WP5 – Integration towards full plant concept, assessment and market replication

D 5.5: Recommendations for eco-efficient new concepts of energy positive WWTP

The project "Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration" (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

Deliverable 5.5	***Recommendations for ecoefficient new concepts of energy positive WWTP***
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Abstract	This study analyses reference and innovative schemes for municipal WWTP in their environmental and economic impacts using life-cycle tools of Life Cycle Assessment and Life Cycle Costing. Hypothetical scenarios for different WWTP size, influent quality, and effluent discharge limits are modelled with process data of pilot and full-scale systems. Results show that enhanced carbon extraction can significantly increase electrical self-sufficiency of WWTPs while still providing the same level of effluent quality. This approach reduces life-cycle energy demand and greenhouse gas emissions and can be realized at competitive annual costs compared to state-of-the-art WWTP schemes. Final recommendations are derived on the way to develop eco-efficient WWTP schemes of the future.

Dissemination level of this document

X	PU	Public
	PP	Restricted to other programme participants (including the Commission Services)
	RE	Restricted to a group specified by the consortium (including the European Commission Services)
	CO	Confidential, only for members of the consortium (including the European Commission Services)

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Abbreviations

AD	Anaerobic digestion
AS	Active substance
CAS	Conventional activated sludge
CED	Cumulative energy demand
CEPT	Chemically enhanced primary treatment
CHP	Combined heat and power plant
COD	Chemical oxygen demand
DAF	Dissolved air flotation
DS	Dry solids
FEP	Freshwater eutrophication potential
GWP	Global warming potential
HRT	Hydraulic retention time
IFAS	Integrated fixed-film activated sludge
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MBBR	Moving bed biofilm reactor
MEM	Sidestream membrane stripping
MEP	Marine eutrophication potential
MOX	Mainstream anammox
MS	Microscreen
ORC	Organic ranking cycle
PE	Population equivalents
P2G	Power-to-gas
SBR	Sequencing batch reactor
SRC	Steam ranking cycle
TN	Total nitrogen
TP	Total phosphorus
UASB	Upflow anaerobic sludge blanket
VFA	Volatile fatty acids
VS	Volatile solids
WWT	Wastewater treatment
WWTP	Wastewater treatment plant

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Executive summary

This study analyses reference and innovative POWERSTEP schemes for municipal WWTP in their environmental and economic impacts using life-cycle tools of Life Cycle Assessment and Life Cycle Costing. Based on hypothetical scenarios at defined boundary conditions for WWTP size, influent quality, and effluent discharge limits, multiple process schemes have been modelled in a mass and energy flow model with a benchmarking software for WWTPs. This process data forms the basis to calculate operational efforts, and it is amended by infrastructure data for material demand and related investment costs. In addition, specific data has been added based on results of the POWERSTEP project (e.g. for N_2O emissions) or information from literature.

The results show that innovative schemes with advanced primary treatment operate with a superior electricity balance compared to current state-of-the-art schemes for municipal wastewater treatment as a reference, increasing electrical self-sufficiency from 27-82% to 80-170%. The POWERSTEP schemes reach this goal without compromising effluent quality targets of the schemes, i.e. reaching the same effluent quality than before. Concentrated influent with high COD levels supports the POWERSTEP approach and enables highly energy efficient schemes. However, nitrogen removal has to be realized with mainstream anammox after enhanced carbon extraction from concentrated influent. This process is still under development, and its performance and stability should be further validated in full-scale references. Sidestream N removal, advanced control of COD extraction and partial bypass of primary treatment are other options to guarantee nitrogen removal after enhanced carbon extraction with conventional denitrification.

In the life-cycle perspective, POWERSTEP schemes significantly decrease primary energy demand of WWTP operation by 29-134% compared to the reference. In favourable conditions, their superior electricity balance can fully compensate life-cycle energy demand for chemical production, sludge disposal and infrastructure, resulting in real energy-positive WWTP schemes. Greenhouse gas emissions can also be substantially reduced with POWERSTEP (- 6 to 43%) due to savings in grid electricity production. GHG benefits of POWERSTEP are smaller than energy benefits on a relative scale, because direct emissions such as N_2O from biological N removal and mono-incineration also deliver a major contribution to overall GHG emission profiles, and they are not reduced with POWERSTEP. In contrast, POWERSTEP schemes with mainstream anammox will most likely increase N_2O emissions, compensating a large part of the electricity-related benefits in GHG emissions.

Total annual costs are in a comparable range for both reference and POWERSTEP schemes. While the latter decrease operational costs by 3-16% due to lower purchase of grid electricity, they require higher investment for primary treatment, increasing capital costs by 4-17%. Overall, effects of POWERSTEP on operational and capital costs off-set each other and result in a net increase of total annual costs of 2-7%, which is within the uncertainty range of this cost calculation. Higher electricity prices (> 0.12 €/kWh) will increase the positive impact of POWERSTEP on operating costs, resulting in fully cost-competitive eco-efficient WWTP schemes at power prices of 0.25 €/kWh. Final recommendations are derived on the way to develop eco-efficient WWTP schemes of the future.

1. Introduction

Within the H2020 innovation project POWERSTEP (www.powerstep.eu), a selection of innovative processes is demonstrated in pilot or full-scale which should significantly improve the energy balance of a municipal wastewater treatment plant (WWTP), finally enabling the operation of energy-positive treatment schemes. In work package 5 of the project, these processes are assessed in their potential to improve the energy balance of WWTPs, but also in their overall environmental and economic impacts. The final goal is to compare conventional WWTP schemes and POWERSTEP concepts and show the benefits of the innovative processes against the current benchmark of best practice in wastewater treatment ("reference").

Developing scenarios for assessment

As a first step of the assessment, specific scenarios have been defined for different boundary conditions (Remy and Cazalet 2016) relating to

- the size of the WWTP
- the type of influent (quality of raw wastewater)
- the discharge standards that apply to the WWTP effluent.

In addition, suitable POWERSTEP schemes have been identified with an extensive screening of potential combinations of individual modules for primary and secondary treatment of municipal wastewater, using an energy benchmarking software (OCEAN tool of Veolia) to determine two schemes with a superior energy balance.

These schemes are now analysed more in detail in the present report and compared to the reference schemes with life-cycle based tools of Life Cycle Assessment or LCA (ISO 14040 2006, ISO 14044 2006) for environmental and Life Cycle Costing or LCC for economic impacts (Figure 1).

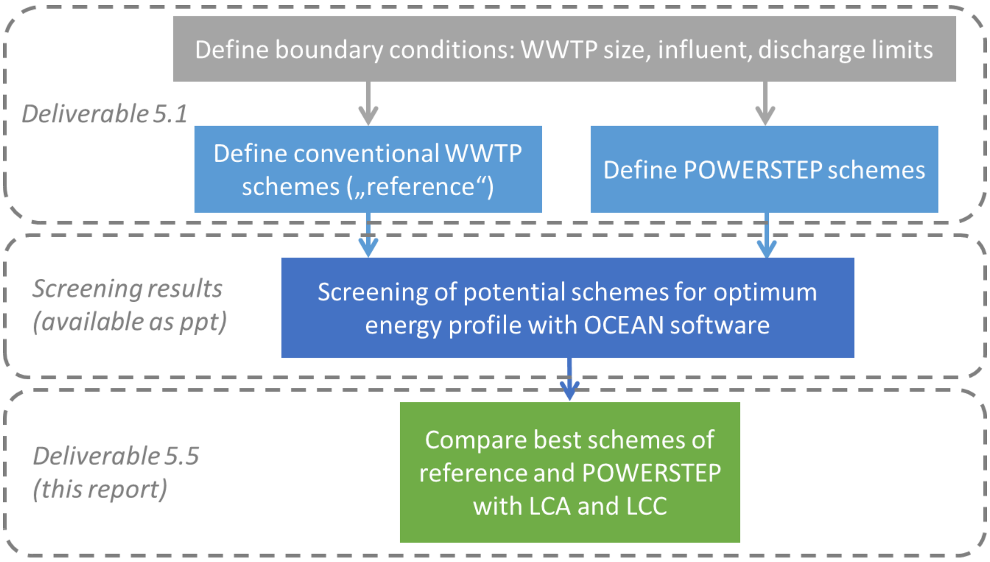

Figure 1: General approach for scenario development and economic and environmental assessment in POWERSTEP

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Using the life-cycle approach

These holistic LCA and LCC tools should enable a comprehensive analysis of relevant effects of the POWERSTEP schemes, including upstream and downstream impacts of the innovative approach on the life cycle of a WWTP. This perspective can help to identify benefits and drawbacks of POWERSTEP and reveal potential trade-offs in environmental or economic terms.

This report describes definitions and methods, input data, and results for environmental and economic impacts for reference and POWERSTEP schemes, building on the process data generated in the project. The goal of the study is to reveal potential environmental and economic benefits and drawbacks of POWERSTEP schemes compared to the state-of-the-art of WWTP technology today.

Limitations of this study

In general, the entire study is based on hypothetical scenarios and should be seen as a theoretical analysis of all WWTP schemes to compare them on a defined basis. Although the underlying process data is seen as representative for today´s WWTP infrastructure, a direct transfer of results of this study to real WWTPs is not possible. Implementing a POWERSTEP concept in an existing WWTP will be another story, as this study only analyses scenarios of newly constructed WWTPs ("greenfield scenario"). However, the results of the present study can still indicate and quantify effects and tendencies of environmental and economic impacts, which can be used as a first estimate for the potential of POWERSTEP schemes.

The report is structured as follows:

- Chapter 2 contains definitions of goal and scope for the LCA
- Chapter 3 describes input data for the LCA
- Chapter 4 shows the results of the LCA
- Chapter 5 gives an interpretation and conclusion of the LCA
- Chapter 6 includes the LCC study
- Chapter 7 summarizes final conclusions of the LCA and LCC assessment and gives general recommendations for developing eco-efficient WWTP schemes

2. LCA: Definition of goal and scope

This chapter presents the definition of goal and scope of the LCA. It contains information about the general goal and target group of the study, the function of the systems and related definitions of functional unit, influent wastewater quality, and effluent discharge limits, the system boundaries of the LCA, and a description of the scenarios which are analysed. Regarding the data collection and impact assessment, the chapter describes general sources and quality of the input data, the set of LCA indicators chosen for evaluation, and the approach for interpretation of the results.

2.1. Goal and target group

The goal of this LCA is to analyse the potential environmental impacts of different WWTP configurations and to compare conventional and innovative process schemes. The focus of the study is on energy-related environmental impacts and effluent quality, as innovative schemes target the reduction of energy demand from external supply (i.e. grid electricity) by exploiting the internal chemical energy potential of the incoming wastewater. Per definition, this should be reached without compromising effluent quality, reaching the same targets with conventional and innovative schemes.

The target group of this LCA study primarily includes professionals and decision makers in the water sector (WWTP operators, engineering companies, and regulators) who are related to planning, construction/upgrading, and operation of WWTPs. They should be informed about innovative WWTP schemes and their potential benefits in environmental terms compared to the conventional process. In addition, the study also targets researchers and scientists in the water sector as well as interested individuals who are working in the field of innovative technologies in WWTPs.

2.2. Function, functional unit, influent wastewater quality, and effluent targets

The primary function of the systems under study is "*the treatment of municipal raw wastewater of defined quality to comply with defined discharge limits*". This function includes the purification of wastewater, and also the disposal of sewage sludge.

Definitions of WWTP size, influent quality and discharge limits have been extensively discussed in Deliverable D5.1 (Remy and Cazalet 2016) and are listed in Table 1 and Table 2. For WWTP size, it was decided to define three size groups representing 5'000, 50'000 or 500'000 population equivalents (pe) for small, medium and large WWTP, respectively. The actual size is defined in relation to the influent load of chemical oxygen demand (COD), accounting for 120 g COD per pe and day (DWA 2016).

To reflect the variations in influent concentrations of WWTPs in Europe, it was decided to calculate two cases for each size group: case 1 for diluted influent (COD = 400-500 mg/L) and case 2 for concentrated influent (COD = 800-1000 mg/L). As medium or large WWTPs are more often connected to combined sewers, more dilution was assumed for these classes. The estimated ranges of COD concentration in the influent are confirmed by actual data e.g. of German WWTPs and corresponding influent qualities, which range from 410 to 1041 mg/L COD in the different federal states (DWA 2016).

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Respective volume and concentrations of total nitrogen (TN) and total phosphorus (TP) are then calculated with the mean daily loads per pe according to German standards (120 g COD, 11 g TN and 1.8 g TP per pe and day (DWA 2016)), while TS concentration was estimated. The ratio of particulate COD to total COD in raw wastewater depends on the residence time of the wastewater in the sewer system: whereas small plant usually have a short sewer system (65% particulate COD), medium and large WWTPs are connected to sewer systems with higher residence time, assuming higher hydrolysis or biological conversion of particles and thus lower fraction of particulate COD (60 or 55%).

Table 1: Definition of influent quality for different WWTP size groups

Parameter		Small WWTP	Medium WWTP	Large WWTP
Size	[pe]	5’000	50’000	500’000
Case 1 (“diluted influent”)				
Influent volume[1]	[m³/pe*a]	87.6	109.5	109.5
Influent TS	[mg/L]	290	214	214
Influent COD	[mg/L]	500	400	400
Influent TN[1]	[mg/L]	45.8	36.7	36.7
Influent TP[1]	[mg/L]	7.5	6	6
Case 2 (“concentrated influent”)				
Influent volume[1]	[m³/pe*a]	43.8	54.8	54.8
Influent TS	[mg/L]	580	429	429
Influent COD	[mg/L]	1000	800	800
Influent TN[1]	[mg/L]	91.7	73.3	73.3
Influent TP[1]	[mg/L]	15	12	12
Ratio of particulate COD (both cases)	[%]	65	60	55

[1] *calculated with 120 g COD/(pe*d), 11 g N/(pe*d) and 1.8 g P/(pe*d) (DWA 2016)*

For the discharge limits, it was decided to define basic standards based on the current German legislation for municipal WWTPs (AbwV 2013) and more advanced standards based on the experience of the project partners for locally stricter regulations. The standard for total nitrogen in WWTP effluent is particularly relevant when analysing the energy balance of WWTPs, as carbon extraction for energy recovery may be limited by the nitrogen removal target if N removal is based on a heterotrophic process (e.g. conventional denitrification). Hence, stricter targets for N removal will have a direct impact on the energy balance of the schemes, and also on possible combinations of process modules for the POWERSTEP schemes.

All schemes will be calculated to comply with the relevant discharge standards (standard or advanced) in Table 2. However, the process models in this study are based on a steady-state approach, which does not reflect dynamic conditions and actual sampling practices (e.g. grab sample, composite sample, monthly or annual mean) in the different EU countries. Thus, a certain "buffer" is applied in steady-state model, assuming that the discharge limits are kept if the annual mean value of effluent quality is < 85% of the discharge limit. As an example, a discharge limit of TN = 13 mg/L will be reflected by an annual mean effluent concentration of TN < 11 mg/L in the model.

Table 2: Definition of discharge limits for different WWTP size groups

Parameter		Small WWTP	Medium WWTP	Large WWTP
Size	[pe]	5'000	50'000	500'000
Case A ("normal standards[1]")				
Discharge limit for COD	[mg/L]	110	90	75
Discharge limit for TN[2] (> 12 °C)[3]	[mg/L]	-	18	13
Discharge limit for TP	[mg/L]	-	2	1
Case B ("advanced standards")				
Discharge limit for COD	[mg/L]	110	75	60
Discharge limit for TN[2] (> 12 °C)[3]	[mg/L]	18	13	10
Discharge limit for TP	[mg/L]	-	0.3	0.3

[1] *minimum discharge limits in Germany (AbwV 2013)*

[2] *Total inorganic nitrogen: sum of NO_3-N, NO_2-N and NH_4-N*

[3] *valid for influent temperature of >12 °C*

All scenarios in this LCA are related to a specific case (A1, A2, B1, B2) depending on the assumed influent quality (1 = diluted and 2 = concentrated) and discharge limits to comply with (A = normal standards and B = advanced standards). It is important in the comparative analysis that only scenarios for the same case can be directly compared in their environmental impacts.

The functional unit of the LCA is defined by delivering the service function "*per population equivalent and year*" or $(pe*a)^{-1}$. Hence, all environmental impacts are related to the annual efforts for treating municipal wastewater for one average person. All impacts and benefits of the system are allocated to this function.

2.3. System boundaries

The system boundaries of this LCA include all relevant processes within a WWTP to treat wastewater and sewage sludge (Figure 2):

- Mechanical treatment (rake, grit and grease removal)
- Primary treatment

- Secondary treatment (biological stage)
- Tertiary treatment (polishing stage, if required for discharge standards)
- Sludge thickening
- Sludge digestion (for small WWTPs: digestion at centralized WWTP)
- Sludge dewatering (including effects of return load to the mainline)
- Treatment of sludge liquor from dewatering (optional)
- Valorization of biogas in a combined heat and power (CHP) plant or by direct injection into the grid (biogas upgrading and Power-to-gas (P2G) unit)
- Sludge transport to disposal
- Mono-incineration of sludge

In addition to the core processes of the foreground system, relevant background processes for construction and operation of the system are included in the LCA:

- Production of electricity for operation
- Production of chemicals for operation (e.g. polymer, $FeCl_3$, NaOH, H_2SO_4, …)
- Materials for infrastructure (only simplified calculation for major contributors: concrete, reinforcing steel, and stainless steel)
- Disposal of ashes from incineration
- Credits for substituted products (= avoided production of electricity, heat, natural gas, and mineral N fertilizer)

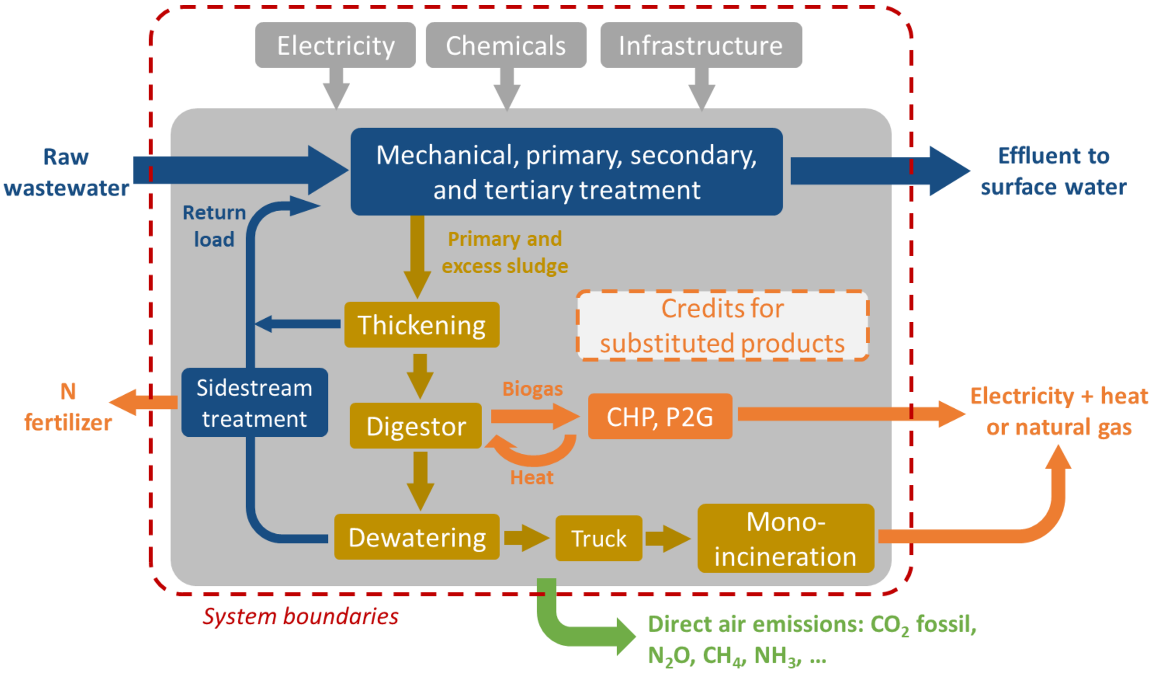

Figure 2: System boundaries of LCA

This LCA focuses on the construction and daily operation of the major process facilities required for water treatment and sludge disposal. It excludes efforts for maintenance and repair of equipment, construction and operation of buildings, and other processes at a WWTP not explicitly described in the inventory.

2.4. Scenarios

The scenarios of this LCA study have been defined in close collaboration with project partners. They are based on a screening process using the energy benchmarking software OCEAN for WWTP modelling, where many potential combinations of innovative processes have been analysed to identify the most promising schemes for the goal of the project (= design an energy positive WWTP scheme). The approach of the screening has been extensively discussed in deliverable D5.1 (Remy and Cazalet 2016). Results of the screening are available in a separate document (ppt slides), and choice of scenarios has been discussed and agreed within the project.

For each WWTP size class and condition (A1, A2, B1, B2), a reference WWTP scheme has been defined, representing the best practice of available conventional technology for this purpose. This reference WWTP serves as a "benchmark" for the comparison, and new innovative schemes with POWERSTEP technology ("POWERSTEP" scenarios) are compared in their environmental profile against this benchmark. The reference WWTP does not reflect the average situation of WWTPs in Europe today, but rather represents an "optimum" of energy efficiency using state-of-the-art aggregates and design.

All scenarios described here are hypothetical, i.e. not related to a specific existing WWTP. They represent theoretical cases in a model environment to compare different process schemes on a fair and equal basis.

2.4.1. Small WWTP (5,000 pe)

The reference WWTP for this size of WWTP is typically built as a sequencing batch reactor (SBR), which gives higher flexibility in operation (Table 3). Raw wastewater is treated in mechanical treatment (rake, grit and grease removal) before entering the SBR without primary treatment. Mixed sewage sludge contains both particulate matter and biological sludge, and is usually stabilised with extended aeration (high sludge age), so that no primary treatment is required. This WWTP size does not have an anaerobic digestor on-site due to prohibitive investment costs. Stabilised sludge is thickened on-site in a static thickener (storage tank) and transported by truck to a central larger WWTP with digestor and CHP, where it is digested and dewatered prior to sludge disposal in mono-incineration. The effort for return load treatment in the central plant is reflected with a simplified model for energy demand and direct N_2O emissions (0.6 % N_2O-N/N_{in}).

For the innovative POWERSTEP scenarios, two types of primary treatment have been added to the process: microscreen or chemical settling (Table 3). Data for the microscreen is adapted from full-scale plants and pilot trials in POWERSTEP, using drum- or disc filters with a 40-100 µm mesh and upstream coagulation/flocculation tanks (Olsson and Pellicer-Nacher 2018). For chemical settling, a multiflo configuration is envisaged with coagulation/flocculation tanks and a downstream lamellar settler.

Both technologies enable the enhanced extraction of COD and some nutrients via physico-chemical treatment into primary sludge, so that the subsequent biological stage has a lower COD load with less aeration demand, but also a lower COD/N ratio. As no TP removal is required for small WWTPs, both types of primary treatment are operated with upstream flocculation (addition of polymer) to enhance COD extraction, but without coagulation (no addition of $FeCl_3$).

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However, sufficient denitrification has to be guaranteed in case of existing discharge limits for TN (case B), which requires an optimised operation of the SBR system. It consists of an adapted feeding regime (only during denitrification phase) and an alternative strategy for aeration control (shifting from time-controlled aeration to oxygen depletion rate) as described in D2.1 (Schubert 2018).

Table 3: Scenarios for small WWTPs (5,000 pe)

	Reference scheme	POWERSTEP scheme 1	POWERSTEP scheme 2
Water line			
A1 (diluted WW, normal standards)	SBR	Microscreen + SBR	Chemical settling + SBR
A2 (concentrated WW, normal standards)	SBR	Microscreen + SBR	Chemical settling + SBR
B1 (diluted WW, advanced standards)	SBR	Microscreen + opt. SBR[2]	Chemical settling + opt. SBR[1]
B2 (concentrated WW, advanced standards)	SBR	Microscreen + opt. SBR[2]	Chemical settling + opt. SBR[1]
Sludge line			
All cases	Transport to centralized WWTP, mesophilic digestion, dewatering[2] and disposal in mono-incineration		

[1] *optimised SBR = advanced control for optimised use of carbon for denitrification (aeration and feeding regime), see D2.1 (Schubert 2018)*

[2] *effect of return load estimated with simplified WWTP model*

2.4.2. **Medium WWTP (50,000 pe)**

For medium-sized WWTPs, the reference scheme includes mechanical treatment (rake, grit and grease removal), primary treatment (settler), a biological stage using a conventional activated sludge (CAS) process, and a final clarifier (Table 4). The biological stage is designed with intermittent denitrification and dosing of $FeCl_3$ for TP removal. Sludge treatment consists of gravity thickening for primary sludge, belt thickener with polymer dosing for excess sludge, digestion of mixed sludge, final dewatering in a centrifuge, and transport by truck to mono-incineration. Return load from sludge thickening and dewatering is recycled upstream of the primary treatment. Biogas from digestion is valorised in a CHP plant, producing electricity and heat on-site. In case of advanced standards for TP (0.3 mg/L), a tertiary treatment is foreseen after final clarifier using a microscreen with upstream dosing of coagulant and polymer.

For the POWERSTEP schemes, primary treatment is changed from simple settling to either microscreen or chemical settling, both with dosing of coagulant and polymer upstream (Table 4), using comparable technology than described for small WWTPs (2.4.1). Thus, an enhanced extraction of COD and TP can be achieved in primary treatment, producing more primary sludge and reducing the load to the subsequent biological stage. However, the low COD/N ratio after enhanced primary treatment requires a modification in the entire treatment scheme in case of concentrated influent and/or advanced TN discharge limits (13 mg/L), because the remaining carbon is not sufficient to safely guarantee the required degree of denitrification.

For diluted influent and advanced standards (case B1), the implementation of a dedicated sidestream treatment (deammonification with partial nitritation and anammox) reduces the return load of TN significantly, thus still enabling the operation of a normal CAS system in these scenarios. However, a small fraction of the incoming wastewater has to bypass primary treatment to increase the COD/N ratio in the influent of the biological stage and guarantee the required degree of denitrification in the steady-state model. This assumption has to be validated in full-scale, and it is expected that bypassing primary treatment is only a backup strategy.

For scenarios with concentrated influent (cases A2 and B2), the required degree of denitrification is even higher (>80%) to reach the defined effluent standards, so that a conventional process of nitrification and denitrification is no longer feasible due to carbon limitation. Here, the implementation of a mainstream process for deammonification (= partial nitritation and anammox in 1-stage IFAS configuration using moving bed biofilm reactor (MBBR) technology) is required which can remove TN without the need of a carbon source. This innovative configuration of biological N removal has been intensively investigated in recent years and is still under development, even though stable operation and adequate elimination ratios have been shown in pilot trials using MBBR technology as described in D2.3 (Stefansdottir, Christensson et al. 2018).

However, the mainstream anammox process described here still has to be implemented at full-scale to prove its long-term stability and operational feasibility in a real WWTP, although current results are promising for a successful implementation in the future.

Table 4: Scenarios for medium WWTPs (50,000 pe)

	Reference scheme	POWERSTEP scheme 1	POWERSTEP scheme 2
Water line			
A1 (diluted WW, normal standards)	Settling + CAS	Microscreen + CAS	Chemical settling + CAS
A2 (concentrated WW, normal standards)	Settling + CAS	Microscreen + MOX	Chemical settling + MOX
B1 (diluted WW, advanced standards)	Settling + CAS + microscreen[1]	Microscreen + CAS[2] + microscreen[1] + mox	Chemical settling + CAS[2] + microscreen[1] + mox
B2 (concentrated WW, advanced standards)	Settling + CAS[2] + microscreen[1]	Microscreen + MOX + microscreen[1]	Chemical settling + MOX + microscreen[1]
Sludge line			
All cases	Gravity thickening of primary sludge, belt thickening of excess sludge, mesophilic digestion, dewatering and disposal in mono-incineration, valorisation of biogas in CHP		

CAS – conventional activated sludge, MOX – Anammox in mainstream with 1-stage IFAS configuration (Stefansdottir, Christensson et al. 2018), mox – Anammox in sidestream

[1] *microscreen as tertiary treatment for enhanced removal of TP*

[2] *partial bypass of primary treatment required to enable full denitrification*

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2.4.3. Large WWTP (500,000 pe)

For large WWTPs, the reference scheme consists of mechanical treatment, primary settling, a biological stage in a CAS process, and final clarifier (Table 5). The biological stage is operated with pre-denitrification and biological P elimination (anaerobic – anoxic – aerobic tanks), as this is a representative state-of-the-art process scheme for large WWTPs. Sludge treatment is fully comparable to medium-size WWTPs.

For the POWERSTEP schemes, primary treatment is again changed to microscreen or chemical settling, both with dosing of coagulant and polymer upstream (Table 5), using comparable technology than described for small WWTPs (2.4.1). For diluted wastewater (cases A1 and B1), a standard CAS process can be operated after enhanced carbon extraction. The better utilisation of carbon in the pre-denitrification design enables this operational mode for these conditions, compared to the less efficient intermittent denitrification for the medium-sized WWTPs.

Due to enhanced extraction of COD and lower COD/N ratio after primary treatment, the following treatment scheme has to be modified for a concentrated effluent (cases A2 and B2) to reach the required TN effluent limits. For both normal and advanced standards, the implementation of a mainstream anammox process is foreseen as biological stage in 1-stage IFAS configuration (Stefansdottir, Christensson et al. 2018). This scheme does not require carbon for N removal, but is still under development as discussed above (2.4.2).

For normal standards (case A2), another option is the use of a dedicated sidestream treatment to reduce the nitrogen return load to the mainline. This sidestream treatment can be either deammonification (partial nitritation and anammox in a 1-stage SBR system) or membrane stripping to recover nitrogen as a liquid fertilizer (Böhler, Hernandez et al. 2018). If sidestream treatment is applied, the mainline can still be operated with a CAS system without carbon limitation. However, a small bypass of primary treatment is foreseen to reach a suitable COD/N ratio in the steady-state model for the required degree of denitrification.

Two other options are also analysed as options for case A2 which are both part of the POWERSTEP project: one option relates to an alternative valorisation strategy for the biogas using a power-to-gas (P2G) approach, while the other is a specific case for Austria where a lot of two-stage CAS systems are in operation.

The P2G approach can be applied both for the reference scheme and also for a POWERSTEP scheme, from which one scheme is chosen here as example. This alternative valorisation strategy for the biogas is based on a biogas upgrading process which separates biomethane and CO_2. While biomethane can be directly injected into the public gas grid, the residual CO_2 can be used in a biological methanation process to be upgraded to biomethane (Lardon 2018). This P2G process uses grid electricity at low prices and low environmental footprint (e.g. wind power at night) to drive an electrolysis process, thus producing H_2, O_2, and heat on-site. While H_2 and CO_2 are further converted to biomethane in biological methanation, the by-products of pure oxygen, heat and metabolic by-water can be utilized directly on-site to supply pure oxygen to the biological treatment stage of the WWTP and heat or by-water to the digestor. Produced biomethane from P2G can again be injected into the public gas grid.

Two-stage plants represent a specific concept of CAS systems, applying a high-load first CAS stage and a low-load second CAS stage. With a dedicated clarifier after each stage, the system operates with two sludge types at different sludge ages (first stage < 5d, second stage > 20d). Thus, more incoming COD is separated into excess sludge in the first stage, while the second stage still guarantees full nitrification (Baumgartner and Valkova 2016). A modification of this scheme is the sidestream treatment of sludge dewatering liquor with nitritation, i.e. converting 50% of the NH_4 load to NO_2. The sidestream is then returned to the influent of the first CAS stage, providing chemically bound oxygen with the NO_2. Due to the higher aeration efficiency in the sidestream (a-factor = 0.8) compared to the high-loaded 1st stage (a-factor = 0.4), electricity for aeration can be saved in this mode. In addition, partially oxidised nitrite requires less COD for conversion into N_2 than nitrate, so that more COD is available for biogas generation. Overall, the modified two-stage process with sidestream nitritation will enable a better energy balance for the entire WWTP (Baumgartner and Valkova 2016).

Table 5: Scenarios for large WWTPs (500,000 pe)

	Reference scheme	POWERSTEP scheme 1	POWERSTEP scheme 2
Water line			
A1 (diluted WW, normal standards)	Settling + CAS	Microscreen + CAS	Chemical settling + CAS
A2 (concentrated WW, normal standards)	Settling + CAS	Microscreen + MOX	Chemical settling + MOX
Options for A2:		Microscreen + CAS[3] + mox	Microscreen + CAS[3] + mem
Options for A2:	Settling + CAS + P2G[2]	Microscreen + MOX + P2G[2]	
Options for A2:	Settling + two-stage CAS	Settling + two-stage CAS + nitrit	
B1 (diluted WW, advanced standards)	Settling + CAS + microscreen[1]	Microscreen + CAS + microscreen[1]	Chemical settling + CAS + microscreen[1]
B2 (concentrated WW, advanced standards)	Settling + CAS + microscreen[1]	Microscreen + MOX + microscreen[1]	Chemical settling + MOX + microscreen[1]
Sludge line			
All cases	Gravity thickening of primary sludge, belt thickening of excess sludge, mesophilic digestion, dewatering and disposal in mono-incineration, valorisation of biogas in CHP (not for P2G)		

CAS – conventional activated sludge, MOX – Anammox in mainstream with 1-stage IFAS configuration (Stefansdottir, Christensson et al. 2018), mox – Anammox in sidestream (1-stage SBR), mem – sidestream membrane stripping (Böhler, Hernandez et al. 2018) , nitrit – nitritation in sidestream, P2G – Power-to-gas

[1] microscreen as tertiary treatment for enhanced removal of TP

[2] biogas upgrading + biological methanation on residual CO2 with direct injection of biomethane into the public grid

[3] partial bypass of primary treatment required to enable full denitrification

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2.5. Accounting of products

Products of WWTP operation and sludge treatment are accounted by avoided production of the related production ("avoided burden approach"). Avoided primary products are listed in Table 6. Products are accounted equivalent to their exploitable content, i.e. energy content in kWh for electricity, heat, and biomethane, or N content for nitrogen fertilizer. Impacts of avoided production are credited as negative environmental impacts to the respective scenarios.

Table 6: Products of WWTP operation and sludge disposal, and related avoided primary products

Product	Avoided primary product	Remarks
Electricity	Grid electricity production	Same electricity mix than electricity demand
Heat	District heating	District heating based on natural gas
Biomethane	Natural gas	Including production and also burning of natural gas in a gas motor with associated emissions to account for avoided emissions of fossil CO2 from natural gas
Nitrogen fertilizer	Mineral N fertilizer	Diammonium sulfate solution

2.6. Data sources and quality

Input data for this LCA originates mainly from the energy benchmarking software OCEAN. Within this software, the entire process of the different WWTP schemes is modelled in steady state with full mass and energy balances and chemical demand. While the reference WWTP models are described based on previously available default data in OCEAN, the innovative POWERSTEP modules have been added to the software in the course of the project (e.g. microscreen, mainstream anammox, biogas upgrading, biological methanation). They reflect the latest knowledge of process performance and integrate collected experience during the project. For the two-stage WWTP, data of the decision support tool is used which was cross-checked with OCEAN before (.

Overall, the data quality of OCEAN is assessed to be high, bearing in mind that the analysis is made with hypothetical scenarios which do not reflect a specific WWTP and its boundary conditions. However, the software has proven to be suitable to accurately depict the real mass and energy balances of large-scale WWTPs in more than 50 energy audits that have been done with OCEAN.

The OCEAN data is amended with some LCA specific data to cover the impacts in the entire life cycle of the WWTP:

- **Direct emissions:** N_2O from biological nitrogen removal in mainstream is calculated via emission factors which are correlated to TN removal, while sidestream N_2O emissions are described with a constant emission factor from literature and pilot trials or full-scale measurements. For N_2O emissions of mainstream anammox, an estimate was taken. Influent NH_4 is partially stripped in the aeration tank as NH_3. Anaerobic sludge treatment results in CH_4 emissions in the centrifuge and some

CH_4 slip in the CHP. For other emissions of biogas burning in CHP, related emission factors are taken from literature.

Table 7: Data sources and quality of LCA

Data type	Data source	Data quality	Remarks
Data of reference WWTP models			
Mass balances of WWTP processes	OCEAN[1] software	High	Data is calculated based on OCEAN modules for treatment processes
Energy demand of WWTP processes	OCEAN[1] software	High	Data is calculated based on OCEAN modules for treatment processes (via efficiencies of aggregates)
Direct emissions at WWTP	Literature	Medium	NH3: constant emission factor, N_2O: emissions factor correlated to TN removal, CH4: estimate of losses in centrifuge and CHP plant
Material for Infrastructure	Estimate based on OCEAN[1] design	Medium	Estimates for concrete, reinforcing steel and stainless steel for tanks and digestor based on size (OCEAN design) and material factors
Emissions of CHP	Literature	Medium	Emission factors estimated from another LCA study
Mono-incineration	KWB model	Medium	Process model of mono-incineration with energy balance and emission profile, incl. auxiliaries demand
Data of POWERSTEP models			
Mass balances of WWTP processes	OCEAN[1] software	High	Data is calculated based on new OCEAN modules for processes
Energy demand of WWTP processes	OCEAN[1] software	High	Data is calculated based on new OCEAN modules for processes
Direct emissions of N_2O	POWERSTEP + Literature	Low-medium	Factors for sidestream from literature and POWERSTEP trials, factor for mainstream anammox is estimated
Biogas upgrading	Literature	High	Energy and mass balances
Biological methanation	POWERSTEP trials	High	Results of POWERSTEP trials
Two-stage plant	POWERSTEP trials	High	Data of decision support tool (D4.4)
Background processes			
All	Ecoinvent v3.3	Medium to high	Electricity, chemicals, mineral N fertilizer, auxiliaries, material for infrastructure, transport, ash disposal

[1] *OCEAN is an energy benchmarking software used for energy audits of WWTPs, using steady-state mass balances of unit processes to calculate energy and chemicals demand, effluent quality, and energy production from biogas valorisation.*

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- **Infrastructure:** the impact of materials for infrastructure is often negligible for the environmental impact of a WWTP due to the long lifetime of the structures (Corominas, Foley et al. 2013). However, this LCA includes infrastructure with a simplified estimate of the most important materials in plant construction (concrete, reinforcing steel, stainless steel) and efforts for excavation. Design data of OCEAN (e.g. tank volumes) is used together with material intensity factors to estimate material amounts for the most important parts of the plant.
- **Mono-incineration**: data for mono-incineration of dewatered sludge is taken from other studies of the authors and describe state-of-the-art mono-incineration. It takes into account auxiliary material for operation as well as process-related emissions (e.g. N_2O from fluidized bed incineration).

More information on individual data sources is also given in the Life Cycle Inventory (cf chapter 3).

For the background data, relevant datasets of ecoinvent v3.3 have been used (Wernet, Bauer et al. 2016). Data quality of these datasets can be described as medium to high, as some datasets may be somewhat outdated while others (e.g. energy mix) represent the latest available LCA data in that field.

Overall, data quality of the present LCA study is deemed sufficient for the goal of the study (hypothetical comparison of conventional and new WWTP schemes). However, specific data (e.g. N_2O emissions of mainstream anammox) have to be further validated to support the results of this study. This aspect is again mentioned in the discussion of the LCA results.

2.7. Indicators for impact assessment

This LCA study focuses on energy demand for WWTPs and related environmental impacts. In addition, high effluent quality of the WWTP is still the highest priority for the operator, so an assessment of effluent quality is mandatory while describing the environmental impacts of a WWTP.

Consequently, this LCA applies four dedicated indicators for impacts assessment: two for energy-related aspects, and two for effluent quality (Table 8):

- Cumulative energy demand (CED) of non-renewable energy sources: this indicator describes the demand of fossil and nuclear fuels associated with construction and operation of the WWTP. It is a good measure to show the overall primary energy demand of the system, considering all different forms of energy (electricity, heat, natural gas).
- Global warming potential (GWP): A prominent impact of energy generation from fossil sources is the emission of greenhouse gases (GHG) such as fossil CO_2. Other direct sources of GHG at a WWTP include biological nitrogen removal which is associated with direct emissions of N_2O, or CH4 which is emitted in anaerobic sludge handling. The time horizon for the GWP is 100a.
- Freshwater eutrophication potential (FEP): this indicator summarizes all emissions of phosphorus in surface and groundwater, thus being an indicator for WWTP effluent quality in terms of TP emission loads.

- Marine eutrophication potential (MEP): this indicator summarizes all emissions of nitrogen in surface waters and marine waters, thus being an indicator for WWTP effluent quality in terms of TN emission loads. It also accounts for gaseous nitrogen emissions via atmospheric deposition on fresh and marine waters.

Table 8: Indicators for impact assessment

Indicator	Abbr	Unit	Reference	Remarks
Cumulative energy demand (non-renewable)	CED	MJ	(VDI 2012)	Non-renewable = sum of fossil and nuclear CED
Global warming potential	GWP	kg CO_2-eq	(IPCC 2007)	GWP for 100a
Freshwater eutrophication potential	FEP	kg P-eq	(Goedkoop, Heijungs et al. 2009)	ReCiPe (H) w/o long-term emissions[1]
Marine eutrophication potential	MEP	kg N-eq	(Goedkoop, Heijungs et al. 2009)	ReCiPe (H) w/o long-term emissions

[1] *long-term emissions > 100a are not accounted in this indicator*

Besides these four indicators, this LCA does not report on results of other available Life Cycle Impact Assessment (LCIA) indicators or endpoint results. The chosen set of indicators represents the environmental impacts that are in the focus of this study, so that more indicators will only dilute the information collected.

2.8. Interpretation

LCA results of the impact assessment are interpreted in different ways:

- **Contribution analysis:** LCIA results are shown in a contribution analysis to identify major drivers for the impact category and the effect of changing from reference to POWERSTEP schemes. Thus, key parameters can be identified which a) are responsible for the difference between conventional and new schemes and b) should be targeted for future optimisation of WWTP process to minimize their environmental impact.
- **Absolute comparison of reference and POWERSTEP scenarios:** for each case (A1, A2, B1, B2), absolute results of both conventional and innovative scenarios can be directly compared to each other, as they serve exactly the same function. Hence, benefits and potential drawbacks of POWERSTEP schemes are immediately visible and can be quantified in an absolute scale.
- **Relative comparison of different cases for reference and POWERSTEP schemes:** setting the individual score of the reference WWTP for each case to 100%, the different cases can be compared on an equal basis in relative terms. With this perspective, it can be concluded for which boundary conditions POWERSTEP yields the highest relative improvements in environmental impact. This will be relevant for the final discussion and help to identify favourable conditions for the innovative concepts.

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The stability of the results towards a change in study definition is tested with a sensitivity analysis. As electricity balance is a major focus of this study, different electricity mixes will be used to show the effect of applying the POWERSTEP concept in countries with higher or lower environmental footprint for grid electricity production compared to the EU average. In particular, the results for CED and GWP will be affected by this

Normalisation is not provided in the present LCA. Previous LCA studies have shown that energy-related impacts of WWTP operation are actually small when normalized to the total energy-related impacts of society (e.g. (Remy 2010, Remy, Miehe et al. 2014). In contrast, effluent-related impacts on water quality are higher, as WWTPs constitute a major point source for water emissions in our society. However, as the present study focuses on energy-related aspects while keeping current effluent quality (per definition), normalisation will not provide any additional insights.

3. LCA: input data for Life Cycle Inventory

Data of Life Cycle Inventory (LCI) is reported in this chapter. Due to the very large number of parameters for each unit process module in the WWTP process model (>100), inventory data is only reported in aggregated form in this study. Actual parameters of unit process models are precisely defined in the OCEAN software, which is the basis for this LCA.

LCI data that is graphically reported here includes:

- Electricity demand and production at the WWTP
- Chemical demand
- Electrical self-sufficiency of the WWTP
- Efficiency of primary treatment in COD removal
- Effluent quality for TN and TP

More detailed LCI data can be found in the annex of this report for small (see 9.1), medium (see 9.2), and large WWTPs (see 9.3).

Substance flow models are built within the LCA software UMBERTO® LCA+ (IFU 2017), using steady-state mass balance models for unit processes and background datasets of ecoinvent v3.3 (Wernet, Bauer et al. 2016).

3.1. Input data for small WWTPs (5,000 pe)

Electricity demand for small WWTP operation ranges between 24.7 and 27.5 kWh/(pe*a) for the reference scenarios and 18.2 and 24.5 kWh/(pe*a) for the POWERSTEP scenarios (Figure 3). The major driver for the electricity demand is SBR operation (aeration, pumping, mixing), while mechanical/primary treatment and sludge handling in centralized WWTP account for 10-21% and 15-26%, respectively. Introducing a primary treatment step in POWERSTEP adds around 0.5-1.5 kWh/(pe*a) in electricity demand.

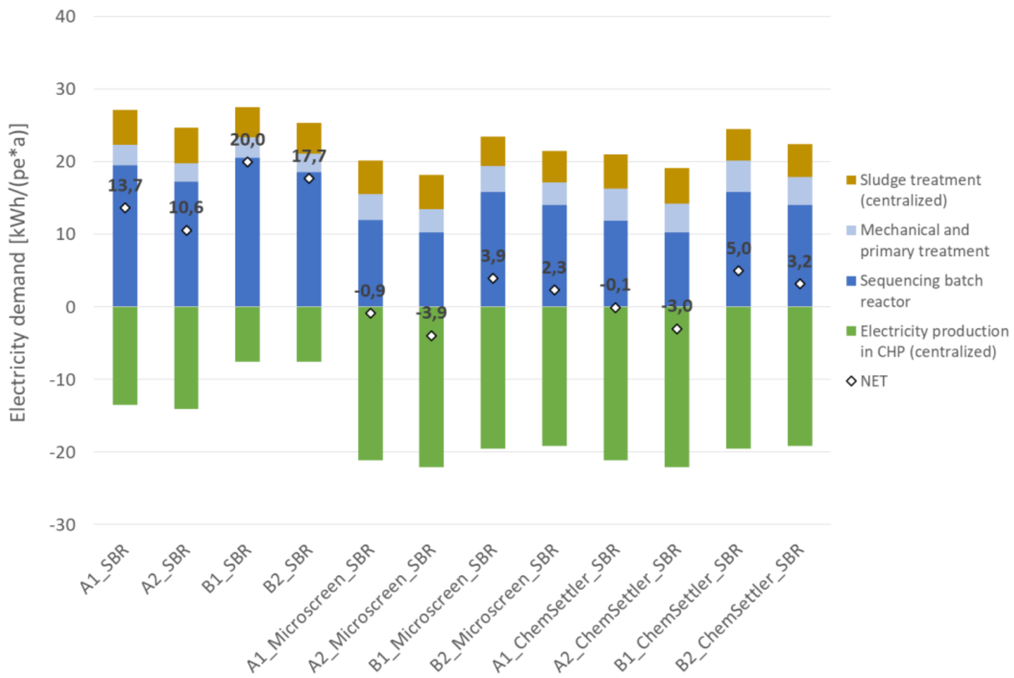

Figure 3: Electricity profile of reference and POWERSTEP scenarios for small WWTP (5,000 pe)

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Looking at the different cases, more concentrated influent decreases electricity demand for all scenarios, while more advanced standards (i.e. dedicated TN removal) increase electricity demand especially for POWERSTEP schemes.

Electricity production ranges between 7.5 and 14.1 kWh/(pe*a) for the reference scenarios and is significantly increased for POWERSTEP to 19.2-22.1 kWh/(pe*a) (Figure 3). Consequently, net electricity demand decreases from 10.6-20 kWh/(pe*a) for the reference schemes to energy-neutral or even energy-positive operation in case of normal standards (case A) and low residual electricity demand for plants with TN removal (case B: 2.3-5.0 kWh/(pe*a)). It has to be kept in mind here that small WWTPs usually do not have an anaerobic digestor on-site, so that the energy-neutral or even energy-positive operation described here is reached in an overall energy balance, accounting for the energy generated during sludge treatment in a larger centralized WWTP.

Introducing a primary treatment step for enhanced carbon extraction increases the amount of polymer by more than 100% for microscreen technology and 30-67% for chemical settling (Figure 4). While the microscreen is operated with a constant polymer dose related to TS load, chemical settling is assumed here with a fixed concentration of polymer dosing, so that more concentrated effluent (case 2) reduces additional polymer demand by 50%. More primary sludge TS also results in a slightly higher polymer demand for sludge thickening and dewatering in the POWERSTEP schemes.

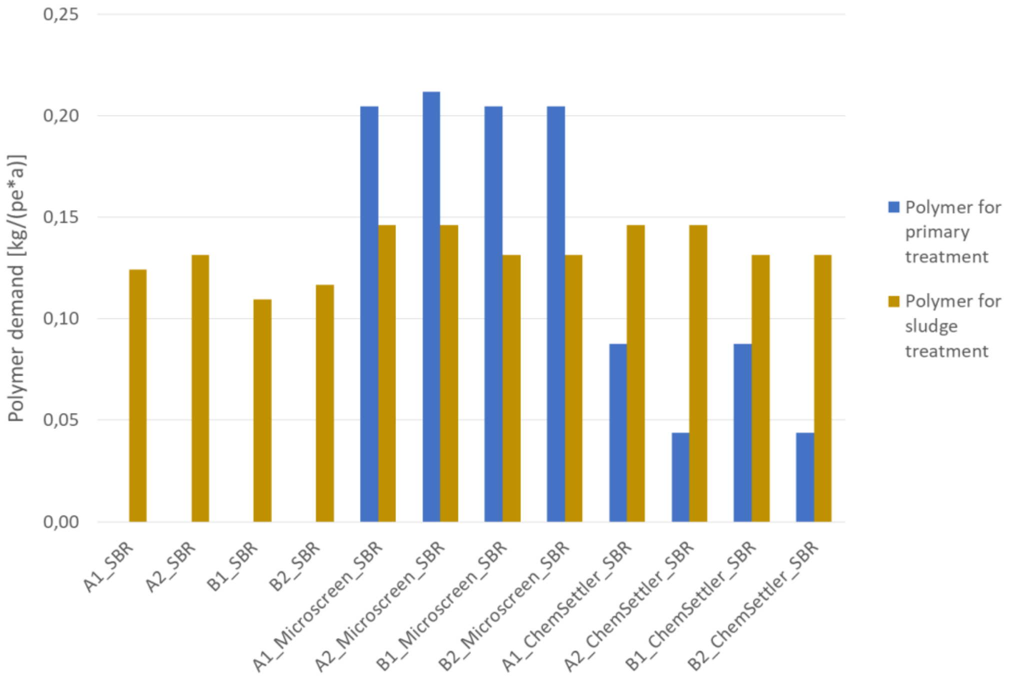

Figure 4: Chemical demand of reference and POWERSTEP scenarios for small WWTP (5,000 pe)

With respective chemical dosing and dedicated primary treatment, COD extraction in the first stage is around 50% for all POWERSTEP scenarios (Figure 5). Consequently, more primary sludge is generated, which results in higher electricity production and increases electrical self-sufficiency of small WWTPs from 27-57% for reference schemes to 80-122% for POWERSTEP schemes. Again, dedicated TN removal (case B) operates with higher sludge age and yields a lower self-sufficiency (80-89%) for small WWTPs than without targeted denitrification (100-122%).

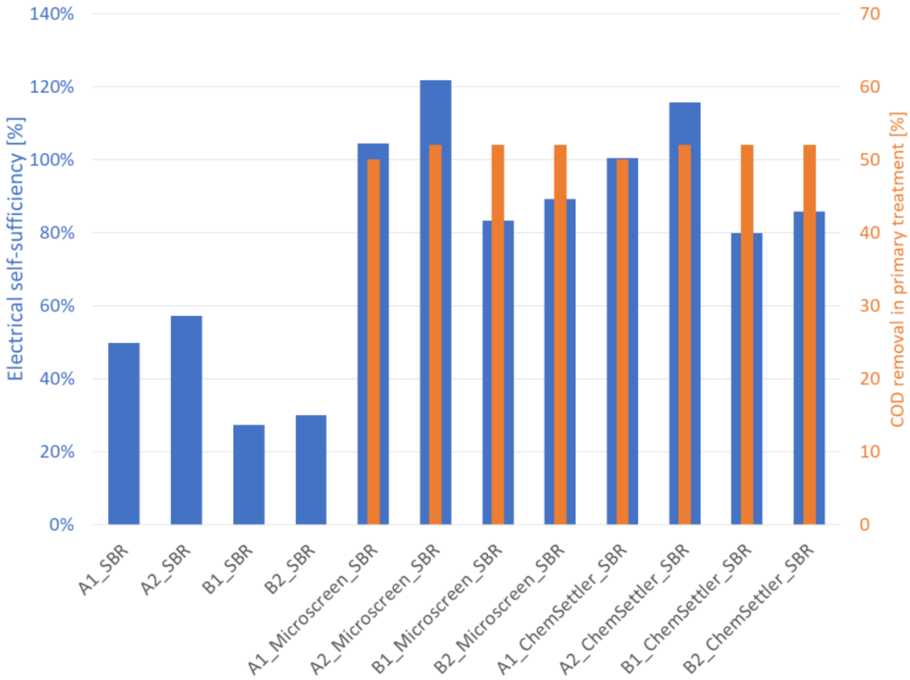

Figure 5: COD removal efficiency in primary treatment and electrical self-sufficiency of reference and POWERSTEP scenarios for small WWTP (5,000 pe)

Effluent quality of small WWTPs is comparable between reference and POWERSTEP scenarios and depends primarily on the respective case (Figure 6). Without nutrient removal targets (case A), TN and TP effluent concentration is rather high, whereas advanced standards and dedicated TN removal decreases nitrogen concentrations in the effluent to 13-14 mg/L TN.

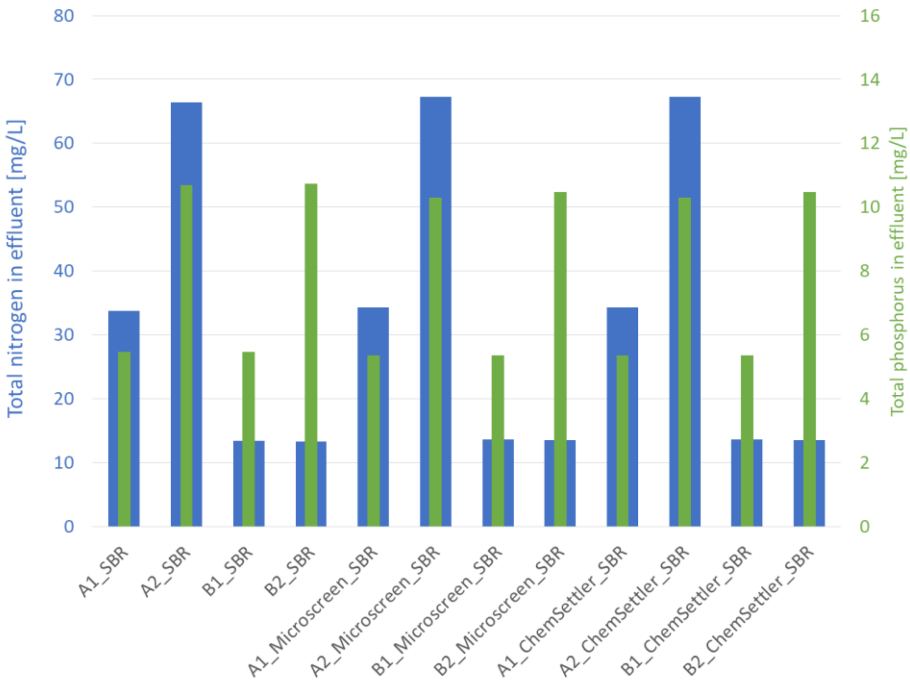

Figure 6: Effluent quality for TN and TP of reference and POWERSTEP scenarios for small WWTP (5,000 pe)

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3.2. Input data for medium WWTPs (50,000 pe)

Electricity demand for medium WWTP operation ranges between 20.9 and 24.7 kWh/(pe*a) for the reference scenarios and 16.5-23.4 kWh/(pe*a) for the POWERSTEP scenarios (Figure 7). The major driver for the electricity demand is the biological treatment stage (51-68% of total, mainly for aeration, pumping, and mixing), while mechanical/primary treatment and sludge handling account for 4-13% and 18-26%, respectively. Introducing a primary treatment step in POWERSTEP adds around 0.3-1.8 kWh/(pe*a) in electricity demand for microscreen or chemical settling. Tertiary treatment in case of advanced standards (case B) adds another 1-2 kWh/(pe*a).

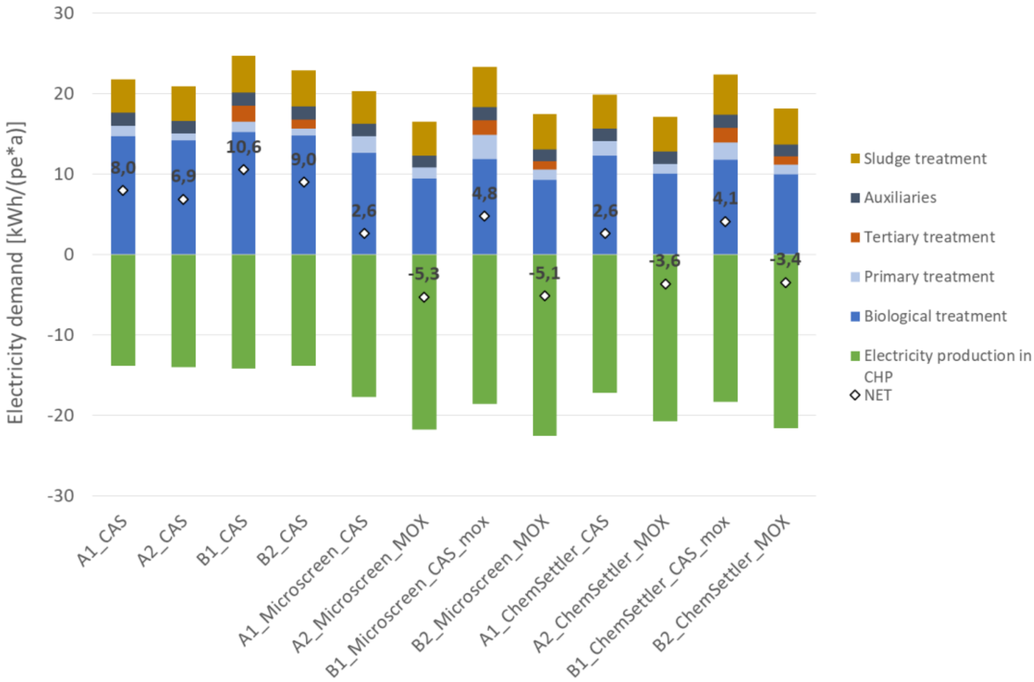

Figure 7: Electricity profile of reference and POWERSTEP scenarios for medium WWTP (50,000 pe)

Again, more concentrated influent (case 2) decreases electricity demand for all scenarios, although the effect is relatively small for reference schemes. For POWERSTEP, concentrated influent represents a major benefit for the energy balance, but this is mainly due to switching from CAS systems to mainstream anammox in this case. More advanced standards (i.e. higher TN and TP removal) increase electricity demand for all schemes due to tertiary treatment (microscreen for TP removal) and higher energy demand for biological stage (e.g. mixing, recirculation).

Electricity production ranges between 13.8 and 14.2 kWh/(pe*a) for the reference scenarios and is significantly increased for POWERSTEP to 17.2-22.6 kWh/(pe*a) (Figure 7). Consequently, net electricity demand decreases from 6.9-10.6 kWh/(pe*a) for the reference schemes to 2.6-4.8 kWh/(pe*a) for POWERSTEP with diluted influent (case 1), still enabling the use of conventional CAS systems combined with advanced primary treatment. For concentrated influent (case 2), mainstream operation has to be switched to anammox systems which render a fully energy-positive operation with an energy surplus of 3.4-5.3 kWh/(pe*a), but are still affected by operational challenges as discussed above.

Heat balance for medium WWTPs is not shown here (detailed data in annex), but the heat self-sufficiency is increased from 177-187% in reference to 204-229% in POWERSTEP schemes due to higher biogas production. This surplus heat of 14.5-26.5 kWh/(pe*a) is not accounted in this LCA, but could be utilized for other purposes or sold to external customers if possible.

Advanced primary treatment requires more polymer for WWTP operation, increasing total polymer use for water and sludge line by 88-115% for microscreen and 29-65% for chemical settling (Figure 8). Dosing of coagulant stays more or less constant at 2.3-3.7 kg $FeCl_3$/(pe*a), as the point of dosing is only shifted from the biological stage (reference) to the primary stage (POWERSTEP). Tertiary treatment also requires some chemicals, adding another 3-11% of polymer demand.

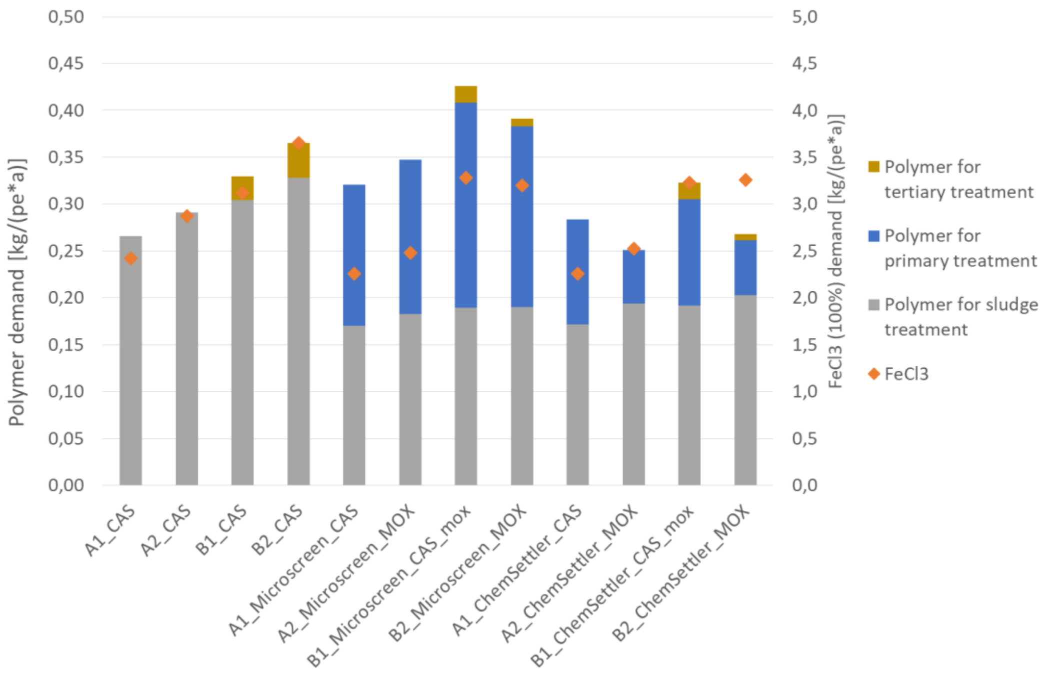

Figure 8: Chemical demand of reference and POWERSTEP scenarios for medium WWTP (50,000 pe)

COD extraction in primary stage is increased from around 30% in the reference schemes (pure sedimentation) to 47-57% with microscreen or chemical settling in the POWERSTEP schemes (Figure 9). With diluted influent (case 1) and CAS systems downstream, COD extraction is limited to 47-53% in POWERSTEP scenarios to enable sufficient denitrification, while 49-57% COD extraction can be reached with downstream anammox. However, advanced standards (case B) will require the operation of a sidestream N removal or limit COD extraction in primary treatment to safely reach low TN effluent limits (TN = 13 mg/L) in POWERSTEP operation.

With enhanced COD extraction, POWERSTEP schemes are significantly raising electricity self-sufficiency of reference schemes (57-67%) to reach levels of 80-87% for diluted influent (case 1) with downstream CAS and 119-132% for concentrated influent (case 2) with mainstream anammox (Figure 9). Again, higher TN standards have a slightly negative effect on the overall electricity balance, lowering self-sufficiency by 2-7%. Overall, POWERSTEP schemes are clearly improving the electricity balance for operation of medium WWTP for all conditions compared to the baseline.

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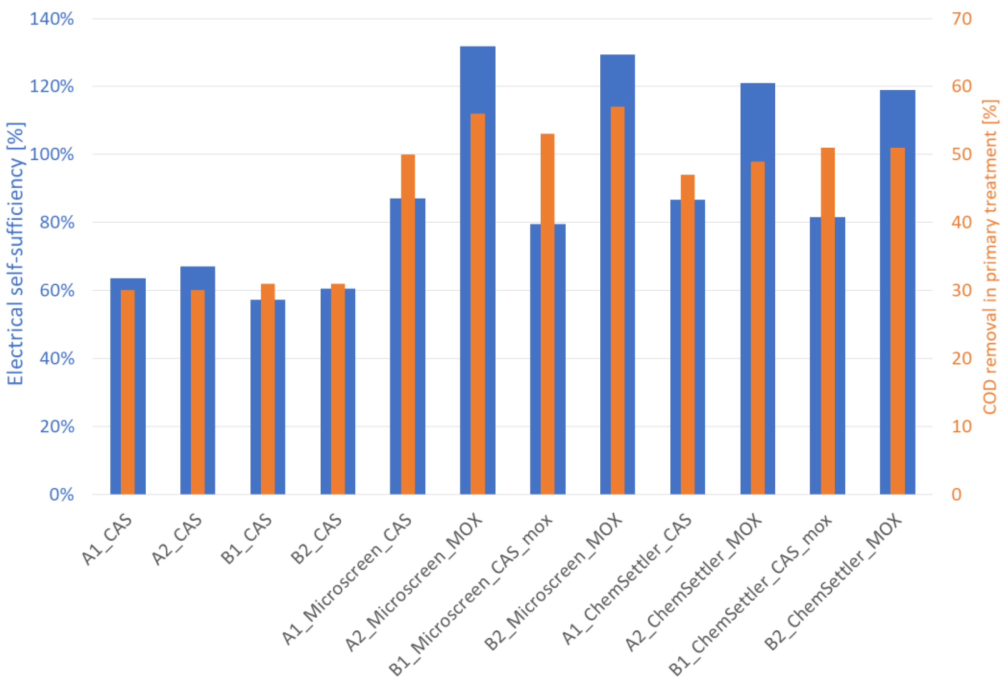

Figure 9: COD removal efficiency in primary treatment and electrical self-sufficiency of reference and POWERSTEP scenarios for medium WWTP (50,000 pe)

Effluent quality is again comparable between reference and POWERSTEP schemes and depends only on the respective effluent targets (Figure 10). Targeting normal standards, effluent concentrations of TN and TP are at 13-14 and 1.4 mg/L, respectively. Advanced standards decrease them to 10-11 mg/L TN and around 0.2 mg/L TP.

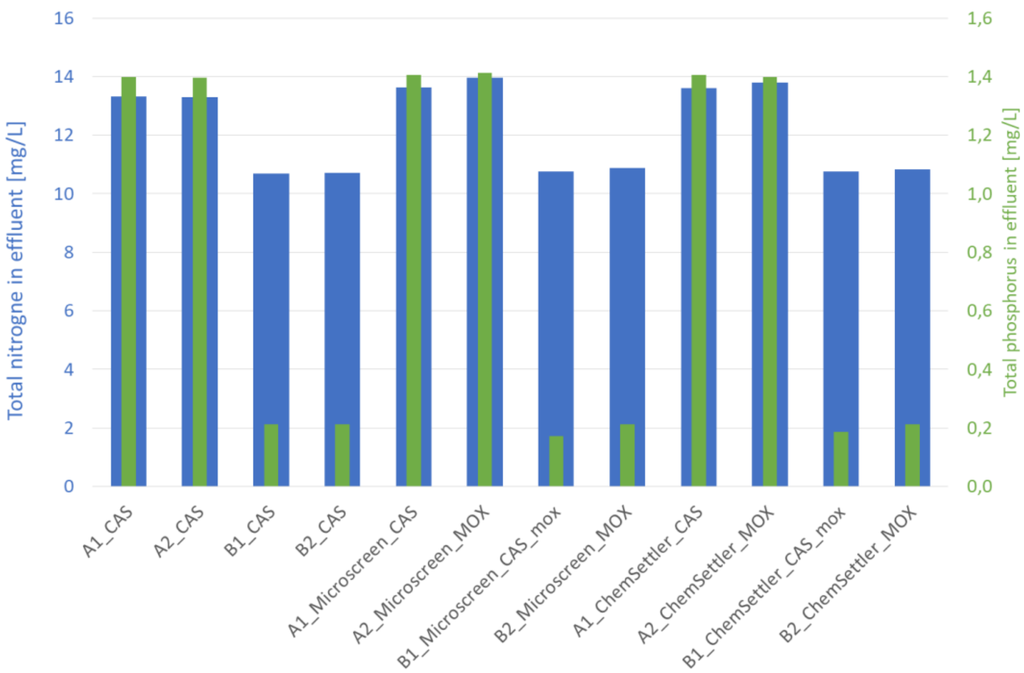

Figure 10: Effluent quality for TN and TP of reference and POWERSTEP scenarios for medium WWTP (50,000 pe)

3.3. Input data for large WWTPs (500,000 pe)

Electricity demand for large WWTP operation ranges between 21.5 and 25.6 kWh/(pe*a) for the reference scenarios and 15.6-24.3 kWh/(pe*a) for the POWERSTEP scenarios (Figure 11). Again, the major driver for the electricity demand is the biological treatment stage (54-71% of total, mainly for aeration, pumping, and mixing), while mechanical/primary treatment and sludge handling account for 2-8% and 16-26%, respectively. Introducing a primary treatment step in POWERSTEP adds around 0.2-0.8 kWh/(pe*a) in electricity demand for microscreen or chemical settling. Tertiary treatment in case of advanced standards (case B) adds another 0.8-1.7 kWh/(pe*a).

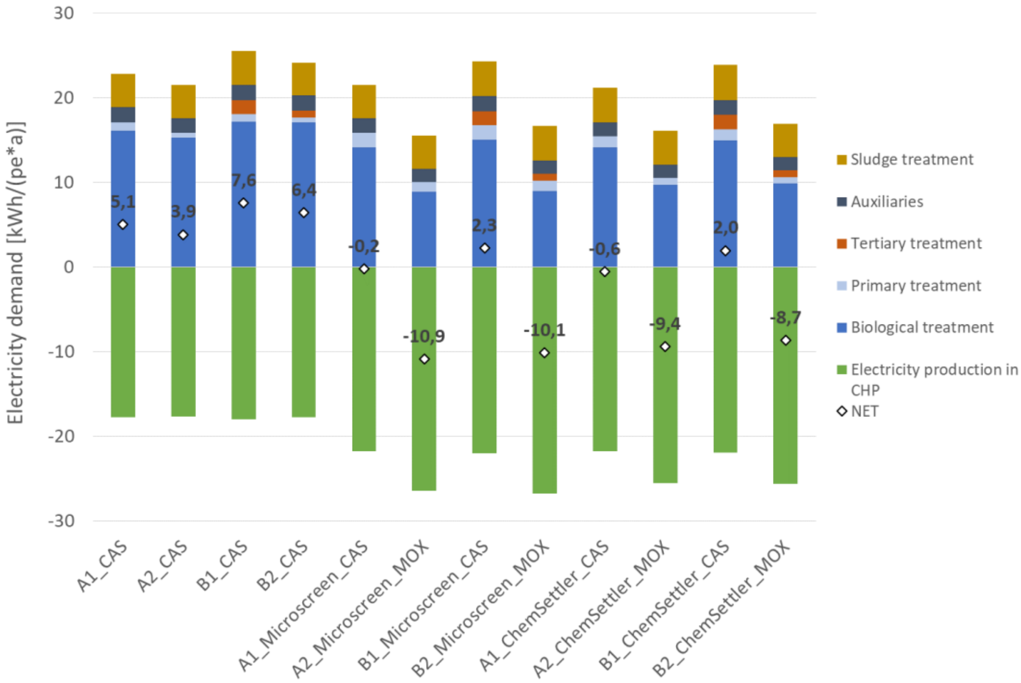

Figure 11: Electricity profile of reference and POWERSTEP scenarios for large WWTP (500,000 pe)

As for small and medium WWTPs, more concentrated influent (case 2) decreases electricity demand for all scenarios, although the effect is relatively small for reference schemes. For POWERSTEP, concentrated influent represents a major benefit for the energy balance, which is mainly due to switching from CAS systems to mainstream anammox for the biological stage. More advanced standards (case B with higher TN and TP removal) increase electricity demand for all schemes due to tertiary treatment (microscreen for TP removal) and higher energy demand for biological stage (e.g. mixing, recirculation).

Electricity production in large WWTPs ranges between 17.6 and 18 kWh/(pe*a) for the reference scenarios and is significantly increased for POWERSTEP to 21.7-26.8 kWh/(pe*a) (Figure 11). Consequently, net electricity demand decreases from 3.9-7.6 kWh/(pe*a) for the reference schemes to -0.6 to 2.3 kWh/(pe*a) for POWERSTEP with diluted influent (case 1), enabling energy-neutral operation with conventional CAS systems combined with advanced primary treatment for normal standards. For concentrated influent (case 2), biological stage has to be switched to anammox systems which render a fully energy-positive operation with high energy surplus of 8.7-10.9 kWh/(pe*a), but these systems are still affected by operational challenges as discussed above.

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Heat balance for large WWTPs is not shown here (detailed data in annex), but the heat self-sufficiency is increased from around 180% in reference to 192-236% in POWERSTEP schemes due to higher biogas production. This surplus heat of 13.4-26.3 kWh/(pe*a) is not accounted in this LCA, but could be utilized for other purposes or sold to external customers if possible.

Alternative schemes

Other options for concentrated influent and normal standards include POWERSTEP scenarios combining enhanced COD extraction with normal CAS systems and sidestream N removal: their operation is also energy-positive with surplus of 2.1-2.6 kWh/(pe*a), providing an alternative to mainstream anammox for these cases (Figure 12). Sidestream systems for N removal are well established technologies with multiple references, while N removal with membrane stripping is still an emerging technology but enables the recovery of a valuable liquid fertilizer.

Another alternative for low-energy WWTP operation are two-stage plants, which can also increase electricity production by extracting more COD into the sludge. These schemes can improve net electricity balance of the reference from 5.1 to 2.6 kWh/(pe*a) with normal operation or even to 1.0 kWh/(pe*a) combined with sidestream nitritation (Figure 12). These options underline that there are several potential ways to achieve energy-neutral operation of WWTPs by combining available and innovative systems in an efficient way.

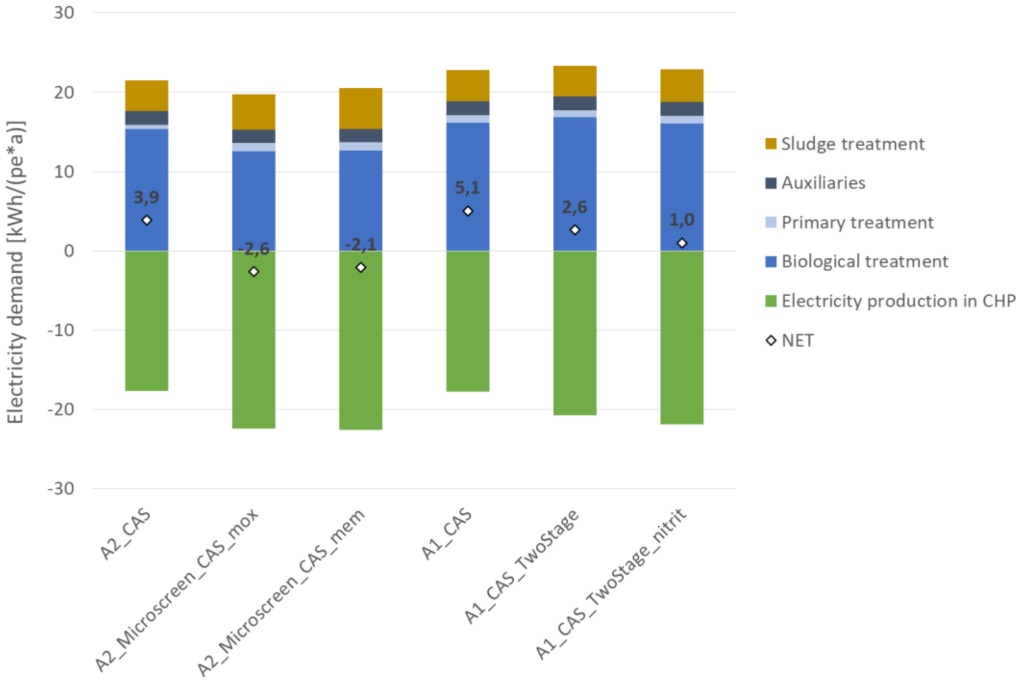

Figure 12: Electricity profile of reference and POWERSTEP scenarios for sidestream treatment (case A2) or two-stage configuration (case A1) for large WWTP (500,000 pe)

Biogas upgrading and P2G

Direct injection of produced biomethane into the grid is another option for valorising energy produced at a WWTP. Operating a biogas upgrading and P2G unit at the WWTP, more than 70 kWh/(pe*a) of biomethane can be produced in the reference scheme for concentrated influent and normal standards (Figure 13). However, electricity demand of WWTP operation (19.7 kWh/(pe*a)) has to be covered from other sources (i.e. grid electricity) in this case, while the P2G unit requires another 55.1 kWh/(pe*a) for operating the electrolyser. These numbers already include the utilisation of pure oxygen as a by-product of electrolysis in supplying oxygen to the biological stage of the WWTP. The effect of P2G technology is even more pronounced in a POWERSTEP scheme, which can produce up to 104.9 kWh/(pe*a) of biomethane while requiring 15.2 kWh/(pe*a) of electricity for WWTP operation and 81.7 kWh/(pe*a) for P2G electrolysis (Figure 13). With these numbers, it is evident that P2G operation exceeds the electricity demand for WWTP operation by a factor of 3-5, adding a large consumer to the overall system. Hence, this approach will most probably be viable in economic and environmental terms only if the additional power required comes from renewable sources and at a relatively low cost.

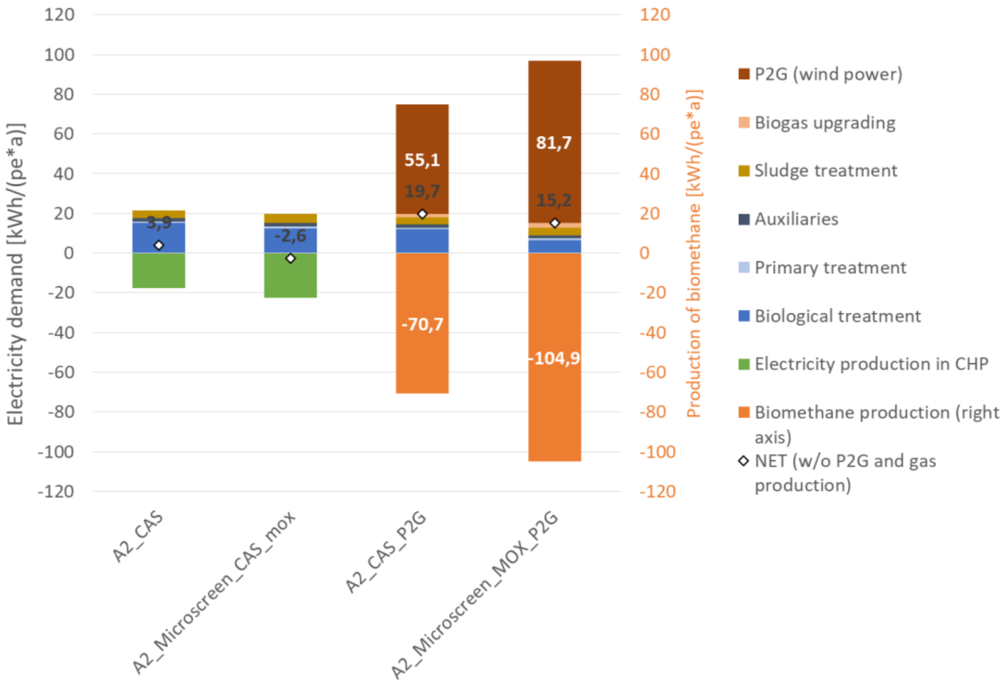

Figure 13: Electricity demand and production and biomethane production of reference and POWERSTEP scenarios for P2G schemes of large WWTP (500,000 pe)

Advanced primary treatment with microscreen or chemical settling requires more polymer for WWTP operation, increasing total polymer use for water and sludge line by 69-103% for microscreen and 29-60% for chemical settling (Figure 14). Tertiary treatment also requires some chemicals, adding another 10-29% of polymer demand.

Dosing of coagulant also increases with the POWERSTEP schemes, mainly because the reference scheme operates with biological P removal for large WWTPs. Consequently, $FeCl_3$ dosing increases by 32-76% with POWERSTEP as P elimination is shifted to chemical precipitation to save on COD which would also be required in biological P removal processes and can now fully be used for denitrification. For mainstream anammox systems, implementation of biological P removal is still under development, so a higher $FeCl_3$ dosing is estimated for these scenarios as conservative estimate.

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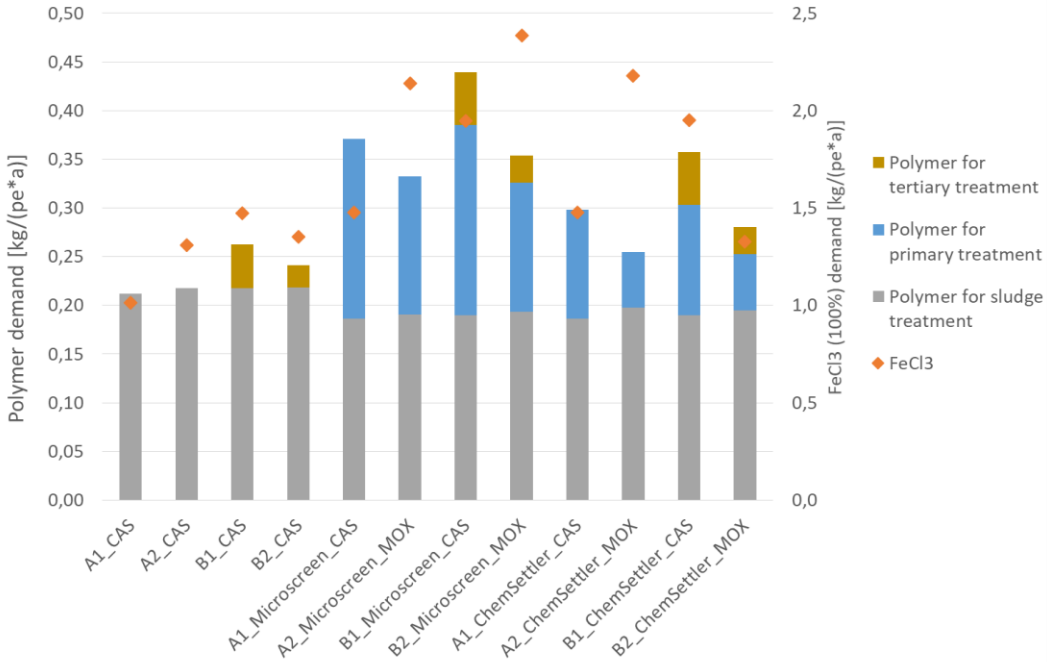

Figure 14: Chemical demand of reference and POWERSTEP scenarios for large WWTP (500,000 pe)

As for medium WWTPs, the introduction of POWERSTEP significantly enhances COD extraction in primary treatment, which is increased from 28% in reference schemes to 44-50% with microscreen or chemical settling (Figure 15). In parallel, electrical self-sufficiency is improved from 70-82% for reference schemes to 91-103% in case of diluted influent (case 1) with conventional CAS systems and to 151-170% for concentrated influent (case 2) and mainstream anammox.

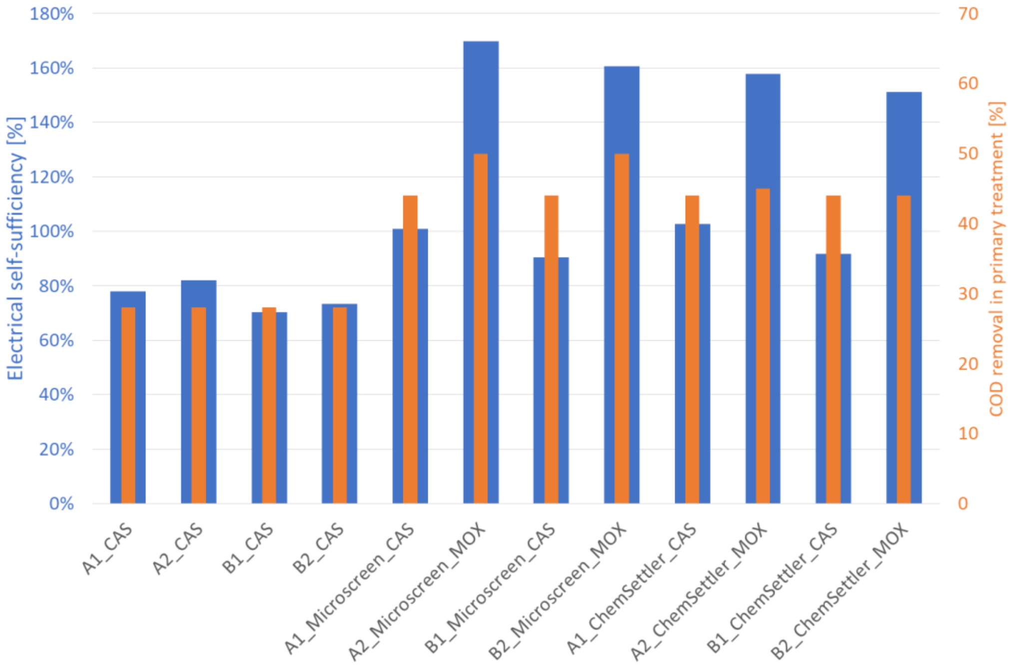

Figure 15: COD removal efficiency in primary treatment and electrical self-sufficiency of reference and POWERSTEP scenarios for large WWTP (500,000 pe)

Again, it has to be stated that mainstream anammox is still under validation at full-scale, but its huge potential for improving the electrical profile of WWTPs and enabling real energy-positive operation is once again visible in this assessment. However, some scenarios also allow energy-neutral operation of large WWTPs with conventional CAS systems, which can form the first step towards an energy-efficient WWTP of the future.

For effluent quality, reference and POWERSTEP schemes are fully comparable by definition (Figure 16). While normal standards yield TN and TP effluent concentrations of 9-10 and 0.7 mg/L, advanced standards result in mean effluent of 7 mg/L TN and 0.2 mg/L TP, representing a high performance of the assessed WWTP configurations in terms of WWTP treatment.

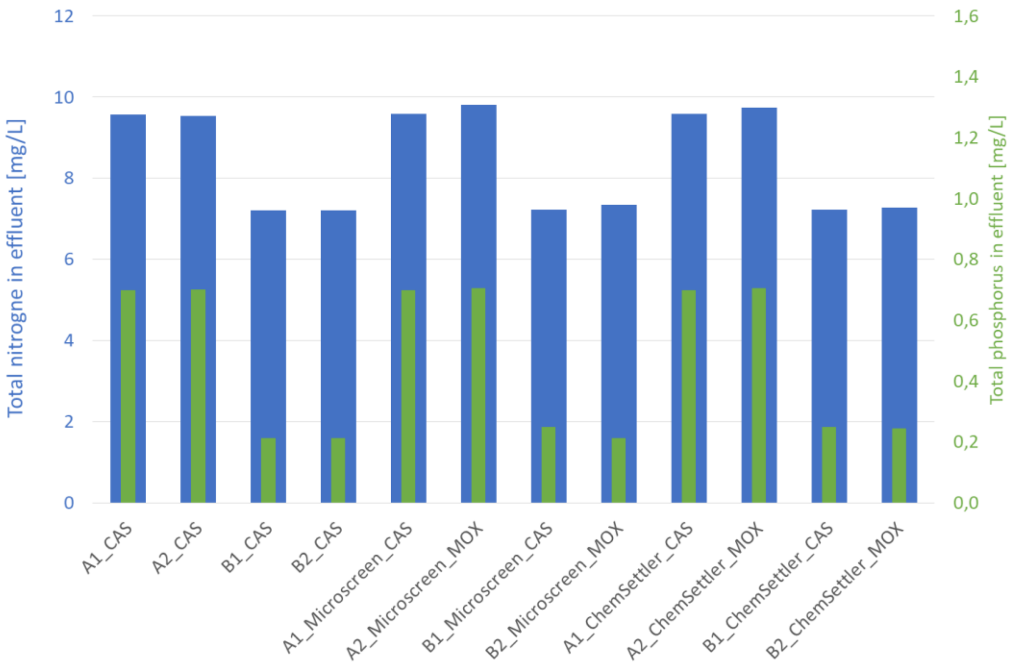

Figure 16: Effluent quality for TN and TP of reference and POWERSTEP scenarios for large WWTP (500,000 pe)

Overall, the collected inventory data based on OCEAN calculations show that POWERSTEP scenarios can significantly improve the energy balance of all sizes of WWTPs while still keeping comparable effluent quality targets as in reference schemes. However, chemical demand will increase with POWERSTEP due to polymer use in advanced primary treatment, and suitable combinations of technologies are required to enable sufficient removal of nitrogen depending on influent conditions and effluent targets. While some configurations shown can be operated today, scenarios based on mainstream anammox are still based on pilot-scale trials and lack full-scale references at this stage. However, results of POWERSTEP trials are encouraging that stable operation of this innovative technology will be available in the near future, preferably starting with favourable conditions for this biological process (i.e. avoiding very low wastewater temperatures and influent concentrations to maintain biological activity and suppress unwanted competing bacteria).

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3.4. Direct emissions at the WWTP: N_2O, NH_3, CH_4, and CHP exhaust gas

Direct emissions at the WWTP are not modelled within the OCEAN software. Instead, emissions are calculated based on emission factors or best estimates in the LCA model, taking mass balance data for the correlation.

Nitrous oxide (N_2O)

A major source of the powerful GHG N_2O at a WWTP is the biological stage, where N_2O can be emitted in significant amounts during the process of biological nitrogen conversion. The precise quantification of N_2O emissions is a difficult task, as it is dependent on various process variables and site-specific conditions such as DO level, influent load dynamics, COD/N ratio, and water temperature (Bellandi, Porro et al. 2018). Many studies have measured N_2O at pilot and full-scale plants (Kampschreur, Poldermans et al. 2009, Ahn, Kim et al. 2010, Foley, de Haas et al. 2010, Aboobakar, Cartmell et al. 2013, Daelman, Van Voorthuizen et al. 2013, Yoshida, Mønster et al. 2014, Daelman, van Voorthuizen et al. 2015, Böhler, Fleiner et al. 2016, Parravicini, Svardal et al. 2016), but a general correlation with process parameters is difficult to find.

As a best estimate for N_2O emissions of CAS systems in this LCA study, a linear correlation is used between the degree of TN removal (%) in the WWTP and the N_2O emission factor (% of influent N emitted as N_2O-N) that was deducted from a series of measurements at full-scale WWTPs (Parravicini, Svardal et al. 2016). Here, a higher TN removal lowers N_2O emissions significantly, based on the assumption that denitrification acts as a sink for dissolved N_2O which is formed as side product during nitrification.

For the present study, the previously reported correlation (Parravicini, Svardal et al. 2016) is updated to account for the TN removal only in the biological stage and not over the entire WWTP including primary treatment (Parravicini et al 2018). The resulting correlation accounts for 1% N_2O-N/N_{in} for TN removal < 65%, a linear decrease from 1.0 to 0.1% N_2O-N/N_{in} for TN removal between 65-90%, and 0.1% N_2O-N/N_{in} for TN removal >90% (Figure 17). Upper and lower limits of N_2O emission factors are artificially set for the linear correlation to account for low data availability of these ranges.

For most scenarios in this LCA, TN removal in the biological stage is between 61 and 90%, except for small WWTP without TN effluent targets (case A) which have a TN removal rate of 14-32% in the SBR. Hence, the full range of the correlation is relevant in this study, with effective N_2O emission factors of 0.1-1% N_2O-N/N_{in}.

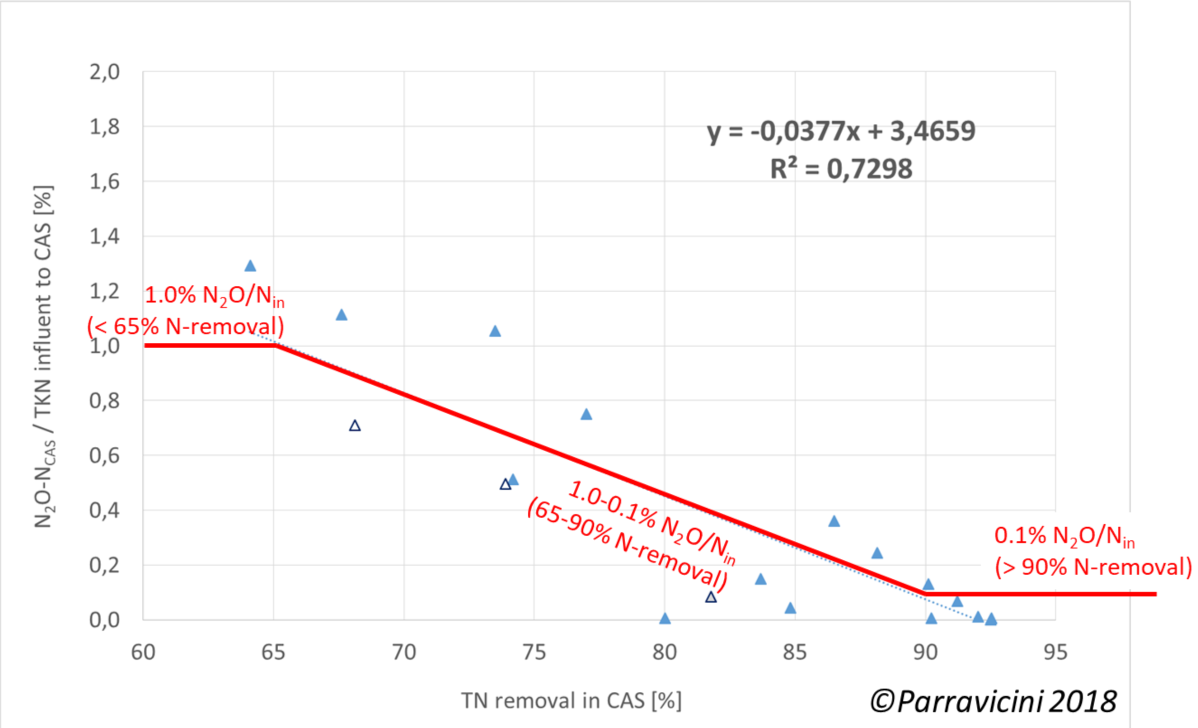

Figure 17: Direct emissions of N_2O from biological stage of conventional WWTPs: correlation between TN removal in biological stage (CAS) and N_2O emission factor (Parravicini 2018) and resulting correlation used in this LCA study (in red)

For the mainstream anammox process, representative data for N_2O emissions at relevant operational conditions could not be collected during the POWERSTEP project. In addition, the literature only reports on N_2O emissions from sidestream anammox processes (e.g. (Kampschreur, Poldermans et al. 2009) which are operated under very different conditions than the mainstream process. However, the process conditions of partial nitritation and anammox in the mainstream suggest that these N_2O emissions may be somewhat higher than in normal CAS systems, because conditions for microbial conversions (e.g. nitritation with limited DO or high NO_2 concentration) are sub-optimal and may trigger higher N_2O emissions. As a conservative estimate, it is assumed that <u>N_2O emission factors for mainstream anammox are 50% higher than those of CAS systems</u>, using the same correlation as presented above (Figure 17). Hence, scenarios with mainstream anammox with a TN removal of 80-90% in the biological process have a corresponding N_2O emission factor of 0.2-0.67% N_2O-N/N_{in}. This assumption should be validated with measurements from pilot and full-scale systems, and may be further supported with latest results of the son-site monitoring of N_2O at the pilot trials in WWTP Sjölunda (Stefansdottir, Christensson et al. 2018).

For sidestream processes of anammox and nitritation, constant N_2O emission factors are assumed based on monitoring results of the project (nitritation) or literature (anammox). For nitritation, monitoring of a full-scale sidestream treatment resulted in a relatively high emission factor of 3.6% N_2O-N/$N_{oxidized}$, probably due to limited DO conditions during nitritation and the higher NH_4 and NO_2 concentrations (Baumgartner and Parravicini 2018). Accounting for partial oxidiation in nitritation (55% of influent NH_4-N is oxidized to NO_2), the N_2O emission factor related to TN influent in the sidestream is 2% N_2O-N/N_{in}. For

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the sidestream anammox in 1-stage SBR configuration, an average emission factor of 2% N_2O-N/$N_{oxidizied}$ is accounted according to literature data (Joss, Salzgeber et al. 2009, Kampschreur, Poldermans et al. 2009). Assuming a partial oxidation of 45% of influent TN in nitritation, the N_2O emission factor for sidestream anammox related to TN influent in the sidestream is 0.9% N_2O-N/N_{in}.

Ammonia (NH_3)

Part of the influent NH_4-N to the biological stage is stripped during aeration. In this study, an emission factor of 0.6% NH_3/TN influent is accounted for all scenarios (CAS and anammox) according to literature (Bardtke, Müller et al. 1994).

Methane (CH_4)

Methane emissions may occur in mechanical or primary treatment if raw wastewater is pumped in anaerobic conditions in the sewer (Guisasola, de Haas et al. 2008). However, this study focuses on the analysis of conventional and innovative processes within the WWTP (neglecting the impact of the sewer system), so this source of methane is not included here.

Anaerobic treatment of sewage sludge in digestion results in a digested sludge which still contains dissolved methane. This methane will most certainly be released to the atmosphere during dewatering in a centrifuge or downstream of the dewatering. However, no emission factors are available to estimate this fraction of CH_4 losses in sludge handling. As a conservative assumption, the maximum solubility of CH_4 at a sludge temperature of 30°C (20 g/m³ sludge) is estimated to be lost to the atmosphere.

CHP exhaust gas

During biogas production, storage and valorisation in CHP, a certain fraction of biogas is assumed to be lost to the atmosphere in gas storage and handling (0.5 Vol-%). In addition, CHP exhaust gas contains a fraction of CH_4 ("methane slip") and other emissions (CO, NMVOC, Dust, NOx, N_2O, SO_2) which are estimated with emission factors from another LCA study (Ronchetti, Bienz et al. 2002). For GHGs, emission factors are 1.6 mg N_2O/MJ and 2.5 mg CH_4/MJ in the CHP exhaust gas.

Finally, a fraction of the produced biogas is usually flared during downtime or maintenance of CHP units. This flared fraction is estimated to 4.5 Vol-% of the total biogas, which does not account for energy production, but is associated with the same exhaust gas factors as discussed above.

CO_2 from biogas combustion is not accounted in global warming potential in this LCA due to its biogenic origin ("regenerative CO_2").

3.5. Sludge transport and mono-incineration

The total amount of dewatered sludge to be disposed is not significantly different between reference and POWERSTEP schemes (not shown, data in annex). Hence, impact of sludge transport and disposal is comparable between reference and POWERSTEP schemes.

Transport of dewatered sludge to mono-incineration is modelled with as truck transport, assuming a distance of 100km to the mono-incinerator. The mono-incineration is modelled as a fluidized bed incinerator with internal pre-drying, building on energy and emission data of a mono-incineration plant in Zurich (Remy and Jossa 2015).

Based on the lower heating value (LHV) of the input sludge, efficiency of the steam turbine is estimated with 14% of LHV as generated electricity, while 73% of LHV are supplied in form of district heating to the nearby heating grid. Electricity demand of the incinerator is estimated with 0.23 kWh/kg TS, while fuel demand is restricted to natural gas for start-up (0.05 MJ/kg TS), assuming auto-thermal incineration of sludge with internal pre-drying. Fluidized bed is realized by sand addition (0.7 g/kg TS).

Off-gas cleaning of mono-incineration requires additives (0.3 g coke, 5 g lime, 16.5 g NaOH (30%), and 12.1 g NH_3 (25%) per kg input TS), and relevant off-gas emissions are estimated with emission factors (61 mg SO_2, 243 mg NO_x, 15 mg NH_3, 61 mg CO, 12 mg dust, 25 mg HCl per kg input TS). N_2O emissions from fluidized bed incinerators are known to be substantially high (Sänger, Werther et al. 2001, Svoboda, Baxter et al. 2006) due to incineration freeboard temperatures of 900°C, so that a high emission factor of 990 mg N_2O/kg TS is assumed for mono-incineration (IPCC 2006).

Ash from mono-incineration is transported by truck (100 km) to final disposal in an underground deposit.

3.6. Infrastructure

Material demand for infrastructure is estimated for all scenarios based on simple linear correlations for the major aggregates of the system: primary tank, biological tank, clarifier, thickener, and digestor. For those system parts, amount of concrete and reinforcing steel and necessary excavation is calculated based on OCEAN design data and linear material intensity factors. In addition, material demand for microscreen is estimated from supplier information for stainless steel. Lifetime of infrastructure is estimated with 50a for tanks and digestor and 12a for microscreen. Details of calculations and infrastructure data of all scenarios can be found in chapter 9.4.

Resulting tank volumes for all scenarios calculated with OCEAN are exemplary shown below for small WWTP (Figure 18), medium WWTP (Figure 19), and large WWTP (Figure 20). As expected, defined reference conditions have a large impact on the size of the WWTP, as influent concentration (diluted or concentrated wastewater) and required effluent targets (especially TN limits) determine the size of the biological tank. Higher influent concentration and lower effluent standards lead to a larger required volume of the biological tank for denitrification, as relative TN removal increases with these parameters. In contrast, more concentrated wastewater reduces total flow and thus the size of the clarifier for medium and large WWTPs.

For the POWERSTEP schemes, enhanced primary treatment reduces the required tank volume considerably, especially in combination with mainstream anammox. Comparing reference and POWERSTEP schemes for concentrated influent in medium or large WWTPs, total tank volume is reduced by 35-50% mainly due to a lower required volume for biological tank and clarifier (mainstream anammox in IFAS configuration with MBBR).

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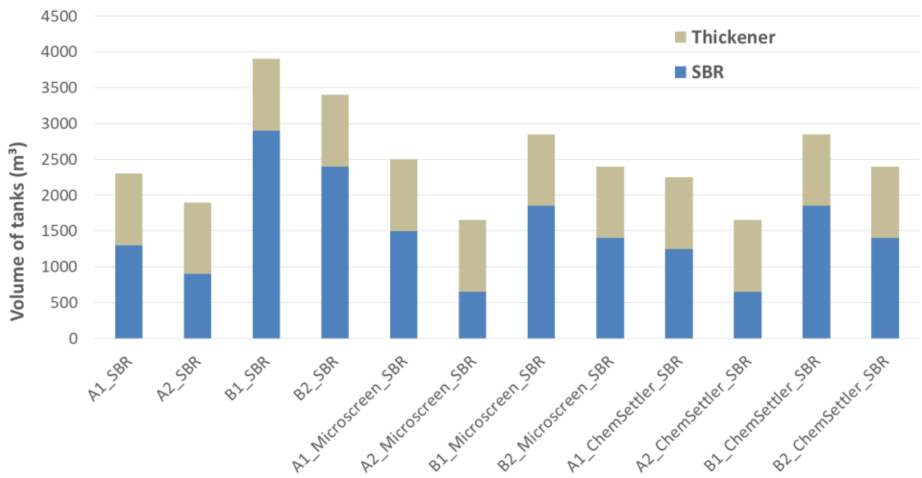

Figure 18: Tank volumes for small WWTP (5,000 pe) for reference and POWERSTEP schemes

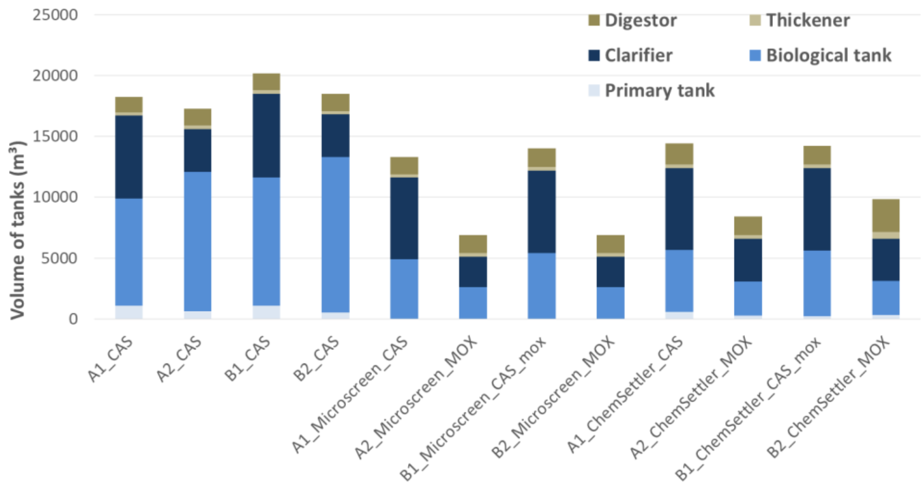

Figure 19: Tank volumes for medium WWTP (50,000 pe) for reference and POWERSTEP schemes

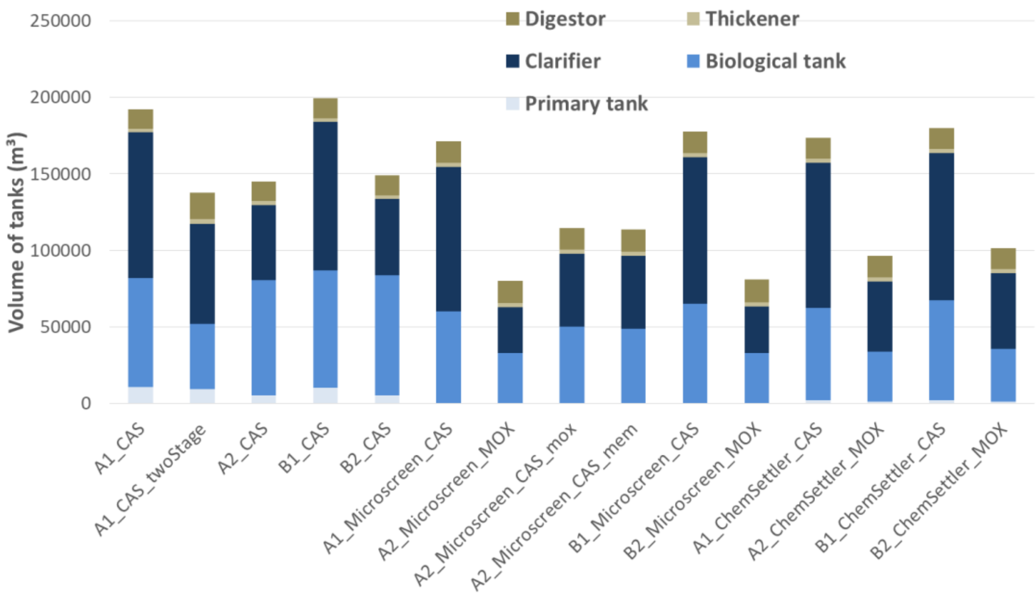

Figure 20: Tank volumes for large WWTP (500,000 pe) for reference and POWERSTEP schemes

3.7. Background processes

For background processes, datasets of the LCA database ecoinvent v3.3 have been used (Wernet, Bauer et al. 2016). Detailed names of all datasets are listed in Table 47 in the annex.

For electricity demand of WWTPs and electricity credits, the average EU mix for 2017 is assumed (dataset "market group for electricity, medium voltage [RER]"). This type of electricity has a GWP of 0.486 kg CO_2-eq/kWh. For electricity demand of P2G options, a dataset for wind power has been applied ("Electricity production, wind, >3MW turbine, onshore [DE]") which has a GWP of 0.029 kg CO_2-eq/kWh.

Heat credits of mono-incineration are accounted with a dataset for district heating based on natural gas consumption. For produced biomethane in P2G schemes, a dataset for natural gas production and burning in a gas motor is applied to account also for the benefits of green biomethane and avoided emissions of fossil CO_2 when substituting natural gas.

Chemicals are modelled with respective datasets including a transport of 300 km by truck. Materials for infrastructure include transport of concrete (50 km by truck) and other materials (200 km by truck).

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4. LCA: results of impact assessment

This chapter presents the results of LCA impact assessment based on the four indicators chosen for this study. It compares the impacts of reference and POWERSTEP schemes by detailed contribution analysis for selected scenarios and summarizes other results in relative comparison. Results are organized per WWTP size, starting with small WWTPs, then medium WWTPs, and finally large WWTPs together with related options defined in chapter 2.4.3.

4.1. Small WWTP (5,000 pe)

Results for reference schemes are discussed in detail first, and then compared to impacts of POWERSTEP scenarios to detect potential benefits and drawbacks of new schemes in their environmental impact.

Reference schemes

CED and GWP of reference schemes shows that both influent quality and effluent targets have a distinct impact on these indicators for small WWTPs (Figure 21). Total CED is between 330 and 373 MJ/(pe*a), and electricity demand for wastewater treatment contributes around 60% to total CED. Sludge transport and treatment at the centralized WWTP accounts for 33-38% including disposal in mono-incineration, while infrastructure of the plant plays only a minor role for CED (4-6%). Electricity production accounts for 90-168 MJ/(pe*a), and effluent standards have a large impact on this parameter: high sludge age required for nitrification leads to a significantly lower biogas potential of the mixed sludge, so that scenarios with advanced standards have a higher net CED (246-267 MJ/(pe*a)) compared to scenarios with normal standards (140-182 MJ/(pe*a)). Comparing scenarios for diluted and concentrated influent, more concentrated influent leads to a better energy balance due to lower electricity needs for pumping (less volume). Overall, electricity plays a major role in this impact category, which yields a high potential for improvement for the POWERSTEP schemes.

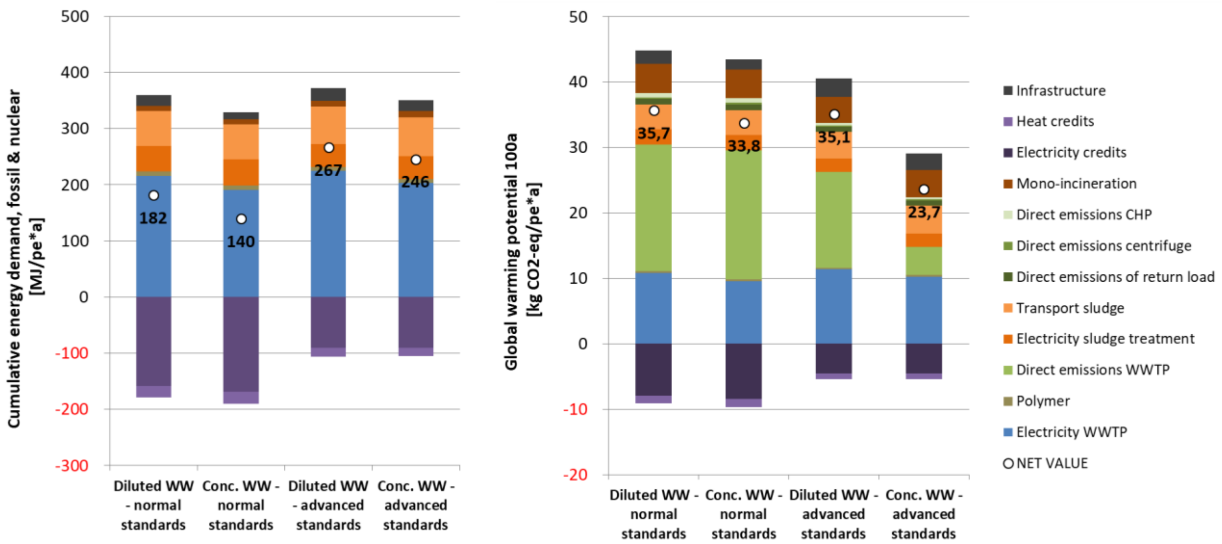

Figure 21: Cumulative energy demand (left) and global warming potential (right) of reference schemes for small WWTP (5,000 pe) for all conditions

For GWP, contribution of direct emissions of processes leads to a change in contribution ranking: N_2O originating from biological nitrogen conversion is responsible for 15-45% of total GWP for small WWTPs, with an exceptional high share in case of normal effluent standards (Figure 21). This is due to the high emission factor that is assumed for these scenarios: 1% of influent TN is converted to N_2O, as no or limited denitrification does not "consume" produced N_2O in nitrification. Another contributor for GWP is mono-incineration of sludge, which is also affected by direct N_2O emissions and thus contributes 10-14% to total GWP. As a consequence of high share of direct emissions, electricity demand and production has a lower impact on net GWP, with electricity demand contributing 28-42% of total GWP and electricity production off-setting 11-18% of total GWP. Finally, net GWP is between 24 and 36 kg CO_2-eq/(pe*a) for reference schemes of small WWTPs, and direct emissions play a significant role for this impact category. Hence, POWERSTEP schemes with better energy balance will potentially have less potential for improving the net GWP due to a lower share of electricity to this impact category.

In terms of effluent quality, only small differences are calculated for P emissions from small WWTPs (Figure 22), as all scenarios do not have to remove TP and thus have comparable effluent TP loads of 468-483 g P-eq/(pe*a). Indirect contributions to this impact category are negligible (< 0.3%). For nitrogen loads, scenarios with TN limits obviously have a lower impact than scenarios without TN limits (Figure 22). TN emissions of around 3000 g N-eq/(pe*a) in scenarios without dedicated TN removal are reduced by 60% for diluted influent and 80% for concentrated effluent: comparable TN effluent limits lead to higher relative TN removal in case of more concentrated influent. Effluent loads of return load treatment at the centralized WWTP are accounted within this category. Indirect emissions are again negligible for this impact category (< 0.8%).

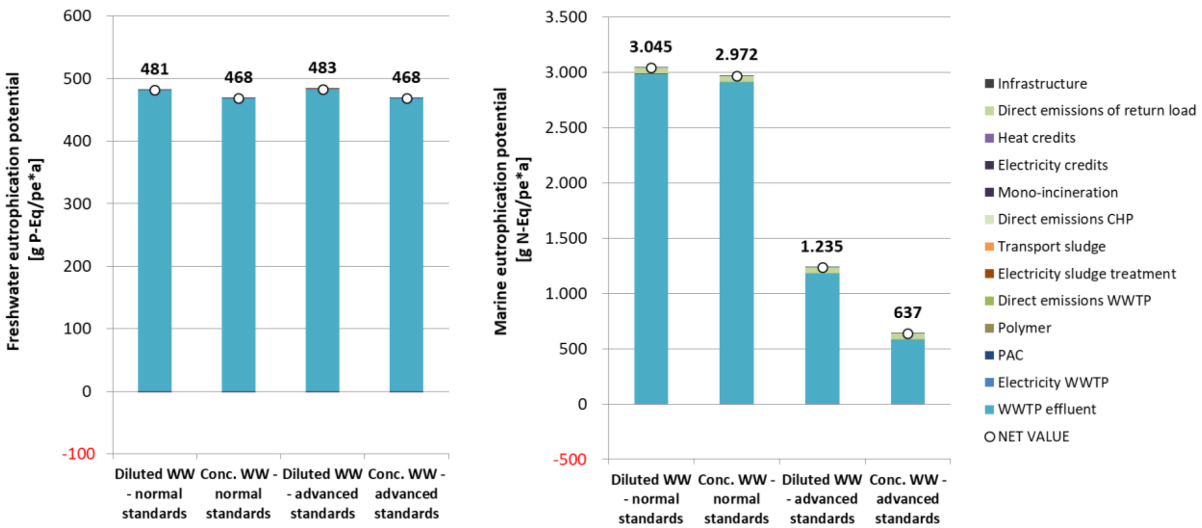

Figure 22: Freshwater (left) and marine eutrophication (right) of reference schemes for small WWTP (5,000 pe) for all conditions

POWERSTEP schemes

CED and GWP of reference and POWERSTEP schemes are compared in detail for diluted influent and normal standards without dedicated TN removal (Figure 23). Due to their superior electricity balance (self-sufficiency of >100%), POWERSTEP schemes can fully compensate CED of WWTP operation and infrastructure, leading to a net energy-neutral operation. Comparing microscreen and chemical settling, both options are comparable in CED, as microscreens require more polymer in operation but also require less electricity for operation.

For GWP, benefits of POWERSTEP are also significant due to the better electricity balance, although the resulting net GWP is still around 24 kg CO_2-eq/(pe*a) due to the high share of indirect emissions (N_2O). However, the LCA model calculates slightly lower N_2O emissions of biological treatment with POWERSTEP (-16% compared to the reference) due to TN removal in primary treatment and resulting lower TN load to the SBR. However, the potential impact of lower COD/N ratios and optimised aeration regime on N_2O emissions in the SBR should be further investigated to confirm that POWERSTEP really reduces N_2O emissions of small WWTPs.

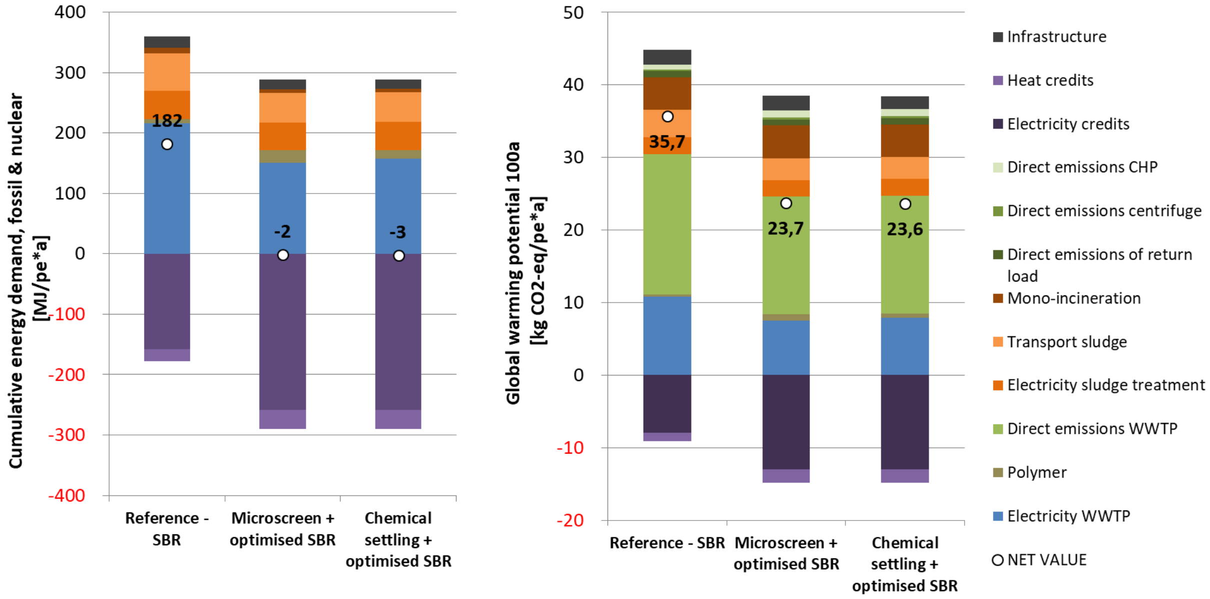

Figure 23: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes for small WWTP (5,000 pe) with diluted influent and normal standards (case A1, no TN limit)

CED and GWP of the same scenarios with concentrated influent show that POWERSTEP benefits are even more pronounced in this condition (Figure 24). Net CED is now negative for the POWERSTEP schemes with -45 MJ/(pe*a), showing a real energy-positive operation of the small WWTPs with advanced primary treatment. Net GWP is still quite high for POWERSTEP, which again confirms the high impact of direct emissions (N_2O) which are not reduced substantially with POWERSTEP. For all scenarios discussed above, it has to be kept in mind that no TN removal is required for these cases, which represents minimum requirements for WWTP operation and thus allows for a large potential of energetic optimisation via enhanced COD extraction in primary treatment (> 50% COD removal), as no COD is required for downstream denitrification.

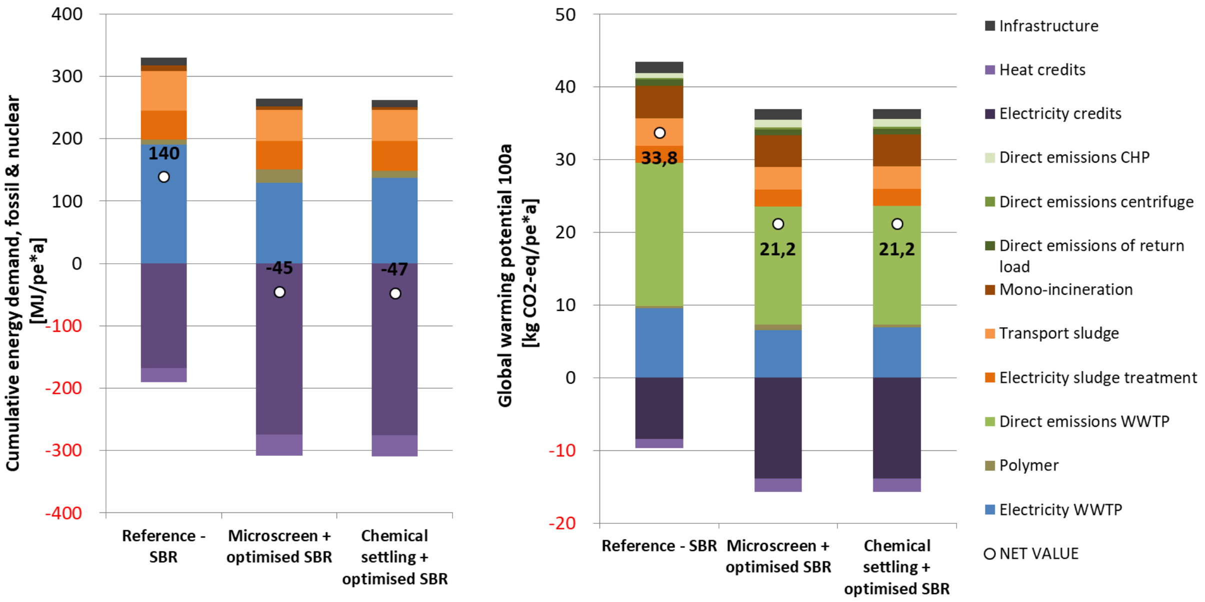

Figure 24: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes for small WWTP (5,000 pe) with concentrated influent and normal standards (case A2, no TN limit)

For small WWTPs with dedicated TN removal, benefits of POWERSTEP in CED and GWP are still substantial (Figure 25). However, net CED is still positive for POWERSTEP schemes, although electricity production is increased by 167% with enhanced primary treatment. Compared to scenarios without TN removal, electricity savings in wastewater treatment are not as pronounced with POWERSTEP if TN removal is required, as COD is consumed to a major part in denitrification in the reference scheme and thus does save on aeration demand if separated in primary treatment of POWERSTEP.

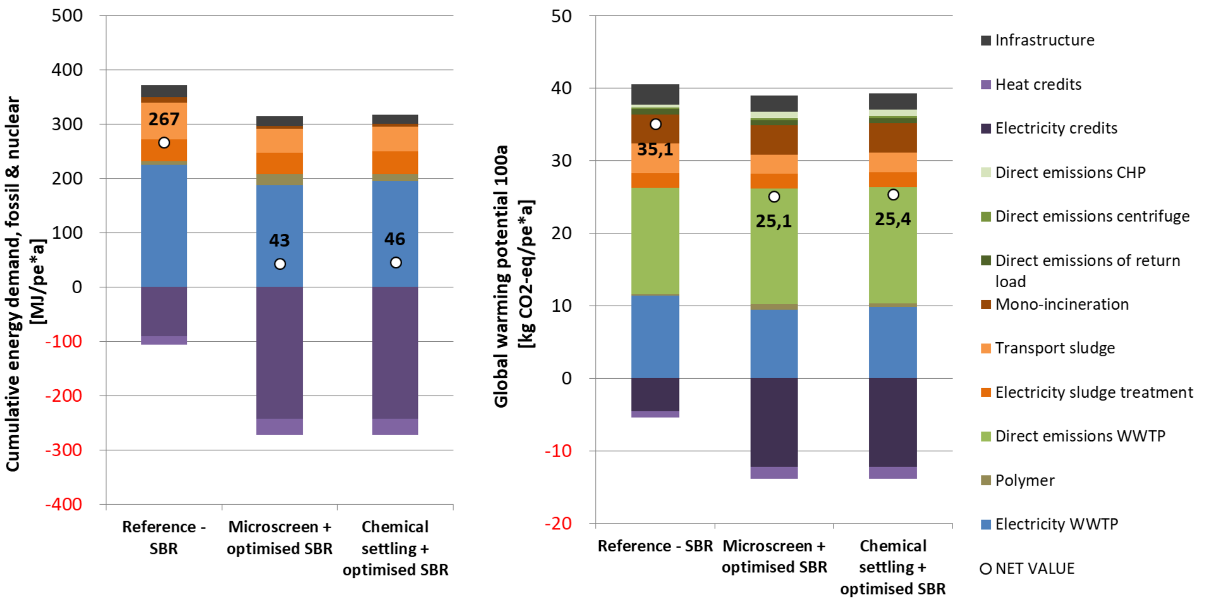

Figure 25: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes for small WWTP (5,000 pe) with diluted influent and advanced standards (case B1, TN limit = 18 mg/L)

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Net GWP accounts for 25 kg CO_2-eq/(pe*a), saving almost 30% in GHG emissions with POWERSTEP (Figure 25). This effect is only due to better electricity balance, as the model calculates comparable N_2O emissions for reference and POWERSTEP schemes.

Summary for all scenarios

Summarizing impacts of all scenarios and conditions for small WWTPs related to the respective reference scheme (= 100%), it can be clearly shown that POWERSTEP saves significantly on CED (-83 to -134%) and less on GHG emissions (-28 to -41%) for all conditions (Figure 26). Relative benefits of POWERSTEP for CED are more significant if no TN removal is required, yielding energy-neutral or even energy-positive operation of the scheme depending on the influent concentration. Relative benefits of POWERSTEP for GWP are somehow limited by the high share of direct emissions (N_2O) to this impact category, so that an improved energy balance has a lower effect for net GHG emissions. In addition, a potential trade-off between lower energy-related GHG emissions and potentially higher direct emissions (N_2O) due to a change in operational mode of the biological process should be further investigated to confirm the overall benefits of POWERSTEP for GWP stated in this study. Marginal difference in CED and GWP can be detected between the two technologies for enhanced primary treatment in any condition, so that both microscreen and chemical settling can be deemed comparable in environmental impacts at small WWTPs.

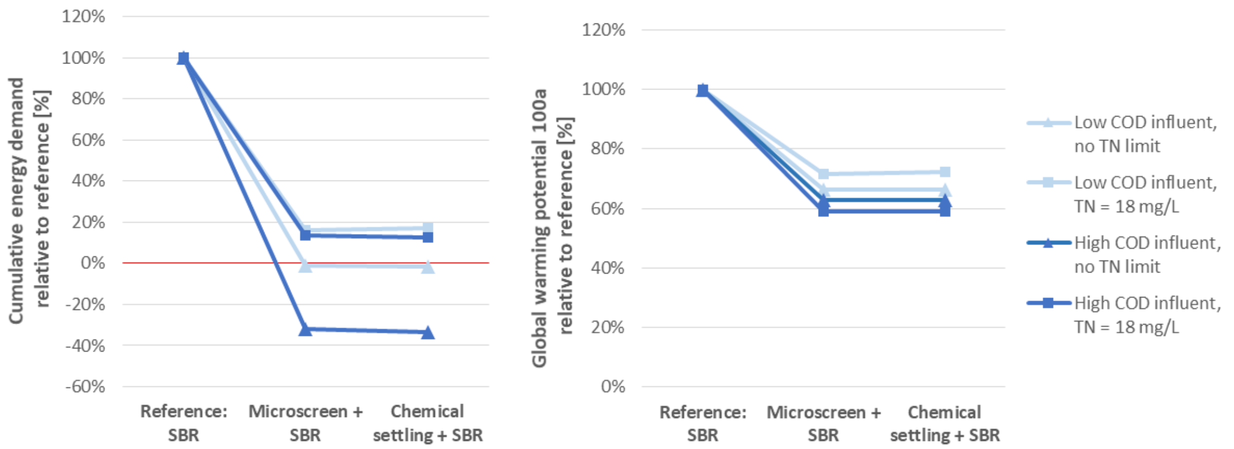

Figure 26: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes for small WWTP (5,000 pe) for all conditions

In terms of effluent quality, reference and POWERSTEP schemes are fully comparable as defined in the scope of the study (Figure 27). Hence, POWERSTEP can significantly improve energy demand and related environmental impacts without deteriorating the primary function of the WWTP, which is the purification of wastewater to defined standards.

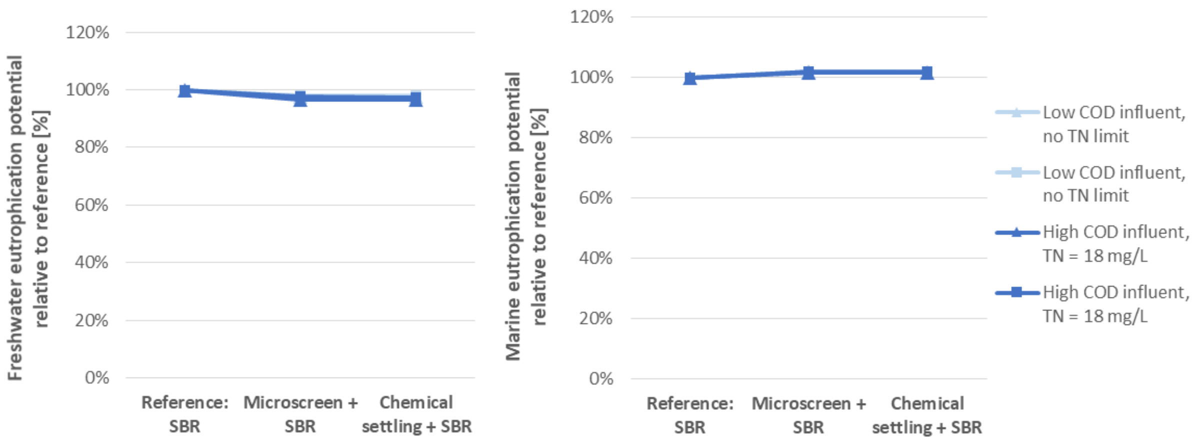

Figure 27: Freshwater (left) and marine eutrophication (right) of reference and POWERSTEP schemes for small WWTP (5,000 pe) for all conditions

4.2. Medium WWTP (50,000 pe)

Results for reference schemes are discussed in detail first, and then compared to impacts of POWERSTEP scenarios to detect potential benefits and drawbacks of new schemes with respect to their environmental impacts.

Reference schemes

CED and GWP of reference schemes for all conditions show a different profile for medium WWTPs than for small WWTPs. For CED, electricity is still the main contributor to total CED (309-361 MJ/(pe*a)) with 63-68%, but chemicals now also contribute 17-22% to CED due to the need of coagulant for chemical P elimination and polymer, especially for advanced standards with tertiary treatment (Figure 28). Sludge transport and disposal in mono-incineration adds another 12-13%, while infrastructure is responsible for the remaining 3-4% of CED.

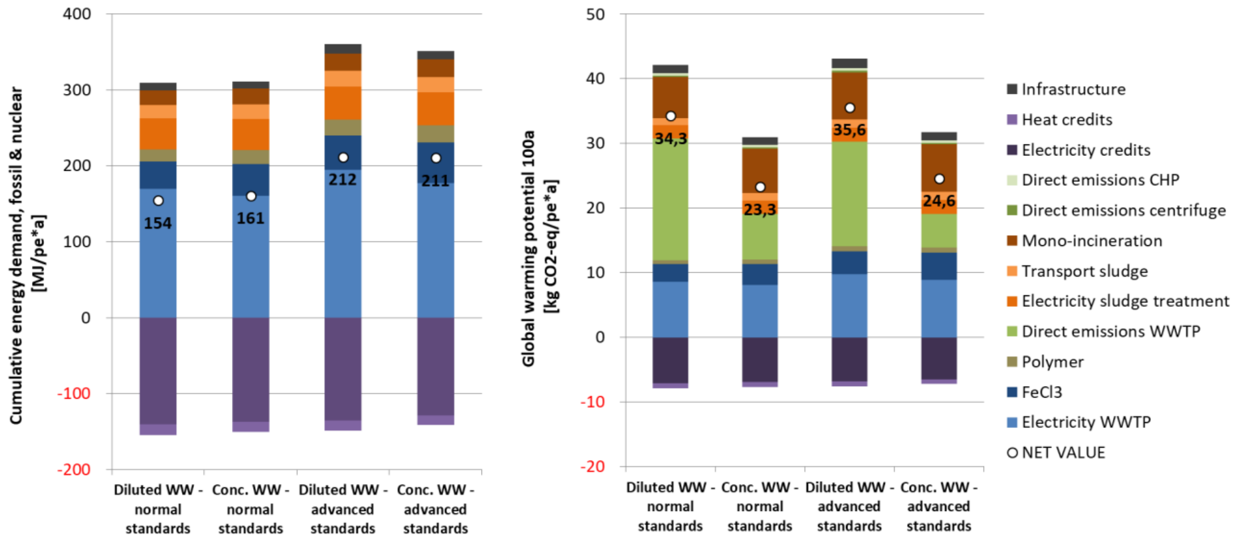

Figure 28: Cumulative energy demand (left) and global warming potential (right) of reference schemes for medium WWTP (50,000 pe) for all conditions

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Energy production is relatively independent of influent concentration and effluent targets, and accounts to 129-140 MJ/(pe*a) for electricity and 12-15 MJ/(pe*a) for heat from mono-incineration, thus off-setting 40-50% of the total CED. Remaining net CED is 154-161 MJ/(pe*a) for normal standards (TN = 18 mg/L) and 211-212 MJ/(pe*a) for advanced standards (TN = 13 mg/L), illustrating that higher standards lead to a higher energy demand of treatment. Influent concentration does not have a major impact on CED for medium WWTPs.

For GWP, influent concentration has a major impact on the net GWP mainly due to direct emissions: diluted influent leads to lower relative TN removal (64-70%) with a specific TN target concentration and a resulting higher N_2O emission factor in the LCA model (cf. Figure 17) than concentrated influent with 82-85% TN removal at the same TN target. In fact, N_2O emission factors of medium WWTPs range between 0.83-1% for diluted and 0.26-0.37% for concentrated influent, respectively. This correlation of N_2O emission factors with relative TN removal leads to the high difference in net GWP between scenarios with diluted influent (34-36 kg CO_2-eq/(pe*a) and concentrated influent (23-25 kg CO_2-eq/(pe*a)). Again, the importance of direct emissions of N_2O from biological processes for the net GWP of WWTP operation is underlined here, which has implications for the potential benefit of POWERSTEP schemes for GWP.

In terms of effluent TN and TP loads, both influent concentration and effluent targets have an impact on final nutrient loads to surface waters (Figure 29). For TP, advanced standards reduce TP emissions by 84% from 79-156 g to13-25 g P-eq/(pe*a), mainly due to tertiary treatment with coagulation/filtration. Similarly, higher requirements for TN removal reduce TN emissions by 20% in this study, decreasing from 750-1500 g to 600-1200 g N-eq/(pe*a) depending on concentration of the influent wastewater.

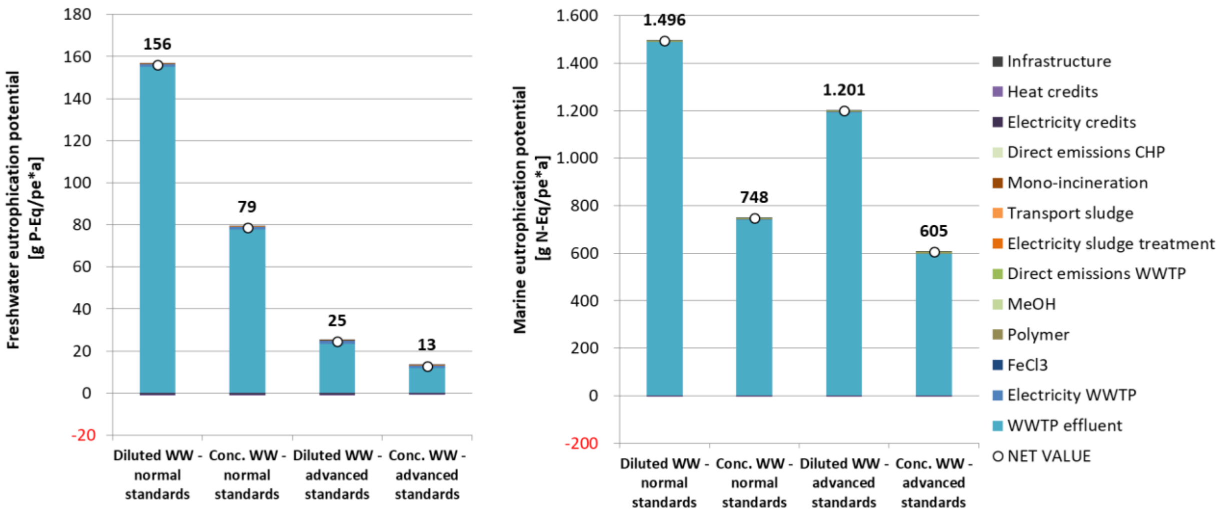

Figure 29: Freshwater (left) and marine eutrophication (right) of reference schemes for medium WWTP (50,000 pe) for all conditions

It is interesting to note that concentrated influent leads to both lower GHG emissions and lower nutrient emissions in this study while having a comparable energy demand for treatment. Hence, it can be concluded that measures to reach higher influent concentration (e.g. rehabilitation of sewer systems to prevent infiltration of rain or groundwater) can have a positive environmental impact on the overall WWTP operation.

POWERSTEP schemes

For POWERSTEP schemes, both CED and GWP can be reduced compared to the reference for the scenarios with diluted influent and normal standards. Due to the better electrical self-sufficiency of POWERSTEP (87%) versus the reference scheme (64%), net CED can be decreased by around 35% (Figure 30), saving around 50 MJ/(pe*a). Higher polymer demand for POWERSTEP schemes has only a negligible impact on CED, thus off-setting only a small fraction of electricity savings.

In parallel, net GWP is only decreased by 11-12% due to the better energy balance of POWERSTEP (Figure 30). Again, N_2O from biological treatment and mono-incineration has a high impact on total GWP, so that electricity savings can only reduce net GWP by 3.9-4.1 kg CO_2-eq/(pe*a).

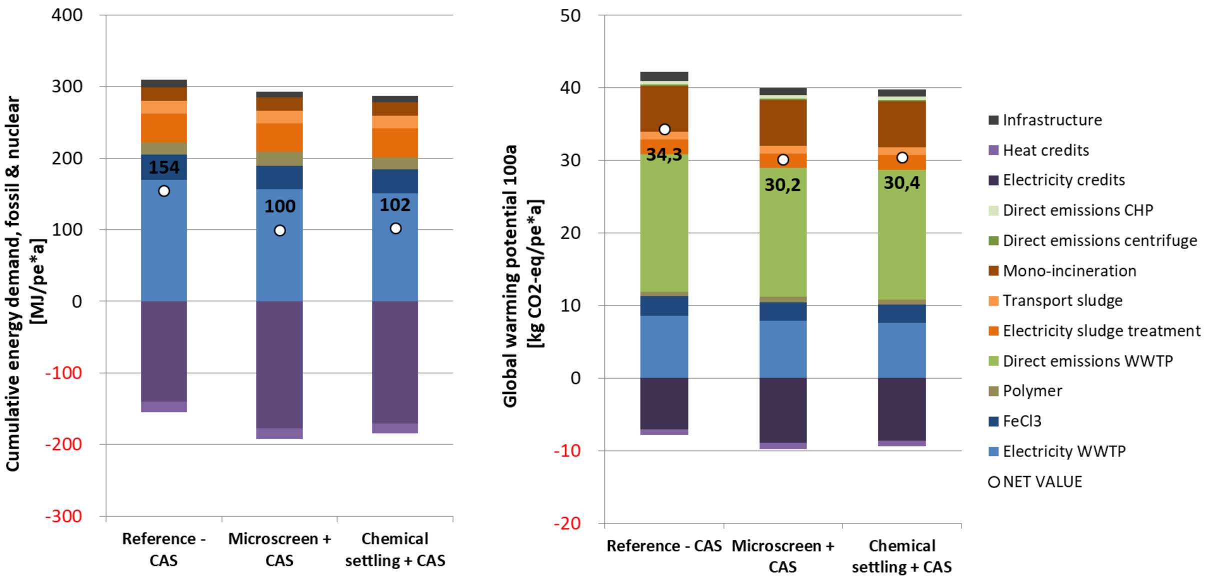

Figure 30: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes for medium WWTP (50,000 pe) with diluted influent and normal standards (case A1, TN limit = 18 mg/L)

With concentrated influent and the same TN limit, benefits of POWERSTEP are more substantial in CED, reducing net CED by 71-80% or 115-130 MJ/(pe*a) (Figure 31). Operating with a mainstream anammox configuration without COD requirements, COD extraction in primary treatment can be maximized in the POWERSTEP schemes so that electricity production is increased by 49-56%. In parallel, electricity demand for WWTP treatment can be reduced by 29-34% with mainstream anammox, yielding an electrical self-sufficiency of 121-132% for the entire WWTP and thus being able to export electricity to the grid. However, POWERSTEP schemes are still not energy-neutral in a life cycle perspective due to the contribution of chemicals, sludge transport and disposal, which leave a residual 31-46 MJ/(pe*a) as net CED.

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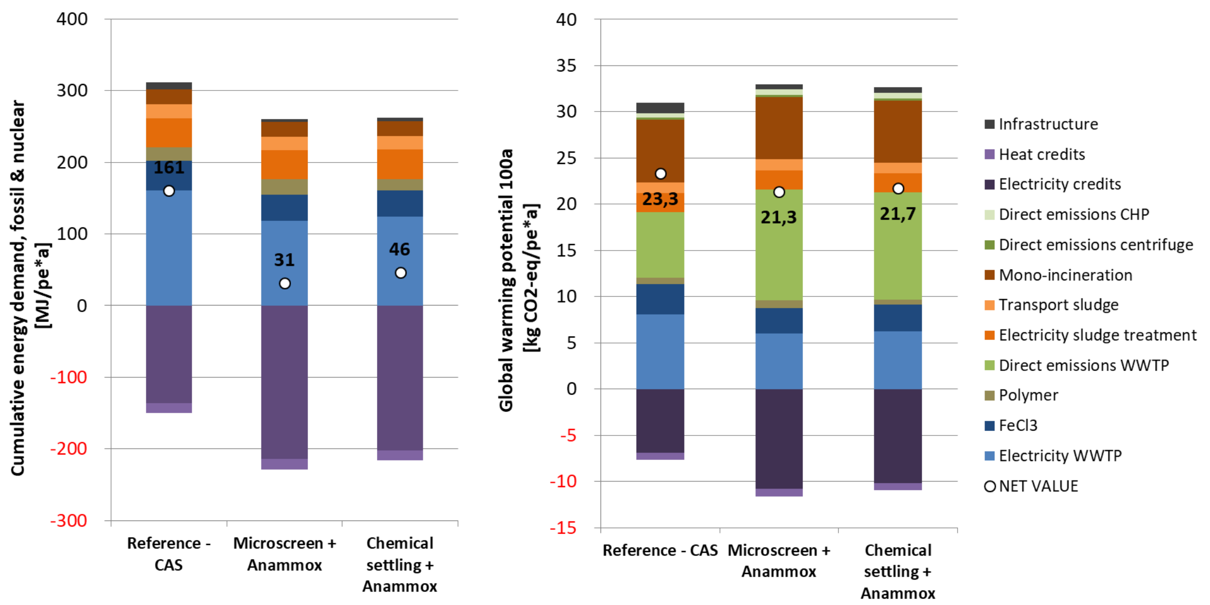

Figure 31: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes for medium WWTP (50,000 pe) with concentrated influent and normal standards (case A2, TN limit = 18 mg/L)

For GWP, the implementation of mainstream anammox only leads to a small decrease of net impact of 1.4-2 kg CO_2-eq/(pe*a) or 7-9% (Figure 31). Here, the trade-off between electricity savings and rising N_2O emissions becomes evident: although the electricity balance is significantly improved by POWERSTEP, the higher N_2O emission factor of mainstream anammox (+50% compared to conventional CAS as a conservative estimate) off-sets most of the benefits in GHG emissions in this LCA study. This result again underlines the importance of correctly assessing N_2O emissions when evaluating life-cycle GHG emissions of WWTP operation and while comparing different schemes. **N_2O emission factors of mainstream anammox have been roughly estimated in this study and should be validated in further studies to confirm the conclusions drawn here**. If higher N_2O emissions of mainstream anammox are confirmed, this fact might present a major drawback of this process when planning WWTP schemes with lower GHG emission profile.

Summary for all scenarios

Relative improvements of net CED and GWP are summarized for all scenarios below (Figure 32). POWERSTEP can reduce net CED by improving electrical self-sufficiency of WWTP operation, having a substantial impact for concentrated influent (-69 to -80%) and less for diluted influent (-27 to -35%). The latter fact is due to the change of CAS for diluted influent to mainstream anammox for concentrated effluent. Although mainstream anammox is superior in energy balance, this technology is still under development and may be affected by operational difficulties as discussed above (cf. chapter 2.4.2).

Reduction in GHG emissions is less pronounced for the POWERSTEP scenarios, only saving between 3 and 19% of net GWP (Figure 32). The high contribution of N_2O is responsible for this low relative effect: N_2O has a very high share for scenarios with diluted influent and thus dominates net GWP in reference and POWERSTEP scenarios, as the improvement in electricity-related GHG emissions is comparatively small. For concentrated influent, electricity-related benefits in GWP are higher, but are compensated to a large extent by increasing N_2O emissions for mainstream anammox. Finally, the relative potential for reducing GHG emissions from wastewater treatment with POWERSTEP is quite small for these scenarios. Interestingly, stricter TN discharge limits will lead to a reduction in N_2O emissions following the correlation of emission factors and relative TN removal (Figure 17), which can pose a win-win situation to reduce both nitrogen effluent loads and direct GHG emissions of WWTP.

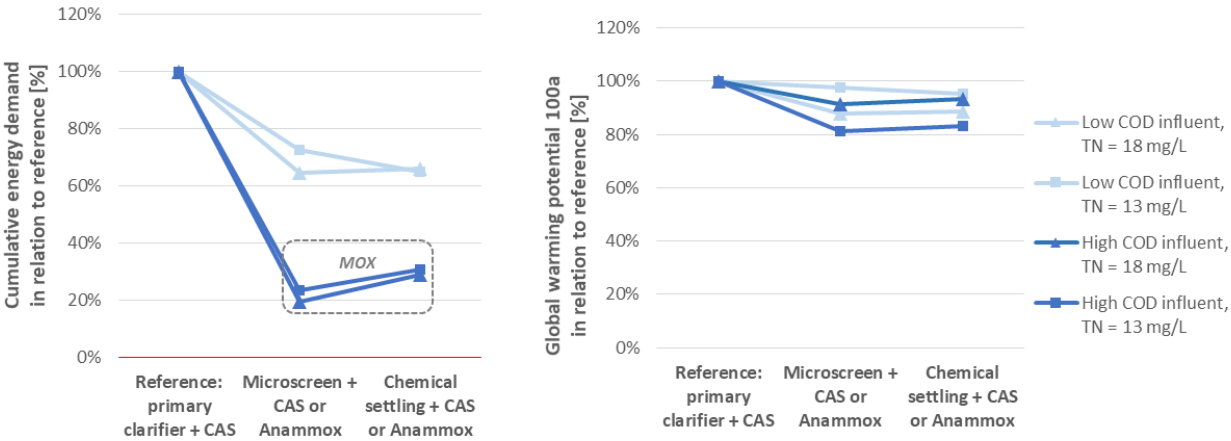

Figure 32: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes for medium WWTP (50,000 pe) for all conditions (MOX: schemes with mainstream anammox)

Again, effluent quality of reference and POWERSTEP schemes is comparable for TN and TP effluent loads (Figure 33), as both should comply with the same effluent standards. Small differences in effluent quality originate from model uncertainty and inaccuracy of OCEAN software predicting mean effluent concentrations. In fact, emission loads should be fully comparable between scenarios by definition in this LCA (Table 2).

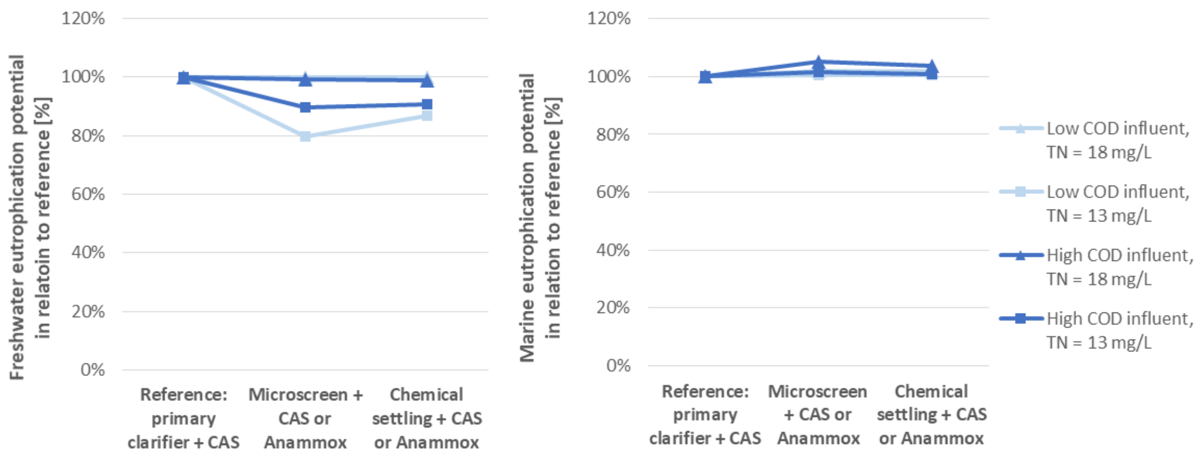

Figure 33: Freshwater (left) and marine eutrophication (right) of reference and POWERSTEP schemes for medium WWTP (50,000 pe) for all conditions

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In summary, POWERSTEP schemes can again improve energy demand and GHG emissions of medium WWTP while delivering comparable effluent quality. However, other processes in the life cycle (e.g. chemical demand, sludge disposal) prevent a fully energy-neutral or energy-positive operation of the POWERSTEP schemes, while a high impact of N_2O emissions limits their potential benefits in GHG emission reduction.

4.3. Large WWTP (500,000 pe)

Results for reference schemes are discussed in detail first, and then compared to impacts of POWERSTEP scenarios to detect potential benefits and drawbacks of new schemes in their environmental impact.

Reference schemes

CED and GWP profiles for reference schemes confirm the results for medium WWTPs, but at a lower overall level of impact. Total CED of reference schemes is between 281 and 325 MJ/(pe*a), and electricity demand for WWTP operation and sludge treatment is the main contributor with 73-75%. Chemicals play a minor role compared to medium WWTPs with 10-12% of total CED, as P removal is mainly reached by biological P elimination in large plants, thus reducing the need for coagulant $FeCl_3$. The remaining CED is caused by sludge disposal (11-12%) and infrastructure (3-4%).

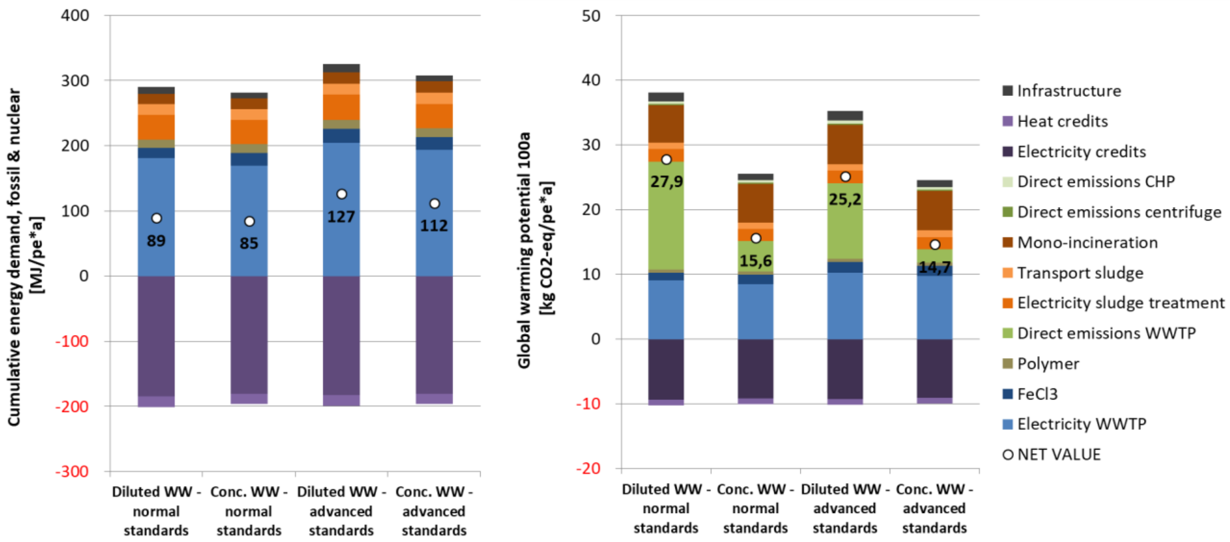

Figure 34: Cumulative energy demand (left) and global warming potential (right) of reference schemes for large WWTP (500,000 pe) for all conditions

Again, energy production is relatively independent of influent conditions and effluent targets, and accounts to 180-185 MJ/(pe*a) for electricity and 16-17 MJ/(pe*a) for heat from mono-incineration, thus off-setting 64-70% of the total CED. Electricity production is higher than for medium plants, mainly due to higher electrical efficiency of large CHP units. Remaining net CED is 85-89 MJ/(pe*a) for normal standards (TN = 13 mg/L) and 112-127 MJ/(pe*a) for advanced standards (TN = 10 mg/L), illustrating again that higher standards lead to a higher energy demand of treatment. Influent concentration has only a minor impact on net CED for medium WWTPs.

Results for GWP are comparable in their trends to medium WWTPs: N_2O emissions are responsible for a high share of net GWP for diluted influent (TN removal: 75-80%), while they are relatively minor for concentrated influent (TN removal: 87-90%). Linear correlation of N_2O emission factors with relative TN removal leads to emission factors of 0.45-0.64% for diluted influent and 0.1-0.19% for concentrated influent. Consequently, net GWP is 25-28 kg CO_2-eq/(pe*a) for diluted and only 15-16 kg CO_2-eq/(pe*a) for concentrated influent.

Effluent loads of TN and TP depend both on the influent concentration and the effluent targets. TP loads are reduced from 39-78 g to 12-24 g P-eq/(pe*a) with advanced standards (-70%), while TN loads decrease by 24% from 538-1074 g to 408-811g N-eq/(pe*a) (Figure 35).

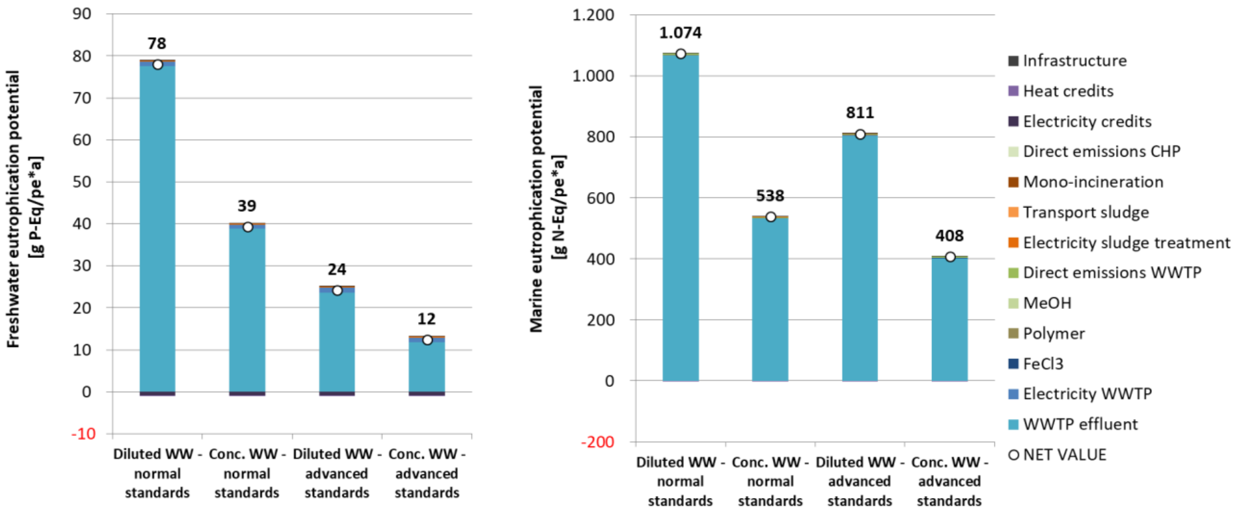

Figure 35: Freshwater (left) and marine eutrophication (right) of reference schemes for large WWTP (500,000 pe) for all conditions

Again, a win-win situation can be detected in environmental terms for the scenarios with concentrated influent: lower effluent loads into surface waters can be reached with lower energy demand and lower GHG emissions, which again promotes rehabilitation strategies to reduce unwanted infiltration of rain or groundwater into the sewer systems and prevent unnecessary dilution of wastewater.

POWERSTEP schemes

For diluted influent and normal standards (TN = 13 mg/L), POWERSTEP improves electrical self-sufficiency from 78% to 101-103% mainly be increasing electricity production from primary sludge. However, some of the energy benefit is compensated by an increase in chemical need (both polymer and coagulant for primary treatment). Overall, net CED can be reduced by 35-43% to a remaining 51-58 MJ/(pe*a) with POWERSTEP (Figure 36).

For net GWP, reduction of POWERSTEP schemes is only marginal with -5 to -6%. Here, benefits in electricity balance a largely compensated by higher chemical demand and more emissions in CHP plant.

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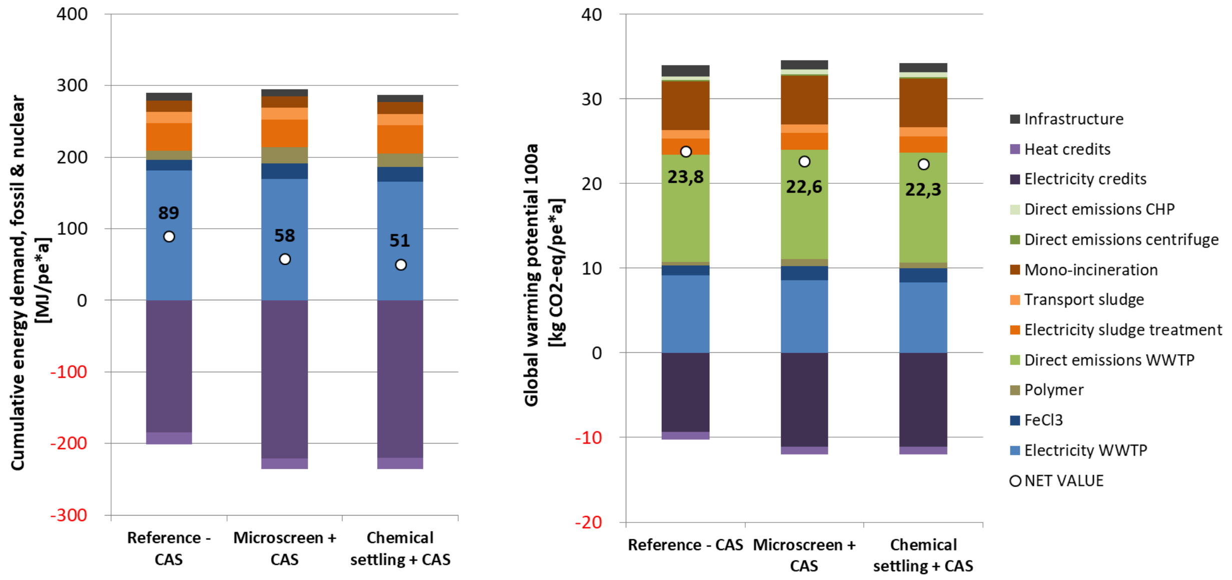

Figure 36: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes for large WWTP (500,000 pe) with diluted influent and normal standards (case A1, TN limit = 13 mg/L)

For concentrated influent, POWERSTEP schemes have a more substantial effect on the electricity balance, increasing self-sufficiency from 82% in reference to 158-170%. This is mainly due to the implementation of the mainstream anammox process, which enables higher COD extraction in primary treatment and also reduces electricity consumption of the biological stage. Altogether, POWERSTEP can completely compensate energy demand of the system, resulting in a net CED of -14 to -28 MJ/(pe*a) (Figure 37).

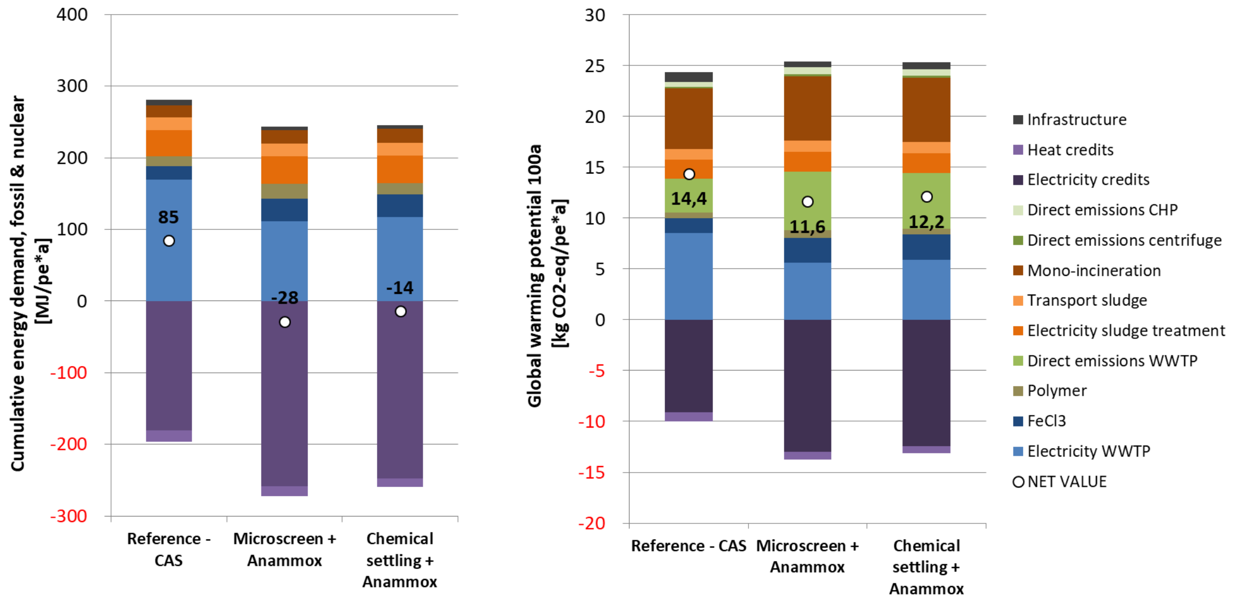

Figure 37: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes for large WWTP (500,000 pe) with concentrated influent and normal standards (case A2, TN limit = 13 mg/L)

For GWP, the trade-off between better energy balance and higher N_2O emissions in mainstream anammox yields only small improvement (-15 to -19%) in net GWP for POWERSTEP, as direct emissions of N_2O are increased by 50%. This conclusion has to be validated with further investigations into N_2O emissions of mainstream anammox systems to prove the rather conservative estimate applied in this study.

Summary for all scenarios

Relative impacts for all scenarios show that POWERSTEP can significantly reduce net CED (-111% to -133%) for concentrated influent, rendering energy-neutral or even energy-positive WWTP schemes (Figure 38). However, the underlying technology of mainstream anammox still has to be validated in full-scale references to confirm design data assumed in this study. For diluted influent, POWERSTEP relies on CAS systems, and savings are less pronounced but still reduce net CED by 23-35%. For GWP, trade-off with chemical demand and direct N_2O emissions yields lower improvement potentials for POWERSTEP, decreasing net GWP by 19-44% for concentrated influent and only 5-6% for diluted influent.

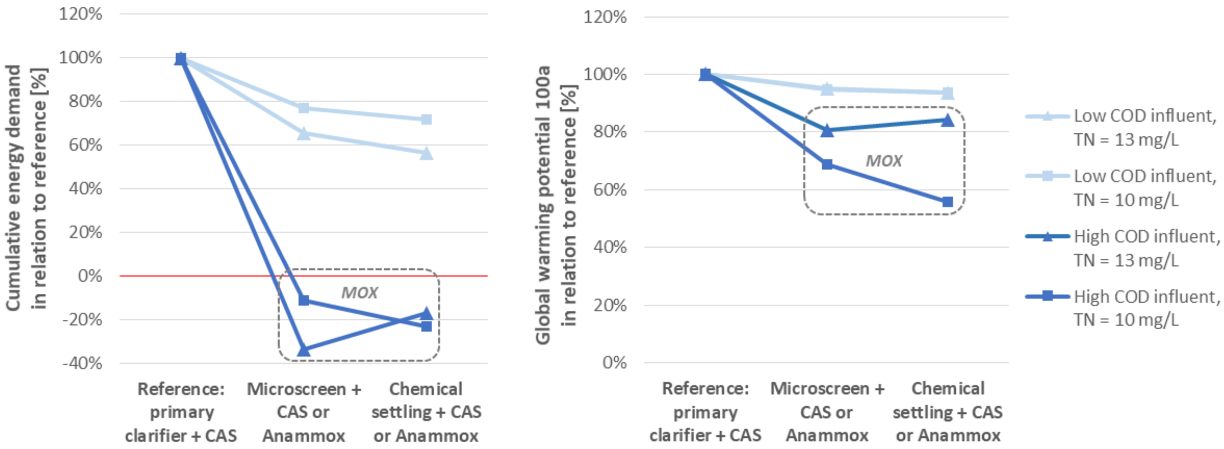

Figure 38: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes for large WWTP (500,000 pe) for all conditions (MOX: schemes with mainstream anammox)

Effluent quality is relatively constant for reference and POWERSTEP schemes for TN and TP (Figure 39), with small variations due to internal calculations in the model and uncertainty in mean effluent estimates by OCEAN software.

In summary, POWERSTEP schemes again improve energy demand and GHG emissions of large WWTP while delivering comparable effluent quality. With mainstream anammox, energy-neutral and even energy-positive operation can be achieved for large plants, provided that full-scale references can confirm design data and operational stability. For GHG emissions, POWERSTEP benefits are lower due to compensation of energy-related benefits with GHG from chemical production and N_2O. If CAS systems are still applied after enhanced carbon extraction, benefits in energy balance and related reduction in CED and GWP are less pronounced, but still enable a lower environmental footprint than the reference schemes.

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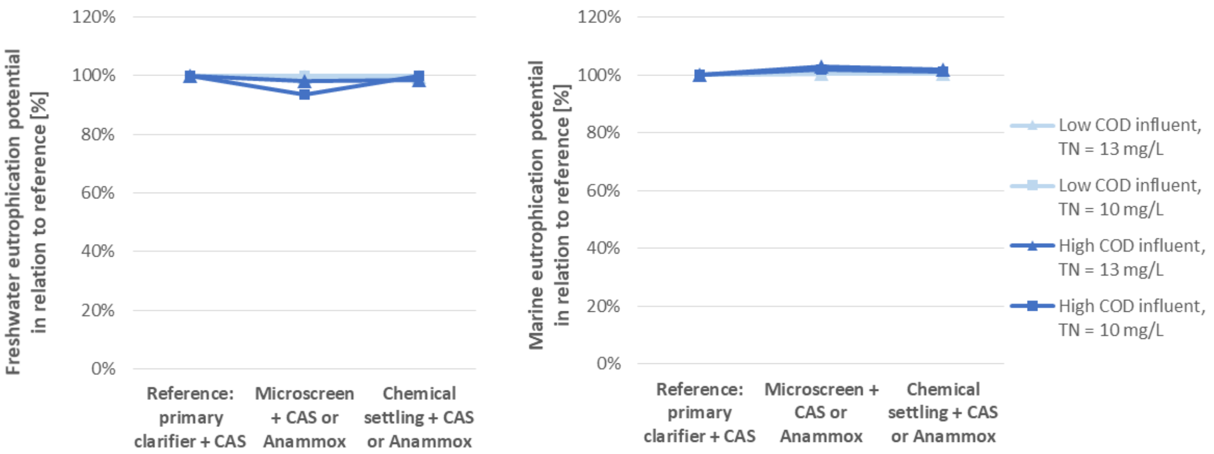

Figure 39: Freshwater (left) and marine eutrophication (right) of reference and POWERSTEP schemes for large WWTP (500,000 pe) for all conditions

4.4. Variations for large WWTP (500,000 pe)

For large WWTPs, a set of scenarios with technical variations has been investigated to analyse specific technologies in their impact on energy demand and GHG emission profile. As effluent quality is comparable by definition, the following chapter focuses on CED and GWP impacts of sidestream treatment, P2G, and two-stage plants.

4.4.1. Sidestream treatment: deammonification and membrane stripping

For concentrated influent, POWERSTEP scenarios consider the implementation of mainstream anammox as biological stage, as not enough COD is available to guarantee sufficient denitrification (TN removal >85%) for the required effluent standards. However, an alternative to mainstream anammox can be the implementation of a sidestream treatment of sludge liquor for N removal, thus reducing the total N load of the plant. Together with a small bypass of primary treatment (6-8%) to transfer more COD to the biological stage, this will enable the operation of a CAS system after enhanced carbon extraction while still complying with TN targets.

Two options for sidestream treatment are compared here: deammonification, and membrane stripping to recover a liquid N fertilizer. However, results of net CED show that sidestream configurations combined with CAS significantly diminish the benefits in energy demand compared to the mainstream anammox scenario: deammonification will decrease net CED by 44%, while membrane stripping only yields a 12% decrease (Figure 40). For the latter, high chemical demand and comparably low value of recovered N fertilizer off-set most of the benefits of advanced primary treatment, so that final CED is quite comparable to the reference scenario. Sidestream deammonification has less efforts and higher benefits, thus is preferable from an energetic point of view.

GWP results for sidestream scenarios show that both options actually increase net GWP compared to the reference (+7-8%). While high chemical demand compensates all GWP benefits of the membrane stripping scenario, sidestream deammonification is prone to higher N_2O emissions (~ 1%) than N removal in the mainstream (0.2%), and increase in N_2O off-sets all energetic benefits in this variant.

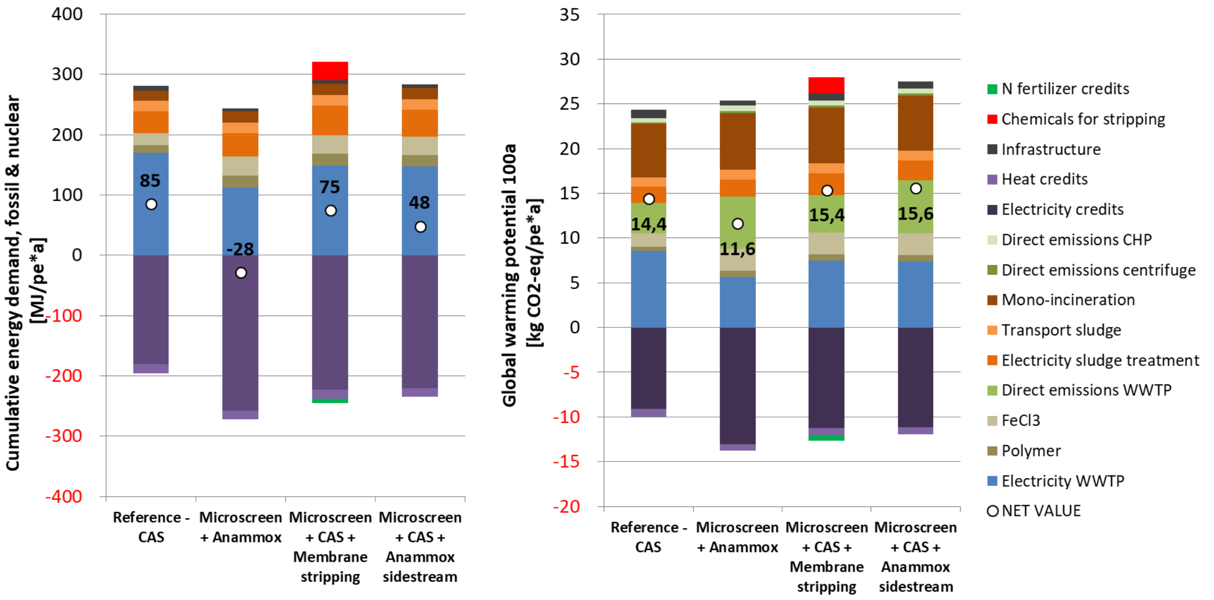

Figure 40: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes with sidestream options for large WWTP (500,000 pe) with concentrated influent and normal standards (case A2)

Analysis of sidestream scenarios shows that a combination of advanced primary treatment with sidestream N removal is beneficial for energy demand, although not as pronounced as with mainstream anammox. Nitrogen recovery with membrane stripping is not competitive in energy demand due to high chemical efforts and relatively low value of the N product. For GHG emissions, sidestream options do not improve the profile of reference schemes due to trade-offs with N_2O or high chemical demand.

Overall, sidestream treatment presents a valid option to implement POWERSTEP in conditions where relative TN removal should be high without relying on the mainstream anammox process. It can be seen as an additional lever to enable enhanced COD extraction in primary stage combined with a CAS system while still enabling high TN removal.

4.4.2. **Power-to-gas**

P2G scenarios enable the direct valorisation of biogas by injecting it into the public gas grid. While the methane fraction of biogas can be directly valorised as biomethane after biogas upgrading, the remaining CO_2 has to be converted into biomethane with methanation, preferably using low-cost renewable energy from the grid during times of high production as assumed in this study (e.g. wind power at night).

Effects of P2G implementation on both reference and POWERSTEP schemes are substantial: while biogas upgrading requires little electricity and P2G relies on renewable sources (= low fossil and nuclear CED, mainly for infrastructure), CED credits for injected biogas are high. In consequence, both reference and POWERSTEP schemes can be operated energy-positive using the P2G approach, i.e. with a surplus of CED of 46-186 MJ/(pe*a) (Figure 41). Biogas credits are substantially higher than electricity credits, because its energy content fully substitutes natural gas of fossil origin, while avoided grid electricity has a renewable share. In addition, CO_2 fraction of the biogas is not valorized

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in CHP plants, while it is converted to usable biomethane in bio-methanation. However, the latter process has to be operated on renewable energy only, which is a pre-requisite for the environmental benefits of P2G. If P2G is operated with grid electricity, the overall balance would be significantly altered, as the energetic conversion efficiency of electricity to biomethane is only 50%.

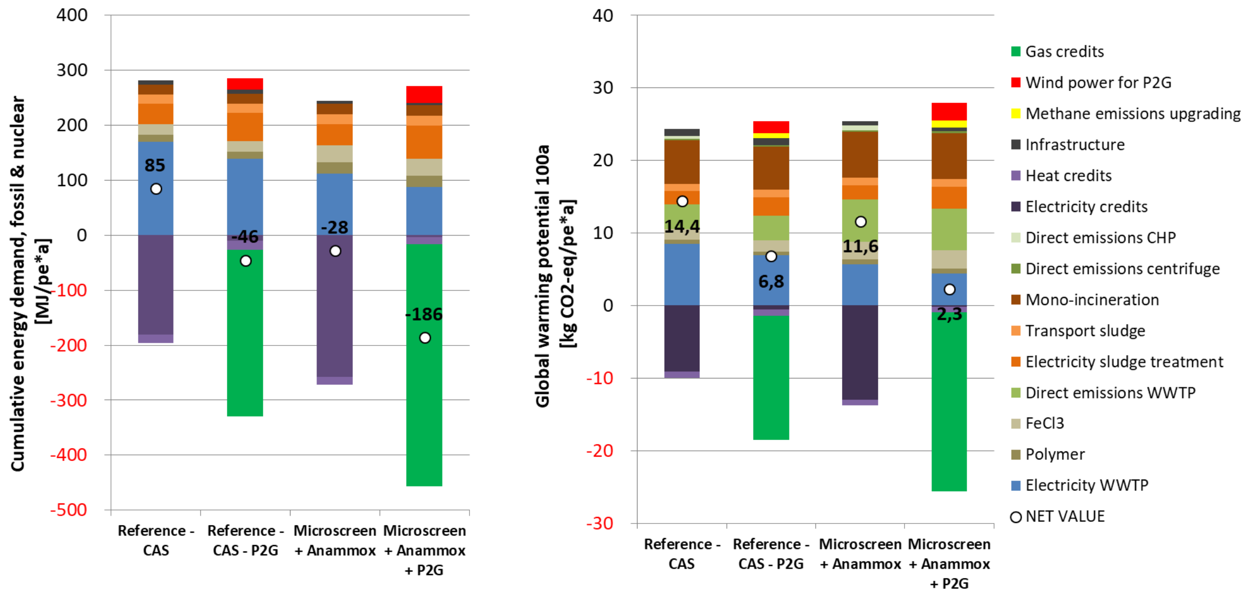

Figure 41: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes with P2G for large WWTP (500,000 pe) with concentrated influent and normal standards (case A2)

GWP benefits of P2G scenarios are also substantial due to the same effect: net GWP is reduced by 53% in reference and 84% in POWERSTEP scheme due to the high credits for injected biomethane (Figure 41). The latter scheme is almost carbon neutral in operation, so that P2G more or less compensates all direct emissions of the system such as N_2O from biological stage and mono-incineration and also some methane emissions during biogas upgrading. In addition, the supply of pure oxygen as P2G by-procut to the biological stage may further decrease N_2O emissions, as N_2O stripping is expected to be minimized while using pure oxygen. However, this effect could not be quantified here.

Overall, it can be concluded that P2G is a valuable approach to reduce environmental impacts of WWTP operation, given that it is operated only on renewable power. Biomethane is a superior product to electricity in the environmental balance, as it fully substitutes fossil natural gas and yields related credits in fossil energy demand and GHG emissions. The impact of P2G is even higher for the POWERSTEP schemes, as more biogas is produced here and thus can be valorised in this approach.

4.4.3. **Two-stage plants**

Two-stage plants enable the production of more sludge, leading to a higher electrical self-sufficiency than one-stage plants. For diluted influent and normal standards (TN = 13 mg/L), two-stage plants reduce net CED of the reference by 15% in this study due to a higher biogas production (Figure 42). A modified two-stage configuration with sidestream nitritation (cf chapter 2.4.3) can even reduce net CED by 31%, saving on aeration energy due to the better alpha factor in the sidestream. However, both options for two-stage plants are still higher in net CED than the configuration with microscreen and CAS.

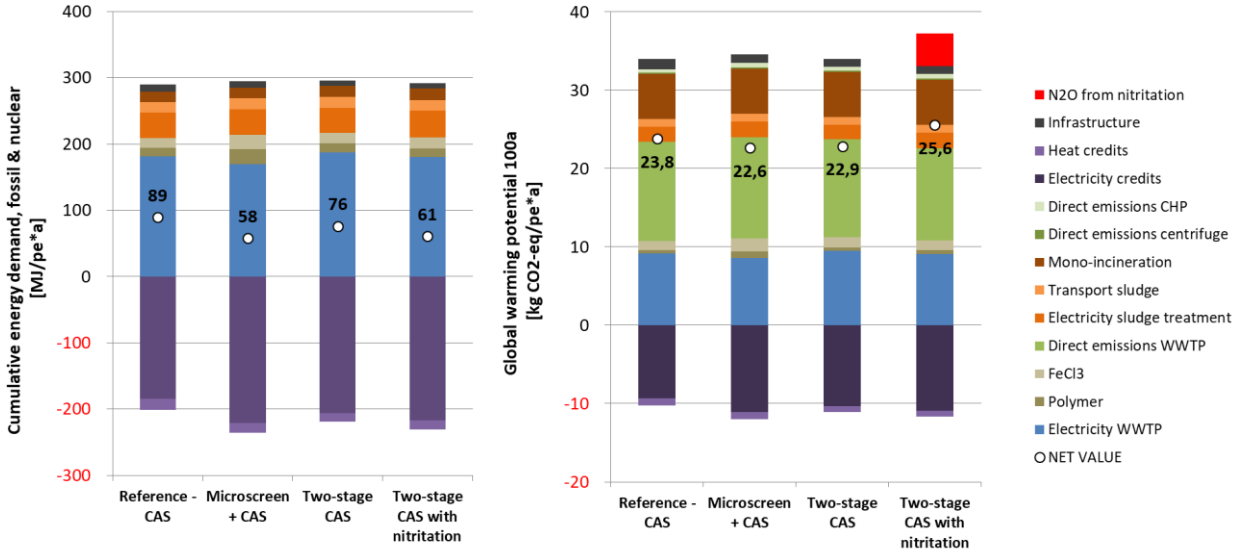

Figure 42: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes with two-stage configuration for large WWTP (500,000 pe) with diluted influent and normal standards (case A1)

Energetic benefits for sidestream nitritation in two-stage systems are fully compensated in GWP due to high N_2O emissions in nitritation (Figure 42): the respective N_2O emission factor is 2% for nitritation compared to 0.64% for N removal in the mainstream. Again, this underlines the importance of assessing consequences of WWTP modification on N_2O emissions, as energetic benefits can be quickly off-set in GWP by higher N_2O emissions.

Overall, two-stage plants also have a potential to decrease energy demand and related GHG emissions, but sidestream treatment with nitritation should be operated with the goal to minimize N_2O emissions.

4.5. Sensitivity analysis

As electricity balance and related environmental impacts are in the focus of this study, the choice of grid electricity mix will have a high impact on the outcomes. This study applies the European electricity mix as default, which has a CED of 9.6 MJ and a GWP of 0.485 kg CO_2-eq per kWh.

For sensitivity analysis, the relative results for large WWTPs are again calculated applying two distinct energy mixes of Poland and Norway. The Polish mix with high fossil share has a CED of 11.8 MJ (+23% to EU mix) and a GWP of 0.989 kg CO_2-eq per kWh (+104% to EU mix). The Norwegian grid mix has a high share of renewables, resulting in a CED of 0.5 MJ (-95% to EU mix) and a GWP of 0.03 kg CO_2-eq per kWh (-94 to EU mix).

Calculating reference and POWERSTEP schemes with the Polish grid mix, benefits of POWERSTEP are more substantial due to higher contribution of electricity in the net indicator result (Figure 43). However, results with superior electricity balance (i.e. scenarios for concentrated influent using mainstream anammox) are highly affected by this change in energy mix, while scenarios with lower share of electricity on the overall profile have lower benefits.

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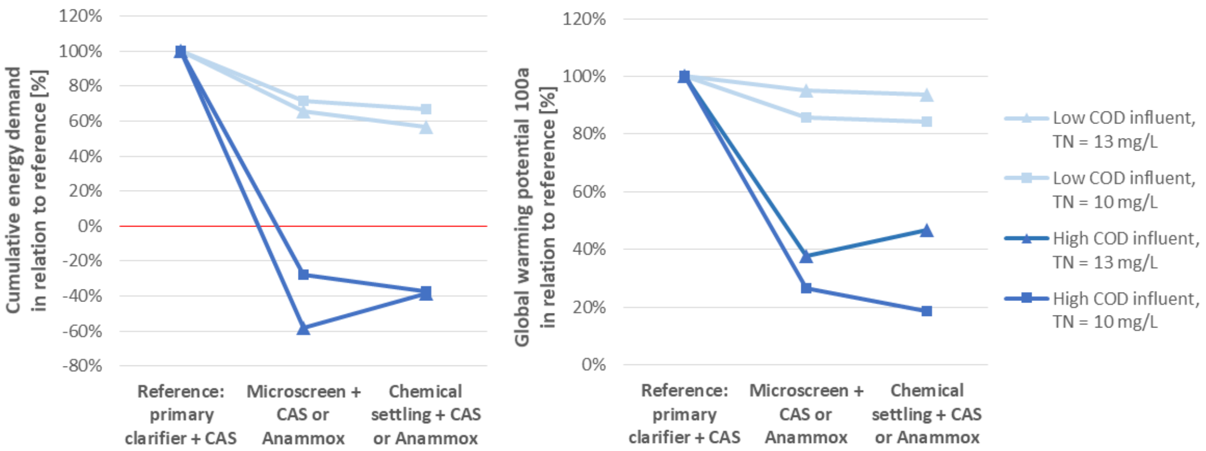

Figure 43: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes for large WWTP (500,000 pe) for all conditions using electricity mix of Poland (high fossil share)

In contrast, calculating with the fully renewable electricity mix of Norway reveals trade-offs for the POWERSTEP scenarios: now, both net CED and GWP increase with the implementation of POWERSTEP for most scenarios (Figure 44). Additional chemical demand and potentially higher N_2O emissions now dominate these impact categories, while electricity demand and production have only a minor share as they are both fully renewable.

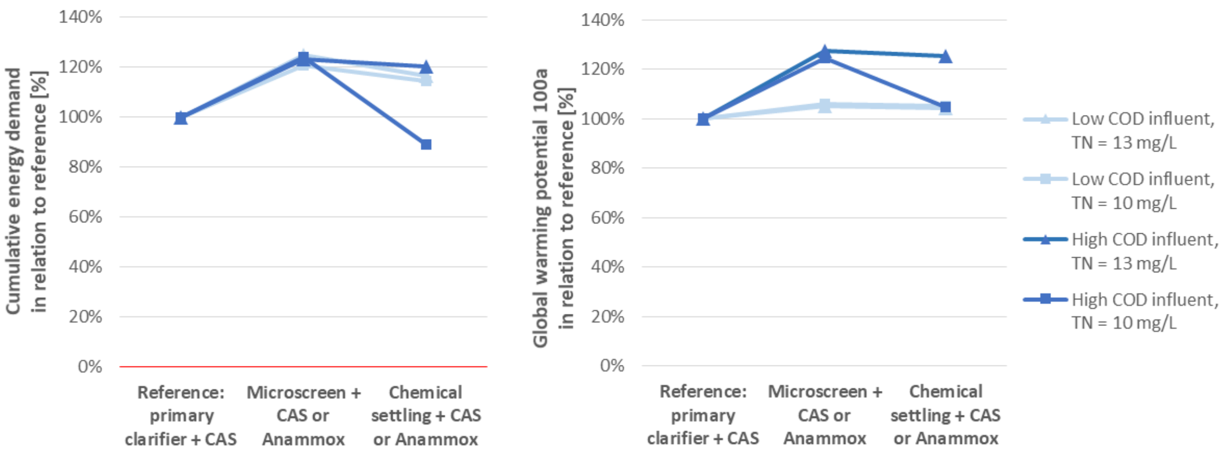

Figure 44: Cumulative energy demand (left) and global warming potential (right) of reference and POWERSTEP schemes for large WWTP (500,000 pe) for all conditions using electricity mix of Norway (high renewable share)

This sensitivity underlines the logical fact that an improvement in electrical self-sufficiency of WWTPs at the cost of chemicals and potentially higher N_2O emissions makes more sense when operating on a grid electricity mix with high fossil share. In case of high renewable share (ca. > 75%), POWERSTEP concepts do not make sense to improve the environmental footprint of WWTP operation, which is then more dominated by direct emissions and energy demand for chemicals and infrastructure.

5. LCA: interpretation and conclusions

This LCA study compares reference and POWERSTEP schemes for municipal wastewater treatment in their environmental impacts, focussing on energy and related emission of GHG and effluent quality. Based on hypothetical scenarios for different influent quality and effluent discharge limits, the study takes mass balance and energy data of an energy benchmarking software (OCEAN tool of Veolia) and calculates four LCA indicators for all scenarios. Process data originates from design rules for activated sludge plants (DWA 2016) combined with results of pilot and full-scale trials of innovative technologies.

Results of the LCA for net cumulative energy demand and global warming potential show that the **innovative schemes are capable to significantly reduce energy demand and related GHG emissions of municipal wastewater treatment** (Table 9). Effluent quality is comparable between respective scenarios, so that **POWERSTEP schemes do not compromise the primary function of WWTPs to keep effluent targets**.

Table 9: Results of LCA for cumulative energy demand and global warming potential for reference and POWERSTEP schemes

WWTP size	Total nitrogen effluent limit	Reference WWTP		POWERSTEP[1] WWTP		Relative savings	
Influent concentration		Low	High	Low	High	Low	High
Net cumulative energy demand [MJ/pe*a]							
5,000 pe	-	182	140	-3	-47	70%	134%
5,000 pe	18 mg/L	267	246	43	31	84%	87%
50,000 pe	18 mg/L	154	161	100	**31**	35%	**81%**
50,000 pe	13 mg/L	212	211	138	**50**	35%	**76%**
500,000 pe	13 mg/L	89	85	51	**-28**	43%	**133%**
500,000 pe	10 mg/L	133	115	95	**-27**	29%	**123%**
Net global warming potential [kg CO_2-eq/pe*a]							
5,000 pe	-	36	34	24	21	33%	37%
5,000 pe	18 mg/L	35	24	25	14	29%	42%
50,000 pe	18 mg/L	34	23	30	**21**	12%	**9%**
50,000 pe	13 mg/L	36	25	34	**20**	6%	**20%**
500,000 pe	13 mg/L	24	14	22	**12**	8%	**14%**
500,000 pe	10 mg/L	23	14	21	**8**	9%	**43%**

BOLD: scenarios with mainstream anammox

[1] *value for POWERSTEP is best-case of microscreen or chemical settling*

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Depending on WWTP size and effluent targets, **energy savings are between 29 and 84% for diluted influent and 76-134% for concentrated influent**, the latter yielding truly energy-positive schemes for WWTP. However, POWERSTEP schemes for medium and large plants with concentrated influent are based on mainstream anammox technology for nitrogen removal, and related process data has to be validated in full-scale references.

For GHG emissions, POWERSTEP schemes can save 6-33% with diluted and 9-43% with concentrated wastewater. Although the superior electricity balance yields some savings for POWERSTEP, direct emissions of N_2O of biological stage and mono-incineration of sludge are still relevant for this impact category or may even form a **trade-off in case of higher N_2O emissions as expected for the mainstream anammox**. Emission factors for N_2O from biological treatment are estimated and have to be confirmed with further data directly comparing conventional and innovative schemes at a specific site.

Overall, benefits of POWERSTEP are higher for cumulative energy demand than for GHG emission profiles (Figure 45). **Stricter targets for nitrogen removal usually increase energy demand, but lower GHG emissions as denitrification can act as a sink for N_2O.** However, carbon-neutral wastewater treatment cannot be reached only with energy-positive POWERSTEP schemes: implementation of alternatives for biogas valorisation such as Power-to-gas may form a way to neutralize direct GHG emissions of WWTPs. **Energy demand and GHG emissions decrease with increasing size of the WWTP** mainly due to higher efficiencies of aggregates (e.g. CHP plants, aeration).

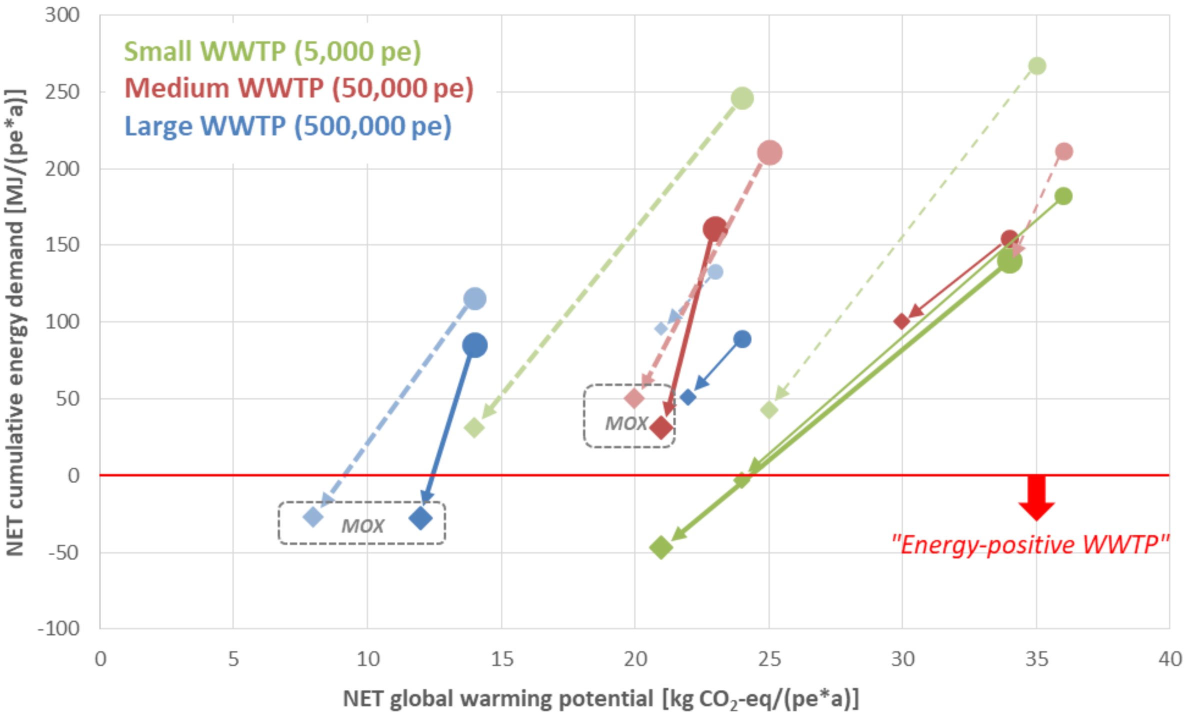

Figure 45: Net cumulative energy demand and net global warming potential of reference and POWERSTEP schemes (small lines: low influent concentration, bold lines: high influent concentration, straight lines: normal standards, dotted lines: advanced standards, MOX: scenarios with mainstream anammox)

Naturally, POWERSTEP has higher benefits in countries with a high fossil share in the electricity mix. If the grid electricity mix is fully renewable (>75%), POWERSTEP schemes do not improve environmental impacts of WWTP operation, mainly due to higher chemical demand.

Based on the results of this LCA, the **following recommendations** can be formulated:

- The implementation of enhanced carbon extraction with advanced primary treatment such as microscreen or chemical settling significantly improves the energy balance and reduces GHG emissions of municipal wastewater treatment.
- Effluent quality of POWERSTEP schemes can be kept at comparable levels as conventional WWTPs. Depending on effluent targets and influent quality, carbon extraction may have to be limited to safely operate an activated sludge process with denitrification. Sidestream treatment of sludge liquor for N removal can help to reduce the nitrogen load to the mainstream and thus limit COD needs.
- Mainstream anammox is an alternative for nitrogen removal without carbon needs and enables energy-positive WWTP schemes, but its performance and stability has to be validated in full-scale.
- N_2O emissions of biological treatment can substantially contribute to GHG emissions of a WWTP. These direct emissions should be closely monitored to minimize trade-offs between energy savings and N_2O emissions, especially for the mainstream anammox process.
- Wastewater with high concentration generally enables to operate at higher energy efficiency and lower GHG emissions. Hence, sewer system management should target to keep wastewater concentration high by limiting the infiltration of rain or groundwater in the sewer.

As discussed, this LCA study also has **several limitations** which should be taken into account when interpreting its results:

- Data for the scenarios is hypothetical and does not represent a specific WWTP. Site-specific conditions can either increase or decrease the impact of POWERSTEP on the overall energy and GHG balance. Hence, the concept should be checked at each site based on local data.
- Effluent quality is predicted following widely recognized guidelines for activated sludge plants and data from pilot studies. However, dynamic simulations are required to validate predicted effluent quality and compliance with effluent discharge limits, also depending on the type of sampling (e.g. grab, composite) and discharge limit (e.g. 80%-ile of grab samples, daily mean, or annual mean).
- Process data for energy demand and performance for innovative schemes is based on full-scale and pilot trials of new processes. Data has to be validated with on-site trials for the respective wastewater quality. Stability and performance of mainstream anammox should be further validated in full-scale references and at different conditions.
- N_2O emission factors are estimated with basic correlations and results of monitoring. They should be further validated with specific monitoring of conventional and POWERSTEP schemes at the same process conditions.

6. Life Cycle Costing

The goal of this LCC is to estimate investment and operational costs of reference and POWERSTEP schemes and to determine the impact of the POWERSTEP concept on the annual average costs of WWTPs. A simplified approach will be used to calculate costs for infrastructure and operation for each relevant size of WWTP (5,000 pe, 50,000 pe, 500,000 pe) and summarize them to annual costs. Due to the large number of cases and scenarios, the LCC study is limited to one case (A2 = concentrated influent, normal standards) and the related scenarios (cf. chapter 2.4). In addition, membrane stripping as a process to recover N fertilizer is investigated in its impact on operational costs.

Operational costs can be calculated based on operational data for electricity and chemicals demand and sludge disposal, taking unit prices for each item. In addition, costs for personnel and maintenance will be estimated. Investment costs for infrastructure are calculated based on design values of processes (e.g. tank volumes, flows, filter size) for medium-sized WWTP by an engineering company (Krüger A/S) within the POWERSTEP project. For large and small WWTPs, investment costs are extrapolated taking relative assumptions.

Naturally, transferability and precision of cost calculations in this study are affected by a number of issues:

- Investment costs are only for a hypothetical greenfield scenario and cannot be transferred to real cases.
- Location and time can have a distinct impact on investment costs, which are not reflected in this study. The investment estimate relates to conditions in central Europe (e.g. DK, DE) for the year 2017.
- In general, uncertainty of investment costs of complex processes such as WWTPs is high in the planning and design stage, which is addressed by an uncertainty margin in this study.
- Up-scaling and down-scaling of investment costs relies on simple relative assumptions of size-specific cost factors.
- Operational costs depend on assumptions of unit prices, which are set based on the experience of the POWERSTEP partners.

As a result, the conclusions of this LCC should be interpreted with care and can only give an indication of the impacts of POWERSTEP concepts on the overall cost balance of WWTPs. However, the results are seen as valuable to illustrate if POWERSTEP concepts will significantly increase or decrease investment and operational costs for WWTPs, or if these are in a comparable range to the reference scenarios.

6.1. Method

This cost calculation is not a full Life Cycle Costing, which also includes an analysis of the cash flow over time. It is rather a simplified calculation of investment and operational costs, which are then summarized to calculate mean annual costs. All costs and prices relate to conditions in central Europe (e.g. DK, DE) in the year 2017 and represent net costs in Euro.

Operating costs are calculated by multiplying annual process data for energy consumption, production and chemical demand with related unit prices. For personnel costs, required working time is estimated based on annual mean values of the German WWTP sector (DWA 2017) and recalculated in full-time equivalents (FTE). Maintenance costs are estimated as a relative fraction of investment costs per year based on different annual rates for civil works (0.5%), mechanical equipment (2.5%) and electrical equipment (1%).

Investment costs for medium WWTPs are directly received from Krüger A/S and include costs for civil works (concrete structures, piping, site preparation), mechanical equipment, electricity equipment (e.g. MCC, PLC, cables), and staff costs for design, project management and commissioning plus outlay for travel and installation. Data quality of investment costs for medium WWTPs are based on a long experience in WWTP design and building, and are thus of high quality for a scientific study. Up-scaling and down-scaling of investment costs for small and large WWTPs is realized with relative changes in specific (i.e. pe–related) costs.

Total investment costs are converted to annual values using a linear depreciation over the lifetime of the infrastructure (LAWA 2005), assuming an interest rate of 3%. Resulting annuity factors are 0.051, 0.0838 and 0.1005 for lifetimes of 30, 15 and 12 years.

6.2. Data

This chapter summarizes underlying data for the cost study.

6.2.1. Unit prices

Unit prices for electricity, chemicals, sludge disposal and manpower are listed below (Table 10). Electricity price is further increased in sensitivity analysis to show the effect of increasing energy prices on the cost balance of the POWERSTEP scheme.

Same price is assumed for electricity purchase from the grid and electricity sale, as most electricity produced will directly substitute on-site demand and thus avoid grid purchase. For polymer, purchase costs are estimated higher for small and medium WWTPs and lower for large WWTP based on experience of project partners. For sludge disposal, mean price for small WWTPs is estimated to 8.8 € per ton related to thickened sludge which is transported to a centralized treatment facility. For medium and large WWTPs, disposal costs of digested dewatered sludge in mono-incineration are estimated to 50 € per ton.

For the scenario with membrane stripping, costs for chemicals and potential revenue of N fertilizer sale are accounted with unit prices of the case study (Böhler, Hernandez et al. 2018).

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Table 10: Unit prices for operational efforts

Parameter	Unit	Net price	Remarks
Electricity consumption	€/kWh	0.12	Estimate for EU mean
Electricity production	€/kWh	0.12	Comparable to consumption
$FeCl_3$ (40%)	€/kg Fe	1.45	Related to Fe content
Polymer (100%)	€/kg	4.4	For medium and small WWTP
Polymer (100%)	€/kg	3	For large WWTP
NaOH (30%)	€/kg	0.16	For membrane stripping
H_2SO_4 (96%)	€/kg	0.16	For membrane stripping
HCl (32%)	€/kg	0.32	For membrane stripping
N fertilizer	€/kg N	0.87	Diammonium sulfate solution
Sludge disposal	€/t	8.8	Price per original substance for thickened raw sludge disposed at centralized sludge facility
Sludge disposal	€/t	50	Price per original substance for dewatered digested sludge to mono-incineration
Manpower	€/FTE	35,000	Per full-time equivalent (FTE)

6.2.2. **Operating costs**

Underlying data to calculate operational costs is presented below.

For small WWTPs, electricity production is realized in the centralized sludge treatment facility, but is accounted here for the cost balance of the small WWTP (Table 11). The amount of thickened raw sludge to be disposed is lower in POWERSTEP scenarios despite the production of primary sludge: improved thickening of the raw sludge due to chemical dosing and characteristics of primary sludge leads to a DM content of 4-5% DM for POWERSTEP sludge compared to 2-3% DM for the reference scheme. This effect results in an overall reduction of sludge amount to be disposed, and consequently savings in operational costs.

No additional efforts for manpower are calculated for the primary treatment stages in POWERSTEP at small WWTPs, as maintenance and cleaning should be covered by maintenance costs of the process.

Table 11: Data for operating costs of small WWTPs (50,000 pe)

Parameter	Unit	Reference scheme	POWERSTEP with microscreen	POWERSTEP with chemical settling
Electricity consumption	kWh/(pe*a)	24.21	21.53	22.46
Electricity production	kWh/(pe*a)	-7.62	-19.18	-19.20
$FeCl_3$ (40%)	kg Fe/(pe*a)	-	-	-
Polymer (100%)	kg/(pe*a)	0.11	0.34	0.18
Sludge disposal	t/(pe*a)	0.968	0.555	0.555
Manpower	FTE/a	1.5	1.5	1.5

For medium WWTPs, operational data shows that an electricity surplus is reached which generates revenues for the WWTP operator. However, polymer demand is increased with POWERSTEP, and also the amount of dewatered sludge to be disposed in mono-incineration (Table 12). Again, no additional personnel is foreseen for the POWERSTEP scenarios, as the existing personnel (8 FTE) should be able to deal with the upgraded primary treatment during normal operation.

Table 12: Data for operating costs of medium WWTPs (50,000 pe)

Parameter	Unit	Reference scheme	POWERSTEP with microscreen	POWERSTEP with chemical settling
Electricity consumption	kWh/(pe*a)	21.94	16.54	17.15
Electricity production	kWh/(pe*a)	-14.61	-21.79	-20.76
$FeCl_3$ (40%)	kg Fe/(pe*a)	0.99	0.86	0.88
Polymer (100%)	kg/(pe*a)	0.22	0.35	0.25
Sludge disposal	t/(pe*a)	0.061	0.064	0.064
Manpower	FTE/a	8	8	8

For large WWTPs, electricity balance of POWERSTEP schemes is also positive which generates revenues from electricity sale. In contrast, their chemical demand is higher for both coagulant and polymer (Table 13). For POWERSTEP, the amount of sludge to be disposed in mono-incineration increases only marginally (< 5%). The scenario with sidestream membrane stripping requires chemicals for this process, but also generates revenues from N fertilizer sale.

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Table 13: Data for operating costs of large WWTPs (500,000 pe)

Parameter	Unit	Reference scheme	POWERSTEP with microscreen	POWERSTEP with chemical settling	POWERSTEP with microscreen, CAS and membrane stripping
Electricity consumption	kWh/(pe*a)	21.43	15.58	16.40	20.50
Electricity production	kWh/(pe*a)	-17.64	-26.44	-25.40	-22.40
$FeCl_3$ (40%)	kg Fe/(pe*a)	0.45	0.74	0.56	0.73
Polymer (100%)	kg/(pe*a)	0.22	0.3	0.25	0.32
NaOH (30%)	kg/(pe*a)	-	-	-	1.04
H_2SO_4 (96%)	kg/(pe*a)	-	-	-	3.8
HCl (32%)	kg/(pe*a)	-	-	-	0.036
N fertilizer	kg N/(pe*a)	-	-	-	0.285
Sludge disposal	t/(pe*a)	0.058	0.060	0.061	0.060
Manpower	FTE/a	50	50	50	50

6.2.3. Investment costs

Data for investment costs is presented in the results section for all sizes of WWTPs.

For medium WWTPs, investment costs are directly taken from cost estimates of the POWERSTEP partner Krüger A/S, who supplied sums for each type of infrastructure (civil works, mechanical equipment, electrical equipment, and staff).

For down-scaling of investment costs of medium WWTPs to small WWTPs, a relative increase of 30% in size-related investment is assumed for all schemes. In addition, a 50% increase in mechanical equipment is added on top to compensate the effect that the reference scheme has no primary treatment stage, and that POWERSTEP scenarios add mechanical complexity to the plant operation of the simple SBR scheme.

For large WWTPs, investment costs of medium WWTPs are related to the size of the plant (factor 10) and then reduced by 20% to account for economies of scale. No further adjustment of investment costs is included in this study.

For all investment costs, a fixed uncertainty factor of ±25% is added to the calculation to illustrate the high variations in investment costs at the planning/design stage of a WWTP.

6.3. Results

Results are presented for small, medium, and large WWTP for one condition (concentrated influent, normal effluent standards), separated in total investment costs (CAPEX), annual operating costs (OPEX), and annual costs.

6.3.1. Small WWTP (5,000 pe)

Investment for a small WWTP amounts to 2.3 Mio € for the reference plant and 2.7 Mio € for the POWERSTEP schemes (Figure 46). Implementation of a microscreen increases costs for mechanical equipment, whereas civil works is comparable to the reference because additional efforts for microscreen are off-set by a smaller tank for the SBR.

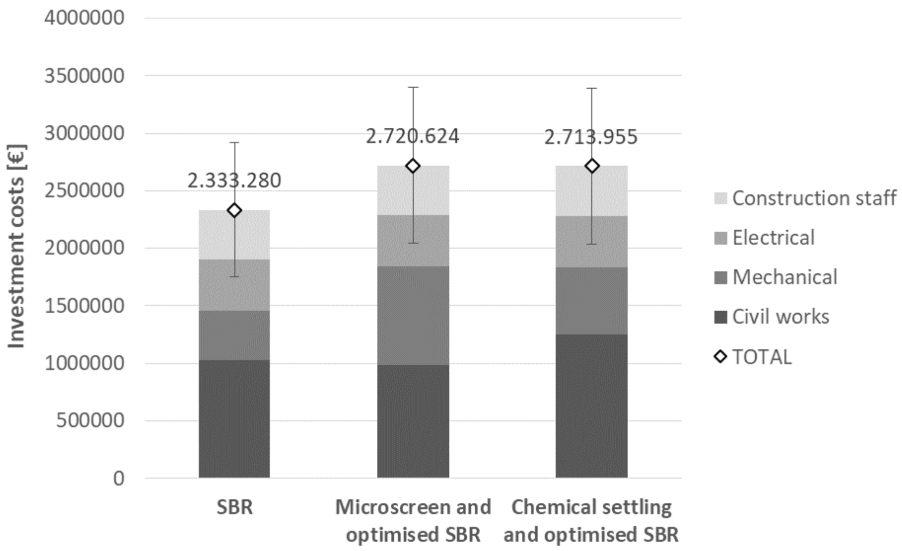

Figure 46: Net investment costs of small WWTPs (5,000 pe) for reference and POWERSTEP schemes (concentrated influent, normal standards)

For the chemical settling (multiflo configuration), civil works are higher than reference for flocculation tanks and lamella settler, but mechanical equipment is not increased significantly. Overall, both POWERSTEP scenarios come out with comparable investment costs for small WWTPs, which are around 17% higher than the reference case. Estimates for extrapolation play a significant role for this result, which should therefore be interpreted with care.

Operational costs of POWERSTEP schemes are between 118 and 126 k€ per year, saving 1-8% of OPEX for the reference scheme (128 k€). The savings are due to an improved energy balance and less costs for electricity purchase, but also due to lower costs for sludge disposal. The latter effect results from the improved thickening of the POWERSTEP primary sludge, so that higher DM content can be reached (4.6% DM instead of 2.8% DM in reference) which decreases the total amount of sludge to be disposed. Costs of polymer increase significantly with POWERSTEP (+57% for chemical settling, +200% for microscreen), but these are completely offset here by savings in electricity and sludge disposal. Finally, POWERSTEP with chemical settling has the lowest OPEX and saves 8% compared to the reference.

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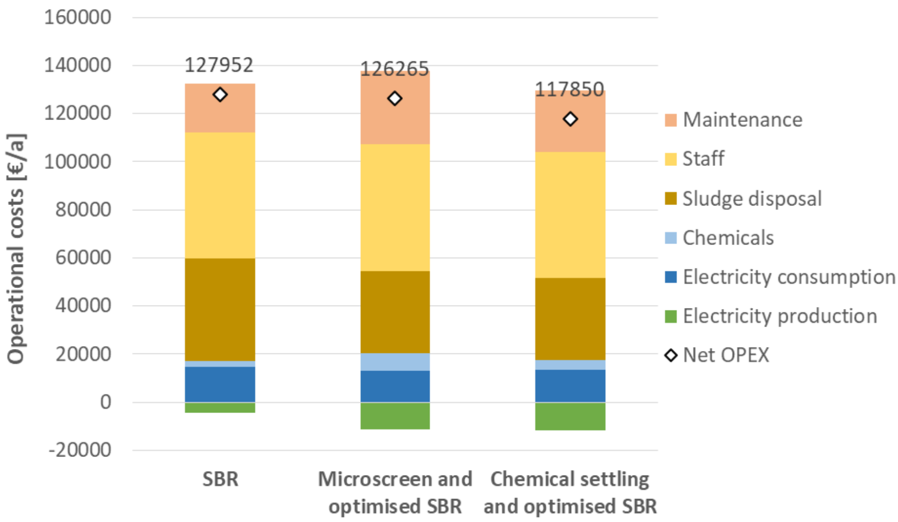

Figure 47: Net annual operating costs of small WWTPs (5,000 pe) for reference and POWERSTEP schemes (concentrated influent, normal standards)

Summarizing CAPEX and OPEX, POWERSTEP schemes increase annual costs by 1 €/(pe*a) or +2% for chemical settling and 4.4 €/(pe*a) or +7% for microscreen compared to the reference with a total of 61 €/(pe*a) (Figure 48). Due to the high share of CAPEX to annual costs (57-65%), POWERSTEP schemes are slightly more expensive as they require a higher investment than the reference plant. Although OPEX savings off-set some of these additional CAPEX of POWERSTEP, the operation of small WWTPs will be more expensive, although working with a superior electricity balance.

Reducing polymer demand of primary treatment and maximizing the positive effect of primary sludge on the thickening efficiency will help to make POWERSTEP schemes fully cost-competitive to the reference SBR.

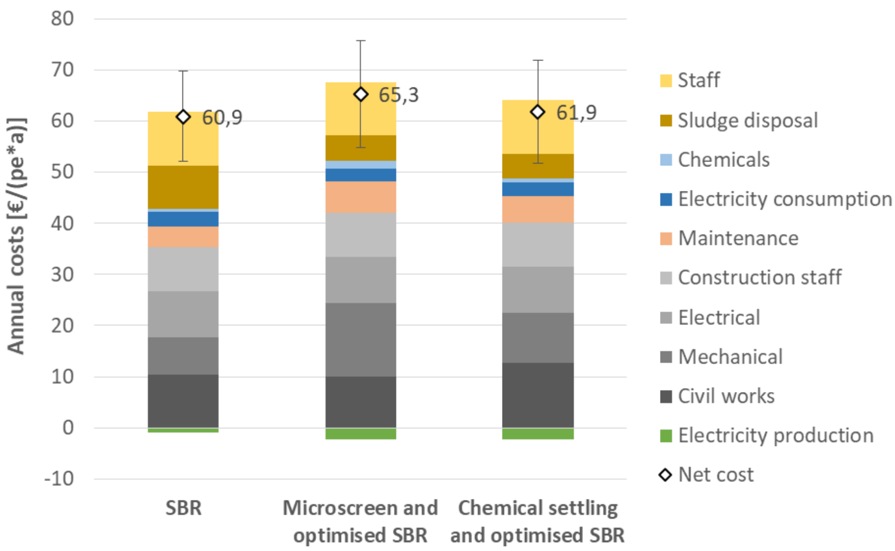

Figure 48: Net annual costs of small WWTPs (5,000 pe) for reference and POWERSTEP schemes (concentrated influent, normal standards)

6.3.2. **Medium WWTP (50,000 pe)**

For medium WWTPs, investment costs of POWERSTEP schemes are 4% higher for both microscreen and chemical settling compared to the reference, increasing CAPEX from 17.9 Mio € to 18.7 Mio € (Figure 49). Here, this is mainly due to higher expenses for mechanical equipment, which is 31-35% higher with POWERSTEP. Civil works is comparable to the reference, although the size of the biological tank can be reduced by a factor of 4 (cf. Table 45) in POWERSTEP. However, additional civil works is required for coagulation and filtration tanks and microscreen or chemical settling, so that overall costs for civil works are comparable. It should be noted here that investment costs for medium WWTPs have been directly produced by an engineering company (Krüger A/S).

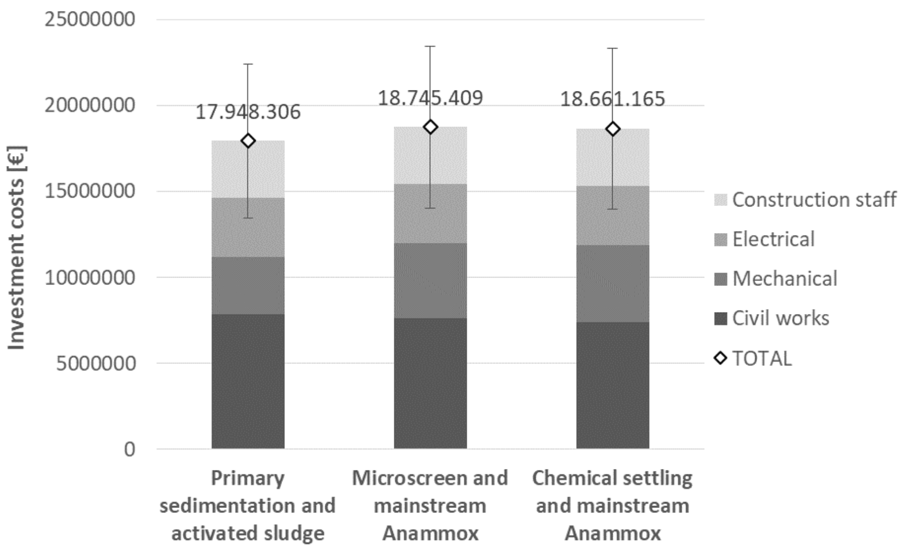

Figure 49: Net investment costs of medium WWTPs (50,000 pe) for reference and POWERSTEP schemes (concentrated influent, normal standards)

For OPEX, POWERSTEP schemes can save 25-35k€ per year or 3-5% from the operating costs of the reference scheme (755k€) (Figure 50). Due to the positive electricity balance of POWERSTEP, revenues can be generated which reduce overall OPEX by 1.3-1.5 €/(pe*a). However, this effect is partly compensated by higher chemical demand for microscreen (+0.4 €/(pe*a)) and higher maintenance costs for both POWERSTEP scenarios (+0.5 €/(pe*a) originating from higher CAPEX.

Overall, it can be concluded that POWERSTEP can slightly reduce OPEX of medium WWTPs due to their superior energy balance, but the effect is partly compensated by higher costs for chemicals and maintenance. It is interesting to note that OPEX for electricity consumption are just 0.9 €/(pe*a) or 6% of the total net OPEX in the reference case with 67% electrical self-sufficiency. Hence, electricity is not a major contributor to net OPEX, which leads to a low savings potential of the POWERSTEP approach.

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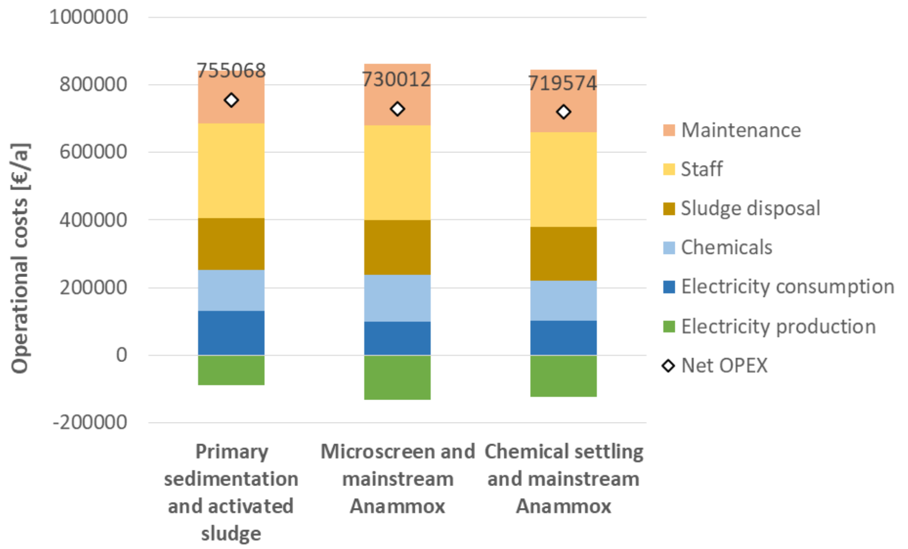

Figure 50: Net annual operating costs of medium WWTPs (50,000 pe) for reference and POWERSTEP schemes (concentrated influent, normal standards)

POWERSTEP scenarios increase annual costs of the reference scheme (42 €/(pe*a)) by 2% or 0.8-1 €/(pe*a) (Figure 51). Again, higher CAPEX of POWERSTEP are compensated by lower OPEX, so that the overall impact of POWERSTEP on annual costs is small. Due to the high uncertainty of investment costs, the small difference between reference and POWERSTEP schemes is within the uncertainty range of annual costs of all scenarios.

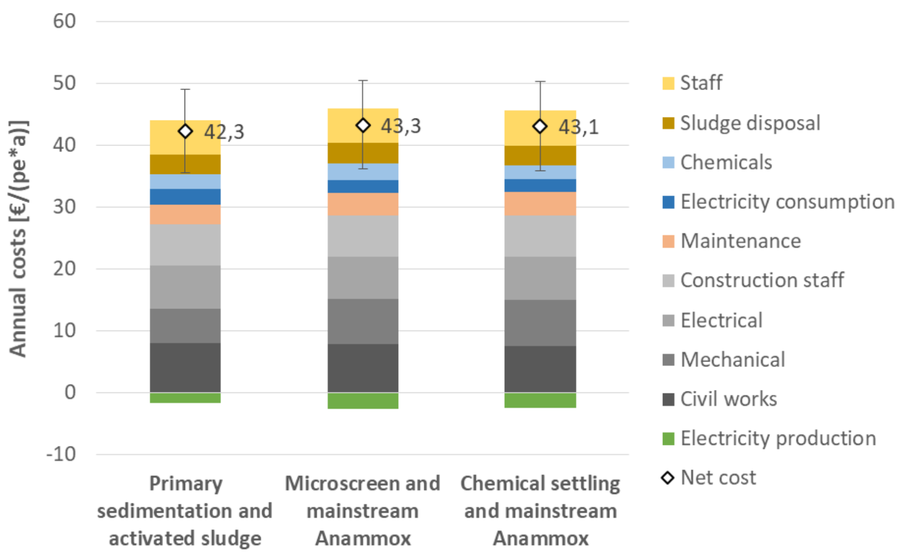

Figure 51: Net annual costs of medium WWTPs (50,000 pe) for reference and POWERSTEP schemes (concentrated influent, normal standards)

6.3.3. **Large WWTP (500,000 pe)**

For large WWTP, POWERSTEP increases CAPEX of reference scheme (143.6 Mio €) by about 4% or 5.7-6.4 Mio € for chemical settling or microscreen (Figure 52). Due to the linear extrapolation from medium WWTPs, the relative effects of POWERSTEP are fully comparable between the two sizes. Again, the main additional CAPEX of POWERSTEP are in the mechanical equipment, which is 31-35% higher than in the reference scheme. Volumes for biological tank and clarifier are smaller in POWERSTEP (cf. Table 46), but additional stages for primary treatment such as coagulation/flocculation tanks compensate this effect and lead to comparable costs for civil works.

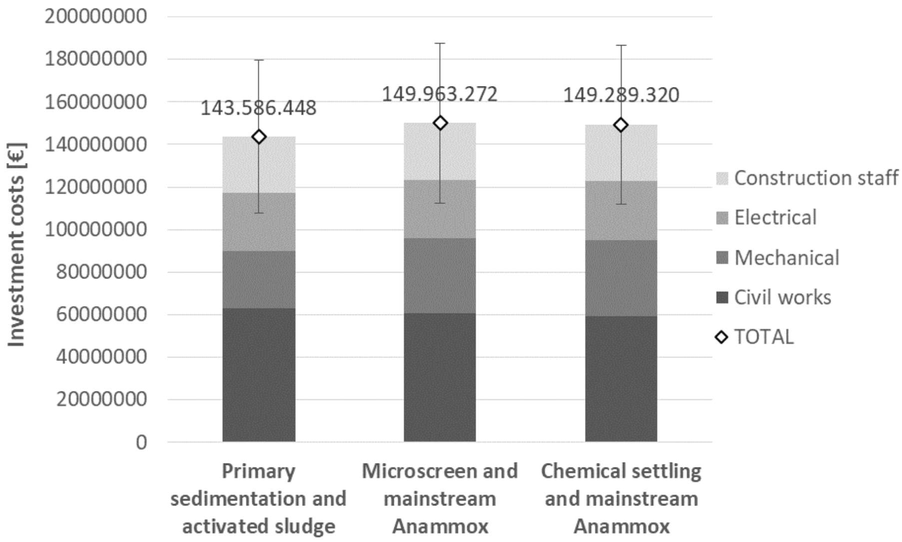

Figure 52: Net investment costs of large WWTPs (500,000 pe) for reference and POWERSTEP schemes (concentrated influent, normal standards)

The linear extrapolation of investment costs for medium WWTPs to larger size may however underestimate the efforts for POWERSTEP: medium WWTPs operate with chemical P elimination and intermediate denitrification as a reference, while large WWTPs have biological P elimination and pre-denitrification. Hence, the reduction in tank volume for the biological stage by POWERSTEP is higher for medium plants (factor 4) then for large plants (factor 1.3), although the impact on costs for civil works is comparable with linear extrapolation. However, these differences could not be further investigated in this study, as detailed cost data for infrastructure items was not available (e.g. €/m³ tank volume).

OPEX of large WWTPs show the same tendency than medium WWTPs: the positive electricity balance of POWERSTEP enables revenues from electricity sale, whereas chemical costs and maintenance are higher than in the reference case (Figure 53). Overall, POWERSTEP schemes decrease operating costs of reference (5.3 Mio €/a) by 242k€ (-5%) and 365k€ (-7%) with microscreen or chemical settling, respectively. Again, electricity is not a major cost factor in the net OPEX of the reference, contributing just over 4% at an electrical self-sufficiency of 82%.

Membrane stripping in combination with CAS systems is clearly not economic in operational costs in this study (Figure 55): costs for chemicals with 0.8 e/(pe*a) exceed revenues from N fertilizer sale (0.25 €/(pe*a)) by a factor of 3. The major cost driver for membrane stripping is NaOH with 77% of chemical costs, so its demand should be minimized to reduce operational costs of membrane stripping. Overall, a POWERSTEP

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scenario with microscreen, CAS and sidestream membrane stripping increases net OPEX of large WWTPs by 10% compared to the reference scheme.

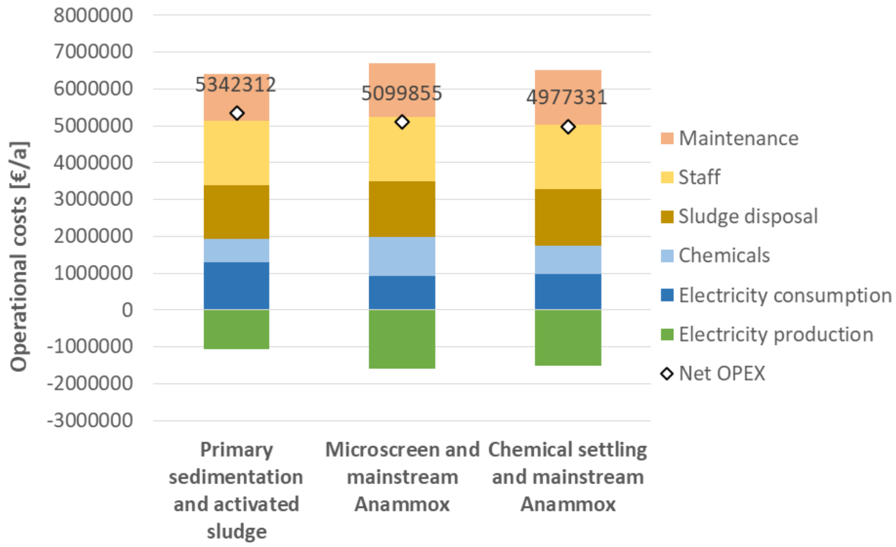

Figure 53: Net annual operating costs of large WWTPs (500,000 pe) for reference and POWERSTEP schemes (concentrated influent, normal standards)

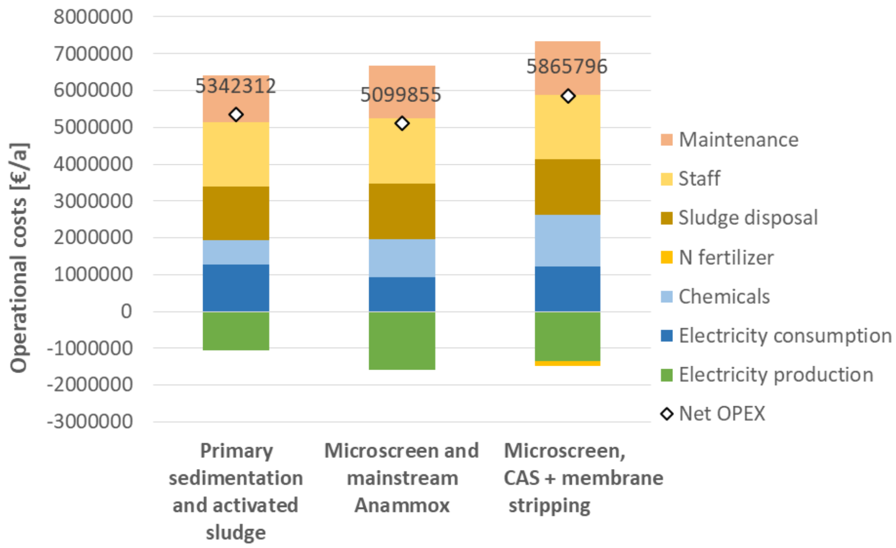

Figure 54: Net annual operating costs of large WWTPs (500,000 pe) for reference and POWERSTEP schemes with mainstream anammox or CAS + membrane stripping (concentrated influent, normal standards)

Summing up CAPEX and OPEX, total annual costs are again comparable between reference scheme with 32 €/(pe*a) and POWERSTEP schemes with 33 €/(pe*a). Compensation of lower OPEX with higher CAPEX leads to higher annual costs of 1€/(pe*a) for the POWERSTEP schemes, which is again within the uncertainty range of the calculation (Figure 55).

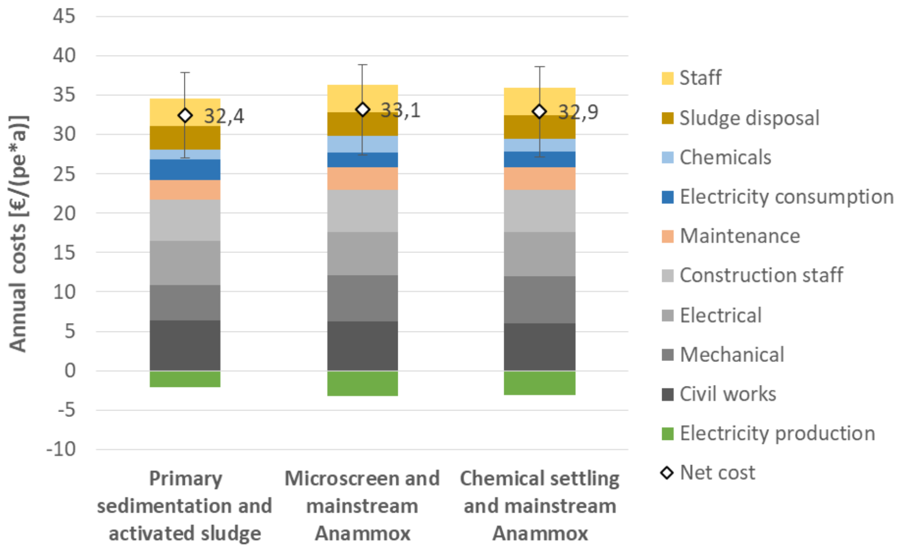

Figure 55: Net annual costs of large WWTPs (500,000 pe) for reference and POWERSTEP schemes (concentrated influent, normal standards)

6.3.4. Sensitivity to electricity prices

The positive effect of POWERSTEP schemes on the OPEX of WWTPs and thus on the annual cost balance is found to be quite low, because remaining electricity costs form only a minor part of the total net OPEX for all reference schemes (4-8%). This is due to the assumed unit prices for electricity (0.12 €/kWh) in relation to prices for chemicals, staff, or sludge disposal. If electricity has a higher share of total OPEX, the POWERSTEP schemes would be more favourable in OPEX and thus maybe also in total annual costs.

This effect is illustrated in sensitivity analysis, where electricity prices are increased to 0.2 and 0.25 €/kWh for all scenarios. Results of this analysis show that an increase of electricity price to 0.2 €/kWh will lead to comparable or lower annual costs of POWERSTEP for all sizes of WWTPs (Figure 56).

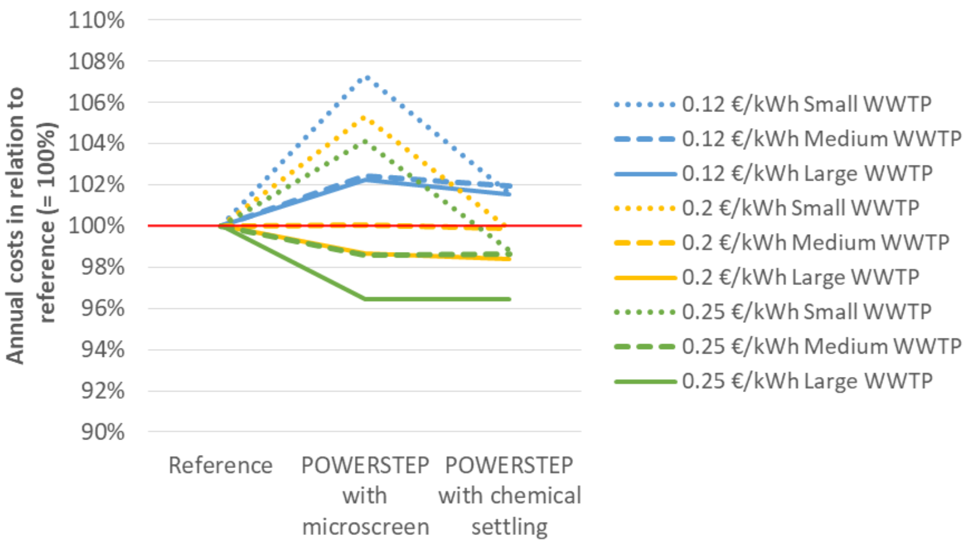

Figure 56: Sensitivity of annual costs for all sizes of WWTP to higher electricity prices

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Raising electricity price to 0.25 €/kWh finally leads to a reduction in annual costs for POWERSTEP with all WWTP sizes. This analysis exemplifies again that electricity prices and related share of electricity purchase to total OPEX play an important role for the economic viability of the POWERSTEP approach. While POWERSTEP may slightly increase annual costs of reference WWTPs at lower electricity prices, higher electricity prices lead to substantial savings in OPEX which can over-compensate additional investment in POWERSTEP technologies.

6.4. LCC: conclusions and interpretation

Investment and operational costs have been calculated for reference and POWERSTEP schemes for all WWTP sizes at conditions of concentrated influent and normal standards. While operational costs are based on process data and unit prices, investment costs were determined for medium WWTPs by an engineering company and extrapolated to small and large plants. Finally, investment and operational costs are summarized into total annual costs, using linear depreciation for the different types of infrastructure over their respective lifetime.

Results show that POWERSTEP schemes increase investment costs by 4% for medium and large WWTPs and by 17% for small WWTPs, mainly due to the mechanical equipment of advanced primary treatment (Table 14). Operating costs can be reduced by POWERSTEP between 9-16% for small WWTPs and 3-7% for medium and large WWTPs, which is due to the lower costs for electricity purchase or – in case of positive electricity balance – the revenues from electricity sale.

Table 14: Results of LCC for investment, operational and total annual costs for reference and POWERSTEP schemes

WWTP size	TN effluent limit	Cost type	Unit	Reference scheme	POWERSTEP scheme	Relative effect
5,000 pe	-	CAPEX[1]	€/pe	467	544	+17%
		OPEX	€/(pe*a)	25.6	21.6-23.3	- 9-16%
		Annual costs	**€/(pe*a)**	**60.9**	**61.9-65.3**	**+2-7%**
50,000 pe	18 mg/L	CAPEX	€/pe	359	374	+4%
		OPEX	€/(pe*a)	15.1	14.4-14.6	- 3-5%
		Annual costs	**€/(pe*a)**	**42.3**	**43.1-43.3**	**+2%**
500,000 pe	13 mg/L	CAPEX[1]	€/pe	287	300	+4%
		OPEX	€/(pe*a)	10.7	10.0-10.2	- 5-7%
		Annual costs	**€/(pe*a)**	**32.4**	**32.9-33.1**	**+2%**

Costs data is for scenarios with concentrated influent

[1] *linear extrapolation from medium WWTPs*

Overall, the annual costs of wastewater treatment are slightly increased by POWERSTEP: +2-7% or 1-4.4 €/(pe*a) for small WWTPs and 4% or around 1 €/(pe*a) for medium and large WWTPs. Sensitivity analysis shows that POWERSTEP schemes get economically beneficial with higher electricity prices (0.2 €/kWh and higher), so that the benefits of higher electrical self-sufficiency are more important for the overall cost balance.

Based on the results, the following conclusions can be drawn from this hypothetical cost study:

- **POWERSTEP schemes increase investment costs for WWTPs by 4-17% due to advanced primary treatment.** Some costs could be compensated by smaller downstream stages (e.g. biological tank), but this effect could not be exactly quantified in this study.
- **POWERSTEP decrease operational costs by 3-16% due to higher electrical self-sufficiency and resulting lower costs for electricity purchase.** Additional costs for chemicals and sludge disposal are fully compensated by savings in electricity purchase. For small plants, better thickening of primary sludge has a high positive impact on operational costs of sludge disposal.
- **Overall, POWERSTEP may increase total annual costs of wastewater treatment by 2-7% or 1-4.4 € per population equivalent and year**. However, differences between POWERSTEP and reference schemes are within the uncertainty range originating from variations in investment cost.
- **Higher electricity prices will lead to an improved cost balance for POWERSTEP, making it economically competitive to the reference schemes**. With electricity prices > 0.2 €/kWh, the effect of a superior electricity balance fully compensates higher investments and will reduce annual costs of wastewater treatment.

All conclusions have to be interpreted with care, as the simple method of cost calculation in this study is affected by several short-comings:

- Investment costs are linearly extrapolated from medium to small and large plants based on best estimates of increasing specific costs with smaller plants. However, extrapolation factors could be different between reference and POWERSTEP schemes, but are kept constant in this study.
- Different types of technology for the reference schemes of small, medium and large WWTPs will certainly have an impact on infrastructure design and resulting costs. This is another short-coming of the linear extrapolation approach used in this study. Further studies should clarify this aspect based on design values provided in this report.
- Uncertainty in investment costs will contribute to high uncertainty in annual costs, so the trade-off "lower OPEX vs. higher CAPEX" could be different for POWERSTEP if investment contribution to total annual cost is changed.

Finally, a valid outcome of this LCC seems to be that **POWERSTEP does not significantly alter total annual costs of wastewater treatment**. Depending on conditions and unit prices, higher investment is partly or fully compensated by lower operational costs, so that **overall the POWERSTEP concept is economically competitive to the "state-of-the-art" scheme of wastewater treatment.**

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7. Summary and conclusions

This study analyses reference and innovative schemes for municipal WWTP in their environmental and economic impacts using life-cycle tools of LCA and LCC. Based on hypothetical scenarios at defined boundary conditions for WWTP size, influent quality, and effluent discharge limits, multiple process schemes have been modelled in a mass and energy flow model with a benchmarking software for WWTPs. This process data forms the basis to calculate operational efforts, and it is amended by infrastructure data for material demand and related investment costs. In addition, specific data has been added based on results of the POWERSTEP project (e.g. for N_2O emissions) or information from literature.

This chapter summarizes the main results of the LCA and LCC and gives recommendations for eco-efficient new schemes of energy-positive WWTP.

7.1. Results of LCA and LCC

Major outcomes of LCA and LCC in this report can be summarized as follows:

Energy efficiency versus effluent quality

- POWERSTEP schemes with advanced primary treatment using microscreen or chemical settling operate with a superior electricity balance compared to current state-of-the-art schemes for municipal wastewater treatment as a reference. They increase electrical self-sufficiency from 27-82% for conventional WWTPs to 80-170% in POWERSTEP WWTPs.
- The POWERSTEP schemes reach this goal without compromising effluent quality targets of the schemes, i.e. reaching the same effluent quality than before. These results are based on static modelling (DWA 2016) and should be confirmed with dynamic modelling.
- Depending on the conditions for influent quality and effluent targets, POWERSTEP schemes can be operated with a positive electricity balance, yielding an electricity surplus at the WWTP. Concentrated influent with high COD levels supports the POWERSTEP effect and enables highly energy efficient schemes. However, nitrogen removal has to be realized with mainstream anammox after enhanced carbon extraction from concentrated influent. This process is still under development, and its performance and stability should be further validated in full-scale references.
- Sidestream N removal can be another option to reduce N loads to the mainstream and still enable the operation of conventional denitrification in POWERSTEP. However, benefits for electricity balance are lower for these schemes compared to POWERSTEP schemes with mainstream anammox.

Life-cycle impacts on environmental aspects

- In the life-cycle perspective, POWERSTEP schemes significantly decrease primary energy demand of WWTP operation by 29-134% compared to state-of-the art WWTPs today. In favourable conditions, the superior electricity balance of

POWERSTEP can fully compensate life-cycle energy demand for chemical production, sludge disposal and infrastructure, resulting in real energy-positive WWTP schemes.

- Greenhouse gas emissions can also be substantially reduced by POWERSTEP (- 6 to 43%) compared to the reference schemes due to savings in grid electricity production. GHG benefits of POWERSTEP are smaller because direct emissions such as N_2O from biological N removal and mono-incineration also deliver a major contribution to overall GHG emission profiles, and they are not reduced with POWERSTEP. In contrast, POWERSTEP schemes with mainstream anammox will most likely increase N_2O emissions, compensating a large part of the electricity-related benefits in GHG emissions.

Life-cycle impacts on economic aspects

- Total annual costs are in a comparable range for both reference and POWERSTEP schemes. While POWERSTEP decreases operational costs by 3-16% due to lower purchase of grid electricity, they require higher investment for primary treatment, increasing capital costs by 4-17%. Overall, effects of POWERSTEP on operational and capital costs off-set each other and result in a net increase of total annual costs of 2-7% which is within the uncertainty range of this cost calculation.
- Higher electricity prices (> 0.12 €/kWh) will increase the positive impact of POWERSTEP on operating costs. With electricity prices at 0.25 €/kWh, POWERSTEP schemes are economically competitive to state-of-the-art WWTP schemes with conventional technology.

7.2. Recommendations for eco-efficient new schemes of energy positive WWTP

From the results of this study, several recommendations can be derived towards the design of innovative schemes for municipal wastewater treatment with high eco-efficiency.

As a prerequisite of all approaches to increase eco-efficiency, **it should be guaranteed that effluent quality of the WWTP process is not deteriorated** by the changes in process setup. The primary function of WWTPs and their main ecological benefit is the purification of wastewater to reduce pollutant loads to receiving waters. Consequently, a degradation of this priority function cannot be accepted while improving their eco-efficiency. The latter goal can only be a second priority in the design process, and should be pursued as such.

In particular, the following aspects should be considered when designing eco-efficient WWTP schemes:

- **Enhanced extraction of organic matter** in primary stage is a suitable way to improve the energy balance of municipal WWTPs and improve the overall eco-efficiency of the process.
- **Concentrated influent** with high COD concentration has a positive impact on the energy efficiency of WWTPs. Hence, sewer system management should target to

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minimize dilution of municipal wastewater by rainwater or infiltrating groundwater to enable eco-efficient wastewater treatment.

- **Downstream nitrogen removal** can be guaranteed by optimizing COD use for denitrification, partial bypassing of primary treatment, reducing of N return load with sidestream treatment, or switching the biological process to mainstream anammox. The latter process should be further investigated in full-scale to validate its performance and stability.
- **Direct N_2O emissions of biological stage** can quickly compensate savings in indirect greenhouse gas emissions due to superior energy balance. Nitrogen removal with limited COD may lead to higher N_2O emissions, so this issue has to be carefully investigated to prevent negative effects on GHG emissions.
- **Annual costs of eco-efficient WWTP schemes are competitive** to conventional schemes, so eco-efficiency can be reached by spending the same amount of money for the same treatment result. Eco-efficient schemes are characterized by lower costs for electricity purchase, but higher investment. The effects compensate each other depending on the price of electricity and the specific cost for infrastructure.
- **High electricity prices** facilitate the design of cost-competitive AND eco-efficient schemes for municipal wastewater treatment.

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9. Annex

9.1. Inventory data of small WWTP (5,000 pe)

Table 15: Electricity, heat and chemical demand and energy production of reference scenarios for small WWTP (5'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Electricity balance					
Mechanical and primary treatment	kWh/(pe*a)	2.8	2.6	2.8	2.6
Sequencing batch reactor	kWh/(pe*a)	19.5	17.2	20.5	18.5
Miscellaneous	kWh/(pe*a)	0.0	0.0	0.0	0.0
Sludge treatment (centralized)	kWh/(pe*a)	4.8	4.9	4.2	4.2
Total electricity demand	kWh/(pe*a)	27.2	24.7	27.5	25.3
Electricity production in CHP (centralized)	kWh/(pe*a)	-13.5	-14.1	-7.5	-7.6
NET electricity demand	**kWh/(pe*a)**	**13.7**	**10.6**	**20.0**	**17.7**
Electrical self sufficiency	%	50%	57%	27%	30%
Heat balance					
Heat demand for digestor	kWh/(pe*a)	16.7	17.1	13.9	14.3
Heat production in CHP	kWh/(pe*a)	30.5	31.6	20.4	20.7
NET heat demand	**kWh/(pe*a)**	**-13.8**	**-14.5**	**-6.4**	**-6.4**
Heat self sufficiency	%	183%	185%	146%	145%
Chemical consumption					
Polymer for primary treatment	kg AS/(pe*a)	0.00	0.00	0.00	0.00
Polymer for sludge treatment	kg AS/(pe*a)	0.12	0.13	0.11	0.12

Table 16: Electricity, heat and chemical demand and energy production of POWERSTEP 1 scenarios with microscreen for small WWTP (5'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Electricity balance					
Mechanical and primary treatment	kWh/(pe*a)	3.6	3.1	3.6	3.1
Sequencing batch reactor	kWh/(pe*a)	12.0	10.3	15.8	14.1
Miscellaneous	kWh/(pe*a)	0.0	0.0	0.0	0.0
Sludge treatment (centralized)	kWh/(pe*a)	4.7	4.7	4.1	4.4
Total electricity demand	kWh/(pe*a)	20.2	18.2	23.5	21.5
Electricity production in CHP (centralized)	kWh/(pe*a)	-21.1	-22.1	-19.6	-19.2
NET electricity demand	**kWh/(pe*a)**	**-0.9**	**-3.9**	**3.9**	**2.3**
Electrical self sufficiency	%	104%	122%	83%	89%
Heat balance					
Heat demand for digestor	kWh/(pe*a)	17.5	18.0	15.5	16.6
Heat production in CHP	kWh/(pe*a)	41.6	43.2	38.0	38.3
NET heat demand	**kWh/(pe*a)**	**-24.1**	**-25.3**	**-22.4**	**-21.6**
Heat self sufficiency	%	238%	241%	244%	230%
Chemical consumption					
Polymer for primary treatment	kg AS/(pe*a)	0.20	0.21	0.20	0.20
Polymer for sludge treatment	kg AS/(pe*a)	0.15	0.15	0.13	0.13

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Table 17: Electricity, heat and chemical demand and energy production of POWERSTEP 2 scenarios with chemical settling for small WWTP (5'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Electricity balance					
Mechanical and primary treatment	kWh/(pe*a)	4.4	3.9	4.4	3.9
Sequencing batch reactor	kWh/(pe*a)	11.9	10.3	15.8	14.0
Miscellaneous	kWh/(pe*a)	0.0	0.0	0.0	0.0
Sludge treatment (centralized)	kWh/(pe*a)	4.7	4.9	4.3	4.5
Total electricity demand	kWh/(pe*a)	21.0	19.1	24.5	22.4
Electricity production in CHP (centralized)	kWh/(pe*a)	-21.1	-22.1	-19.6	-19.2
NET electricity demand	**kWh/(pe*a)**	**-0.1**	**-3.0**	**5.0**	**3.2**
Electrical self sufficiency	%	100%	116%	80%	86%
Heat balance					
Heat demand for digestor	kWh/(pe*a)	17.5	18.0	16.0	16.6
Heat production in CHP	kWh/(pe*a)	41.5	43.2	38.3	38.3
NET heat demand	**kWh/(pe*a)**	**-24.0**	**-25.3**	**-22.3**	**-21.7**
Heat self sufficiency	%	237%	241%	240%	230%
Chemical consumption					
Polymer for primary treatment	kg AS/(pe*a)	0.09	0.04	0.09	0.04
Polymer for sludge treatment	kg AS/(pe*a)	0.15	0.15	0.13	0.13

Table 18: Treatment efficiencies of primary treatment and SBR and effluent quality of reference scenarios for small WWTP (5'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Primary treatment					
TS removal	%	0	0	0	0
COD removal	%	0	0	0	0
TN removal	%	0	0	0	0
TP removal	%	0	0	0	0
SBR					
TS removal	%	93	97	93	97
COD removal	%	91	93	92	93
TN removal	%	29	32	72	86
TP removal	%	29	32	29	32
WWTP effluent					
Volume	$m^3/(pe*a)$	86.8	43.0	86.7	42.9
TS	mg/L	20	20	20	20
COD	mg/L	44	66	42	65
TN	mg/L	34	66	13	13
TP	mg/L	5	11	5	11

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Table 19: Treatment efficiencies of primary treatment and SBR and effluent quality of POWERSTEP1 scenarios with microscreen for small WWTP (5'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Primary treatment					
TS removal	%	80	80	80	80
COD removal	%	50	52	52	52
TN removal	%	15	16	16	16
TP removal	%	18	19	19	19
SBR					
TS removal	%	66	83	66	88
COD removal	%	81	85	81	87
TN removal	%	14	16	66	83
TP removal	%	15	18	14	19
WWTP effluent					
Volume	$m^3/(pe*a)$	87.0	43.2	87.1	43.2
TS	mg/L	20	20	20	20
COD	mg/L	48	71	45	68
TN	mg/L	34	67	14	14
TP	mg/L	5	10	5	10

Table 20: Treatment efficiencies of primary treatment and SBR and effluent quality of POWERSTEP2 scenarios with chemical settling for small WWTP (5'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Primary treatment					
TS removal	%	80	80	80	80
COD removal	%	50	52	52	52
TN removal	%	16	17	16	17
TP removal	%	19	20	19	20
SBR					
TS removal	%	67	83	66	88
COD removal	%	81	85	81	87
TN removal	%	14	16	66	83
TP removal	%	15	18	14	19
WWTP effluent					
Volume	$m^3/(pe*a)$	87.0	43.2	87.1	43.2
TS	mg/L	20	20	20	20
COD	mg/L	47	71	45	68
TN	mg/L	34	67	14	14
TP	mg/L	5	10	5	10

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Table 21: Raw and digested sludge, biogas production and valorisation, and return load of reference scenarios for small WWTP (5'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Thickened mixed sludge					
VOL	$m^3/(pe*a)$	0.8	0.8	0.9	1.0
TS	kg/(pe*a)	23.4	23.9	19.6	20.1
COD	kg/(pe*a)	22.2	23.1	17.9	18.1
TN	kg/(pe*a)	1.1	1.2	0.7	0.7
TP	kg/(pe*a)	0.2	0.2	0.2	0.2
Biogas utilization					
Volume	$Nm^3/(pe*a)$	6.3	6.6	3.5	3.6
	NL/(kg VS in)	327	328	227	226
Methane content	Vol-%	62	62	62	62
CHP electrical efficiency	%	38	38	38	38
CHP thermal efficiency	%	52	52	52	52
Dewatered digested sludge					
Mass	kg/(pe*a)	48.3	48.5	41.7	42.9
TS	kg/(pe*a)	12.0	12.1	10.4	10.7
COD	kg/(pe*a)	10.7	11.2	8.6	8.7
TN	kg/(pe*a)	0.8	0.9	0.5	0.5
TP	kg/(pe*a)	0.2	0.2	0.2	0.2
Return load[1]					
Volume	$m^3/(pe*a)$	0.8	0.8	0.9	0.9
TS	mg/L	2358	2315	1694	1641
COD	mg/L	528	537	556	555
TN	mg/L	358	352	274	266
TP	mg/L	19	19	16	16

[1] only for dewatering in centralized WWTP

Table 22: Raw and digested sludge, biogas production and valorisation, and return load of POWERSTEP scenarios with microscreen for small WWTP (5'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Thickened mixed sludge					
VOL	$m^3/(pe*a)$	0.6	0.6	0.5	0.6
TS	kg/(pe*a)	27.4	28.0	25.0	25.0
COD	kg/(pe*a)	30.0	31.4	27.8	27.3
TN	kg/(pe*a)	1.0	1.1	0.8	0.8
TP	kg/(pe*a)	0.2	0.2	0.2	0.2
Biogas utilization					
Volume	$Nm^3/(pe*a)$	9.9	10.3	9.2	9.0
	NL/(kg VS in)	379	379	379	378
Methane content	Vol-%	62	62	62	62
CHP electrical efficiency	%	38	38	38	38
CHP thermal efficiency	%	52	52	52	52
Dewatered digested sludge					
Mass	kg/(pe*a)	54.7	54.8	49.3	49.9
TS	kg/(pe*a)	13.7	13.7	12.3	12.5
COD	kg/(pe*a)	14.7	15.4	13.7	13.4
TN	kg/(pe*a)	0.8	0.8	0.6	0.6
TP	kg/(pe*a)	0.2	0.2	0.2	0.2
Return load[1]					
Volume	$m^3/(pe*a)$	0.5	0.6	0.5	0.5
TS	mg/L	1338	1303	1369	1286
COD	mg/L	500	500	508	500
TN	mg/L	500	500	508	500
TP	mg/L	27	26	15	20

[1] only for dewatering in centralized WWTP

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Table 23: Raw and digested sludge, biogas production and valorisation, and return load of POWERSTEP scenarios with chemical settling for small WWTP (5’000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Thickened mixed sludge					
VOL	m³/(pe*a)	0.6	0.6	0.5	0.6
TS	kg/(pe*a)	27.4	28.0	25.0	25.0
COD	kg/(pe*a)	30.0	31.4	27.8	27.3
TN	kg/(pe*a)	1.0	1.1	0.8	0.8
TP	kg/(pe*a)	0.2	0.2	0.2	0.2
Biogas utilization					
Volume	Nm³/(pe*a)	9.9	10.3	9.2	9.0
	NL/(kg VS in)	378	379	379	379
Methane content	Vol-%	62	62	62	62
CHP electrical efficiency	%	38	38	38	38
CHP thermal efficiency	%	52	52	52	52
Dewatered digested sludge					
Mass	kg/(pe*a)	54.7	54.6	49.3	49.9
TS	kg/(pe*a)	13.7	13.7	12.3	12.5
COD	kg/(pe*a)	14.7	15.4	13.7	13.4
TN	kg/(pe*a)	0.8	0.8	0.6	0.6
TP	kg/(pe*a)	0.2	0.2	0.2	0.2
Return load[1]					
Volume	m³/(pe*a)	0.5	0.6	0.5	0.5
TS	mg/L	1338	1289	1328	1286
COD	mg/L	500	500	507	500
TN	mg/L	500	500	507	500
TP	mg/L	20	20	19	20

[1] only for dewatering in centralized WWTP

9.2. Inventory data of medium WWTP (50,000 pe)

Table 24: Electricity, heat and chemical demand and energy production of reference scenarios for medium WWTP (50'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Electricity balance					
Mechanical and primary treatment	kWh/(pe*a)	1.3	0.9	1.3	0.9
Biological treatment	kWh/(pe*a)	14.7	14.2	15.2	14.8
Tertiary treatment	kWh/(pe*a)	0.0	0.0	2.0	1.1
Miscellaneous	kWh/(pe*a)	1.6	1.6	1.6	1.6
Sludge treatment	kWh/(pe*a)	4.2	4.2	4.6	4.4
Total electricity demand	kWh/(pe*a)	21.8	20.9	24.7	22.9
Electricity production in CHP	kWh/(pe*a)	-13.9	-14.0	-14.2	-13.8
NET electricity demand	**kWh/(pe*a)**	**8.0**	**6.9**	**10.6**	**9.0**
Electrical self sufficiency	%	64%	67%	57%	61%
Heat balance					
Heat demand for digestor	kWh/(pe*a)	17.3	18.0	18.8	18.9
Heat production in CHP	kWh/(pe*a)	32.3	33.0	33.9	33.4
NET heat demand	**kWh/(pe*a)**	**-15.0**	**-15.0**	**-15.0**	**-14.5**
Heat self sufficiency	%	187%	183%	180%	177%
Chemical consumption					
Polymer for primary treatment	kg AS/(pe*a)	0.00	0.00	0.00	0.00
Polymer for tertiary treatment	kg AS/(pe*a)	0.00	0.00	0.02	0.04
$FeCl_3$ (100%)	kg $FeCl_3$/(pe*a)	2.42	2.88	3.12	3.65
Polymer for sludge treatment	kg AS/(pe*a)	0.27	0.29	0.30	0.33

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Table 25: Electricity, heat and chemical demand and energy production of POWERSTEP scenarios with microscreen for medium WWTP (50'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Electricity balance					
Mechanical and primary treatment	kWh/(pe*a)	2.1	1.4	3.1	1.3
Biological treatment	kWh/(pe*a)	12.6	9.4	11.8	9.3
Tertiary treatment	kWh/(pe*a)	0.0	0.0	1.8	1.0
Miscellaneous	kWh/(pe*a)	1.5	1.4	1.6	1.5
Sludge treatment	kWh/(pe*a)	4.1	4.3	5.0	4.4
Total electricity demand	kWh/(pe*a)	20.4	16.5	23.4	17.4
Electricity production in CHP	kWh/(pe*a)	-17.7	-21.8	-18.6	-22.6
NET electricity demand	**kWh/(pe*a)**	**2.6**	**-5.3**	**4.8**	**-5.1**
Electrical self sufficiency	%	87%	132%	80%	129%
Heat balance					
Heat demand for digestor	kWh/(pe*a)	18.4	19.8	19.9	20.6
Heat production in CHP	kWh/(pe*a)	38.6	45.4	40.9	47.2
NET heat demand	**kWh/(pe*a)**	**-20.2**	**-25.6**	**-21.0**	**-26.5**
Heat self sufficiency	%	210%	229%	205%	228%
Chemical consumption					
Polymer for primary treatment	kg AS/(pe*a)	0.15	0.16	0.22	0.19
Polymer for tertiary treatment	kg AS/(pe*a)	0.00	0.00	0.02	0.01
$FeCl_3$ (100%)	kg $FeCl_3$/(pe*a)	2.26	2.48	3.28	3.20
Polymer for sludge treatment	kg AS/(pe*a)	0.17	0.18	0.19	0.19

Table 26: Electricity, heat and chemical demand and energy production of POWERSTEP scenarios with chemical settling for medium WWTP (50'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Electricity balance					
Mechanical and primary treatment	kWh/(pe*a)	1.9	1.2	2.1	1.2
Biological treatment	kWh/(pe*a)	12.3	10.1	11.8	10.0
Tertiary treatment	kWh/(pe*a)	0.0	0.0	1.8	1.1
Miscellaneous	kWh/(pe*a)	1.5	1.5	1.6	1.5
Sludge treatment	kWh/(pe*a)	4.2	4.3	5.1	4.5
Total electricity demand	kWh/(pe*a)	19.9	17.1	22.4	18.2
Electricity production in CHP	kWh/(pe*a)	-17.2	-20.8	-18.3	-21.6
NET electricity demand	**kWh/(pe*a)**	**2.6**	**-3.6**	**4.1**	**-3.4**
Electrical self sufficiency	%	87%	121%	82%	119%
Heat balance					
Heat demand for digestor	kWh/(pe*a)	18.3	19.2	19.9	20.0
Heat production in CHP	kWh/(pe*a)	37.8	43.5	40.5	45.3
NET heat demand	**kWh/(pe*a)**	**-19.5**	**-24.3**	**-20.6**	**-25.3**
Heat self sufficiency	%	206%	226%	204%	226%
Chemical consumption					
Polymer for primary treatment	kg AS/(pe*a)	0.11	0.06	0.11	0.06
Polymer for tertiary treatment	kg AS/(pe*a)	0.00	0.00	0.02	0.01
$FeCl_3$ (100%)	kg $FeCl_3$/(pe*a)	2.26	2.53	3.23	3.26
Polymer for sludge treatment	kg AS/(pe*a)	0.17	0.19	0.19	0.20

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Table 27: Treatment efficiencies of primary treatment, biological stage and tertiary treatment and effluent quality of reference scenarios for medium WWTP (50’000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Primary treatment					
TS removal	%	50	50	50	51
COD removal	%	30	30	31	31
TN removal	%	9	10	10	11
TP removal	%	15	16	19	21
Bypass	Vol-%	0	0	0	10,1
B-stage					
TS removal	%	83	91	84	92
COD removal	%	86	90	87	90
TN removal	%	64	82	70	85
TP removal	%	77	88	90	91
Tertiary treatment					
TS removal	%	0	0	75	78
COD removal	%	0	0	29	19
TN removal	%	0	0	6	6
TP removal	%	0	0	65	81
WWTP effluent					
Volume	$m^3/(pe*a)$	109.6	54.9	109.6	54.8
TS	mg/L	20	20	6	6
COD	mg/L	38	59	27	48
TN	mg/L	13.3	13.3	10.7	10.7
TP	mg/L	1.4	1.4	0.2	0.2

Table 28: Treatment efficiencies of primary treatment, biological stage and tertiary treatment and effluent quality of POWERSTEP scenarios with microscreen for medium WWTP (50’000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Primary treatment					
TS removal	%	82	91	85	91
COD removal	%	50	56	53	57
TN removal	%	14	16	17	17
TP removal	%	70	79	89	86
Bypass	Vol-%	0	0	4,5	0
B-stage					
TS removal	%	50	51	59	51
COD removal	%	79	81	79	81
TN removal	%	61	80	65	83
TP removal	%	31	51	62	70
Tertiary treatment					
TS removal	%	0	0	74	75
COD removal	%	0	0	35	26
TN removal	%	0	0	8	10
TP removal	%	0	0	58	65
WWTP effluent					
Volume	$m^3/(pe*a)$	109.6	54.8	109.6	54.8
TS	mg/L	20	20	5	6
COD	mg/L	44	68	28	51
TN	mg/L	13.6	14.0	10.8	10.9
TP	mg/L	1.4	1.4	0.2	0.2

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Table 29: Treatment efficiencies of primary treatment, biological stage and tertiary treatment and effluent quality of POWERSTEP scenarios with chemical settling for medium WWTP (50’000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Primary treatment					
TS removal	%	80	80	82	80
COD removal	%	47	49	51	51
TN removal	%	14	15	16	16
TP removal	%	70	77	85	84
Bypass	Vol-%	0	0	0,2	0
B-stage					
TS removal	%	56	78	59	79
COD removal	%	79	84	79	84
TN removal	%	61	81	65	84
TP removal	%	32	56	61	75
Tertiary treatment					
TS removal	%	0	0	74	75
COD removal	%	0	0	35	24
TN removal	%	0	0	8	9
TP removal	%	0	0	56	64
WWTP effluent					
Volume	$m^3/(pe*a)$	109.6	54.8	109.6	54.8
TS	mg/L	20	20	5	8
COD	mg/L	44	66	28	51
TN	mg/L	13.6	13.8	10.8	10.8
TP	mg/L	1.4	1.4	0.2	0.2

Table 30: Raw and digested sludge, biogas production and valorisation, and return load of reference scenarios for medium WWTP (50'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Thickened mixed sludge					
VOL	$m^3/(pe*a)$	0.5	0.5	0.5	0.5
TS	kg/(pe*a)	24.2	25.2	26.4	26.1
COD	kg/(pe*a)	23.4	23.5	24.1	23.3
TN	kg/(pe*a)	0.8	0.8	0.8	0.8
TP	kg/(pe*a)	0.6	0.6	0.7	0.7
Biogas utilization					
Volume	$Nm^3/(pe*a)$	6.8	6.9	7.0	6.8
	NL/(kg VS in)	334	335	335	335
Methane content	Vol-%	61.5	61.6	61	61.5
CHP electrical efficiency	%	35	35	35	35
CHP thermal efficiency	%	50	50	50	50
Dewatered digested sludge					
Mass	kg/(pe*a)	61.2	64.6	68.5	68.4
TS	kg/(pe*a)	15.3	16.2	17.1	17.1
COD	kg/(pe*a)	10.5	10.5	10.8	10.4
TN	kg/(pe*a)	0.4	0.4	0.4	0.4
TP	kg/(pe*a)	0.5	0.6	0.6	0.6
Return load					
Volume	$m^3/(pe*a)$	3.1	3.2	5.1[1]	4.4[1]
TS	mg/L	880	877	947	968
COD	mg/L	916	936	798	839
TN	mg/L	143	146	102	116
TP	mg/L	38	42	35	44

[1] including backwash from tertiary treatment

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Table 31: Raw and digested sludge, biogas production and valorisation, and return load of POWERSTEP scenarios with microscreen for medium WWTP (50’000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Thickened mixed sludge					
VOL	m³/(pe*a)	0.5	0.5	0.5	0.6
TS	kg/(pe*a)	25.9	29.2	28.0	30.4
COD	kg/(pe*a)	26.8	30.8	28.1	31.9
TN	kg/(pe*a)	0.8	1.0	0.8	1.0
TP	kg/(pe*a)	0.6	0.6	0.7	0.7
Biogas utilization					
Volume	Nm³/(pe*a)	8.5	10.4	8.9	10.8
	NL/(kg VS in)	364	390	363	388
Methane content	Vol-%	63	63	63.1	63.2
CHP electrical efficiency	%	35	35	35	35
CHP thermal efficiency	%	50	50	50	50
Dewatered digested sludge					
Mass	kg/(pe*a)	60.6	64.4	66.9	67.5
TS	kg/(pe*a)	15.1	16.1	16.7	16.9
COD	kg/(pe*a)	10.4	10.8	11.0	11.1
TN	kg/(pe*a)	0.4	0.4	0.4	0.5
TP	kg/(pe*a)	0.5	0.6	0.6	0.6
Return load					
Volume	m³/(pe*a)	1.6	1.6	3.5[1]	2.2[1]
TS	mg/L	1430	1582	1220	1639
COD	mg/L	1676	1964	1224	1916
TN	mg/L	260	355	85	296
TP	mg/L	55	63	38	61

[1] including backwash from tertiary treatment

Table 32: Raw and digested sludge, biogas production and valorisation, and return load of POWERSTEP scenarios with chemical settling for medium WWTP (50'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Thickened mixed sludge					
VOL	m³/(pe*a)	0.5	0.5	0.5	0.5
TS	kg/(pe*a)	25.7	28.5	28.0	29.7
COD	kg/(pe*a)	26.0	29.6	28.1	30.5
TN	kg/(pe*a)	0.8	1.0	0.8	1.0
TP	kg/(pe*a)	0.6	0.6	0.7	0.7
Biogas utilization					
Volume	Nm³/(pe*a)	8.2	10.0	8.7	10.3
	NL/(kg VS in)	364	388	357	389
Methane content	Vol-%	63	62.8	63.1	63.1
CHP electrical efficiency	%	35	35	35	35
CHP thermal efficiency	%	50	50	50	50
Dewatered digested sludge					
Mass	kg/(pe*a)	60.3	63.5	67.5	66.8
TS	kg/(pe*a)	15.1	15.9	16.9	16.7
COD	kg/(pe*a)	10.1	10.3	11.2	10.7
TN	kg/(pe*a)	0.4	0.4	0.4	0.5
TP	kg/(pe*a)	0.5	0.6	0.6	0.6
Return load					
Volume	m³/(pe*a)	2.1	2.5	4.0[1]	3.5[1]
TS	mg/L	1097	1057	1055	1056
COD	mg/L	1313	1356	1080	1267
TN	mg/L	207	251	78	204
TP	mg/L	42	42	33	38

[1] including backwash from tertiary treatment

X

X

9.3. Inventory data of large WWTP (500,000 pe)

Table 33: Electricity, heat and chemical demand and energy production of reference scenarios for large WWTP (500'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Electricity balance					
Mechanical and primary treatment	kWh/(pe*a)	0.9	0.6	1.0	0.6
Biological treatment	kWh/(pe*a)	16.1	15.3	17.2	17.1
Tertiary treatment	kWh/(pe*a)	0.0	0.0	1.6	0.8
Miscellaneous	kWh/(pe*a)	1.8	1.7	1.8	1.8
Sludge treatment	kWh/(pe*a)	3.9	3.9	4.0	3.9
Total electricity demand	kWh/(pe*a)	22.8	21.5	25.6	24.2
Electricity production in CHP	kWh/(pe*a)	-17.8	-17.6	-18.0	-17.7
NET electricity demand	**kWh/(pe*a)**	**5.1**	**3.9**	**7.6**	**6.4**
Electrical self sufficiency	%	78%	82%	70%	73%
Heat balance					
Heat demand for digestor	kWh/(pe*a)	17.1	17.3	17.5	17.4
Heat production in CHP	kWh/(pe*a)	30.7	30.7	31.2	30.8
NET heat demand	**kWh/(pe*a)**	**-13.6**	**-13.4**	**-13.7**	**-13.5**
Heat self sufficiency	%	179%	177%	178%	177%
Chemical consumption					
Polymer for primary treatment	kg AS/(pe*a)	0.00	0.00	0.00	0.00
Polymer for tertiary treatment	kg AS/(pe*a)	0.00	0.00	0.05	0.02
$FeCl_3$ (100%)	kg $FeCl_3$/(pe*a)	1.01	1.31	1.47	1.35
Polymer for sludge treatment	kg AS/(pe*a)	0.21	0.22	0.22	0.22

Table 34: Electricity, heat and chemical demand and energy production of POWERSTEP scenarios with microscreen for large WWTP (500'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Electricity balance					
Mechanical and primary treatment	kWh/(pe*a)	1.7	1.1	1.8	1.3
Biological treatment	kWh/(pe*a)	14.1	8.9	15.0	9.0
Tertiary treatment	kWh/(pe*a)	0.0	0.0	1.6	0.8
Miscellaneous	kWh/(pe*a)	1.7	1.5	1.8	1.6
Sludge treatment	kWh/(pe*a)	4.0	4.0	4.1	4.0
Total electricity demand	kWh/(pe*a)	21.6	15.6	24.3	16.7
Electricity production in CHP	kWh/(pe*a)	-21.8	-26.4	-22.0	-26.8
NET electricity demand	**kWh/(pe*a)**	**-0.2**	**-10.9**	**2.3**	**-10.1**
Electrical self sufficiency	%	101%	170%	91%	161%
Heat balance					
Heat demand for digestor	kWh/(pe*a)	18.6	19.3	19.0	19.7
Heat production in CHP	kWh/(pe*a)	35.9	45.7	36.4	41.8
NET heat demand	**kWh/(pe*a)**	**-17.3**	**-26.3**	**-17.4**	**-22.2**
Heat self sufficiency	%	193%	236%	192%	213%
Chemical consumption					
Polymer for primary treatment	kg AS/(pe*a)	0.18	0.14	0.20	0.13
Polymer for tertiary treatment	kg AS/(pe*a)	0.00	0.00	0.05	0.03
$FeCl_3$ (100%)	kg $FeCl_3$/(pe*a)	1.48	2.14	1.95	2.38
Polymer for sludge treatment	kg AS/(pe*a)	0.19	0.19	0.19	0.19

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Table 35: Electricity, heat and chemical demand and energy production of POWERSTEP scenarios with chemical settling for large WWTP (500'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Electricity balance					
Mechanical and primary treatment	kWh/(pe*a)	1.3	0.9	1.3	0.7
Biological treatment	kWh/(pe*a)	14.1	9.7	15.0	9.9
Tertiary treatment	kWh/(pe*a)	0.0	0.0	1.7	0.8
Miscellaneous	kWh/(pe*a)	1.7	1.5	1.8	1.5
Sludge treatment	kWh/(pe*a)	4.1	4.0	4.1	3.9
Total electricity demand	kWh/(pe*a)	21.2	16.1	23.9	16.9
Electricity production in CHP	kWh/(pe*a)	-21.7	-25.5	-21.9	-25.6
NET electricity demand	**kWh/(pe*a)**	**-0.6**	**-9.4**	**2.0**	**-8.7**
Electrical self sufficiency	%	103%	158%	92%	151%
Heat balance					
Heat demand for digestor	kWh/(pe*a)	18.6	18.8	19.0	18.4
Heat production in CHP	kWh/(pe*a)	35.9	39.9	36.4	39.6
NET heat demand	**kWh/(pe*a)**	**-17.3**	**-21.1**	**-17.3**	**-21.3**
Heat self sufficiency	%	193%	212%	191%	216%
Chemical consumption					
Polymer for primary treatment	kg AS/(pe*a)	0.11	0.06	0.11	0.06
Polymer for tertiary treatment	kg AS/(pe*a)	0.00	0.00	0.05	0.03
$FeCl_3$ (100%)	kg $FeCl_3$/(pe*a)	1.48	2.18	1.95	1.33
Polymer for sludge treatment	kg AS/(pe*a)	0.19	0.20	0.19	0.19

Table 36: Electricity, heat and chemical demand and energy and fertilizer production of POWERSTEP scenarios with sidestream treatment or two-stage configuration for large WWTP (500'000 pe) for concentrated influent and normal standards (case A2)

Parameter	Unit	MS[2] + CAS + mox[1]	MS[2] + CAS + mem[1]	CAS two stage	CAS two stage + nitrit[1]
Electricity balance					
Mechanical and primary treatment	kWh/(pe*a)	1.1	1.1	0.9	0.9
Biological treatment	kWh/(pe*a)	12.5	12.6	16.8	16.1
Tertiary treatment	kWh/(pe*a)	0.0	0.0	0.0	0.0
Miscellaneous	kWh/(pe*a)	1.6	1.7	1.8	1.8
Sludge treatment	kWh/(pe*a)	4.5	5.1	3.9	4.2
Total electricity demand	kWh/(pe*a)	19.8	20.5	23.3	22.9
Electricity production in CHP	kWh/(pe*a)	-22.4	-22.6	-20.7	-21.9
NET electricity demand	**kWh/(pe*a)**	**-2.6**	**-2.1**	**2.6**	**1.0**
Electrical self sufficiency	%	113%	110%	89%	96%
Heat balance					
Heat demand for digestor	kWh/(pe*a)	19.0	21.6	16.9	16.9
Heat production in CHP	kWh/(pe*a)	36.9	38.9	33.6	34.8
NET heat demand	**kWh/(pe*a)**	**-17.8**	**-17.3**	**-16.7**	**-17.9**
Heat self sufficiency	%	194%	180%	199%	206%
Chemical consumption					
Polymer for primary treatment	kg AS/(pe*a)	0.13	0.13	0.00	0.00
Polymer for tertiary treatment	kg AS/(pe*a)	0.00	0.00	0.00	0.00
$FeCl_3$ (100%)	kg $FeCl_3$/(pe*a)	2.09	2.09	1.13	1.13
Polymer for sludge treatment	kg AS/(pe*a)	0.19	0.19	0.21	0.21
NaOH (100%)	kg/(pe*a)		1.14		
H_2SO_4 (100%)	kg/(pe*a)		1.00		
HCl (100%)	kg/(pe*a)		0.01		
N fertilizer production	kg N/(pe*a)		0.29		

[1] Sidestream processes: mox – anammox, mem – membrane stripping, nitrit – nitritation

[2] bypass of primary treatment for 6.5 Vol-% (mox) and 8.2 Vol-% (mem) required to stabilize denitrification in CAS system

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Table 37: Electricity, heat and chemical demand and biomethane production of reference and POWERSTEP scenarios with P2G scheme for large WWTP (500'000 pe) for concentrated influent and normal standards (case A2)

Parameter	Unit	CAS + P2G	Microscreen + MOX + P2G
Electricity balance			
Mechanical and primary treatment	kWh/(pe*a)	0.6	1.1
Biological treatment[1]	kWh/(pe*a)	12.1	6.4
Tertiary treatment	kWh/(pe*a)	0.0	0.0
Miscellaneous	kWh/(pe*a)	1.7	1.5
Sludge treatment	kWh/(pe*a)	3.7	3.9
Biogas upgrading	kWh/(pe*a)	1.6	2.4
Total electricity demand	kWh/(pe*a)	19.7	15.2
Electricity production in CHP	kWh/(pe*a)	0.0	0.0
NET electricity demand	**kWh/(pe*a)**	19.7	15.2
Electrical self sufficiency	%	0%	0%
P2G operation			
Electricity for P2G (wind power)	kWh/(pe*a)	55.1	81.7
Biomethane injected	kWh/(pe*a)	-70.7	-104.9
Heat balance			
Heat demand for digestor	kWh/(pe*a)	17.3	19.3
Heat production in P2G	kWh/(pe*a)	17.3	19.8
NET heat demand	**kWh/(pe*a)**	0.0	-0.5
Heat self sufficiency	%	100%	103%
Chemical consumption			
Polymer for primary treatment	kg AS/(pe*a)	0.00	0.14
Polymer for tertiary treatment	kg AS/(pe*a)	0.00	0.00
$FeCl_3$ (100%)	kg $FeCl_3$/(pe*a)	1.31	2.14
Polymer for sludge treatment	kg AS/(pe*a)	0.22	0.19

[1] reduced aeration demand due to oxygen utilisation from P2G electrolyser

Table 38: Treatment efficiencies of primary treatment, biological stage and tertiary treatment and effluent quality of reference scenarios for large WWTP (500'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Primary treatment					
TS removal	%	50	50	51	50
COD removal	%	28	28	28	28
TN removal	%	9	10	9	10
TP removal	%	14	15	19	17
Bypass	Vol-%	0	0	0	0
B-stage					
TS removal	%	91	95	91	95
COD removal	%	89	91	89	91
TN removal	%	75	87	80	90
TP removal	%	89	95	88	94
Tertiary treatment					
TS removal	%	0	0	69	69
COD removal	%	0	0	16	11
TN removal	%	0	0	5	5
TP removal	%	0	0	74	74
WWTP effluent					
Volume	$m^3/(pe*a)$	109.6	54.8	109.6	54.8
TS	mg/L	10	10	5	5
COD	mg/L	32	55	27	50
TN	mg/L	9.6	9.5	7.2	7.2
TP	mg/L	0.7	0.7	0.2	0.2

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Table 39: Treatment efficiencies of primary treatment, biological stage and tertiary treatment and effluent quality of POWERSTEP scenarios with microscreen for large WWTP (500’000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Primary treatment					
TS removal	%	80	90	80	91
COD removal	%	44	50	44	50
TN removal	%	13	15	13	15
TP removal	%	21	72	27	71
Bypass	Vol-%	0	0	0	0
B-stage					
TS removal	%	76	75	77	75
COD removal	%	86	86	86	86
TN removal	%	73	86	79	89
TP removal	%	88	82	85	80
Tertiary treatment					
TS removal	%	0	0	70	70
COD removal	%	0	0	17	13
TN removal	%	0	0	5	6
TP removal	%	0	0	73	76
WWTP effluent					
Volume	$m^3/(pe*a)$	109.6	54.8	109.6	54.8
TS	mg/L	10	10	5	5
COD	mg/L	32	58	27	51
TN	mg/L	9.6	9.8	7.2	7.3
TP	mg/L	0.7	0.7	0.2	0.2

Table 40: Treatment efficiencies of primary treatment, biological stage and tertiary treatment and effluent quality of POWERSTEP scenarios with chemical settling for large WWTP (500'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Primary treatment					
TS removal	%	80	80	80	80
COD removal	%	44	45	44	44
TN removal	%	13	14	14	14
TP removal	%	22	70	28	26
Bypass	Vol-%	0	0	0	0
B-stage					
TS removal	%	76	88	77	88
COD removal	%	86	87	86	88
TN removal	%	73	87	79	90
TP removal	%	88	83	85	93
Tertiary treatment					
TS removal	%	0	0	70	70
COD removal	%	0	0	17	12
TN removal	%	0	0	5	5
TP removal	%	0	0	73	73
WWTP effluent					
Volume	$m^3/(pe*a)$	109.6	54.8	109.6	54.8
TS	mg/L	10	10	5	5
COD	mg/L	32	57	28	50
TN	mg/L	9.6	9.7	7.2	7.3
TP	mg/L	0.7	0.7	0.2	0.2

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Table 41: Raw and digested sludge, biogas production and valorisation, and return load of reference scenarios for large WWTP (500'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Thickened mixed sludge					
VOL	m³/(pe*a)	0.5	0.5	0.5	0.5
TS	kg/(pe*a)	23.7	24.0	24.4	24.2
COD	kg/(pe*a)	24.4	24.2	24.5	24.3
TN	kg/(pe*a)	0.9	0.9	0.9	0.9
TP	kg/(pe*a)	0.7	0.7	0.8	0.8
Biogas utilization					
Volume	Nm³/(pe*a)	7.3	7.3	7.4	7.3
	NL/(kg VS in)	346	345	349	347
Methane content	Vol-%	61.2	61.4	61.2	61.4
CHP electrical efficiency	%	41.7	41.7	41.7	41.7
CHP thermal efficiency	%	43	43	43	43
Dewatered digested sludge					
Mass	kg/(pe*a)	56.8	58.2	59.0	58.8
TS	kg/(pe*a)	14.2	14.6	14.7	14.7
COD	kg/(pe*a)	10.5	10.4	10.5	10.4
TN	kg/(pe*a)	0.5	0.5	0.5	0.5
TP	kg/(pe*a)	0.6	0.6	0.6	0.6
Return load					
Volume	m³/(pe*a)	3.0	3.1	4.7[1]	3.9[1]
TS	mg/L	870	874	811	836
COD	mg/L	997	1041	771	908
TN	mg/L	168	173	117	141
TP	mg/L	63	66	56	62

[1] including backwash from tertiary treatment

Table 42: Raw and digested sludge, biogas production and valorisation, and return load of POWERSTEP scenarios with microscreen for large WWTP (500'000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Thickened mixed sludge					
VOL	$m^3/(pe*a)$	0.5	0.5	0.5	0.5
TS	kg/(pe*a)	25.4	28.6	26.1	29.1
COD	kg/(pe*a)	27.1	30.4	27.2	30.7
TN	kg/(pe*a)	0.9	1.1	2.8	1.1
TP	kg/(pe*a)	0.7	0.7	0.7	0.7
Biogas utilization					
Volume	$Nm^3/(pe*a)$	8.9	10.7	9.0	10.9
	NL/(kg VS in)	378	406	382	408
Methane content	Vol-%	61.9	62.4	61.9	62.3
CHP electrical efficiency	%	41.7	41.7	41.7	41.7
CHP thermal efficiency	%	43	43	43	43
Dewatered digested sludge					
Mass	kg/(pe*a)	56.5	67.7	58.5	61.5
TS	kg/(pe*a)	14.1	15.1	14.6	15.4
COD	kg/(pe*a)	10.2	10.0	10.1	10.1
TN	kg/(pe*a)	0.5	0.5	2.2	0.5
TP	kg/(pe*a)	0.6	0.6	0.6	0.6
Return load					
Volume	$m^3/(pe*a)$	1.8	1.6	3.4[1]	2.3[1]
TS	mg/L	1395	1676	1095	1398
COD	mg/L	1640	2076	1029	1564
TN	mg/L	284	408	159	287
TP	mg/L	100	81	75	73

[1] including backwash from tertiary treatment

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Table 43: Raw and digested sludge, biogas production and valorisation, and return load of POWERSTEP scenarios with chemical settling for large WWTP (500’000 pe)

Parameter	Unit	Case A1	Case A2	Case B1	Case B2
Thickened mixed sludge					
VOL	m³/(pe*a)	0.5	0.5	0.5	0.5
TS	kg/(pe*a)	25.4	28.0	26.1	27.4
COD	kg/(pe*a)	27.0	29.3	27.0	29.5
TN	kg/(pe*a)	0.9	1.1	0.9	1.1
TP	kg/(pe*a)	0.7	0.7	0.7	0.8
Biogas utilization					
Volume	Nm³/(pe*a)	8.9	10.4	9.0	10.5
	NL/(kg VS in)	378	407	382	408
Methane content	Vol-%	61.9	62.2	61.9	61.8
CHP electrical efficiency	%	41.7	41.7	41.7	41.7
CHP thermal efficiency	%	43	43	43	43
Dewatered digested sludge					
Mass	kg/(pe*a)	56.5	59.8	58.5	57.0
TS	kg/(pe*a)	14.1	14.9	14.6	14.2
COD	kg/(pe*a)	10.2	9.7	10.0	9.8
TN	kg/(pe*a)	0.5	0.5	0.4	0.5
TP	kg/(pe*a)	0.6	0.6	0.6	0.6
Return load					
Volume	m³/(pe*a)	2.4	2.6	4.0[1]	3.4[1]
TS	mg/L	1037	1029	920	946
COD	mg/L	1263	1356	894	1132
TN	mg/L	220	268	139	210
TP	mg/L	76	50	64	71

[1] including backwash from tertiary treatment

9.4. Material for infrastructure for all scenarios

Material demand for infrastructure was estimated only for the main aggregates of the WWTP: primary and secondary tanks, sludge thickener, and digestor. For these aggregates, the amount of concrete and reinforcing steel and the required excavation has been calculated based on their size. In addition, stainless steel demand for microscreen has been estimated based on supplier information and filter surface.

Design information comes from OCEAN software (tank volumes) and estimates (thickener, digestor, sand and grease removal). Volumes have been converted to material demand using fixed correlations:

- SBR, biological tank, clarifier, thickener: 0.25 m^3 concrete and 30 kg reinforcing steel per m^3 tank volume
- Primary settler: 0.5 m^3 concrete and 60 kg reinforcing steel per m^3 tank volume
- Digestor: 0.2 m^3 concrete and 15 kg reinforcing steel per m^3 tank volume
- Microscreen: 60 kg stainless steel per m^2 filter surface
- Volume of digestor: 20d retention time
- Volume of thickener: 20% of digestor, min. 1000 m^3 for small WWTPs
- Excavation: 100% of tank volume for medium and large plants (sub-surface tanks for primary/biological tank and clarifier), 20% for SBR (above-ground construction)

All other infrastructure was neglected in this LCA study.

Resulting infrastructure data is summarized below for small WWTP (Table 44), medium WWTP (Table 45), and large WWTP (Table 46) including options for sidestream treatment and two-stage configuration

Lifetime of infrastructure is estimated to 50a for concrete, reinforcing steel and excavation, and 12a for microscreen.

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Table 44: Infrastructure data for small WWTP (5,000 pe)

		Reference				Microscreen + optimised SBR				CEPT + optimised SBR			
Standards		**Normal**	**Normal**	**Advanced**	**Advanced**	**Normal**	**Normal**	**Advanced**	**Advanced**	**Normal**	**Normal**	**Advanced**	**Advanced**
Size	pe	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000
Influent volume	m³/d	1200	600	1200	600	1200	600	1200	600	1200	600	1200	600
COD in influent	mg/L	500	1000	500	1000	500	1000	500	1000	500	1000	500	1000
Primary tank	m³ volume	0	0	0	0	0	0	0	0	45	24	45	21
Secondary tank	m³ volume	1300	900	2900	2400	1500	650	1850	1400	1250	650	1850	1400
Clarifier	m³ volume	0	0	0	0	0	0	0	0	0	0	0	0
Filter	m² surface					22,4	22,4	22,4	22,4				
Thickener/storage	m³ volume	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Digestor	m³ volume	0	0	0	0	0	0	0	0	0	0	0	0
Total tank volume	**m³ volume**	**1300**	**900**	**2900**	**2400**	**1500**	**650**	**1850**	**1400**	**1295**	**674**	**1895**	**1421**
Tank volume per pe	**m³/pe**	**0,26**	**0,18**	**0,58**	**0,48**	**0,30**	**0,13**	**0,37**	**0,28**	**0,26**	**0,13**	**0,38**	**0,28**
Tank volume per influent	**1/d**	**1,1**	**1,5**	**2,4**	**4,0**	**1,3**	**1,1**	**1,5**	**2,3**	**1,1**	**1,1**	**1,6**	**2,4**
Concrete	**m³**	**695**	**595**	**1095**	**970**	**745**	**532,5**	**832,5**	**720**	**705**	**544,5**	**855**	**730,5**
Steel	**kg**	**84000**	**72000**	**132000**	**117000**	**90000**	**64500**	**100500**	**87000**	**85200**	**65940**	**103200**	**88260**
Excavation	**m³**	**260**	**180**	**580**	**480**	**300**	**130**	**370**	**280**	**259**	**134,8**	**379**	**284,2**
Stainless steel	**kg**	**0**	**0**	**0**	**0**	**1344**	**1344**	**1344**	**1344**	**0**	**0**	**0**	**0**

Table 45: Infrastructure data for medium WWTP (5,000 pe)

		Reference				Microscreen + CAS or Anammox				CEPT + CAS or Anammox			
Standards		**Normal**	**Normal**	**Advanced**	**Advanced**	**Normal**	**Normal**	**Advanced**	**Advanced**	**Normal**	**Normal**	**Advanced**	**Advanced**
Size	pe	50000	50000	50000	50000	50000	50000	50000	50000	50000	50000	50000	50000
Influent volume	m³/d	15000	7500	15000	7500	15000	7500	15000	7500	15000	7500	15000	7500
COD in influent	mg/L	400	800	400	800	400	800	400	800	400	800	400	800
Primary tank	m³ volume	1100	600	1100	500	0	0	0	0	573	294	200	300
Secondary tank	m³ volume	8800	11500	10500	12800	4900	2600	5400	2600	5100	2800	5400	2800
Clarifier	m³ volume	6800	3500	6900	3500	6700	2500	6800	2500	6700	3500	6800	3500
Filter	m² surface			270	135	67,5	67,5	325	201,6	0	0	270	135
Thickener/storage	m³ volume	260	280	280	280	280	300	300	300	340	300	300	540
Digestor	m³ volume	1300	1400	1400	1400	1400	1500	1500	1500	1700	1500	1500	2700
Total tank volume	**m³ volume**	**16700**	**15600**	**18500**	**16800**	**11600**	**5100**	**12200**	**5100**	**12373**	**6594**	**12400**	**6600**
Tank volume per pe	**m³/pe**	**0,33**	**0,31**	**0,37**	**0,34**	**0,23**	**0,10**	**0,24**	**0,10**	**0,25**	**0,13**	**0,25**	**0,13**
Tank volume per influent	**1/d**	**1,1**	**2,1**	**1,2**	**2,2**	**0,8**	**0,7**	**0,8**	**0,7**	**0,8**	**0,9**	**0,8**	**0,9**
Concrete	**m³**	**5001**	**4628**	**5478**	**4903**	**3478**	**1880**	**3655**	**1880**	**3895,5**	**2327**	**3755**	**2654**
Steel	**kg**	**594420**	**548760**	**650760**	**581760**	**410760**	**218100**	**431100**	**218100**	**458160**	**271740**	**443100**	**300180**
Excavation	**m³**	**16700**	**15600**	**18500**	**16800**	**11600**	**5100**	**12200**	**5100**	**12373**	**6594**	**12400**	**6600**
Stainless steel	**kg**	**0**	**0**	**16200**	**8100**	**4050**	**4050**	**19500**	**12096**	**0**	**0**	**16200**	**8100**

Table 46: Infrastructure data for large WWTP (500,000 pe) including sidestream options and two-stage configuration

		Reference					Microscreen + CAS/Anammox						CEPT + CAS/Anammox			
Standards		**Normal**	**Normal**	**Normal**	**Advanced**	**Advanced**	**Normal**	**Normal**	**Normal**	**Normal**	**Advanced**	**Advanced**	**Normal**	**Normal**	**Advanced**	**Advanced**
Size	pe	500000	500000	500000	500000	500000	500000	500000	500000	500000	500000	500000	500000	500000	500000	500000
Influent volume	m³/d	150000	150000	75000	150000	75000	150000	75000	75000	75000	150000	75000	150000	75000	150000	75000
COD in influent	mg/L	400	400	800	400	800	400	800	800	800	400	800	400	800	400	800
Variant			**two-stage**						**Anitamox**	**membrane**						
Primary tank	m³ volume	10500	9400	5300	10400	5400	0	0	0	0	0	0	2000	1000	2000	1000
Secondary tank	m³ volume	71200	42600	75200	76600	78300	60100	32800	50000	48700	65300	32900	60200	32900	65200	34700
Clarifier	m³ volume	95400	65100	49000	96800	49700	94300	29800	47600	47600	95700	30300	94800	45600	96200	49300
Filter	m² surface				2500	1370	600	460	460	460	3100	1840		0	2500	1370
Thickener/storage	m³ volume	2540	3400	2580	2600	2600	2780	2880	2840	2860	2780	2940	2780	2820	2780	2740
Digestor	m³ volume	12700	17000	12900	13000	13000	13900	14400	14200	14300	13900	14700	13900	14100	13900	13700
Total tank volume	**m³ volume**	**177100**	**117100**	**129500**	**183800**	**133400**	**154400**	**62600**	**97600**	**96300**	**161000**	**63200**	**157000**	**79500**	**163400**	**85000**
Tank volume per pe	**m³/pe**	**0,35**	**0,23**	**0,26**	**0,37**	**0,27**	**0,31**	**0,13**	**0,20**	**0,19**	**0,32**	**0,13**	**0,31**	**0,16**	**0,33**	**0,17**
Tank volume per influent	**1/d**	**1,2**	**0,8**	**1,7**	**1,2**	**1,8**	**1,0**	**0,8**	**1,3**	**1,3**	**1,1**	**0,8**	**1,0**	**1,1**	**1,1**	**1,1**
Concrete	**m³**	**52329**	**38215**	**39183**	**54060**	**40210**	**44353**	**21538**	**30234**	**29936**	**46003**	**21769**	**45503**	**25932**	**47103**	**27199**
Steel	**kg**	**6225180**	**4492800**	**4645860**	**6430200**	**4768200**	**5257260**	**2514960**	**3560280**	**3523620**	**5455260**	**2539980**	**5395260**	**3044940**	**5587260**	**3200580**
Excavation	**m³**	**177100**	**117100**	**129500**	**183800**	**133400**	**154400**	**62600**	**97600**	**96300**	**161000**	**63200**	**157000**	**79500**	**163400**	**85000**
Stainless steel	**kg**	**0**	**0**	**0**	**150000**	**82200**	**36000**	**27600**	**27600**	**27600**	**186000**	**110400**	**0**	**0**	**150000**	**82200**

9.5. Datasets for background processes

Table 47: Datasets for background processes from ecoinvent v3.3(Wernet, Bauer et al. 2016)

Material/process	Dataset	Remarks
Energy		
Electricity production	market group for electricity, medium voltage [RER]	WWTP demand and credits from CHP production
	market for medium voltage [PL]	For sensitivity analysis
	market for medium voltage [NO]	For sensitivity analysis
Electricity production	Electricity production, wind, >3MW turbine, onshore [DE]	For P2G operation
Heat production	market for heat, district or industrial, natural gas [Europe without Switzerland]	Credits for district heating
Natural gas	natural gas, burned in gas motor, for storage [RoW]	Credits for biomethane, incl. natural gas production and emissions from usage (fossil CO^2)
Chemicals		
$FeCl_3$	market for iron (III) chloride, without water, in 40% solution state [GLO]	
Polymer	market for acrylonitrile [GLO]	Basic material for polyacrylamide
NaOH	market for sodium hydroxide, without water, in 50% solution state [GLO]	
H_2SO_4	market for sulfuric acid [GLO]	
HCl	market for hydrochloric acid, without water, in 30% solution state [RER]	
Mineral N fertilizer	market for ammonium sulfate, as N [GLO]	N in diammonium sulfate
Transport		
Truck transport	transport, freight, lorry 16-32 metric ton, EURO5 [RER]	Sludge, ash, chemicals, materials for infrastructure
Mono-incineration		
Natural gas	market for natural gas, high pressure [DE]	For start-up of incinerator
NH_3	market for ammonia, liquid [RER]	For exhaust gas treatment
Coke	market for coke [GLO]	For exhaust gas treatment
Lime	lime production, hydrated, loose weight [RoW]	For exhaust gas treatment
Silica sand	silica sand production [DE]	For fluidized bed

The project "Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration" (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

Ash disposal	treatment of hazardous waste, underground deposit [DE]	
Infrastructure		
Concrete	market for concrete, for de-icing salt contact [RoW]	
Reinforcing steel	reinforcing steel production [RoW]	
Stainless steel	steel production, electric, chromium steel 18/8 [RoW]	
Excavation	excavation, hydraulic digger [RER]	