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

D 5.1: *Proposition of POWERSTEP process schemes and WWTP reference models*

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 5.1	***Proposition of POWERSTEP process schemes and WWTP reference models***
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Abstract	This report summarizes the definitions and schemes that will be used for the process assessment within POWERSTEP. A general approach is described to screen potential schemes for wastewater treatment plants (WWTPs) in their energy profile with the energy audit software OCEAN, focussing on reference schemes as benchmark and potential POWERSTEP schemes with innovative process modules

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	RE	Restricted to a group specified by the consortium (including the European Commission Services)
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Glossary

AD	Anaerobic digestion
CAS	Conventional activated sludge
CEPT	Chemically enhanced primary treatment
CHP	Combined heat and power plant
COD	Chemical oxygen demand
DAF	Dissolved air flotation
DS	Dry solids
HRT	Hydraulic retention time
IFAS	Integrated fixed-film activated sludge
MBBR	Moving bed biofilm reactor
MS	Microscreen
ORC	Organic ranking cycle
PE	Population equivalents
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 report summarizes the definitions and schemes that will be used for the process assessment within POWERSTEP. A general approach is described to screen potential schemes for wastewater treatment plants (WWTPs) in their energy profile with the energy audit software OCEAN, focussing on reference schemes as benchmark and potential POWERSTEP schemes with innovative process modules.

Definitions for the screening include WWTP size, influent wastewater composition, and effluent discharge limits. For the screening, three WWTP sizes with 5'000, 50'000 and 500'000 population equivalents (pe) will be assessed, with influent wastewater being either diluted (400-500 mg/L chemical oxygen demand (COD)) or concentrated (800-1000 mg/L COD). Discharge limits for COD and nutrients nitrogen and phosphorus are set with standard or advanced limits according to national and EC regulations.

For the benchmark, reference process schemes are defined and characterised in their energy balances for electricity and heat consumption and production based on OCEAN calculations, using state-of-the-art efficiencies and optimum load conditions. For small WWTPs, net electricity demand is calculated to 18.3 and 23.5 kWh/(pe*a) depending on influent concentration and discharge limits, without energy recovery from anaerobic sludge treatment. For medium WWTPs, net electricity demand is between 4.8 and 9.7 kWh/(pe*a), accounting for the recovered electricity via anaerobic digestion and biogas valorisation in combined heat and power (CHP) plant. This electricity production covers 63-76% of the internal electricity demand of the WWTP. Electrical self-sufficiency is even higher in large WWTPs (74-92%) due to higher efficiencies of CHP plants and aeration aggregates, resulting in a net electricity demand of only 1.4 to 6.5 kWh/(pe*a). In addition, all configurations can cover their projected heat demand via the heat production from the CHP.

Comparing the calculated gross electricity demand for the reference schemes with real benchmarking data of WWTPs in Germany, they are within the best 5-20% of all full-scale plants. This underlines that the reference schemes defined in this report represent state-of-the-art in energy efficient WWTPs and provide a strong benchmark for future comparison with the POWERSTEP concepts.

Finally, building blocks for POWERSTEP schemes are defined and described which will be used for the screening of potential combinations in OCEAN. This includes different processes for carbon removal ("A-stage"), nitrogen removal ("B-stage"), sidestream treatment, and biogas valorisation. They will be combined in different modes to assess a variety of potential schemes and identify those with a superior energy balance compared to the reference schemes. These promising combinations will then be further assessed in detail with life-cycle based tools of LCA and LCC in their environmental and economic profile.

1. Introduction

Within the POWERSTEP project, a selection of innovative processes is demonstrated in pilot or full-scale which should improve the energy balance of a wastewater treatment plant (WWTP), finally enabling the operation of energy-positive treatment schemes. In work package 5 of the project, these processes will be assessed in their potential to improve the energy balance of WWTPs, but also in their overall environmental and economic impacts. The overall goal of WP5 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.

The different case studies in POWERSTEP are mostly testing singular modules of a full treatment scheme (e.g. primary treatment, biogas valorisation), focussing on specific aspects of the process trains of a WWTP and demonstrate their performance and efficiency. However, new concepts have to include all required stages of a WWTP and should represent full treatment schemes (i.e. wastewater treatment, sludge treatment, and biogas valorisation). Hence, the singular POWERSTEP modules have to be combined with existing or new processes into entire treatment schemes to be able to compare these treatment schemes and their energy balance to current best-practice of conventional WWTP technology.

Besides the need to combine single POWERSTEP modules into full treatment schemes, the assessment has to take into account the different boundary conditions that are relevant for WWTPs in the European context. In particular, this relates to:

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

These conditions can vary over a range of values, and will have an impact on the type of treatment required, the respective process to be chosen for the treatment, and consequentially on the energy balance of the related treatment schemes. The assessment in WP5 aims to address the different boundary conditions in selected ranges and analyse conventional and POWERSTEP schemes in relation to these conditions. This will result in a selection of process schemes which may be best suitable for specific conditions and can then be recommended for this particular local situation.

However, the combination of different boundary conditions and different potential combinations of POWERSTEP and conventional modules for WWTPs leads to a huge matrix of possible cases which have to be analysed. Hence, it was decided to take a simplified approach and make a first "screening" of potential schemes in relation to different boundary conditions (Figure 1), and then conduct a more detailed analysis of the most promising schemes with life-cycle based tools (LCA, LCC) which are more time-consuming and data-intensive.

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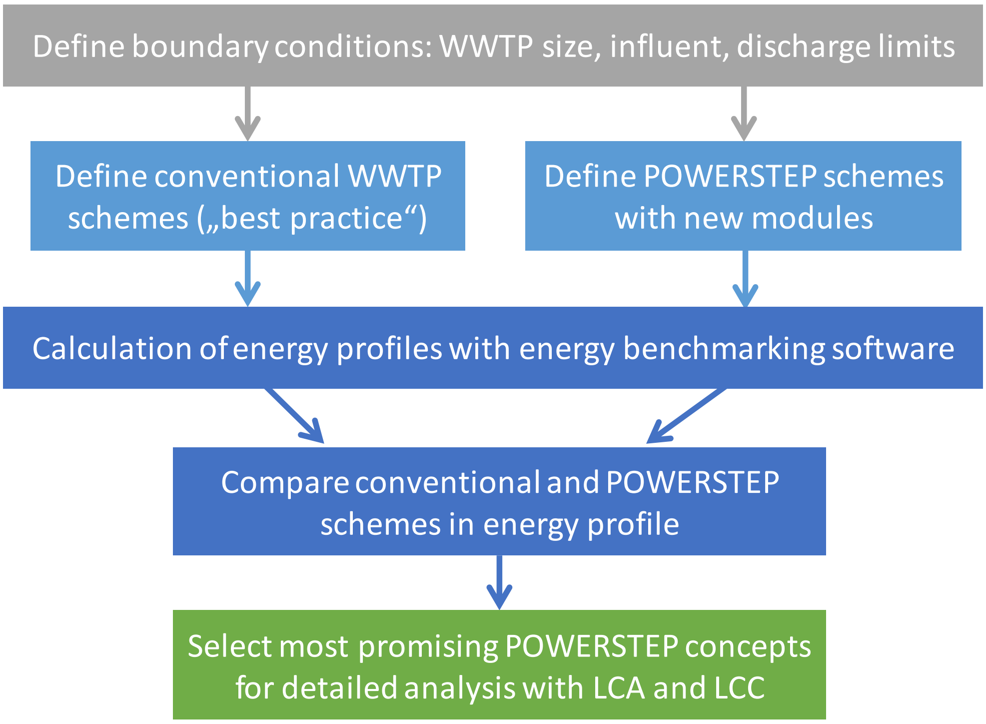

Figure 1: General approach for screening process in POWERSTEP

The simplified assessment will be based on the energy benchmarking software OCEAN, which is a commercial software developed and used by the project parter Veolia. This software uses a static substance flow model of a WWTP and available or new process modules for the different treatment steps to calculate electricity and heat consumption and production of each stage, which results in an overall energy profile for a WWTP scheme. The OCEAN software has been expanded with the new POWERSTEP processes in the course of the project, reflecting the process data which is already available or will be collected in the course of the project.

This report describes the required definitions for this screening procedure and first results for the benchmark energy profile of conventional WWTP schemes:

- Definition of boundary conditions (WWTP size, influent quality, discharge limits)
- Process schemes of conventional WWTPs representing current best practice
- Energy profiles (electricity and heat demand and supply) of these conventional WWTP schemes
- List of new POWERSTEP modules that will be used in the screening for the development of new WWTP schemes
- Step-by-step procedure that will be applied in the screening process to calculate energy profiles of selected POWERSTEP schemes.

Definitions reported in this document have been discussed and validated with the POWERSTEP partners in a separate process group. They are based on the know-how and experience of the POWERSTEP partners together with available data from literature.

2. Definition of boundary conditions and reference WWTP schemes

This chapter presents the definitions which are used to reflect the boundary conditions of WWTP in the European context as well as best-practice of WWTP schemes in relation to these conditions.

2.1. WWTP size, influent quality and discharge limits

Definition for WWTP size, variations in influent quality and potential discharge limits are listed in Table 1. For WWTP size, it was decided to split the range into three groups representing small, medium and large systems. The actual size is defined in relation to the COD influent load, and is fixed at 5'000, 50'000 or 500'000 population equivalents (pe) for small, medium and large WWTP, respectively. Whereas large plants usually serve the majority of the population in urbanised EU countries, medium and small plants are more relevant in the total number of plants. In addition, large plants are often more efficient in terms of energy demand and also energy production, while smaller plants have a larger potential for improvement in their net energy balance.

Table 1: Definition of size, influent quality, and discharge limits for different WWTP classes

Parameter		Small WWTP	Medium WWTP	Large WWTP
Size	[pe]	5'000	50'000	500'000
Influent volume4	[m³/pe*a]	44-88	55-110	55-110
Influent COD	[mg/L]	500-1000	400-800	400-800
Influent N4	[-]	46-92	37-73	37-73
Ratio of particulate COD	[%]	65	60	55
Discharge limit1 for COD	[mg/L]	110	90 **(75)**	75 **(60)**
Discharge limit1 for TN2 (> 12 °C)3	[mg/L]	- **(18 or >70%)**	18 or > 70% **(15)**	13 or > 70% **(10)**
Discharge limit1 for TP	[mg/L]	-	2 **(0.3)**	1 **(0.3)**

1 discharge limits: minimum standards (AbwV 2013) or **advanced standards**
2 Total inorganic nitrogen: sum of NO_3-N, NO_2-N and NH_4-N
3 valid for influent temperature of >12 °C
4 calculated with 120 g COD/(pe*d) and 11 g N/(pe*d) (ATV 2000)

Influent quality is defined with 500-1000 mg/L chemical oxygen demand (COD) in the raw wastewater after mechanical treatment (rake, grit and grease removal for larger plants) for small plants and 400-800 mg/L COD for medium and large plants. This range represents more or less dilution of municipal wastewater, e.g. caused by variations in water consumption of the population, by rainwater mixed with wastewater in combined sewer systems, or by water drainage into the sewer systems in case of compromised pipes. As medium or large WWTPs are more often connected to combined sew-

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ers, 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).

Influent volume per pe is directly calculated from COD load, assuming an average COD load of 120 g COD/(pe*d) for all sizes (ATV 2000). TN concentration in the influent and related COD to N ratio is calculated for municipal wastewater with an average N load of 11 g TN/(pe*d) (ATV 2000). A high contribution of industrial contribution may either increase N or COD load of the raw wastewater for medium and large plants, changing the COD/N ratio between 9 and 12. 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%).

For the discharge limits, many different regulations are in place in each EU member state. Although the EU directive for urban wastewater sets a certain framework, each member state has different regulations for discharge standards, depending on WWTP size but also on the type of receiving water (e.g. sensitive ecosystems) or other local criteria. In addition, monitoring frequency of the discharge limits (e.g. annual mean, daily average, grab sample) and related impact on the WWTP operation cannot be reflected in this study. Finally, 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 (minimum or advanced) in Table 1. However, the modelling with the energy benchmarking software does not reflect dynamic operation of the WWTP, so the discharge limits are interpreted as annual average that have to be guaranteed regardless of the actual legal regulations.

2.2. Process schemes of reference WWTP

Reference WWTP schemes should reflect the current best practice of municipal wastewater treatment in Europe in terms of treatment process, performance, and energy balance. However, a wide range of different process configurations are currently in use in the different EU countries, and the definition of a general “best practice” cannot be made straightforward.

To overcome this issue, the POWERSTEP partners defined a current best practice based on their experience of the wastewater sector in the different countries of origin (i.e.

GER, AT, CH, SE, DK, NL). Thus, a representative treatment scheme is defined for each size of system to serve as a benchmark for comparison with the new POWERSTEP schemes (Table 2):

- **Small WWTP (5'000 pe):** This type of system is typically built as a sequencing batch reactor, which gives higher flexibility in operation. Sludge is usually stabilised with extended aeration (high sludge age), so that no primary treatment is required (Figure 2). This WWTP size does not have an anaerobic digestor due to prohibitive investment costs, so energy cannot be recovered from the sludge. Stabilised sludge is dewatered on-site and transported to sludge disposal.
- **Medium WWTP (50'000 pe):** This size of WWTP is usually operated in a traditional continuous activated sludge process, with primary sedimentation, biological stage, and final clarifier (Figure 3). Nitrogen removal is realised in an anoxic tank upstream of the aeration tank, and nitrified N is recirculated from the effluent of the aerobic stage to the anoxic tank. Some of these medium-sized plants are equipped with an anaerobic digestor for sludge stabilisation, while others may still stabilise their sludge aerobically or chemically. If a digestor is in operation, biogas is usually valorised in a combined heat and power (CHP) plant. Stabilised sludge is dewatered on-site and transported to sludge disposal.
- **Large WWTP (500'000 pe):** The process for large WWTP is comparable to the process scheme for medium WWTPs, with primary sedimentation, biological stage with pre-denitrification, and final clarifier (Figure 3). Sludge is usually stabilised in anaerobic digestion in large WWTPs, and biogas is valorised in a CHP plant to recover electricity and heat for digestor heating. This scheme may be enhanced with a post-treatment step if advanced standards for N removal (e.g. 10 mg/L TN) are required.

Disposal of stabilised sludge is not in the focus of this screening study, as the OCEAN software is designed to calculate the energy balance on-site at the WWTP. Hence, disposal of sludge is assumed to mono-incineration for all schemes, even though smaller WWTPs may still be able to dispose their sludge in other routes (e.g. agriculture). As sludge disposal is not included in the OCEAN energy balance, this aspect will not be addressed in the present report, but will be further specified in the LCA task.

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Table 2: Process schemes for reference WWTPs

Stage	Small WWTP	Medium WWTP	Large WWTP
Size	5'000	50'000	500'000
Primary treatment	Mechanical	Mechanical + sedimentation	Mechanical + sedimentation
Biological treatment	Sequencing batch reactor (SBR)	Continuous activated sludge with pre-denitrification[2]	Continuous activated sludge with pre-denitrification[2]
Sludge treatment	Simultaneous aerobic stabilisation and dewatering	Thickening + anaerobic digestion[1] + dewatering	Thickening + anaerobic digestion + dewatering
Biogas valorisation	-	CHP[1]	CHP

[1] can also be aerobic stabilisation and dewatering (i.e. without energy recovery)
[2] post-treatment in biofilter required for advanced discharge limits (= low TN)

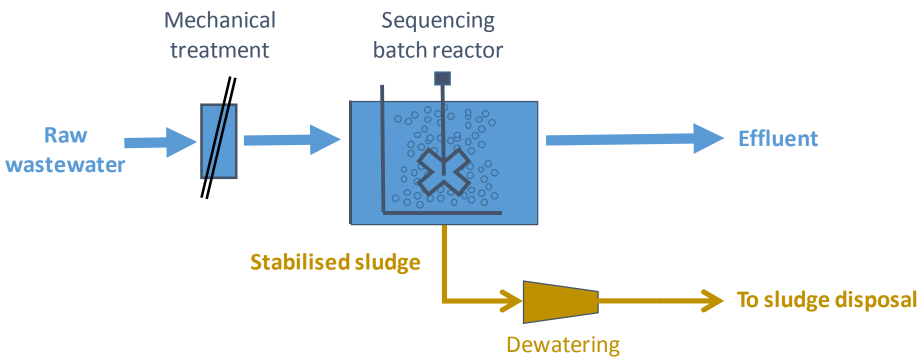

Figure 2: Reference scheme for small WWTP: SBR and simultaneous stabilisation

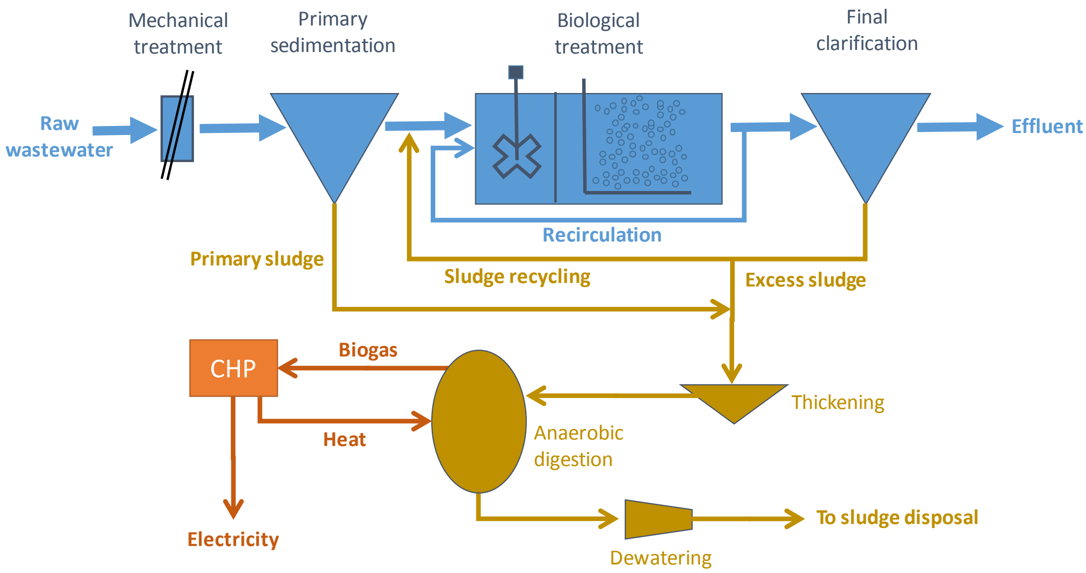

Figure 3: Reference scheme for medium and large WWTP: activated sludge process with anaerobic digestion of sludge

3. Energy balance for reference WWTP schemes

Reference schemes have been implemented in the OCEAN software to calculate a representative energy balance for each scheme, taking into account the different boundary conditions (influent quality, discharge limits). Process efficiencies and other parameters of importance in the OCEAN model were estimated with data for best practice based on previous experience of the OCEAN developers and expert judgements of POWERSTEP partners. Electricity and heat demand includes mechanical and primary treatment, biological treatment, sludge treatment, and other processes (e.g. odour treatment). Energy balance for disposal of dewatered sludge (e.g. mono-incineration) is not included in this report.

Results of the energy balance of small, medium and large WWTPs are presented below for different influent concentrations and discharge limits.

Table 3: Electricity consumption of reference small WWTP (5'000 pe)

Parameter		Low COD influent	Low COD influent	High COD influent	High COD influent
Influent volume[1]	[m³/pe*a]	87.6	87.6	43.8	43.8
Influent COD	[mg/L]	500	500	1000	1000
Influent TN[2]	[mg/L]	46	46	92	92
Discharge limit for COD	[mg/L]	110	110	110	110
Discharge limit for TN (> 12 °C)	[mg/L]	-	18 or >70%	-	18 or >70%
Discharge limit for TP	[mg/L]	-	-	-	-
Electricity balance					
Primary treatment	[kWh/(pe*a)]	2.8	2.8	2.6	2.6
Biological treatment + clarifier	[kWh/(pe*a)]	14.7	17.8	14.2	16.9
Sludge treatment	[kWh/(pe*a)]	0.1	0.1	0.1	0.1
Other	[kWh/(pe*a)]	2.7	2.7	1.5	1.5
TOTAL electricity demand	[kWh/pe*a]	20.4	23.5	18.3	21.0

[1] calculated from influent COD load and 120 g COD/pe*d (ATV 2000)
[2] calculated with N = 11 g/pe*d (ATV 2000)

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Table 4: Electricity and heat balance of reference medium WWTP (50'000 pe)

Parameter		Low COD influent	Low COD influent	High COD influent	High COD influent
Influent volume[1]	[m³/pe*a]	109.5	109.5	54.8	54.8
Influent COD	[mg/L]	400	400	800	800
Influent TN[2]	[mg/L]	37	37	73	73
Discharge limit for COD	[mg/L]	90	75	90	75
Discharge limit for TN (> 12 °C)	[mg/L]	18 or >70%	15	18 or >70%	15
Discharge limit for TP	[mg/L]	2	0.3	2	0.3
Electricity balance					
Primary treatment	[kWh/pe*a]	1.0	1.0	0.6	0.6
Biological treatment + clarifier	[kWh/pe*a]	15.0	15.5	13.4	13.6
Sludge treatment	[kWh/pe*a]	3.1	3.5	3.3	3.6
Other	[kWh/pe*a]	4.1	6.4	2.7	3.9
TOTAL electricity balance	[kWh/pe*a]	23.2	26.4	20.1	21.7
Electricity from CHP	[kWh/pe*a]	14.7	16.7	15.3	16.3
NET electricity balance	[kWh/pe*a]	8.5	9.7	4.8	5.4
Self-sufficiency	[%]	63	63	76	75
Heat balance					
Heat demand	[kWh/pe*a]	14.8	17.0	16.0	17.3
Heat production	[kWh/pe*a]	22.1	25.1	22.9	24.4
NET heat balance	[kWh/pe*a]	-7.3	-8.0	-6.8	-7.1

[1] calculated from influent COD load and 120 g COD/pe*d (ATV 2000)
[2] calculated with N = 11 g/pe*d (ATV 2000)

Table 5: Electricity and heat balance of reference large WWTP (500'000 pe)

Parameter		Low COD influent	Low COD influent	High COD influent	High COD influent
Influent volume[1]	[m³/pe*a]	109.5	109.5	54.8	54.8
Influent COD	[mg/L]	400	400	800	800
Influent TN[2]	[mg/L]	37	37	73	73
Discharge limit for COD	[mg/L]	75	60	75	60
Discharge limit for TN (> 12 °C)	[mg/L]	13 or >70%	10	13 or >70%	10
Discharge limit for TP	[mg/L]	1	0.3	1	0.3
Electricity balance					
Primary treatment	[kWh/pe*a]	0.7	0.7	0.4	0.4
Biological treatment + clarifier	[kWh/pe*a]	14.0	15.4	12.4	13.5
Sludge treatment	[kWh/pe*a]	3.0	3.2	3.2	3.3
Other	[kWh/pe*a]	3.8	5.9	2.5	3.5
TOTAL electricity balance	[kWh/pe*a]	21.6	25.2	18.5	20.7
Electricity from CHP	[kWh/pe*a]	16.5	18.7	17.1	18.2
NET electricity balance	[kWh/pe*a]	5.1	6.5	1.4	2.5
Self-sufficiency	[%]	76	74	92	88
Heat balance					
Heat demand	[kWh/pe*a]	14.9	16.4	15.9	16.7
Heat production	[kWh/pe*a]	18.9	21.5	19.6	20.9
NET heat balance	[kWh/pe*a]	-4.0	-5.1	-3.6	-4.2

[1] calculated from influent COD load and 120 g COD/pe*d (ATV 2000)
[2] calculated with N = 11 g/pe*d (ATV 2000)

3.1. Electricity balance

Electricity balances for all sizes and conditions are shown in Figure 4. For all WWTP sizes, diluted wastewater requires higher electricity demand than concentrated wastewater, mainly due to more pumping required in the plant for recirculation and return activated sludge. Discharge limits with more strict targets in nitrogen removal lead to slightly higher electricity demand (+ 8-17%) compared to less strict discharge limits for all WWTP sizes

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and conditions, mainly due to more recirculation/mixing time required or the need for an additional post-treatment step (e.g. biofilter) for the medium and large plants. It has to be noted that all configurations do not need to add an external carbon source in this theoretical model, as the available carbon after primary treatment is sufficient to achieve the targeted nitrogen removal in the conventional mode for all cases.

Energy demand for small WWTPs is between 18 and 24 kWh/(pe*a) depending on dilution and discharge standards. Medium WWTPs need between 20 and 26 kWh/(pe*a) for the treatment, whereas large WWTPs require 19-25 kWh/(pe*a) due to better efficiency of the aggegrates. Medium and large WWTPs can supply some of their electricity demand via biogas valorisation in CHP plants, accounting for an electricity production of 15-19 kWh/(pe*a). Combining demand and production into a balance, the degree of self-sufficiency in electricity is around 63 to 76% for medium plants and 74-92% for large plants.

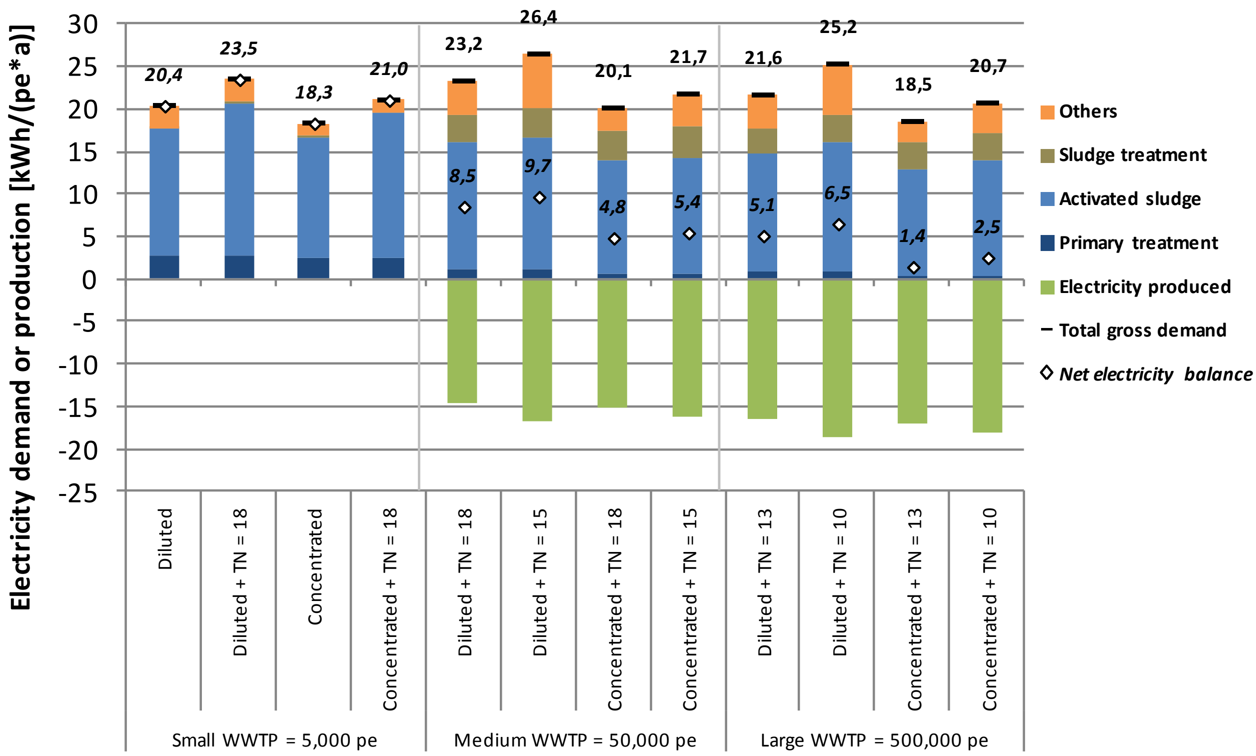

Figure 4: Electricity balance for reference WWTP schemes

If electricity demand for WWTPs is compared to the current benchmark of conventional WWTPs (e.g. as described in German benchmarking DWA A216 (DWA 2015)), **the POWERSTEP reference schemes are among the best 5% of the benchmark for small SBR plants and among the best 20% for medium and large activated sludge plants with anaerobic digestor**, thus representing the state-of-the-art of energy-efficient WWTPs. Compared to the mean electricity demand for medium WWTPs (34 kWh/(pe*a) or large WWTPs (30.5 kWh/(pe*a)) in Germany (Figure 5), the POWERSTEP reference schemes are around 25-40% below the mean value, again indicating that these schemes are fully optimized in energetic terms. It has to be noted that the OCEAN calculations represent "ideal" conditions in terms of utilization of the different stages, meaning that all aggregates (e.g. pumps, mixers) run at maximum efficiency with optimum load factors.

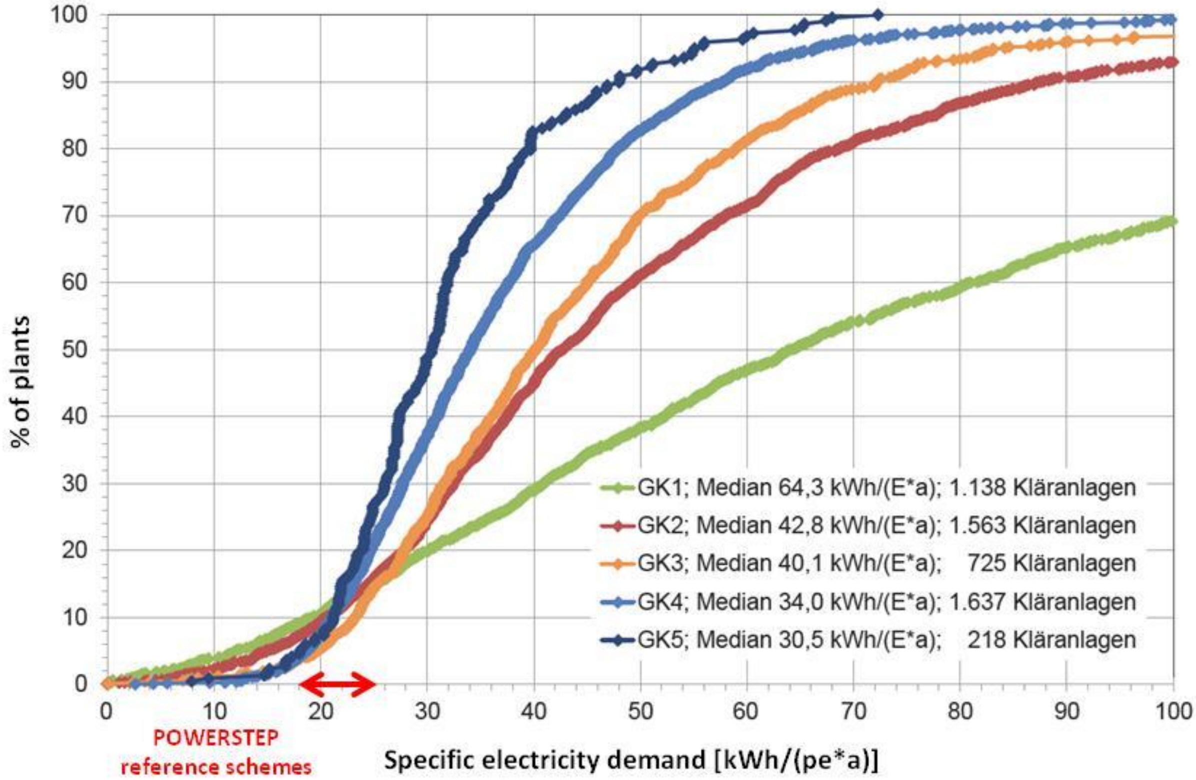

Figure 5: Benchmarking of gross electricity demand of German WWTPs (DWA 2016) (GK1: <1,000 pe, GK2: 1-5,000 pe, GK3: 5-10,000 pe, GK4: 10-100,000 pe, GK5: >100,000 pe)

In summary, the reported energy balance for the reference WWTP schemes can be regarded as the lowest energy demand possible under "best practice" conditions:

- No site-specific energy drivers (e.g. no lifting of influent wastewater)
- State-of-the-art efficiency of processes and aggregates
- Optimum load factors for process design, no idle time

Hence, comparing these reference schemes with the POWERSTEP concepts will give an idea of the minimum potential of improvement while shifting to a POWERSTEP approach, having in mind that most WWTPs nowadays will have a less favourable energy profile compared to the reference schemes in this report.

3.2. Heat balance

Heat demand and production are shown for all cases in Figure 6. Small WWTPs do not produce or require any heat for WWTP operation (aside from small heat demand for buildings, hot water etc.). Medium and large plants need most heat for digestor heating, but they also produce heat from the valorisation of biogas in the CHP unit. Heat demand for the reference medium and large WWTPs is between 15 and 17 kWh/(pe*a), whereas heat production is between 19 and 25 kWh/(pe*a). Hence, heat production is larger than heat demand at the WWTP (Figure 6) for all conditions, so that the operation

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of the WWTP scheme does not require external fuels for heat production. This situation is fairly common at WWTPs which have a digestor and CHP unit and do not operate under unfavourable conditions for the heat balance (e.g. cold climate, low insulation of digestor, thermophilic operation, low biogas yield), although in winter time the heat demand of a WWTPP may surpass the heat producing, causing temporary purchase of fuel or gas.

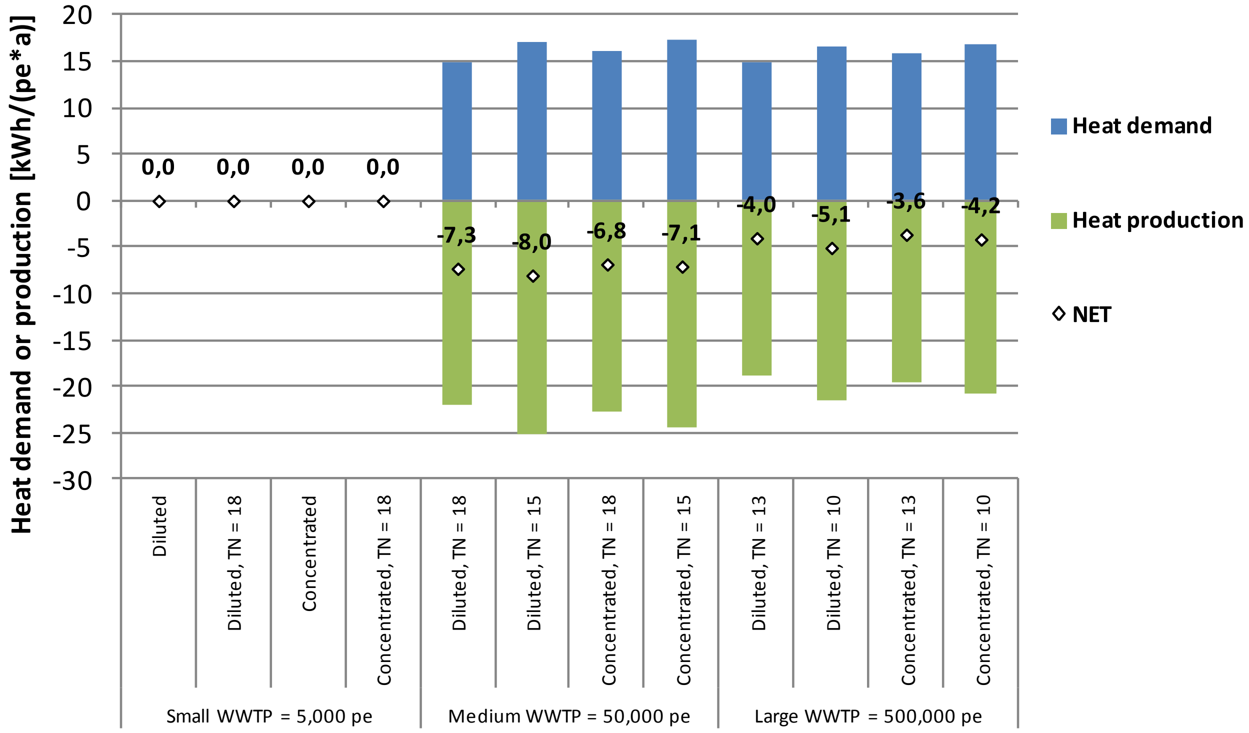

Figure 6: Heat balance for reference WWTP schemes

The utilitation of available heat at the WWTP can be optimized following different concepts, e.g. using heat-to-power technologies of SRC/ORC or thermoelectric generators (as in case study 4 of POWERSTEP). This conversion of excess heat into electricity can improve the overall energy balance, but has to be carefully checked for its economic feasibility. Another way of using the excess heat is the optimisation of existing processes with heat demand, e.g. using heat for thermal sludge treatment (e.g. thermal hydrolysis) to improve biogas yield and dewaterability. Although these concepts are not directly in the scope of POWERSTEP, heat utilization will be discussed as a further means for energy optimisation in work package 3 (D3.3).

4. Definition of POWERSTEP schemes

The definition of innovative process schemes for WWTP ("POWERSTEP schemes") is based upon the selection of singular POWERSTEP modules. These modules represent different processes for specific steps within the WWTP process:

- Carbon removal
- Nitrogen removal
- Sidestream treatment
- Biogas valorisation

The first part of this chapter lists the available process modules for each step, while the second part outlines a step-by-step procedure for the screening process.

4.1. State-of-the-art processes and innovative POWERSTEP modules

Process modules for the mainline WWTP are split into those processes which are relevant for carbon removal ("A-stage") and those who are primarily used for nitrogen removal ("B-stage"). Naturally, both stages can contribute to both goals: the A-stage may also remove particulate nitrogen, while the B-stage also removes residual carbon. Both stages in combination should lead to an effluent quality which is suitable for discharge. If this quality cannot be reached (e.g. due to carbon limitation or process restrictions), a biological polishing step can be required (e.g. post-treatment in a biofilter, MBBR or comparable). This post-treatment is not a major focus in the POWERSTEP project, but has to be added "on-demand" in the screening procedure if the selected combination cannot reach the defined effluent quality.

Processes for the A-stage of the WWTP are listed in Table 6. They include all processes that are useful to extract or exploit the carbon content of the raw wastewater without major biological conversion, focussing on the generation of sludge which can then be used for biogas production in the digestor. The losses of carbon due to aerobic biological degradation should be minimised in this stage. A-stage processes include:

- Processes which focus on a **physico-chemical removal of carbon**, i.e. the combination of chemical dosing with physical separation. These are chemically enhanced primary sedimentation, flocculation and microscreen, or flocculation and dissolved air flotation.
- Processes with **high-load activated sludge**, which try to foster biological uptake of dissolved carbon and inclusion into the sludge, but without major aerobic degradation. They work with high-load conditions (i.e. high COD input per m³ tank volume) and low sludge age. These processes include continuous activated sludge systems with high load (typical "A-stage" of an A/B process) but also high-load attached biofilm systems such as the Moving Bed Biofilm Reactor (MBBR).
- Processes which rely on **anaerobic treatment**, i.e. upflow anaerobic sludge blanket (UASB) process. These biological processes work without oxygen input and try to convert incoming COD directly to CH_4. However, they are known to require high COD concentration and temperature due to the slow kinetics of anaerobic metabolism. In addition, they can be negatively affected by particulate matter, which may restrict their use as a primary stage for municipal WWTPs. Hence, it

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has to be checked if they are suitable for the POWERSTEP concepts with relevant experts.

Table 6: POWERSTEP modules in mainline WWTP for A-stage (C removal)

Process for A-stage	Description	Data sources	Expected COD removal[1]
Chemically enhanced pre-treatment (CEPT)	Coagulant and/or polymer dosing upstream of primary sedimentation tank	Literature	40-60%
High-rate conventional activated sludge (CAS)	A-stage of an A/B- or two-stage process with low sludge age and high COD load	Literature + case study 5 (WWTP Kirchbichl)	40-50%
High-rate Moving Bed Biofilm reactor (MBBR)	A-stage with MBBR technology and high COD load	Literature + case study 2 (WWTP Sjölunda)	40-50%
Microscreen (MS)	Direct filtration with MS (disc or drum filter)	Case study 1 (WWTP Westewitz) and 2 (WWTP Sjölunda)	30-40%
Flocculation + microscreen	Dosing of polymer before MS		50-60%
Coagulation + flocculation + microscreen	Dosing of coagulant and polymer before MS		70-80%
Upflow anaerobic sludge blanket (UASB)[1]	UASB process as primary treatment for high-strength wastewater	Literature	40-70%
Flocculation and dissolved air flotation (DAF)	Dosing of polymer and flotation of primary sludge	Literature	40-60%

[1] estimates based on (Remy et al. 2014, Ødegaard 2016, Väänänen et al. 2016, Wan et al. 2016)

[2] to be checked if suitable for municipal wastewater (COD concentration, particulate matter)

Processes for the B-stage of the WWTP are listed in Table 7. They primarily target the removal of nitrogen with biological processes, but also remove residual organic carbon. In particular, two different approaches can be used:

- **Nitrification – denitrification:** this combination of processes is usually applied in WWTPs for N removal. It relies on the aerobic nitrification of incoming ammonia to nitrate by slow-growing nitrifiying microorganisms, which require a high sludge age > 20 days to be enriched in the activated sludge. In a second step, the nitrate is reduced to gaseous N_2 in denitrification under anoxic conditions, i.e. without aeration. As denitrification requires a carbon source (heterotrophic process), WWTPs are often operated in a "pre-denitrification" mode, so that the first stage of biological treatment is operated in anoxic conditions while recirculating the nitrate from the second stage of nitrification to the first stage (cf. Figure 3). This process of N removal needs high tank volumes and pumping energy due to recirculation of water (up to 400% of the input flow), and consumes carbon for denitrification.

- **Mainstream Anammox:** this process is also a two-step process for N removal, but it is based on anammox bacteria which are able to reduce NH_4 and NO_2 to gaseous N_2 without using a carbon source. As a first step, around 50% of the incoming ammonia is converted to nitrite (NO_2) by ammonia-oxidizing bacteria (AOB) with low oxygen supply. The second step uses slow-growing anammox bacteria to convert NH_4 and NO_2 into N_2, leaving around 10% of nitrate after the process due to the stoichiometry of the reaction. The challenge in this process is to prevent further oxidation of NO_2 to NO_3 (following the conventional pathway of nitrification) by nitrite-oxidizing bacteria (NOB) in the first step, which can be realized by low oxygen supply and by providing unfavourable conditions for NOB species. In addition, anammox bacteria are slow-growing organisms, so that they have to be enriched in the system. In the POWERSTEP project, a two-stage anammox process based on two biofilm reactors (MBBR) is tested in case study 2, and selected strategies are used to suppress NOB growth (e.g. regular feeding of sidestream water with high NH_4 content to the nitritation stage) and enrich anammox bacteria in the biofilm (Piculell et al. 2016). A particular challenge is the operation of anammox processes at low wastewater temperatures due to the slow kinetics of this reaction. Another option is the operation of single-stage Nitritation-Anammox process, where the two steps take place in the same reactor (e.g. with an Integrated Fixed-Film Activated Sludge (IFAS) configuration combined with an MBBR (Veuillet et al. 2014)). The latter configuration benefits from a more rapid start-up of the process and some operational advantages over the two-stage process.

Table 7: POWERSTEP modules in mainline WWTP for B-stage (N removal)

Process for B-stage	Description	Data sources
Nitrification and denitrification	Nitrification with high sludge age and pre-denitrification with recirculation flow	Literature
Mainstream Anammox in 2-stage MBBR	Two-stage process with partial nitritation[1] and anammox in separate MBBR reactors	Case study 2 (WWTP Sjölunda)
Mainstream Anammox in 1-stage MBBR	One-stage process with partial nitritation and anammox in the same reactor (e.g. IFAS-MBBR configuration)	Literature

[1] can be supported with regular feeding of sidestream water

A challenge in combining A-stage and B-stage processes is the optimisation of carbon management: If too much carbon is extracted upfront in the A-stage, dosing of an external carbon source may be required to reach expected N removal with conventional denitrification. Different strategies are available to optimise carbon extraction depending on carbon needs for N removal, e.g. variation of chemical dosing in A-stage, bypass of raw wastewater to B-stage, or longer hydraulic residence time in B-stage to induce endogeneous denitrification. However, these strategies will reduce the carbon in

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the sludge which is available for energy recovery. Hence, an optimal B-stage process for maximum energy recovery will be based on mainstream anammox, but the stability and efficiency of this process in various conditions still has to be validated for mainstream WWTP in full-scale. Hence, different combinations of A-stage and B-stage processes should be evaluated to come up with different options for an optimised WWTP treatment scheme with the best energy balance.

Another challenge of nitrogen management comes with the use of an anaerobic digestor: anaerobic degradation of organic matter into CH_4 also leads to the conversion of nitrogen content of the sludge into ammonia again. This dissolved NH_4 is diverted into the sludge liquor in dewatering of digested sludge and will be recycled to the inlet of the WWTP, where it increases the N load of the main line considerably. This effect may be even more pronounced if carbon extraction is maximised, which may generate more sludge and thus more ammonia load in the return liquor.

To overcome this problem of N return load, different processes are available to remove nitrogen from the sludge liquor in a separate stage ("sidestream treatment") (Table 8):

- **Nitrification and denitrification:** this conventional process can be applied in an SBR configuration for sludge liquor treatment, although it may need dosing of an external carbon source depending on the COD content in the liquor.
- **Nitritation:** this process operates a nitritiation stage, converting ammonia to nitrite with low oxygen demand. This nitrite can then be recycled to the first stage of a two-stage WWTP as source for chemical oxygen. As oxygen transfer efficiency is higher in the sidestream process, it can also save on aeration energy. This strategy is demonstrated at WWTP Kirchbichl, and will be evaluated by dynamic modelling of the entire system.
- **Anammox:** sludge liquor can also be treated with a nitritation-anammox process for N removal without the need of a carbon source. The conditions in sludge liquor (high NH_4 concentration, high temperatures) are more favourable for this process than in mainstream. It can be realized with different configurations (one or two stage), but is tested within the POWERSTEP project in a two-stage MBBR configuration.
- **Membrane stripping:** this process is based on physical removal and recovery of NH_4 from sludge liquor with a membrane-based configuration. After removing scaling potential of struvite and residual particles, pH and temperature of sludge liquor are increased to maximise the fraction of free NH_3. This dissolved NH_3 can then diffuse through a gas-permeable membrane, which is fed with a concentrated acid (H_2SO_4) at the permeate side. NH_3 is absorbed into the acid and forms $(NH_4)_2SO_4$, which can be extracted and used as a fertilizer in agriculture. The challenge in this process is the optimisation of pre-treatment to prevent damage to the membrane module and increase efficiency of N recovery without spending excessive chemicals for pH control (NaOH) and heat.

Sidestream processes are an "add-on" to the mainstream configurations to minimize the negative impacts of high N loads on the overall energy balance of the WWTP scheme. Combining sidestream and mainstream technologies can also lead to more synergies, e.g. with recycling of nitrite in two-stage plants or bio-augmentation of a mainstream anammox process.

Table 8: POWERSTEP modules in sidestream treatment (N removal or recovery)

Process for sidestream treatment	Description	Data sources
Nitrification and denitrification	SBR reactor for nitrification and denitrification with dosing of carbon source on demand	Literature
Nitritation	Nitritation in continuous activated sludge and recycling to first stage of two-stage process[1]	Case study 5 (WWTP Kirchbichl)
Anammox	SBR reactor for partial nitritation and anammox in MBBR (2-stage)	Case study 2 (WWTP Sjölunda)
Membrane stripping	Pre-treatment of sludge liquor (pH increase, struvite precipitation) and stripping of NH_3 in membrane process for N recovery as fertilizer $(NH_4)_2SO_4$	Case study 6 (WWTP Altenrhein)[2]

[1] evaluated with dynamic modelling (TU Vienna)
[2] depending on full-scale realisation, or data from other full-scale installation (e.g. WWTP Yverdon)

The final process for energy recovery at the WWTP is the valorisation of biogas. Typically, produced biogas is stored and used on-site to produce electricity and heat, which can then meet the internal demand of the WWTP process. Biogas can also be upgraded to meet specifications for natural gas, which can then be injected into the public gas grid or used as car fuel.

In particular, the following modules will be used for biogas valorisation in the POWERSTEP schemes:

- **CHP plant:** this process represents the traditional route for biogas valorisation on-site. Burning the biogas in a CHP plant, electricity and heat are produced locally and can be used to meet the demands at the WWTP. Heat from CHP units is typically available at two different temperature levels: around 50% of the produced heat is available at 90°C from the cooling cycle of the gas motor, while the rest is contained in the off-gas at temperatures of 450°C. Both heat sources can be exploited with heat exchangers and are often used for heating of digestors, buildings, or other processes with heat demand (e.g. thermal hydrolysis).
- **SRC or ORC:** the implementation of a steam rankine cycle (SRC) or organic rankine cycle (ORC) process can valorise excess heat from the CHP unit which is not utilized for other purposes. The total amount of heat produced at the CHP is often not fully exploited in a WWTP, as heat supply from the cooling cycle is usually more than sufficient to heat digestors and buildings. Excess heat from cooling or off-gas can then be used to heat a thermal fluid (either steam or an organic fluid) which can drive an engine with a generator to produce electricity ("rankine cycle"). SRC or ORC processes can work on different heat gradients and provide

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electricity as a "heat-to-power" technology, improving the efficiency of biogas valorisation.

- **Biological methanation:** this process uses specific microorganisms to convert residual CO_2 in the biogas from digestor (35-40 Vol-%) into CH4 by using hydrogen (H_2), a process called biomethanation. Hydrogen is produced in an electrolyzer and fed to a biological reactor where biogas is also injected to promote biomethanation, leading to a final CH_4 content >95 Vol-% in the biogas. After cleaning and mixing, this gas can comply with the specifications of natural gas and is fed into the gas grid or can be used as fuel supply for cars. The electrolyzer should ideally be operated in times of low electricity prices to maximise the economic feasibility of this "power-to-gas" technology. Produced oxygen from the electrolyzer can be injected into the aeration system of the mainline WWTP to support oxygen transfer efficiency.

Biogas valorisation will be typically realized with a CHP unit in the POWERSTEP schemes. Efficiency of heat use may be increased with SRC/ORC processes if economic feasibilty can be shown. In contrast, biomethanation offers a second route for direct biogas valorisation as equivalent to natural gas (e.g. grid injection, car fuel). This power-to-gas technology can be especially relevant in combination with a "smart-grid" approach which integrates the WWTP into the fluctuating energy market, e.g. by using electricity for biomethanation depending on the real-time electricity price.

Table 9: POWERSTEP modules for biogas valorisation

Process for biogas valorisation	Description	Data sources
Combined heat and power (CHP) plant	Operation of CHP with gas cleaning	Literature
Steam Rankine Cycle (SRC) or Organic Rankine Cycle (ORC)	Recovery of excess heat from CHP and conversion to electricity in SRC/ORC	Literature + case study 4 (WWTP Braunschweig)
Biological methanation	Operation of electrolyzer to produce H_2 and biological conversion with residual CO_2 of biogas into CH_4 to upgrade biogas for grid injection	Case study 3 (WWTP Avedore)

4.2. Combining modules to entire treatment schemes

The different modules for A-stage, B-stage, sidestream treatment and biogas valorisation can now be combined to potential full treatment schemes for a WWTP. At this stage of the project, the scenarios will be developed in a "greenfield" approach without any limits on building area, economics, or else.

For combining the modules, some considerations should be taken into account:

- Combinations should be **technically feasible** based on process characteristics and preliminary mass balances. They should also fit to the WWTP size in terms of technical complexity, having less complex trains for smaller WWTPs.

- Combinations should be able to **meet the required discharge standards** (Table 1). If effluent quality cannot be met after two stages, a polishing step can be added in the OCEAN model.

The following procedure will be adopted to calculate energy balances for the different combinations (Figure 7):

- Combine A-stage and B-stage → check effluent quality and adjust process parameters to realize effluent quality targets
- Add polishing step if required → validate final effluent quality with target limits
- Add anaerobic digestor and CHP plant
- Check energy balance against benchmark WWTPs (cf. Table 3, Table 4, Table 5) and pre-select most promising options

In a next step, additional modules for sidestream treatment can be added to each scheme:

- Add sidestream treatment to reduce N return load
- Re-check effluent quality and adjust treatment train accordingly
- Check energy balance against benchmark WWTPs and select most promising options

In a final step, biogas valorisation can be optimised by improving efficiency or implementing the "power-to-gas" approach of biomethanation. This step may be more relevant for improving the economics of POWERSTEP schemes than for improving the overall energy balance. It is recommended to add these options for improved biogas valorisation to pre-selected schemes with most promising energy balances in LCA and LCC.

This procedure should results in a selection of most promising POWERSTEP schemes for the different boundary conditions (WWTP size, influent quality, discharge limits). It is expected that process combinations correlate in their energy balance with regards to specific influent quality and discharge limits. Hence, it is recommended to start this analysis with a specific setup (e.g. low COD in influent, normal discharge limits) and learn about the effect of different combinations on the overall energy balance. This way, the vast number of potential combinations (e.g. 12 boundary conditions x 12 combinations of A- and B-stage x 2 sidestream treatments = 288 combinations) can be reduced to prevent excessive calculation work in the screening process.

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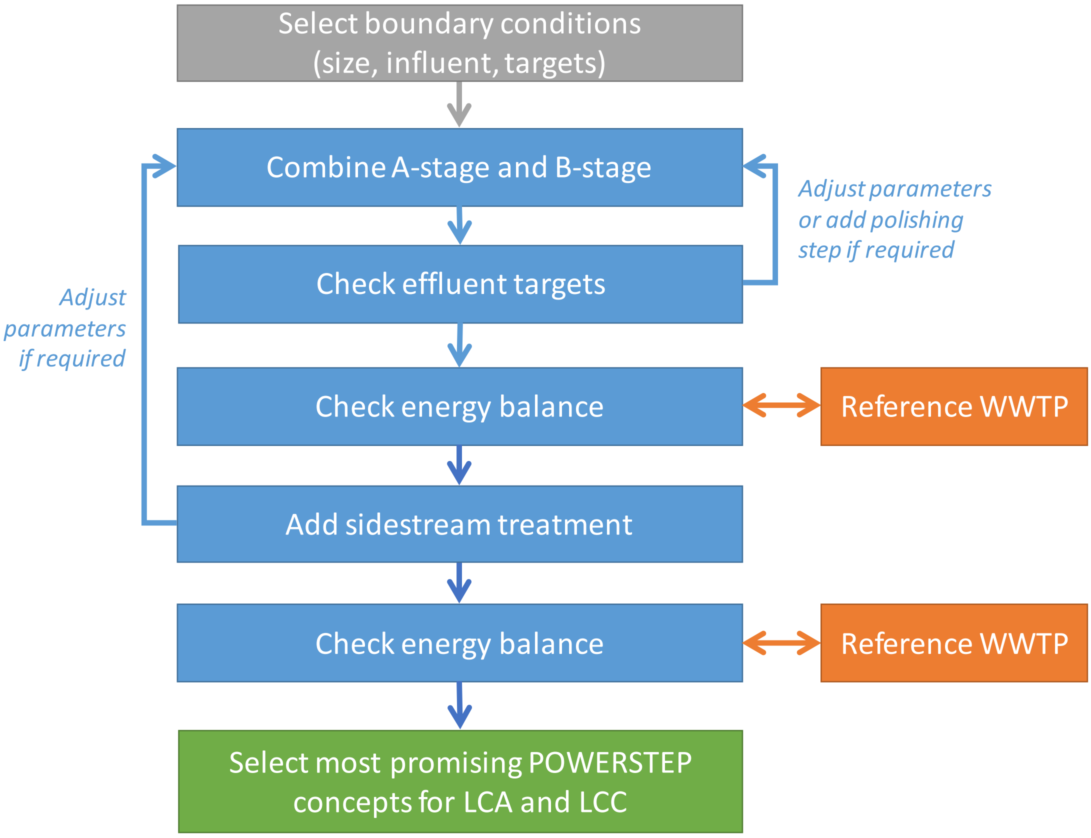

Figure 7: Step-by-step procedure for screening of potential combinations with OCEAN

Finally, this procedure should lead to a final short-list of POWERSTEP schemes that are most promising in their energy balance for each condition. This short-list is then transferred to the detailed analysis with life-cycle based tools which will enable a more in-depth assessment of their environmental and economic profiles.

5. Conclusion

This report describes the definitions of specific boundary conditions which are relevant for the further assessment of different WWTP schemes in POWERSTEP:

- WWTP sizes (5,000, 50,000 and 500,000 pe)
- Characteristics of raw wastewater (diluted, concentrated)
- Discharge limits (standard, advanced)

For all conditions, respective definitions have been discussed and presented in this report. Building on these definitions, reference schemes for conventional WWTPs have been defined and characterized in their energy profile, using the energy audit software OCEAN of Veolia. Demand and production of electricity and heat have been calculated for all conditions and reference schemes in OCEAN, using best-practice efficiencies and optimum load factors to derive a "state-of-the-art" WWTP with optimised energy demand.

Resulting gross electricity demand ranges between **18 and 25 kWh/(pe*a) for all WWTP sizes and conditions**. In general, dilution of influent wastewater leads to higher electricity demand compared to more concentrated influent. Similarly, more strict discharge standards for TN increase electricity demand by 8-17% compared to standard targets. Overall, **gross electricity demand of the WWTP reference schemes are within the best 5-20% of the German benchmark of WWTPs**, indicating that the schemes and input data used in this report reflect best-practice conditions and can be seen as a "state-of-the-art" of energy-efficient WWTP operation.

Taking into account anaerobic digestion and biogas valorisation in medium and large WWTPs, an electricity production of 15-19 kWh/(pe*a) is predicted with the OCEAN model. This results in relatively **high degrees of self-sufficiency of 63-92% depending on WWTP size and discharge limits**, corresponding to a remaining net electricity demand of only 1-10 kWh/(pe*a). The high self-sufficiency underlines again that the reference schemes represent best practice in energy consumption and production, with the best cases approaching an energy-neutral operation.

Heat balances indicate that all configurations can cover their internal heat demand with the produced heat of the CHP units, which is common at WWTPs with anaerobic digestion/CHP and can be regarded as realistic benchmark.

Apart from the reference WWTPs, this report lists a number of innovative process steps which can serve as building blocks for new POWERSTEP schemes. Based on the demonstration in the respective case studies of POWERSTEP, different processes for carbon removal ("A-stage"), nitrogen removal ("B-stage"), biogas valorisation and sidestream treatment are available to be assembled to full treatment lines. After implementation of these modules in the OCEAN software, potential combinations for full treatment schemes will be checked in their energy balance to screen the large number of possible options in a systematic way. These screening results will be compared to the benchmark values established in the present report to identify promising combinations of POWERSTEP schemes which are clearly superior in energy balance against "state-of-the-art" conventional WWTPs. Promising innovative schemes will then be assessed in detail using life-cycle based tools (LCA and LCC).

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