ± 6	2.34 ± 0.04	1.64 ± 0.04	3.90 ± 0.11	21.8 ± 1.2	0.29 ± 0.00	0.53 ± 0.02	<0.01
CaP.3 (UK)	2406 ± 71	3.7± 0.4	1.63 ± 0.17	3.57 ± 0.30	74.0 ± 2.6	0.62 ± 0.02	0.63 ± 0.01	<0.01
Struvite (IT)	$1.42 \cdot 10^5 \pm 3 \cdot 10^3$	19.6 ± 0.3	10.8 ± 0.4	16.0 ± 0.4	83.4 ± 7.8	0.08 ± 0.00	2.55 ± 0.05	0.086 ± 0.003
P-rich sludge (IT)	5390 ± 309	8.1 ± 0.3	6.9 ± 0.4	54.0 ± 5.5	226 ± 18	0.24 ± 0.02	9.53 ± 0.77	0.436 ± 0.099
P-rich compost (IT)	6959 ± 103	24.4 ± 1.4	16.0 ± 0.9	63.2 ± 1.2	290 ± 3	0.32 ± 0.01	15.8 ± 0.4	0.482 ± 0.231
Excess sludge (GR)	6604 ± 307	331 ± 6	42.9 ± 0.2	178 ± 5	459 ± 7	0.67 ± 0.02	92.6 ± 1.1	1.061 ± 0.051
PHA-rich sludge (IT)	5424 ± 143	2.26 ± 0.08	2.11 ± 0.01	11.48 ± 0.08	54.9 ± 0.2	0.08 ± 0.00	3.38 ± 0.08	0.085 ± 0.037
PHA-rich sludge (ES)	7926 ± 78	3.54 ± 0.08	5.04 ± 0.06	32.1 ± 0.4	381.5 ± 1.4	0.84 ± 0.01	6.55 ± 0.03	0.147 ± 0.007
PHA	76.3 ± 1.4	< 0.5	0.39 ± 0.02	< 0.5	< 5	< 0.05	0.11 ± 0.00	<0.01
Cellulose	693 ± 6	10.0 ± 0.6	5.19 ± 0.21	51.5 ± 0.2	176 ± 3	0.13 ± 0.00	6.9 ± 0.7	0.082 ± 0.021
WPC	3451 ± 313	43.1 ± 4.2	16.0 ± 1.6	197 ± 19	224 ± 18	< 0.1	11.5 ± 2.8	0.01 ± 0.001
SPC.50	461 ± 24	11.9 ± 0.8	5.31 ± 0.06	42.9 ± 0.8	161 ± 3	0.12 ± 0.01	9.99 ± 0.12	0.058 ± 0.006
SPC.100	585 ± 15	15.9 ± 0.7	7.66 ± 0.16	59.1 ± 1.3	217 ± 5	0.15 ± 0.00	15.3 ± 0.7	0.084 ± 0.002
SCC	180 ± 47	1.4 ± 1.2	< 0.2	5.06 ± 2.04	23 ± 12	0.10 ± 0.03	0.27 ± 0.26	0.022 ± 0.021

Table 8-8: Limit values for heavy metals according to Regulation (EU) 2019/1009 (EC, 2019)

Limit value	Mg (mg/kg)	Cr (VI) (mg/kg)	Ni (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Cd (mg/kg)	Pb (mg/kg)	Hg (mg/kg)
Regulation (EU) 2019/1009	No limit	2	100	600	1500	3 or 60*	120	1

** limit value depends on the total phosphorus (P) content of the fertiliser. If P content is < 5% P_2O_5 by mass, limit is 3 mg/kg. If P content is >5% P_2O_5 by mass, limit is 60 mg/kg.*

All the heavy metals were below the limits except for the case of Hg in “Excess sludge (GR)”. Therefore, excess sludge (GR) was the only sample that was not suitable as a fertiliser, although the Hg value obtained (1.061 ± 0.051) is very close to the limit of 1 mg/kg. Moreover, all samples accomplish the more restrictive limit for Cd of 3 mg/kg, independently of their total phosphorus content.

Other outdated legislations, such as RD 999/2017 (BOE, 2017) (in the case of Spain), which is the transposition of the European Regulation No. 2003/2003 (EC, 2003) have more restrictive limits for heavy metals compared to the most recent normative (Regulation (EU) 2019/1009).
These directives categorise compost in five kinds (according to the raw materials used) and in three quality levels (Class A, B and C) depending only on the heavy metals content of compost (**Table 8-9**).
In Spain the legal use of a specific compost is determined by its heavy metals content. Compost Class A has the lowest heavy metal content and it can be employed in organic farming. Class C has the highest content and it can only be applied at a maximum rate of 5 Mg ha^{-1} (Puyuelo et al., 2019). The explanation of the three quality levels are shown below:

- Class A: Fertiliser product, which content in heavy metals does not exceed values of file A.
- Class B: Fertiliser product, which content in heavy metals does not exceed values of file B.
- Class C: Fertiliser product, which content in heavy metals does not exceed values of file C.

With these more restrictive limits, samples struvite (IT), P-rich compost (IT), and excess sludge (GR) were class B, because exceeded, at least, one of the values of class A. Sample of excess sludge (GR) exceeded the values of class A for the following heavy metals: Cr, Ni, Cu, Zn, Pb and Hg so is the sample with the highest heavy metals content.

Table 8-9: Different legislations on the maximum heavy metals content permitted in compost and related quality level

Legal basis of standard	Quality or standard	Maximum concentration values [mg/kg DM]								
		As	Cr (Tot)	Cr (VI)	Ni	Cu	Zn	Cd	Pb	Hg
EU - End-of-waste criteria on biodegradable waste subject to biological treatment (Saveyn and Eder, 2013)		-	100	-	50	200	600	1.5	120	1.0
Spain - RD 506/2013 on Fertiliser Products (BOE, 2017)	Class A	-	70	nd	25	70	200	0.7	45	0.4
	Class B	-	250	nd	90	300	500	2.0	150	1.5
	Class C	-	300	nd	100	400	1000	3.0	200	2.5
Austria - Compost Ordinance BGB1.I I 292/2001 (Austrian Compost Ordinance, 2001)	Class A+	-	70	-	25	70	200	0.7	45	0.4
	Class A	-	70	-	60	150	500	1.0	120	0.7
	Class B	-	250	-	100	500	1800	3.0	200	3.0
Canada - Guidelines for Compost Canada Council of Ministers of the Environment (CCME, 2005)	Category A	13	210	-	62	400	700	3.0	150	0.8
	Category B	75	-	-	180	-	1850	4.0	500	5.0
Portugal - Law Decree (No 103/2015) on Fertiliser Products (DRE, 2015)	Class I	-	100	-	50	100	200	0.7	100	0.7
	Class II	-	150	-	100	200	500	1.5	150	1.5
	Class IIA	-	300	-	200	400	1000	3.0	300	3.0
	Class III	-	400	-	200	600	1500	5.0	500	5.0

PHA-rich samples (PHA, PHA-rich sludge (IT), PHA-rich sludge (ES)) could be used for food packaging, however, the materials that are in contact with food during its production, processing, storage, preparation and serving (called food contact materials, FCM) have to be regulated to protect consumers' health. FCMs should be sufficiently inert so that their constituents neither adversely affect consumer health nor influence the quality of food. Therefore, FCM placed on the EU market are subject to EU rules (Regulation (EC) No 1935/2004 of the European Parliament and of the Council of 27 October 2004 on materials and articles intended to come into contact with food) (EC, 2011).
PHA are bioplastics, therefore, the Commission Regulation (EU) No 10/2011 on plastic materials and articles intended to come into contact with food established the list of authorised substances (EC, 2011). Moreover, general restrictions on plastic materials and articles, such as the specific migration limits (SML) are also considered. Plastic materials and articles shall not transfer their constituents to foods in quantities exceeding the SML set out in Annex I of the abovementioned Regulation. Those SML are expressed in mg of substance per kg of food (mg/kg). The SML for the substances considered in the regulation are listed in **Table 8-10**.

Table 8-10: Specific migration limit for heavy metals (EC, 2011)

Substance	Specific migration limit (SML) [mg/kg food]
Cu	5
Ni	0.02
Zn	5

Assuming a complete migration of the heavy metals from the samples to food as worst case, only extracted PHA is below the migration limit for Cu and Zn, although Ni value in the sample is higher than SML. However, the potential migration of heavy metals bound in bioplastics is expected to be rather low, also depending on the food to bioplastic ratio (i.e. amount of packaging material per food).

8.2.2 Polycyclic aromatic hydrocarbons

PAHs are known as one of the most widespread organic pollutants in soils due to natural or anthropogenic activities. They are carcinogenic and mutagenic. PAH compounds are known to be biodegradable, but biodegradation rates differ widely, depending on the compound and the environmental conditions, with half-lives reported from days to several years (Saveyn and Eder, 2013). Only seven PAH were detected in some samples. Data obtained for these detected PAHs are reported in **Table 8-11**, where the average values obtained from two determinations for each PAH are shown.

Table 8-11: Analytical results for polycyclic aromatic hydrocarbons (PAH)

PAHs [mg/kg dry matter]	CaP.2 (UK)	Struvite (IT)	P-rich sludge (IT)	Excess sludge (GR)	PHA-rich sludge (IT)
Sum					
Anthracene	0.034	0.131 ± 0.169			
Benzo(b)fluoranthene	0.043	<LD			
Chrysene	0.047	0.12			
Fluoranthene	0.332	0.022 ± 0.006		0.016	
Fluorene	0.027 ± 0.003	0.013			
Naphthalene	0.018	0.029 ± 0.012	0.014 ± 0.002		0.012
Phenanthrene	0.121	0.022 ± 0.009	0.020		0.018

LD: Limit of detection (0.010 mg/kg)

The third draft on the Working Document on Sludge (EC, 2000) proposed limit values for certain synthetic organic compounds, such as halogenated organic compounds, PAHs, polychlorinated dibenzodioxins/dibenzofurans (PCBs) among others. **Table 8-12** shows the related limit values for PAHs. A report from JRC also gives an overview of legally binding limits and guide values for organic pollutants in compost/digestate and similar materials in different European countries (Saveyn and Eder, 2013) (**Table 8-12**).

Most limits or guide values in legislation refer to a subset of the full set of the 16 principal PAH compounds on the US EPA's priority pollutants list (**Table 8-2**) (Saveyn and Eder, 2013). However, the French compost norm NF U44-051 sets limit values for 3 individual PAH compounds (**Table 8-12**).

Table 8-12: Reported limits of PAH for sludge use in agriculture

Regulation	Sum of PAH	Fluoranthene	Benzo(b)fluoranthene	Benzo(a)pyrene
	[mg/kg dry matter]			
EC (2000)	6[a]			
Austria (Carinthia)[c]	6[a]			
Austria (Steiermark)[c]	6[b]			
Bulgaria[d]	6.5			
Denmark[c]	3[a]			
France[c]		5	2.5	2
Portugal[d]	6			
Sweden[d]	3[a]			
Hungary[d]	10[b]			
Luxembourg[d]	20[b]			

a: Sum of acenaphthene, fluorene, phenanthrene, fluoranthene, pyrene, benzo(b+j+k)fluoranthene, benzo(a)pyrene, benzo(ghi)perylene, indeno(1,2,3-c,d)pyrene.

b: Sum of 16 US EPA PAU (naphthalene, acenaphthene, acenaphthylene, fluorene, fenanthrene, fluoranthene, pyrene, anthracene, benz(a)antrhacene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, dibenzo(a,h)anthracene, indeno(1,2,3-c,d)pyrene and venzo(ghi)perylene.

c: (Saveyn and Eder, 2013)

d: (Hudvoca et al., 2019)

The sum of PAHs detected in all the samples (**Table 8-11**) was below the limits for any of the countries shown in **Table 8-12**. Among the PAHs detected only naphtalene appeared in the EU pesticides database, the status under Reg. (EC) No 1107/2009 is not approved and the MLR for food is the default (0.01 mg/kg) according to Art 18 (1) (b) Reg 396/2005.

8.2.3 Chloroalkanes

Chloroakanes between 10 and 13 carbons were detected only in the following samples (**Table 8-13**). No specific legal standard or guideline could be identified for chloroalkanes presence in recovered products. Thus, a risk assessment for these class of contaminants could not be carried out within the scope of this project. However, contamination data is now available and could be used in the future to estimated a potential risk of these class of substances in the use of SMART products.

Table 8-13: Analytical results for chloroalkanes

Sample	Chloroalkanes (C10-C13) in [mg/kg dry matter]
CaP.1 (UK)	0.016 ± 0.003
CaP.2 (UK)	0.018 ± 0.007
CaP.3 (UK)	0.018 ± 0.007
Struvite (IT)	0.078 ± 0.006
P-rich sludge (IT)	0.036 ± 0.004
Excess sludge (GR)	0.015 ± 0.006
PHA-rich sludge (IT)	0.025 ± 0.000
PHA-rich sludge (ES)	0.025 ± 0.000
SPC.50	0.013

8.2.4 Pesticides

A ‘pesticide’ is a substance that prevents, destroys, or controls a harmful organism or disease, or protects plants or plant products during production, storage and transport (herbicides, fungicides, insecticides, acaricides, repellents biocides, etc). Moreover, plant protection products are ‘pesticides’ that protect crops or desirable or useful plants. They contain at least one active substance which is any chemical, plant extract, pheromone or microorganism that has action against pests or on plants, parts of plants or plant products. These active substances entering the soil can bring environmental hazards, and influence soil properties involved in biochemical and microbial aspects. Before an active substance can be used within a plant protection product in the EU, it must be approved by the European Commission.

When looking for legislation related to pesticides presence in recovered products, no specific legal standard or guideline was identified. In relation to the food industry, there is an EU pesticides database where the approved and not approved active substances and their maximum residue limit (MRL) in several groups of food can be found. A MRL is the highest level of a pesticide residue that is legally tolerated in or on food or animal feed when pesticides are applied correctly (“good agricultural practice”). The MRL for each pesticide or active substance depends on the type of food (fruits, vegetables, cereals, spices, etc). These values reported for food will be used as a framework to compare the values in the recovered products, although it has to be noted that these are the most restrictive pesticide limits that can be used, and that the legal limits for non-edible materials are expected to be much higher than these values.

To simplify the interpretation and comparison of the values measured and the MLR, only the highest and the lowest MRL are shown in **Table 8-14**. Only six pesticides were detected in two samples: struvite (IT) and CaP.2 (UK). Five of the pesticides appeared as active substances in the EU pesticides database, status under Regulation (EC) No 1107/2009. Cyprodinil is the only approved substance, however, the value detected was slightly higher compared with the more restrictive value (0.02 mg/kg) included in the Annex II of the Regulation (EC) No 396/2005. The rest of pesticides were not approved and the detected values were higher than the lowest MRL.

Table 8-14: Analytical results for pesticides and maximum value tolerated in or on food.

Pesticide (mg/kg)	CaP.2 (UK)	Struvite (IT)	Status under Reg. (EC) No 1107/2009	Maximum Residue Level (MRL)* (mg/kg)
Bifenthrin	0.018	<LD	-	-
Cyprodinil	<LD	0.022 ± 0.011	Approved	0.02 - 40^{a} (Annex II)
Flusilazole	0.023 ± 0.013	<LD	Not approved	0.01 - 0.05 (Annex V)
L-Cyhalothrin	0.068 ± 0.040	<LD	Not approved	0.01 - 3
Propiconazole	0.028 ± 0.013	<LD	Not approved	0.01 - 9^{b} (Annex II)
Terbutryn	0.155 ± 0.065	<LD	Not approved	Default MRL of 0.01

LD: Limit of detection (0.010 mg/kg)
**Reg. (EC) No 396/2005*
a: 40 mg/kg for herbs and edible flowers
b: 9 mg/kg for orange

The MRL is the tolerated value on food, but these samples would be used as plant protection products. Therefore, the impact of a possible migration of the pesticide from the recovered material to the plant and the final product should be studied to determine the usability of these materials as fertilizer.

8.2.5 Contaminants of emerging concern (EU watch list)

For this group of substances, no legal regulation or guideline value could be found in existing legislation related to the use of recovered products from wastewater. As they are "emerging" contaminants, development and implementation of legal standards is on-going. Thus, the risk assessment for these substances is based on a simplified chemical risk assessment by comparing the measures concentrations in the products to data from related studies in the literature. The focus of this risk assessment is on those materials that are used as fertilizers in agriculture. The SMART products with this destination are sludges (P-rich sludge (IT) + Excess sludge (GR)), compost (P-rich compost (IT)), calcium phosphate (CaP.1 (UK), CaP.2 (UK), CaP.3 (UK)) and struvite (Struvite (IT)).

Whereas potential transfer of these substances from soil into food is yet under study, their application on agricultural land poses direct risks for the related ecosystem. Therefore, the risk assessment is limited here to the ecotoxicological risk of product application, considering both organisms of soil and groundwater. In order to allow a safe use of these products, a guideline is needed on maximum amounts of these materials which can be applied in agriculture annually without generating an ecotoxicological risk.

The resources of this project did not allow a detailed quantitative chemical risk assessment as described e.g. in the EU TGD model (ECB, 2003). However, previous projects have assessed similar substances from the group of CECs and determined their acceptable application limit on soil (Kraus et al., 2019). Using a simplified approach described below, this evaluation can be performed by considering only three characteristics of the individual substances:

- quantitation results in the fertilizer products
- predicted no effect concentration (PNEC) of the analytes for the ecosystem

- biological half-life of the analytes as measure for their accumulation or biological degradation in soil

These parameters allow to estimate the maximum annual input of a specific chemical to agricultural land associated to acceptable risk for the soil ecosystem when compared to previously assessed substances.

Due to a lack of data, few assumptions had to be taken to be able to characterize the CECs of the EU watch list for both groundwater and soil organisms:

- A lower PNEC for surface water also corresponds to a higher sensitivity of the soil ecosystem
- If substance A has a) an equal or higher PNEC and/or b) has a shorter biological half-life as the substance B previously assessed, the minimal low risk input of substance B can also be adopted for substance A.

Table 8-15 summarizes the required data for this simplified risk assessment for those CECs that have been detected in the SMART products for use as fertilizer.

Table 8-15: Risk assessment data for the detected CECs

Pollutant	PNEC$_{\text{Water}}$[a]	Assumed maximal biological half-life[b]	Low risk – yearly input to agricultural land (Kraus et al., 2019)
	µg L^{-1}	*d*	*mg/(ha*a)*
Clarithromycin	0.2	300	>6000
Azithromycin	0.019	5000	3000
Ciprofloxacin	0.036	5000	6000
Imidacloprid	0.013	<5000	2000
Estrone	10-4	10	150
17α-Ethinylestradiol	10-5	10	15

a- *Source for PNECs (chronic): https://www.ecotoxcentre.ch/expert-service/quality-standards/proposals-for-acute-and-chronic-quality-standards/*

b- *If biological half life values were not available, “worst-case” assumptions have been made, based on known data for similar chemicals.*

These values are used for the estimation of the acceptable amount of fertilizer safe to be used in an annual timeframe. In fact, once the low risk-annual input and the contamination level of a specific compound in the SMART products are known, the maximum amount which can be applied of this product as fertilizer per year (acceptable fertilizer application, AFA) can be determined, by the following formula:

$$AFA(\mathrm{kg/(ha*a)}) = \frac{Low\ Risk\ Input\ (\mathrm{mg/(ha*a)})}{C\ (\mathrm{mg/kg})}$$

where “*Low Risk Input*” is the low risk-annual input to agricultural land and *C* is the concentration of a chemical in the SMART product. It follows that for each SMART product, AFA values for each CEC could be calculated. The lowest AFA of all CECs detected in one sample determines the actual amount of fertilizer which can be applied of this material without unacceptable negative effects on the ecosystem. For the evaluation. the concentration values of the contaminants used for the AFA calculation were taken at the higher limit of the confidence interval (determined average concentration + uncertainty value) in order to assume the worst case.

Analytical results for CECs and material used in agriculture are shown below in **Table 8-16**. Only few analytes from the list were detected, mainly belonging to the antibiotics class, with ciprofloxacin quantified in all samples, at higher levels than the other compounds (up to 600 ng g^{-1}). Low concentrations of estrone (approximately 20 ng g^{-1}) were detected in some samples; on the contrary, the other hormones were under the detection limit in all samples. Pesticides were not detected in any of the samples, except for P-rich compost (IT), in which a very low concentration of imidacloprid was determined (6 ng g^{-1}). This value was near LOQ, i.e. characterized by a high uncertainty.

Table 8-16: Analytical results for CEC (EU watch list)

Substance	CaP1 (UK)	CaP2 (UK)	CaP3 (UK)	P-rich sludge (IT)	Excess sludge (GR)	Struvite (IT)	P-rich compost (ES)
	[µg kg^{-1} dry matter]						
Clarithromycin	- [a]	-	-	50 ±8	-	30 ±8	31 ±8
Azythromycin	-	-	-	506 ±18	30 ±19	29 ±19	342 ±19
Ciprofloxacin	11 ±6[b]	14 ±5[b]	8 ±6[b]	597 ±6	507 ±6	54 ±6	217 ±8
Imidacloprid	-	-	-	-	-	-	6 ±1[b]
Estrone	-	-	-	22 ±11	27 ±12	24 ±12	-

a- *not detected peaks or peak area < LOD*
b- *concentrations < LOQ; estimated by extending calibration below the lower limit of the linearity range*

On the basis of the PNEC values, the most concerning compound is estrone, potentially hazardous to aquatic organisms at very low concentrations. Even though a low biological half-life has been reported, its continuous input to soil could constitute a hazard to the environment. Therefore, for the products which contained estrone, its concentration was determinant in defining the maximum amount of fertilizer associated to low risk for the ecosystem. Azithromycin and ciprofloxacin were the other two determinant substances, given their concentrations in the samples. **Table 8-17** shows the AFA values calculated for all the contaminants in each sample. For interpretation, the minimum AFA value should be taken as a precautionary upper limit for the amount of SMART-product application in agriculture.

Table 8-17: Acceptable Field Application (AFA) values related to CECs detected in samples

Substance	CaP1 (UK)	CaP2 (UK)	CaP3 (UK)	Struvite (IT)	P-rich sludge (IT)	Excess sludge (GR)	P-rich compost (ES)
	[kg/(ha*a)]						
AFA Clarithromycin				157895	103448		153846
AFA Azythromycin				62500	5725	61224	8310
AFA Ciprofloxacin	352941	315789	428571	100000	9950	11696	26667
AFA Imidacloprid							285429
AFA Estrone				417	455	385	
minimum AFA	**352941**	**315789**	**428571**	**417**	**455**	**385**	**8310**

Based on these data, maximum amounts of SMART products to be applied to agriculture can be deduced that pose no unacceptable risk for ecosystems. Whereas calcium phosphate can be applied in high amounts (> 300 ton/(ha*a)), the application of SMART struvite may be limited by its content of estrone to around 400 kg/(ha*a). The same range of application can be reached for the sludges, where estrone is also the limiting compound. The use of P-rich compost is limited here by its content of azithromycin to ca. 8 ton/(ha*a).

It has to be noted here that this preliminary risk assessment identified “potential” risks of these materials taking a simplified approach. Overall, contamination levels of CECs in SMART products are low and will not pose an unacceptable risk for their application compared to usual practice of fertilisation in Europe (e.g. application of sewage sludge or manure in agriculture). However, the findings indicate that especially for hormones, negative effects on the ecosystem may not always be fully excluded. This should be taken into account during the application of SMART products, but also in the future development of related legislation in Europe.

8.3 Conclusions

To assess potential risks of SMART products application for human health and ecosystems during their application, 15 samples have been analysed for a wide range of contaminants. These substances included heavy metals, polycyclic aromatic hydrocarbons (PAH), chloroalkanes, pesticides, and also contaminants of emerging concern (EU watch list 2018).

Results show that low contamination of SMART products can be detected for selected contaminants, which is of course due to their origin from municipal wastewater. In particular, sludge and sludge-based products such as compost contain a range of inorganic and organic substances which may pose a potential hazard for human health or ecosystems during their application in agriculture.

For heavy metals, all SMART products were below the legal limits for use in agriculture of the EC. Only one sample of excess sludge exceeded the limit of mercury and may not be suitable for agricultural application. Taking more strict regulations on EU or national level on composts, some SMART products cannot be used in the primary class of application, but are still suitable for agricultural use.

For PAH, very low contamination was present for some substances in some samples, but these levels are well below the legal thresholds for sludge use in agriculture.

For chloroalkanes, low concentrations have been detected which could not be related to any legal standard or guideline value. Taking the measured analytical results, more work is required to check if this is associated with any risk during SMART product application.

For pesticides, only few substances have been detected in two samples. Lacking any legal regulation of pesticides for recovered fertilizer materials, future studies should evaluate a potential risk from these pesticides on ecosystems and human health.

For contaminants of emerging concern of the EU watch list (2018), some compounds have been detected in selected samples. Comparing those results with previous studies and other substances, a maximum amount of SMART products to be applied in agriculture without unacceptable risk on ecosystems could be derived. Especially for hormones such as estrone, a potential risk from application of sludge and sludge-based products on ecosystems cannot be fully excluded at this point. However, existing practice of sludge recycling to agricultural land faces the same problem, and future legal regulation in this sector should be developed on acceptable levels of these contaminants in fertilizers from wastewater or sludge.

Overall, no excessive transfer of hazardous pollutants from wastewater into SMART products could be detected. Detected risk potentials from heavy metals or organic compounds in SMART products used on agriculture are low, but should be further investigated and legally regulated in the future. In general, new legislation in this sector is required to define acceptable levels of contamination in recovered materials from municipal wastewater, especially for application as fertilizer in agriculture.

9. CONCLUSIONS

9.1 Life Cycle Assessment

In this study, all SMARTechs for material recovery at municipal WWTPs have been assessed with LCA to quantify their environmental benefits and potential drawbacks in relation to a conventional WWTP operation. The different SMARTechs have been assessed at their respective site of demonstration, taking the existing WWTP as reference for the comparison.

Overall, the results show that material recovery can lead to environmental benefits for WWTP operation if assessed over the entire value chain, i.e. including the valorisation of valuable end-products. In particular, efforts for wastewater treatment in terms of primary energy demand and related greenhouse gas emissions can be reduced without compromising the treatment quality of the plants (**Table 8-1**).

Table 9-1: Results of environmental assessment for all SMARTechs

Case study location	**SMARTechs**	**Material recovered**	**Primary energy demand**		**Global warming potential**		**Water emissions (N, P)**	
			Min	*Max*	*Min*	*Max*	*Min*	*Max*
NL	Cellvation + Biodrying	Cellulose	-4%	-23%	-2%	-19%	No effect*	
	Cellvation + Bio-composites	Cellulose	-2%	-18%	-1%	-15%	No effect*	
IL	Anaerobic biofilter	Biogas	-62%	-68%	+37%	-22%	No effect*	
ES	SCEPPHAR mainstream + PHA extraction	PHA, struvite	+6%	-18%	+8%	-12%	No effect*	
UK	Ion exchange	CaP, NH$_3$	+32%	-52%	+3%	-71%	-2%	-62%
IT	SCENA + Dynamic composting	P-rich compost	+8%	-2%	+1%	+4%	No effect*	
	SCEPPHAR sidestream + PHA extraction	PHA, struvite	-5%	-8%	-4%	-7%	No effect*	
GR	SCENA after TH	-	+19%	+6%	+9%	+6%	-10%	-10%

** impact on water quality could not be predicted based on the available data. Assumption: comparable effluent quality than reference WWTP*

Based on the results of the case study LCAs, the following general conclusions can be drawn:

- Depending on the SMARTech and material recovered, **up to 68% of primary energy demand and 71% of greenhouse gas emissions could be mitigated by integration of material recovery at a municipal WWTP**. The different SMARTechs and materials recovered show a wide range of potential improvement, ranging from savings in the lower % range for sidestream SMARTechs (e.g. SCENA and SCEPPHAR) up to significant improvements for mainline SMARTechs (e.g. CELLVATION, Anaerobic bilfilter, or Ion exchange).

- For all SMARTechs, these savings relate not only to the credits for recovered materials, but also and often **predominantly to operational savings at the WWTP** such as reduced aeration energy, less chemicals, or a lower sludge amount to be disposed. Based on the different case studies analysed in this report, it is **crucial for the environmental benefits of material recovery that it is also connected to operational improvements at the plant**. In other words, avoided impacts from **substitution of primary products with recovered resources alone do not justify the efforts required for material recovery at WWTPs**.
- Another crucial point for environmental benefits of material recovery is a **low-impact downstream processing into valuable end products**. The example of PHA-rich sludge from SCEPPHAR shows that a high concentration of PHA (> 20% of dry matter) can justify the efforts of chemical extraction in the overall balance, whereas a lower content of PHA leads to preference of other valorisation routes with low impact of processing. In particular, **thermal energy requirements for processing of products should be minimised** by using excess heat at the site or low-impact processes such as bio-drying to end up with a favourable energy and GHG balance for the recovered material.
- Direct emission of greenhouse gases at WWTPs such as **N_2O and CH_4 are a relevant contribution for the overall GHG footprint** and should not be increased at all by processes for material recovery. Otherwise, potential life-cycle **benefits from reduced energy consumption are easily off-set by increased direct emissions of GHGs** and will then lead to an overall increase in the impact of WWTPs on climate change. This is especially important for short-cut nitrogen removal processes prone to increased N_2O emissions (SCENA, SCEPPHAR) and anaerobic processes releasing CH_4 to atmosphere (anaerobic biofilter). **Mitigation measures to avoid excessive emission of GHGs should be integrated** for those SMARTechs to minimise the risk of increasing the overall carbon footprint with material recovery. In addition, a **close monitoring of direct GHG emissions** of SMARTechs should be targeted for the first full-scale references to collect more data on this aspect from full-scale plants.
- Some SMARTechs reduced water emissions below the level of the existing WWTP, thus having a **potential to improve the treatment performance of the plant**. For other SMARTechs, their impact on water quality could not be predicted with the available data. However, for these cases it is expected that a comparable effluent quality can be reached after SMARTech integration, i.e. the **primary function of the WWTP is not compromised by material recovery**.

Due to the prospective nature of the LCA case studies analysed in SMART-PLANT, a number of inherent limitations are connected to the outcomes of this report and should be carefully reflected in the interpretation of the results:

- Environmental benefits of material recovery often depend on the extent of operational savings at the WWTP. However, these **operational savings have not been monitored or quantified with real data** in this study, as most SMARTechs have been demonstrated in pilot-scale only. In addition, various factors can affect operational parameters at a full-scale WWTP such as variation in influent quality, seasonal performance of the biological system, upgrades or maintenance/repair of process units, and other operational optimisation measures. These effects may prohibit to identify a clear correlation between integration of SMARTechs and a change in operational parameters at the WWTP. Finally, **mainline impacts of SMARTech integration have been estimated for all case studies** by project partners based on their experience of the WWTP processes. The underlying uncertainty of prediction should be taken into account in the interpretation of the LCA results.
- The potential **impact of SMARTech integration on the biological performance of the WWTP could not be validated** here. Extraction of organic material upstream of the biological

treatment could have negative impacts on biological nitrogen removal if COD/N ratio becomes limiting for denitrification, whereas a reduced return load with sidestream treatment can improve plant operation or extend capacity. Hence, these aspects should be investigated in future work to determine potential positive or negative impacts of material recovery on the performance of the mainline WWTP process.

- Process data for direct GHG emissions was available for most SMARTechs from pilot monitoring campaigns during the project. However, these results are affected with some uncertainty and potential pilot artefacts (e.g. suboptimal operational control, reactor geometry). Finally, **GHG emission factors are projected here based on monitoring results in combination with expert judgment**. In particular, N_2O emissions of existing WWTPs have not been monitored but for one WWTP, so that **baseline N_2O emissions have been estimated for most WWTPs from literature.** Given the high contribution of direct GHG emissions on the overall carbon footprint, both the assumptions for baseline WWTPs and the emission factors of SMARTechs should be further validated with more intensive monitoring campaigns of full-scale references under realistic operational conditions in the future.
- The LCA outcomes for selected SMARTechs **depend on the local conditions at the respective WWTP**, such as the existing process configuration in the baseline, the sludge disposal route, or the actual energy balance at the plant. These local conditions should be carefully reflected when transferring the LCA results to other sites or national conditions, as they may have a significant impact on the overall environmental profile.

9.2 Product quality assessment

Selected samples of recovered materials from all SMARTechs have been analysed for a wide range of inorganic and organic contaminants to assess potential risks of SMART products application for human health and ecosystems during their application. In total, 15 samples have been analysed for a wide range of contaminants. These substances included heavy metals, polycyclic aromatic hydrocarbons (PAH), chloroalkanes, pesticides, and also contaminants of emerging concern (EU watch list 2018).

Results show that low contamination of SMART products can be detected for selected contaminants, which is of course due to their origin from municipal wastewater. In particular, sludge and sludge-based products such as compost contain a range of inorganic and organic substances which may pose a potential hazard for human health or ecosystems during their application in agriculture.

Overall, no excessive transfer of hazardous pollutants from wastewater into SMART products could be detected. Detected risk potentials from heavy metals or organic compounds in SMART products used on agriculture are low, but should be further investigated and legally regulated in the future. In general, new legislation in this sector is required to define acceptable levels of contamination in recovered materials from municipal wastewater, especially for application as fertilizer in agriculture.

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