WP4 – Nitrogen management in side stream

D 4.4: Decision support for finding the appropriate resource and energy optimized SDE treatment technology

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 4.4	***Decision support for finding the appropriate resource and energy optimized SDE treatment technology***
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Abstract	Sludge dewatering effluent (SDE) resulting from the dewatering of digested sewage sludge is rich in ammonium nitrogen and needs to be returned to the mainstream activated sludge tank for treatment. Alternatively, sidestream treatment of SDE applying e.g. nitritation, anammox, air or membrane stripping can be advantageous from an energetic and economic point of view, the impact depending on plant configuration (single v. 2-stage WWTP) and wastewater composition. A calculation tool called "Decision Tool" based on performance data of full-scale WWTPs was developed within WP4 to allow a techno-economical comparison among different SDE treatment options and plant configurations. The ecological impact was included in form of a carbon footprint.

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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Executive summary

This report describes the Decision Tool that has been developed as part of the work package 4 of the PowerStep project. The Decision Tool aims to support decisions in relation to treatment plant layout and sidestream treatment options for the sludge dewatering effluent for WWTP design and upgrades. In addition to the description of the relevant parameter, basic assumptions and core variables, this report compares the results of the Decision Tool with results from the OCEAN tool (WP 5) to ensure that a fair comparison of all evaluated technologies across the different work packages is possible. Finally, the results in relation to energy consumption and carbon footprint for the different technologies considered in WP4 are compared and general trends are explained to give an idea how the tool can be used in future and what it is able to deliver.

From a treatment perspective the tool allows to compare conventional activated sludge processes in a single stage and 2-stage configuration. Both technologies can be expanded with a primary sedimentation step. For anaerobic stabilization, single stage mesophilic digestion is included in the model. Co-substrates and external sludge can be directly added to the anaerobic sludge digestion stage. The influent composition of the sewage and the external substrates can be varied in a wide range to suit the requirements for different countries and circumstances. The sidestream treatment options for the sludge dewatering effluent evaluated in the Decision Tool are partial nitritation, the Anammox process, air stripping and membrane stripping.

Based on the input date the tool estimates the required reactor sizes and the flows between the different stages of the process (e.g. RAS, WAS). The estimated volumes are used to estimate the investment costs based on Central European experience. It is however possible to use own data for specific costs as a basis for the cost calculation. For the whole treatment process including sidestream treatment mass balances for relevant parameter are provided. Based on the mass balances and the specific flows the electrical energy for the whole process is calculated. The results are broken down in the different treatment stages, so that it is easy for the user to compare the results with general benchmarks that are available for processes or individual plants. Finally, the carbon footprint for the processes are calculated based on direct and indirect emissions. To be enphasized is that the assumptions in Decision Tool mainly rely on performance data of full-scale plant.

For a demonstration of the functions of the tool, some setups have been calculated. Based on single and 2-stage activated sludge plants all relevant treatment options for the sidestream treatment are compared with the tool. Some of the key findings are:

- Regardless of the side stream treatment process, 2-stage activated sludge processes are more energy efficient than single stage WWTPs
- The construction costs and the operating costs for 2-stage activated sludge plants are lower than the costs for single stage activated sludge plants.
- When comparing the different sidestream options the ease of operation, process stability as well as the carbon footprint have to be considered for a useful assessment. These factors might have a bigger impact on the decision than the energy consumption and costs.

The outcomes of this work package and the assessment with the decision tool will be fully fed into work package 5 where a full LCC and LCA of all PowerStep technologies will be conducted.

1. Aim of the Decision Tool

Nitrogen bound in organic matter of sewage sludge is hydrolysed to ammonium during anaerobic sludge digestion. Whereas soluble biodegradable organic carbon is converted via the intermediate acidification step into biogas (CH_4 and CO_2), the nitrogen remains in form of ammonium (NH_4^+) in the sludge. Dewatering of digested sludge leads to a separation of solids from water. The resulting ammonium loaded sludge dewatering effluent (SDE) is returned to the mainstream activated sludge tank where NH_4^+ is removed per nitrification and denitrification, leading to higher energy demand for aeration and, depending on sewage composition, to lower N-removal capacity. The nitrogen load in SDE amounts to approximately 20 % of the influent load of a wastewater treatment plant (WWTP). This amount of nitrogen also results in a bigger activated sludge tank (AST) volume.

SDE can be treated also in sidestream before being retuned to the mainstream (see PowerStep Deliverable 4.1). Depending on the selected SDE sidestream treatment option, the ammonium load to the AST can be significantly reduced in sidestream, releaving the main-stream treatment. Different biological, chemical and physical treatment options are available. The chemical sidestream-treatment aims at removing nitrogen and phosphate from SDE via precipitation of for example magnesium-ammonium-phosphate (MAP). The application of MAP precipitation for advanced N removal in SDE does not seem to be a feasible option from an ecological and economic point of view, because of the huge amount of external chemicals and energy needed to increase the poor N-removal degree of the treatment. For this reason, this option was not considered within this work.

Nitritation and the **Anammox** process represent suitable sidestream treatment options. Due to the compostion of SDE (high ammonium concentration, high temperature, high pH value) the nitrification process can be stopped at nitrite by exposing nitrite oxidizing bacteria (NOB) to high ammonia concentrations. The conversion of ammonium to nitrite is limited in SDE by the alkalinity and is in a range of 55 % (full-scale results of case study 5). This means, that the treated SDE contains 55 % nitrite and 45 % ammonium. The nitrite produced can be used für denitrification when returned into mainstream in a not aerated tank. This provides several operating advantages especially when applied at a two stage WWTP (see also Deliverable 4.1). In case of further Anammox treatment, the resulting nitrite is converted with ammonium to elementary nitrogen (N_2) and thus removed from SDE. Only a small proportion of ammonium remains in SDE (about 3 % based on the NH_4-N in SDE). Additionally, nitrate is produced by Anammox bacteria in a range of 20 % based on the converted ammonium-nitrogen.

Practicable options for physical SDE treatment are **air-stripping** and **membrane-stripping**. It is assumed that both physical treatment options lead to a reduction of 90 % of ammonium in SDE (Information by Marc Böhler, EAWAG, leader case study 6). The pre-treated SDE therefore contains only 10 % of the initial ammonium load.

Summarising, the SDE sidestream treatment option has a decisive influence on the nitrogen load returned to the AST. Thus, the SDE sidestram treatment also influences the required tank volume of the AST, which is reflected in the calculated costs (infrastructure and operating costs) for the WWTP. Additionally, to ensure extensive nitrogen removal at 2-stage WWTPs pumping of treated wastewater from WWTP effluent back to the AST 1st stage (nitrate recirculation) or bypassing a part of the effluent of primary sedimentation to the AST 2nd stage can be necessary. These additional volume flows influence the hydraulic load of the sedimentation tanks (intermediate sedimentation and secondary sedimentation) which is reflected in higher required volume and correspondingly higher costs due to both, construction and energy for pumping. In addition to that, the bypass and nitrate recirculation influence the loading rate (mainly COD) to the AST 1st and 2nd stage with the consequence of higher/lower oxygen demand for aeration, higher/lower biogas yield in digestion, higher/lower nitrogen in SDE pre-treatment, etc.

The aim of the calculation tool (Decision Tool) presented in this report is to provide a decision support for finding the appropriate resource and energy optimized SDE sidestream treatment technology considering on-site conditions. On the basis of the results obtained within the case studies (nitritation and membrane stripping) as well as collected at existing state of the art full-scale plants (Anammox and air-stripping), the Decision Tool provides a valuable data pool for comparing different SDE treatment options and evaluating their impact when implemented at conventional WWTP. The results can be discussed taking into account technico-economical criteria, the use of resources (energy, footprint, chemicals and products) and performances (TN removal or recovery, process stability and flexibility) as well as impacts on WWTP related specific conditions (e.g. influent composition).

The technical-economic analysis and the detailed calculation of all relevant parameters are built up in the Decision Tool on detailed flows, COD and TN mass balances that is a prerequisite for comparing the different SDE treatment options in terms of energy demand for wastewater treatment, energy from biogas utilization, construction costs, running costs of operation, operational materials, etc. Additionally, the carbonfootprint of the WWTPs operating with different SDE treatment options is estimated comprising direct and indirect greenhouse gases emissions.

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2. Description of the Decision Tool

The calculation tool is designed to calculate single-stage as well as two-stage WWTPs. In case of a single stage WWTP, the tank volume of the 1st stage (AST 1st stage and intermediate sedimentation tank) is set to zero and considered as a transiting pipe where no biological reactions take place. Specifications and advantages of a two-stage configuration are thoroughly described in PowerStep Deliverable 4.1. The system layout of the 2-stage WWTP is shown in the Figure 1.

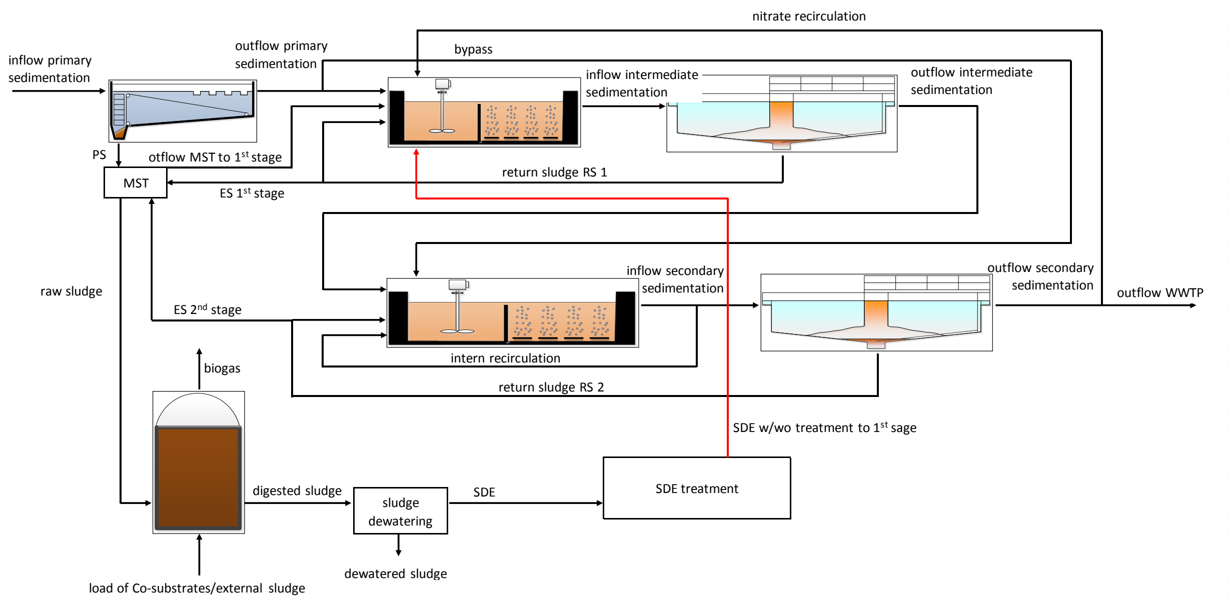

Figure 1: Flow scheme of the 2-stage WWTP implemented in the Decision Tool

The Decision Tool can be used for a broad variety of influent compositions, since all relevant parameters can be selected via an input mask. Further, it was considered that each part of the plant (primary clarification, AST 1st stage, intermediate sedimentation tank, AST 2nd stage, secondary sedimentation tank, digestion, SDE treatment and thickening of raw sludge as well as dewatering digested sludge) can be adapted to the desired assumptions by selecting the appropriate parameters. Thus, the Decision Tool can be used to calculate a wide variety of plant treatment conditions.

The Decision Tool calculates the mass balances of wastewater relevant parameters according to the chosen assumptions. The Q-balance shows all relevant volume flows and thus the hydraulic load of the different parts of the plant. The COD-balance provides the basis to calculate sludge production and available organic carbon for denitrification. The TN-balance provides the information regarding nitrifying and denitrifying nitrogen loads, which is also included in the dimensioning of the plant. Based on these balances (Q, COD, TN) the total energy required for the WWTP is calculated in detail for the individual plant components. Some data that can not be calculated (energy demand for screens, sand and grease trap, settling tanks, heating of the plant and energy for other infrastructure on the site) are assumed with figures from the benchmark report of Austrian WWTP (Benchmarking für Kläranlagen, Öffentlicher Bericht ARA 2015, WWTP group 6).

The parameter values set for 2-stage WWTP result from longterm experiental data of Austrian WWTPs (Müller-Rechberger *et al*., 2001; Wandl *et al*., 2006; Svardal & Kroiss, 2011).

In addition, the Decision Tool calculates the required tank volumes for single - and 2-stage WWTP based on a calculation in analogy to the DWA Standard A 131E (Dimensioning of Single-Stage Activated Sludge Plants). By linking with specific building costs for each part of the plant derived from the praxis in Central European countries, the total costs as well as the operating costs of the plant are calculated. The energy costs, the construction costs and operating costs of the different options of SDE treatment are estimated as well and compared against the whole WWTP.

2.1. Input parameters

All specific assumptions with mentioned spread of range apply to wastewater treatment plants with municipal inflow. In case of co-treatment of industrial wastewater, the composition of wastewater inflow as well as temperature can be significantly above or below the stated range. For the calculation it is assumed that ammonium is completely oxydized which means, that there is no nitrogen in form of ammonium in the WWTP effluent. The figures stated in this report are mostly empirical values from the operation of a 2-stage WWTP (Müller-Rechberger *et al*., 2001; Wandl *et al*., 2006; Svardal & Kroiss, 2011) which could be checked in many cases within the framework of case study 5 at the WWTP Kirchbichl.

2.1.1. WWTP size and influent composition

Size WWTP (120 PE): The first parameter of calculation to select is the specific load (PE_{120}) of the WWTP. 1-stage as well as 2-stage WWTP can be calculated with the tool. When selecting the size, it is important to consider, that the design as a 2-stage WWTP is practical only for plants with size of 100,000 PE_{120} (load of the WWTP with 100,000 PE, which deliver a specific COD load of 120 g/PE/d) and higher. 2-stage WWTP are more adaptable to different wastewater compositions due to many possible adjustments that can be done, but also require a more extensive equipment.

Specific wastewater production: The specific amount of wastewater per inhabitant must be entered. The amount of wastewater depends heavily on the respective catchment area and is usually in the range of 150 to 200 L/PE/d for municipal wastewater.

Temperature (for dimensioning): The temperature for which the calculation should be made is to enter here. The wastewater temperature is a decisive factor for the activity of bacteria and is included in the calculation of the required aerobic sludge age. The amount of sludge in the system is calculated via the sludge age, which subsequently significantly influences the required size of the activated sludge tank (AST). In adition, the temperature influences the oxygen supply in the aerated zone (oxygen saturation in the water depends on the temperature and decreases with increasing temperature). Thus, the temperature has an influence on the required energy for aeration, if only to a low degree. The temperature in the inlet of the plant is highly dependent on the season and the geographical situation and is usually in the range of 5 to 20 °C for municipal wastewater.

COD (daily load per PE): Input of the inhabitant-specific daily COD load in WWTP influent. This value should be taken as 120 g/PE/d.

TN (daily load per PE): Input of the inhabitant-specific daily total nitrogen (TN) load in WWTP influent. This value may vary and is usually in a range of 8 to 12 gN/PE/d.

P (daily load per PE): Input of the inhabitant-specific daily phosphorus (P) load in WWTP influent. This value may vary and is usually in a range of 1.5 to 2.0 gN/PE/d.

COD-removal WWTP: Input of COD reduction in the WWTP. The possible COD removal depends on several factors, mainly the proportion of inert, dissolved COD in the entire COD in WWTP influent. Usually 90 to 95 % of the incoming COD load is removed in the WWTP.

TN-removal WWTP: The nitrogen removal indicates how much nitrogen is removed in relation to the incoming load. A nitrogen removal of 75 % therefore means that the effluent still contains 25 % of the influent load. With a specific influent load of 10 gTN/PE/d 7.5 gTN/PE/d are removed (via denitrification and TN in the stabilized sludge), the effluent still contains 2.5 gTN/PE/d. The achievable nitrogen removal significantly depends on the available organic carbon and is usually in a range of 70 to 80 %. Regarding an energy-efficient wastewater treatment, the aim should be to ensure TN-removal to a great extent. In addition, extensive nitrogen removal has the positive effect of reducing emissions of GHG (N_2O) (Parravicini *et al*., 2016).

2.1.2. Primary settling

COD-removal: The efficiency of primary sedimentation depends significantly on the selected flow time through the settling tank. A higher retention time of wastewater in the primary sedimentation results in higher achievable removal of particulate settleable solids. This leads to a higher amount of primary sludge (PS), lower amount of excess sludge (ES) in AST, higher gas yield in anaerobic stabilization and thereby to a higher power production in the combined heat and power plant (CHP). A high efficiency of primary sedimentation may cause a lack of organic carbon in the denitrification zone of AST and corresponding a deterioration of nitrogen removal. The retention time of wastewater in primary sedimentation is in a range of 0.75 to 2.0 h, based on the average daily dry weather inflow. The separation efficiency of primary settling is usually in the range of 25 to 35 % of the incoming COD load.

TN/COD in primary sludge PS: This parameter describes the proportion of nitrogen in PS relative to the COD and can be assumed to be 2.5 %.

TSS in PS: TSS in PS after settling and thickening in primary sedimentation. This value is usually in a range of 20 to 40 g/L, depending on type and frequency of sludge removal.

COD/VSS in PS: This value describes the ratio of COD to volatile suspended solids in PS. Due to the energy-rich sludge, the ratio in PS is higher than in ES and can be assumed to be in a range of 1.7 to 1.8.

Bypass (outflow primary sedimentation to activated sludge tank 2nd stage): This parameter is only for 2-stage WWTP. Removal of COD in primary sedimentation and the high removal of COD in the 1st stage of a 2-stage WWTP may lead to a COD limitation in the anoxic zone of AST 2nd stage. As a result, the required nitrogen removal cannot be achieved. In case of COD limitation, a bypass from outflow primary sedimentation to denitrification zone of AST 2nd stage can ensure the required amount of organic carbon in 2nd stage. If the bypass is selected with 0 %, the whole wastewater from primary sedimentation runs through the 1st stage. If the bypass is selected with 100 %, the whole wastewater passes the 1st stage and is directly pumped to the 2nd stage. The selection of 100 % Bypass would therefore correspond procedurally the concept of a 1-stage WWTP.

2.1.3. Activated sludge tank 1st-stage

COD-removal 1st stage: The achievable COD-reduction in AST 1st stage must be entered here. In case of single-stage WWTP this value must be selected with 0 %. Thus, there is no COD-removal in the 1st stage. The required tank volume is assumed to be 0 in further calculations, the 1st stage corresponds procedurally to a pipeline. In case of 2-stage WWTP the possible COD-removal in the 1st stage depends on several factors and is in a range of 55 to 65 %, based on experiences on existing 2-stage WWTP.

TSS 1st stage: The TSS in AST 1st stage depends inter alia mainly on the design of the intermediate sedimentation tank and is usually in a range of 2 to 5 g/L.

Percentage of respired COD: Percentage of respired COD in the 1st stage. Depending on the selected COD-removal in the 1st stage, this value quantifies the respired COD. Due to the low sludge age in the AST 1st stage the percentage of respired COD is usually in the range of 25 to 35 %. The remaining 65 to 75 % of COD are converted to biomass or bound in ES.

COD/VSS in excess sludge (ES) 1st stage: This value describes the ratio of COD to volatile suspended solids in ES 1st stage. Due to the low sludge age in the 1st stage and organic compounds bound in ES, this ratio is slightly higher than in the ES 2nd stage or in ES from singe-stage WWTP. The COD/VSS ratio is usually in the range of 1.45 to 1.55.

Loss of ignition in ES 1st stage: The loss of ignition indicates the organic amount of the ES 1st stage. According to experiences, this value also depends on the efficiency of primary sedimentation and is in a higher range (higher organic content) compared to ES from 2nd stage. The loss of ignition in the ES 1st stage is usually in a range of 75 to 80 %.

DO (dissolved oxygen) concentration in 1st stage: The concentration of dissolved oxygen in the 1st stage of a 2-stage WWTP must be selected. The O_2-concentration in aerobic zones is usually in a range of 1 to 2 mg/L.

SAE aeration system in clear water: The standard aeration efficiency (SAE) describes the amount of oxygen which can be transfered to clean water per kilowatt hour (kgO_2/kWh). This value depends on a variety of factors, among others significantly on the density of disk diffusor arrangement on the bottom of tank, age and condition of aeration system and blow-in depth. The range of this value is correspondingly high. In an AST this value is in a range of 2.5 to 4.0 kgO_2/kWh (clean water) averangly. Under particularly unfavorable conditions also lower, under particularly favorable conditions also higher.

α-value: The α-value is the ratio of SAE in wastewater to SAE in clean water. Due to many factors (e.g. high TSS in AST, surfactants), the SAE in wastewater is lower (α-value is

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getting smaller). In the AST 1st stage of a 2-stage WWTP the α-value is in a range of 0.3 to 0.4, mainly due to the high COD load.

Sludge return ratio RS1: The sludge return ratio is calculated from the amount of return sludge from intermediate sedimentation divided by the inflow. Depending on the hydraulic load of the sedimentation tank, the return ratio is usually in a range of 0.5 to 1.5.

TN/COD in ES 1st stage: This parameter describes the proportion of nitrogen in ES 1st stage relative to the COD and can be assumed to be in a range of 5 to 6 %.

Mixing energy: Energy for mixing the AST 1st stage. The required energy for sufficient mixing is usually in a range of 1 to 5 W/m³.

2.1.4. Activated sludge tank 2nd-stage

For calculation of a 2-stage WWTP, the following informations must be given in accordance with the AST 2nd stage. In case of single-stage WWTP, the AST 2nd stage corresponds to the AST of the single-stage WTTP.

TSS 2nd stage: The TSS in AST 2nd stage depends inter alia mainly on the design of the secondary sedimentation tank and is usually in a range of 2 to 4 g/L.

Percentage of respired COD: Percentage of respired COD in the AST 2nd stage or AST of single-stage WWTP. In case of a 2-stage WWTP the COD-removal in the 1st stage has already been selected. The COD-removal in the 2nd stage is calculated as difference of COD inflow, COD outflow and COD removed in the 1st stage. The percentage of respired COD in the 2nd stage is significantly higher compared to the 1st stage and can be assumed to be in a range of 60 to 65 %. The remaining 35 to 40 % of COD are converted to biomass. In case of single-stage WWTP the recommended assumption of respired COD in in the range of 50 to 55 %. The remaining 45 to 50 % are converted to biomass.

COD/VSS in ES 2nd stage: This value describes the ratio of COD to volatile suspended solids in ES 2nd stage or ES from single-stage WWTP. The COD/VSS ratio is usually in the range of 1.40 to 1.45.

Loss of ignition in ES 2nd stage: The loss of ignition indicates the organic amount of the ES 2nd stage or ES from single-stage WWTP. The loss of ignition is usually in a range of 70 to 75 %.

DO concentration in 2nd stage: The concentration of dissolved oxygen in the AST 2nd or AST of single-stage WWTP must be selected. The O_2-concentration in aerobic zones is usually in a range of 1 to 2 mg/L.

SAE aeration system in clear water: The standard aeration efficiency (SAE) describes the amount of oxygen which can be transfered to clean water per kilowatt hour (kgO_2/kWh). This value depends on a variety of factors, among others significantly on the density of disk diffusor arrangement on the bottom of tank, age and condition of aeration system and blow-in depth. The range of this value is correspondingly high. In an AST this value is in a range of 2.5 to 4.0 kgO_2/kWh (clean water) averangly. Under particularly unfavorable conditions also lower, under particularly favorable conditions also higher.

α-value: The α-value is the ratio of SAE in wastewater to SAE in clean water. Due to many influencing factors (e.g. high TSS in AST, surfacants concentration), the SAE in wastewater is lower and therefore α-value < 1. In the AST 2nd stage of a 2-stage WWTP the α-value is usually in a range of 0.55 to 0.60, mainly due to low COD load. In AST of single-stage WWTP the α -value is usually in a range of 0.50 to 0.60 (Rosso et al., 2008).

Sludge return ratio RS2: The sludge return ratio is calculated from the amount of return sludge from secondary sedimentation divided by the inflow. Depending on the hydraulic load of the sedimentation tank, the return ratio is usually in a range of 0.5 to 1.5.

TN/COD in ES 2nd stage: This parameter describes the proportion of nitrogen in ES 2nd stage or ES from single-stage WWTP relative to the COD and can be assumed to be in a range of 5 to 6 %.

Maximal ratio of $OU_{DN}2/OU_C2$: This value specifies the demand of oxygen for COD-removal (OU_C2) that can be covered by denitrification ($OU_{DN}2$) in the 2nd stage of a 2-stage WWTP or in the AST of a single-stage WWTP. This value can be selected up to a maximum of 50 %. The selection of 50 % means that half of the demand for OU_C can be covered by anoxic respiration from the formed nitite or nitrate. If OU_{DN} is higher than 50 % of OU_C, the nitrate-concentration in the effluent of the WWTP will increase corresponding to a lower percentage of nitrogen removal. Nitrate recirculation from the effluent of the WWTP to the denitrification zone of the AST 1st stage or increasing the bypass from effluent of primary sedimentation to the denitrification zone of the AST 2nd stage counteracts the deterioration of the nitrogen removal in case of a 2-stage WWTP.

Mixing energy: Energy for mixing the AST 2nd stage or AST of a single-stage WTTP. The required energy for sufficient mixing is usually in a range of 1 to 5 W/m^3.

2.1.5. Anaerobic sludge digestion

COD in digested sludge (DS): COD of the anaerobically stabilized sludge. Numerous investigations on WWTP of different size and configuration have shown, that anaerobically well stabilized sludge contains 30 gCOD/PE/d (Parravicini *et al*., 2006; assuming for the conversion of gVSS/PE/d into gCOD/PE/d a COD/VSS ratio of 1.4). Unfavorable conditions (e.g. temperature, mixing) or insufficient stabilization time may lead to a higher COD in digested sludge.

Loss of ignition in DS: The loss of ignition indicates the organic amount of the anaerobically stabilized sludge. Investigations on several plants have shown, that the loss of ignition is usually in a range of 55 to 65 %.

COD/VSS in DS: This value describes the ratio of COD to volatile suspended solids in anaerobically stabilized sludge. The COD/VSS ratio is usually in the range of 1.40 to 1.45.

TSS in raw sludge: PS is mechanically thickened with ES from 1st stage and ES from 2nd stage and subsequently called raw sludge. The TSS after thickening is usually in a range of 50 to 70 g/L.

TSS in dewatered sludge: Different types of dewatering units are used for dewatering sludge from anaerobic stabilization. In case of dewatering via centrifuge the reachable TSS in in a range of 250 to 350 g/L.

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$N_{released}$/COD_{Biogas}: First step of digestion is the hydrolyzation of organic compounds. Organic carbon is further converted to methane and carbon dioxide. The formaly organically bound nitrogen is released and leads to high ammonium concentration. The parameter $N_{released}$/COD_{Biogas} indicates the amount of nitrogen released due to the conversion of COD into biogas. Regarding the converted COD, 3.5 % is usually released as ammonium. This means, that after dewatering the sludge dewatering effluent (SDE) contains 3.5 % of the converted COD as ammonium.

Mixing energy: Digesters are usually mixed by the continuous gas production. In addition, a stirring unit is installed to ensure complete mixing of sludge. The required mixing energy depends on the shape of the digester and is in a range of 0 to 5 W/m³.

Circulation (pumps) of digester volume: In addition to mixing by gas production and stirring unit, digesters are mixed with circulation pumps. On the one hand, the raw sludge is thereby mixed with digested sludge, on the other hand the sludge is passed through a heat exchanger and is tempered with these pumps. With this value the circulation of digester is selected. A typical value is 1 circulation/d.

Efficiency of CHP unit (electricity): The resulting gas from anaerobic digestion is utilized in a combined heat and power plant (CHP), where electicity and heat is generated. A modern CHP unit reaches an electrical efficiency of 35 % and a thermal efficiency of 45 %.

Energy demand for mechanical sludge thickening (MST): This value mentions the required energy for mechanical sludge thickening of PS and ES. The energy demand varies depending on size and type of machine and can be expected with 30 Wh/m³, based on raw sludge.

Polymer dosage for mechancal sludge thickening (MST): In order to ensure a high TSS in the thickened sludge as well as a low concentration of suspended solids in effluent the dosage of a flocculant (polymer) is necessary. The amount of polymer respectively active substance (AS) used depends on the properties of sludge and the desired result of thickening. The amount of AS is in a range of 2 to 5 gAS/kgTSS for an appropriate TSS in raw sludge.

Energy demand for dewatering: The energy demand for dewatering is in a wide range and depends mainly on size and type of machine as well as the amount of sludge to be treated. The required energy for dewatering via centrifuge is in a range of 1 to 2 kWh/m³.

Polymer dosage for dewatering: In order to ensure a high TSS in the dewatered sludge as well as a low concentration of suspended solids in SDE the dosage of a flocculant (polymer) is necessary even in centrifuge. The amount of polymer respectively active substance (AS) used depends on the properties of sludge (stabilization) and the desired result of dewatering (more polymer leads to a higher TSS within a certain range). The amount of AS is in a range of 10 to 15 gAS/kgTSS for an appropriate TSS in dewatered sludge.

Costs for polymer: The costs for polymer vary greatly depending on several factors such as manufacturer and quantity ordered. If there is no information of actual costs, 6 €/kgAS for liquid polymer can be expected.

2.1.6. Co-substrates and external sludge

With this input mask it is possible to consider the co-treatment of external substrates (e.g. grease and food waste) or external sludge in the digesters of the WWTP. The composition of co-substrates depends on the substrate and must be specified.

Load of CoS/external sludge: Amount of co-substrate or external sludge in kgTSS/d.

TSS CoS/external sludge: Concentration of TSS in co-substrate or external sludge (e.g. 60 g/L).

Loss of ignition CoS/external sludge: Percentage of volatile suspended solids in the substrate to be treated (e.g. 75 %).

COD/VSS CoS/external sludge: This value describes the ratio of COD to volatile suspended solids in co-substrate or external sludge. For external sludge from municipal WWTP the COD/VSS ratio is usually in the range of 1.40 to 1.45.

VSS degradation: The degradation of organic compounds in anaerobic digestion is greatly dependent on the type of substrate and on the degree of stabilization achieved. The achievable VSS degradation of grease is in a very high level of about 90 %, in case of external sludge from municipal WWTP in a lower range of about 50 %.

TN/COD CoS/external sludge: This parameter describes the proportion of nitrogen in co-substrate or external sludge relative to the COD and can be assumed to be in a range of 5 to 6 % in case of external sludge. The TN/COD ratio of grease is 0 %.

2.1.7. SDE treatment

The first step of calculation concerning the SDE treatment is the selection of SDE treatment concept. The effluent from dewatering of digested sludge contains a high load of nitrogen, which is entirely in form of ammonium. The following SDE treatment options are available.

Without treatment: Without SDE sidestream treatment the whole SDE is dosed untreated to the AST 2nd stage (in case of 2-stage WWTP) or AST of single-stage WWTP. The additional nitrogen (100 % ammonium) is nitrified and denitrified in the AST.

Nitritation: If the option Nitritation is selected, the whole SDE is pre-treated in a sidestream tank. 55 % of the ammonium is converted to nitrite, therefore the SDE treatment effluent still contains 45 % of ammonium. This limitation of conversion is due to the alkalinity in wastewater and is confirmed by numerous experiences from laboratory-scale and full-scale SDE Nitritation tanks, as e.g. at the WWTP Kirchbihl (case study 5). The effluent from sidestream treatment is pumped to the anoxic zone of the AST, as far as single-stage WWTP are calculated. The incoming nitrite is denitritied, the incoming ammonium is further oxidized to nitrate and denitrified. In case of 2-stage WWTP the effluent from SDE treatment is pumped to the anoxic zone of the AST 1st stage and denitritied. The usage of readily degradable organic carbon for nitrogen removal ($OU_{DN}1$) leads to a reduction of the oxygen demand for respiration of organic carbon (OU_C1). Due to the lack of nitrifying bacteria in the 1st stage of a 2-stage WWTP the Ammonium from SDE treatment goes untreated to the AST 2nd stage. The high sludge age in 2nd stage ensures the nitrification of ammonium and the further removal of nitrate in the anoxic zone.

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Anammox: First step of Anammox is Nitritation of SDE. As mentioned before, 55 % of ammonium is converted to nintrite (45 % of ammonium remaining) due to alkalinity. Second step of Anammox is the anaerobic ammonium oxidation. Anammox-bacteria convert ammonium and nitrite into elementary nitrogen (N_2). The bacteria require 1 mol of ammonium-nitrogen and 1.3 mol nitrite-nitrogen for this second step of treatment. In addition to elementary nitrogen, the Anammox-process produces nitrate-nitrogen in the amount of 0.2 mol based on the converted ammonium. Without consideration of biomass, the relating stoichiometric equation of Anammox is as follows: $NH_4^+ + 1{,}3\ NO_2^- \rightarrow 1{,}05\ N_2 + 0{,}2\ NO_3^- + 2\ H_2O$. The effluent from sidestream treatment is pumped to the anoxic zone of the AST, as far as single-stage WWTP are calculated. The incoming nitrate is denitrified, the incoming ammonium is further oxidized to nitrate and denitrified. In case of 2-stage WWTP the effluent from SDE treatment is pumped to the anoxic zone of the AST 1st stage and denitrified. The usage of readily degradable organic carbon for nitrogen removal ($OU_{DN}1$) leads to a slightly reduction of the oxygen demand for respiration of organic carbon (OU_C1). Due to the lack of nitrifying bacteria in the 1st stage of a 2-stage WWTP the Ammonium from SDE treatment goes untreated to the AST 2nd stage. The high sludge age in 2nd stage ensures the nitrification of ammonium and the further removal of nitrate in the anoxic zone.

Air-stripping with CO_2-Stripping: The SDE is supplied to the physical treatment of air-stripping. A removal of 90 % of ammonium is assumed. The remaining 10 % of ammonium from SDE are oxidized in the AST (single-stage WWTP) or in the 2nd stage of a 2-stage WWTP and further denitrified.

Membrane-stripping with CO_2-Stripping: The SDE is supplied to the physical treatment of membrane-stripping. A removal of 90 % of ammonium is assumed. The remaining 10 % of ammonium from SDE are oxidized in the AST (single-stage WWTP) or in the 2nd stage of a 2-stage WWTP and further denitrified.

Temperature in SDE treatment tank: The temperature in the tank for Nitritation must be selected. If the digested sludge is directly dewatered without puffering the SDE has approximately the same temperature as in the digesters. The temperature in SDE treatment tank is in the range of 22 to 32 °C, depending on the season temperature (experiences from CS 5). The activity of bacteria strongly depends on the temperature. Thus, temperature of 15 °C requires a sludge age of about 3 d, 25 °C requires a sludge age of 1.2 d and temperature of 35 °C requires a sludge age of 0.5 d (growth rate of ammonium oxidizing bacteria AOB) to ensure nitritation. Since an adequate SDE treatment is desired even in winter, the temperature for calculation should be selected in a range of 20 to 25 °C. The chosen temperature influences the volume of treatment tank for Nitritation.

DO concentration in SDE treatment tank: The concentration of dissolved oxygen in the SDE treatment tank must be selected. The O_2-concentration is usually in a range of 1 to 2 mg/L.

SAE aeration system in clear water: The standard aeration efficiency (SAE) describes the amount of oxygen which can be transfered to clean water per kilowatt hour (kgO_2/kWh). This value depends on a variety of factors, among others significantly on the density of disk diffusor arrangement on the bottom of tank, age and condition of aeration system and blow-in depth. The range of this value is correspondingly high. In an AST this value is in a range of 2.5 to 4.0 kgO_2/kWh (clean water) averangly. Under particularly unfavorable conditions also lower, under particularly favorable conditions also higher.

α-value: The α-value is the ratio of SAE in wastewater to SAE in clean water. Due to many factors (e.g. high TSS in AST, surfacants), the SAE in wastewater is lower (α-value is getting smaller). In the SDE treatment tank the α-value is in a range of 0.7 to 0.8, mainly due to low concentration of suspended solids.

Mixing energy: Energy for mixing the SDE treatment tank. The required energy for sufficient mixing is usually in a range of 1 to 5 W/m³.

Thermal energy for air-stripping: Required thermal energy for air-stripping to reach the desired temperature-range in the system. The recommenden temperature range is between 60 and 65 °C. In order to reach this temperature, 16 $kWh_{primary}$/kgN (primary energy related to 1 kg nitrogen removed) are necessary.

Thermal energy for membrane-stripping: Required thermal energy for membrane-stripping to reach the desired temperature-range in the system. The recommenden temperature range is between 60 and 65 °C or between 40 and 45 °C. In case of higher temperature range (60 to 65 °C) 18 $kWh_{primary}$/kgN (primary energy related to 1 kg nitrogen removed) are necessary. In case of lower temperature range (40 to 45 °C) 9.5 $kWh_{primary}$/kgN are necessary.

Electric energy for air-stripping: Required electric energy for air-stripping can be assumed with 4.5 $kWh_{primary}$/kgN.

Electric energy for membrane-stripping: Required electric energy for membrane-stripping can be assumed with 6 $kWh_{primary}$/kgN.

Efficiency of power production: Describes the efficiency of produced electric energy from primary energy. This efficiency is usually in a range of 30 to 35 %.

Demand H_2SO_4 (air- and membrane-stripping): Sulfuric acid in the amount of 0.5 mol/molN (mol of sulfuric acid per mol nitrogen removed) is required for dissolution of ammonia in the sorber unit.

Costs for H_2SO_4 98 %: The costs for chemicals vary widely and can be assumed with 220 €/m³ for H_2SO_4 98 %.

Demand NaOH (air- and membrane-stripping): NaOH is used for raising the pH (transfer of ammonium to ammonia in the stripper unit). In consideration of a first increase of pH in a CO_2-stripper unit, the demand of NaOH can be assumed with 0.7 mol/molN (60 to 65 °C) or 1.2 mol/molN (40 to 45 °C).

Costs for NaOH 50 %: The costs for chemicals vary widely and can be assumed with 250 €/m³ for NaOH 50 %.

Other costs stripping: Other additional costs for stripping (e.g. cleaning with chemicals). These costs can be assumed with 0.05 €/kgN.

2.1.8. Pumps

Calculation of energy for pumps assumes that the influent is lifted in the inlet area and then flows by gravity without the need of further pumps. The sludge dewatering unit is placed in such way that the hydrostatic pressure from digestion is used for bringing the

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sludge to the centrifuge. The SDE can thus also flow to the treatment tank without further pumps.

Energy: Specific energy to lift water by a defined height. Based on the calculation of the potential energy (E = m*g*h), the energy for pumping is 9.81 Ws/L/m.

Efficiency of pumps: Depending on the design, this value is usually in a range of 50 to 70 %.

Δh for inflow pump: Discharge head including all losses in the inlet area of the WWTP.

Δh for Bypass: Discharge head including all losses for pumping the bypass from outflow primary sedimentation to the 2nd stage of a 2-stage WWTP. This value is relevant only at 2-stage WWTP an can be assumed to be 0 m (flows by gravity).

Δh for return sludge RS1: Discharge head including all losses for pumping the RS from intermediate sedimentation back to the 1st stage of a 2-stage WWTP. This value is relevant only at 2-stage WWTP an can be assumed to be 2.5 m.

Δh for return sludge RS2: Discharge head including all losses for pumping the RS from secondary sedimentation back to the 2nd stage of a 2-stage WWTP or to the AST of single-stage WWTP. This value is relevant for single-stage WWTP as well as 2-stage WWTP an can be assumed to be 2.5 m.

Δh for internal recirculation: Discharge head including all losses for intern recirculation from outflow AST back to the anoxic zone of the 2nd stage of a 2-stage WWTP or to the anoxic zone of the AST of single-stage WWTP. This value is relevant for single-stage WWTP as well as 2-stage WWTP an can be assumed to be 0.5 m.

Δh for nitrate recirculation: Discharge head including all losses for pumping the nitrate recirculation from outflow WWTP to the anoxic zone of the 1st stage of a 2-stage WWTP. This value is relevant only at 2-stage WWTP an can be assumed to be 3.0 m.

Δh for digester circulation and heating: Discharge head including all losses for mixing the digester volume and for heating up the raw sludge via heat exchanger. This value strongly depends on the design of the digester and heat exchange unit and can be assumed to be 3.0 m.

2.2. Estimation of plant size

The following assumptions are necessary for estimation of the required tank volumes. The calculations are based on the DWA-Standard DWA-A 131E (Dimensioning of Single-StageActivated Sludge Plants) which is designed for calculation of single-stage WWTP. The DWA-Standard can also be applied for calculation of a 2-stage WWTP, in consideration of the specific characteristic of this 2-stage process.

HRT primary settling tank: The hydraulic retention time is in a range of 0.75 to 2.0 h. The required volume of primary settling tank is calculated by multiplying the volume flow (m^3/h) with the selected HRT.

Anoxic respiration: In denitrification process, nitrate is reduced to elementary nitrogen by usage of organic carbon. The amount of respired COD can be described as oxygen consumption in relation to volume and time (mgO_2/L/h). The COD balance displays this demand of respired organic carbon for denitrification as oxygen utilization for denitrification (OU_{DN}). Depending on this OU_{DN}, the required volume for denitrification can be calculated with the assumption of anoxic respiration. For the estimation of the required anoxic volume an anoxic respiration of 30 $mgO_2/L/h$ can be expected.

SRT 1st stage: In case of a 2-stage WWTP, this value describes the sludge retention time (SRT) in the 1st stage and can be assumed to be usually in a range of 1 to 2 d.

P in Biomass (related to COD): This value states the amount of phosphorus for biomass production and can be assumed to be 0.5 % in relation to degraded COD.

P in WWTP effluent: P-concentration in the WWTP effluent. This value depends on legal framework and is approximately 1 mg/L.

Specific requirement of iron (β=1,5): The amount of Fe for P-precipitation must be selected. Theoretically, the amount of Fe is calculated to 1.8 kgFe/kgP. A usual value for overdosage of precipitant is 1.5 (β-value). With this safety factor the amount of precipitant is calculated to 2.7 kgFe/kgP.

Sludge from P-precipitation: Due to P-precipitation additional sludge is formed. This amount of additional sludge (2.5 kgTSS/kgFe) must be considered for calculation of AST volume.

Depth of intermediate sedimentation tank: The intermediate sedimentation tank is calculated as horizontal flowed sedimentation tank. A usual depth of these kind of sedimendation tanks is between 3 and 4 m.

Surface charging of intermediate sedimentation tank: With this value the required surface of intermediate sedimentation tank is calculated. Permissible value for secondary sedimentation tank is 1.6 m/h (DWA-A 131) for dryweather inflow usually. This value can be reduced taking account of the settling of sludge from the 1st stage of a 2-stage WWTP and the fact that suspended solids in the effluent from intermediate sedimentation lead to no deterioration of COD- and N-removal (due to the following 2nd stage). Nevertehless, it must be considered, that a higher inflow (e.g. heavy rain) does not exceed the permissible surface charge. For the calculation of the intermediate sedimentation tank an assumption of maximum 1.2 m/h is therefore recommended without further detailed hydraulic calculation.

Depth of secondary sedimentation tank: The secondary sedimentation tank is calculated as horizontal flowed sedimentation tank. A usual depth of these kind of sedimendation tanks is between 4 and 6 m.

Surface charging of secondary sedimentation tank: With this value the required surface of secondary sedimentation tank is calculated. Permissible value for secondary sedimentation tank is 1.6 m/h (DWA-A 131) for dryweather inflow usually. It must be considered, that a higher inflow (e.g. heavy rain) does not exceed the permissible surface charge. Furthermore, the effluent from secondary sedimentation tank should be free from suspended solids. In consideration of higher inflow especially at stormwater, the permissible surface charge is recommended to 0.6 m/h (calculation with dry weather flow).

Safety factor for SDE nitritation tank: SRT and HRT are in fact of completely mixed tank volume (CSTR) still the same. The calculation of the required tank volume depends on the SRT, assuming that the feeding of SDE is equal distributed over the day. In the majority of cases SDE is produced in 10 or 12 h/d and fed to the treatment tank. The

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safety factor takes this aspect into account and can be selected in an appropriate range for completely mixed (HRT=SRT) treatment tanks (Nitritation).

HRT Nitritation tank: Based on the long-term results at full-scale at the WWTP Kirchbichl (Case study 5), the HRT for sidestream nitritation is calculated to 1.2 d at 25°C.

HRT Anammox SBR: It is assumed, that the treatment tank for Anammox is designed as sequencing batch reactor (SBR). With this design the HRT is uncoupled from SRT. For the calculation of the required volume the assumption of a HRT of 2 d at 25°C is recommended.

HRT digester: For anaerobic stabilization a HRT of 25 d is recommended.

2.3. Cost estimatation for the construction of a wastewater treatment plant

The following costs are intended to be basis for a rough estimation of the building costs for WWTP in central Europe. All prices quoted are subject to strong fluctuations and must be adapted to local cprice level for a more accurate calculation. The

Costs for infrastructure, design and construction:

Primary sedimentation: 400 €/m³

Activated sludge tanks: 600 €/m³

Intermediate and secondary sedimentation: 900 €/m³

Digestion: 1.800 €/m³

Fixed costs for electrical engineering: 100.000 €

Fixed costs for measurement technology: 75.000 €/Line

Depreciation period: 15 a for the entire plant.

SDE treatment Nitritation:

- Fixed costs for electrical engineering: 100.000 €
- Fixed costs for measurement technology: 25.000 €/tank
- Costs for infrastructure, design and construction: 2.700 €/kgN

SDE treatment Anammox:

- Fixed costs for electrical engineering: 100.000 €
- Fixed costs for measurement technology: 50.000 €/tank
- Costs for infrastructure, design and construction: 2.700 €/kgN

SDE treatment air-stripping with CO_2-stripping:

- Fixed costs for electrical engineering and chemical storage: 250.000 €
- Costs for design and construction: 4.100 €/kgN
- Costs for infrastructure: 1.000 €/kgN
- Depreciation period: 10 a

SDE treatment membrane-stripping with CO_2-stripping:

- Fixed costs for electrical engineering and chemical storage: 250.000 €
- Costs for infrastructure, design and construction: 4.000 €/kgN
- Durability of membranes: 5 a

Costs for membranes: 600 €/kgN

Depreciation period: 10 a

2.4. Carbon Footprint

The carbon footprint represents the total set of GHG emissions caused directly or indirectly by an activity or resulting from the different life cycle stages of a product. The global warming potential (GWP) of GHGs is referred to carbon dioxide (CO_2) as reference gas and usually expressed as equivalent carbon dioxide (CO_2e).

Direct and indirect greenhouse gases (GHG) emissions of the model municipal WWTP with/without SDE treatment were estimated using carbon footprint analysis. Direct GHG emissions include emissions of methane (CH_4) and nitrous oxide (N_2O) that are biologically produced and emitted at WWTPs during wastewater and sewage sludge treatment. CO_2 is also emitted at WWTPs but it is usually not considered in the CO_2-balance, being predominantly biogenic and therefore climate neutral. Indirect GHG emissions occur at WWTPs mainly by the consumption of electricity, by burning fossil fuel for transportation, by the use of chemicals (e.g. for phosphate precipitation and sludge dewatering) and by the disposal of sewage sludge (biosolids). CO_2 credits arise when the produced biogas is converted in CHP to electricity and heat and when ammonia (NH_3) is recovered out of SDE e.g. through air or membrane stripping and reused as nitrogen fertiliser.

In the Decision Tool, the balance boundary of the CO_2-balance was set by the sewage sludge treatment, still including anaerobic digestion and sludge dewatering. In contrast, the following processes were not considered in the CO_2-balance:

- <u>GHG emissions resulting from the disposal of biosolids:</u> this topic is discussed elsewhere (Alvarez-Gaitan *et al*., 2016; Lederer & Rechberger, 2010) and it is of no relevance when comparing the impact of SDE side-stream treatment options.
- <u>GHG emissions from the sewer system:</u> the range of CH_4 and N_2O emissions in sewer systems is influenced by several factors (e.g. sewer type, lengths, slope, sewage temperature) and still controversial.
- <u>GHG emissions during the construction phase of WWTPs:</u> in this regards Hable (2017) showed that GHG emissions resulting from the use of raw materials (mainly concrete and steel) and energy in the construction phase of a 30.000 PE WWTP correspond in average to 13% of the total GHG emission of the WWTP for a service life of 30 years. Since the total tank volume of a single-stage and of a two-stage WWTP is comparable, differences in CO_2e-emissions of the model WWTPs derive mainly from plant operation. CO_2e-emissions resulting from the construction of SDE side-stream treatment can be neglected when compared to the whole WWTP.

The calculation of the climate impact of N_2O and CH_4 was performed applying the GWP of 298 kg CO_2e/kg N_2O and of 25 kg CO_2e /kg CH_4 respectively, referring to a time framework of 100 years and including climate carbon feedbacks (IPCC 2007).

<u>The emission factors (EF) applied in the CO_2-balance of the Decision Tool were harmonized with the values implemented in the LCA of the PowerStep WWTPs (WP5).</u>

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2.4.1. Direct GHG emissions

N_2O Emission: Nitrifying activated sludge tanks have shown to be the main source of N_2O at WWTP. A more detailed discussion on the formation mechanisms of N_2O emissions in activated sludge tank can be found in PowerStep Deliverable 4.1 (2016). According to current understanding, N_2O production and emission during nitrification can be reduced by optimizing process conditions but not completely avoided. During denitrification N_2O is produced as obligate intermediate. However, under favourable process conditions (e.g. low dissolved oxygen and nitrite concentrations, sufficient COD availability) denitrification can become a significant N_2O sink promoting the reduction of N_2O to gaseous N_2.

The variability range of direct N_2O emissions measured at WWTPs so far is wide (PowerStep Deliverable 4.1, 2016). This pronounced variability mainly derives from the significant impact that operating conditions have on N_2O production and emission (e.g. Kampschreuer *et al.*, 2009). The degree of TN removal and the loading conditions in activated sludge tanks were identified as the major operating parameters affecting direct N_2O emission within long-term measurement campaigns at eight municipal WWTPs in Austria (ReLaKO, 2015). The measurements took place in activated sludge tanks applying long-term online measurements in the exhausted aeration air (floating gas hood connected to a IR-Spectrometer) as well as in the bulk liquid (Unisense micro-sensor) over several weeks. Results revealed a decreasing EF (g N_2O-N/ g $N_{influent}$ WWTP) with an increasing TN removal efficiency at the WWTP. The observed correlation with the TN removal performance confirms the role of the denitrification as N_2O sink in activated sludge tanks. Considering that lower TN removal was mostly coupled with high volumetric loading rates in the activated sludge tanks, the regression model probably reflects also the influence of this operating parameter.

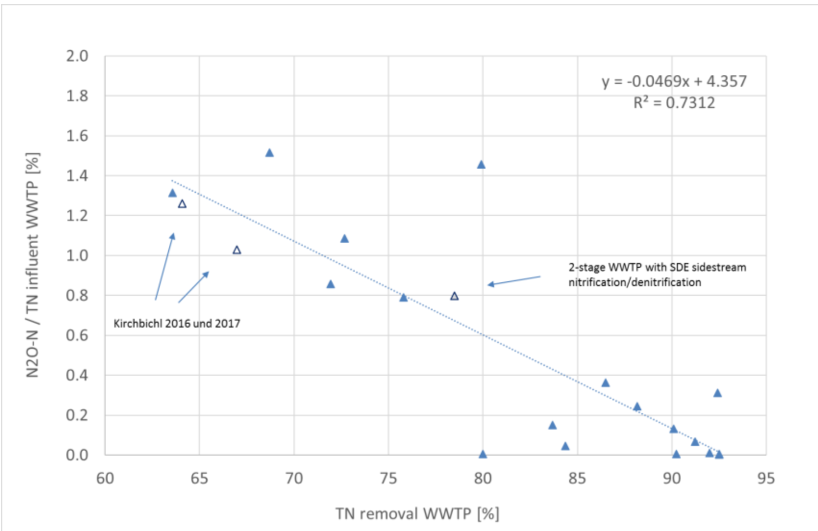

Figure 2: Scatter plot of direct N_2O emissions from activated sludge tanks (g N_2O-N/g $N_{influent\ WWTP}$*100) and TN removal efficiency of WWTP (%) comprising 18 measurement campaigns at eight Austrian WWTPs (ReLaKO, 2015) and three new measurements performed within Powerstep at two-stage WWTPs (2016-2017). Each point in the diagram represents the average overall direct N_2O emissions of activated sludge treatment resulting from every single measurement campaign.

Based on the project results an Austrian country-specific estimation method of direct N_2O emissions from activated sludge tanks depending on TN removal was developed (NIR, 2015), in objection to the less representative EF of 3.2 g N_2O/person/a suggested by the IPCC guidelines (IPCC 2006). The IPCC EF is based on measurements (grab samples, no online measurements) performed at only one single WWTP of not specified TN removal efficiency and not receiving any wastewater from industrial sources (Czepiel *et al.*, 1995).

Further measurements at the Case Study 5 WWTP Kirchbichl (10.08.-04.09.2016 and 31.7.-07.09.2017) after the implementation of SDE nitritation as well as at a second two-stage WWTP applying SDE sidestream nitrification/denitrification (19.07.-12.08.2016) corroborate the correlation between EF and N-removal of the WWTP (empty circles Figure 2). The measurement method applied in PowerStep was the same of the survey ReLaKO (2015), as described in Deliverable 4.1.

To highlight the contribution of the SDE sidestream treatment on the whole direct N2O emission of the WWTP, in the decision Tool direct N2O emission were estimated separately for the mainstream activated sludge tank (AST) and the SDE sidestream treatment. On this purpose, a second correlation line valid for N2O-emission in mainstream AST was evaluated based on the measured data (Figure 3) and used for estimation of N_2O emissions in mainstream.

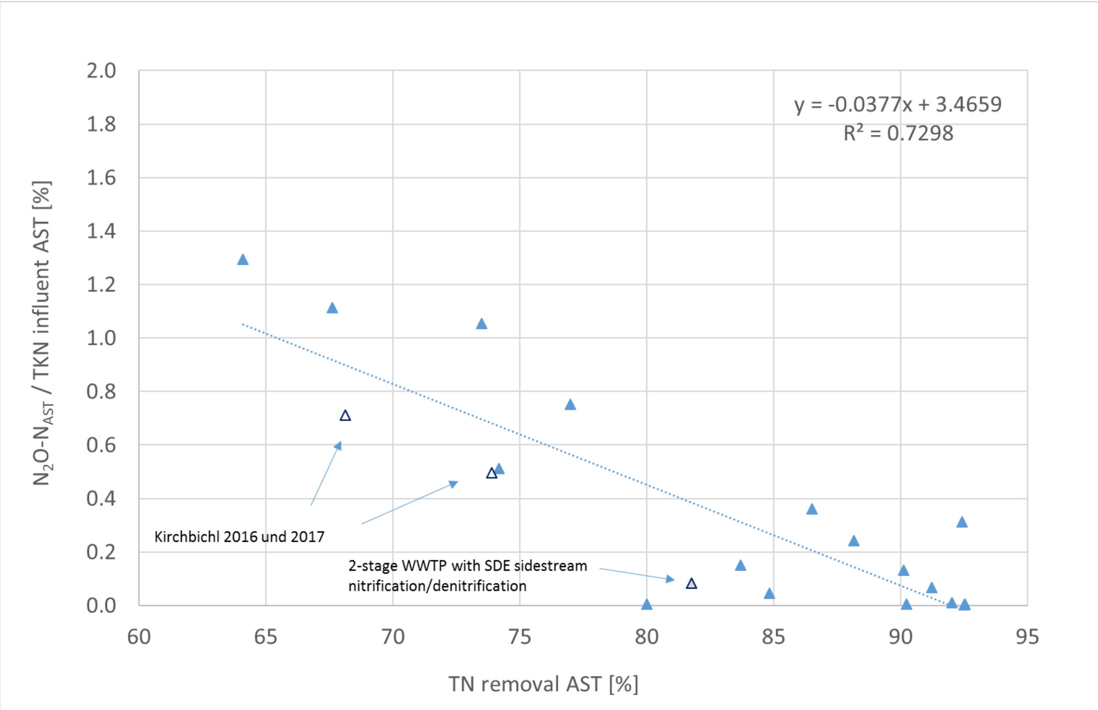

Figure 3: Scatter plot of direct N_2O emissions from activated sludge tanks (g N_2O-N_{AST}/g $N_{influent\ AST}$*100) and TN removal efficiency of AST (%) comprising 18 measurement campaigns at eight Austrian WWTPs (ReLaKO, 2015) and three new measurements performed within Powerstep at two-stage WWTPs (2016-2017). Each point in the diagram represents the average overall direct N_2O emissions of activated sludge treatment resulting from every single measurement campaign.

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N_2O-emissions in SDE sidestream treatment were estimated for the nitritation and nitritation/anammox processes. The N_2O production potential arising from the deposition on soils of NH_3 stripped in the CO_2 stripper was assumed negligible compared to the emission occurring in biological nitrogen removal processes at the WWTP.

N_2O emissions during the treatment of SDE have been extensively reported at full-scale and laboratory scale systems. These emissions are normally higher than those detected during the treatment of domestic sewage in mainstream. In the SDE **nitritation** tank in Kirchbichl the measured EF was 4.5% N_2O-N/ $N_{oxidized}$ in the first measurement campaign and 3.6% N_2O-N/ $N_{oxidized}$ in the second measurement campaign under optimized process conditions (higher DO). The latter value was applied in the Decision Tool. This value lies in the average range of the values given in the literature (Table 1). Results of lab-scale investigation using synesthetic SDE are somewhat lower (~1% N_2O-N/ $N_{oxidized}$) and are not reported in the table (Law *et al.* 2011; Rodriguez-Caballero & Pijuan, 2013; Ahn *et al*., 2011).

In case the nitritation process is coupled with **anammox** in a single-stage configuration, the measured N_2O-emission factor is according to values given in the literature lower (Table 2). For the calculation in Decision Tool the EF was set by 2% N_2O-N/ $N_{oxidized}$.

N_2O-emissions occurring in receiving water bodies was not considered in the CO_2-balance, being of relevance only at WWTP with low nitrogen removal degree.

Table 1: N_2O-Emission Factor from full-scale and lab-scale plants treating real reject wastewater by nitritation.

Wastewater (Reference)	Process type	Emission factor (% N_2O-N/ $N_{oxidized}$)
Anaerobically digested industrial wastewater (Desloover *et al*., 2011)	Nitritation+anammox (2-stage, full-scale)	8.1 - 11.2*
Concentrated black water (de Graff, 2010)	Nitritation in continuous reactor (lab-scale)	3.2
Real sludge dewatering effluent (Kampschreur *et al*., 2008)	Nitritation+anammox (2-stage, full-scale)	3.4*
Real sludge dewatering effluent (Pijuan *et al*., 2014)	Nitritation (pilot-scale, granular airlift)	6.1 - 2.2**
Real sludge dewatering effluent (Schneider *et al*., 2013)	Nitritation (lab-scale CSTR)	2.9***
Real sludge dewatering effluent (Mampaey *et al*., 2016)	Nitritation (full-scale)	7.1

**emissions from nitritation reactor; ** depending on operating conditions; ***formation factor measured in liquid phase*

Table 2: N_2O-Emission Factor from full-scale and lab-scale plants treating reject wastewater by single-stage Anammox

Wastewater (reference)	Process type	Emission factor (% N_2O-N/ $N_{oxidized}$)
Real sludge dewatering effluent (Joss *et al*., 2009)	Nitritation + Anammox (1-stage, SBR full-scale)	0.8
Real sludge dewatering effluent (Kampschreur *et al*., 2009)	Nitritation + Anammox (1-stage, full-scale)	2.5
Real sludge dewatering effluent (Castro-Barros *et al*., 2015)	Nitritation + Anammox (1-stage, full-scale)	4.0

CH_4 Emission: The state of knowledge of direct CH_4 emissions at WWTPs is not so comprehensive as for N_2O, since few field measurements have been published in literature so far. The percentage of unburned CH_4 measured in the combustion air of CHP was set according to literature values to 1.5% of the CH_4 produced (Daelman *et al*., 2012; Woess-Gallash *et al*., 2010). Similarly as for N_2O, also CH_4 emissions in the receiving water bodies were neglected in the Decision Tool, due to the high COD removal degree of the model WWTP.

2.4.2. Indirect GHG emissions

Indirect GHG emissions and CO_2-credits were estimated using emission factors available in reliable data bases as Ecoinvent 3.3. and 3.4 (Table 3). For the Decision Tool the same EF of PowerStep LCA were adopted. The complete upstream chain of chemical application at WWTPs (extraction of raw material, production and distribution) was considered.

Credits deriving from the use of surplus heat of the CHP were not included in the CO_2-balance. Based on rough calculation it can be assumed that either in the single-stage or in the two-stage WWTP enough heat is available to cover the demand for side-stream stripping at 60-65°C.

Table 3: Emission factors (as CO_2e) used for the calculation of indirect GHG emissions in Decision Tool as well as in PowerStep LCA.

	Emission Factor	Unit	Source: Ecoinvent 3.3. and 3.4
Electricity	0.0458	$kgCO_2e/kWh$	market group for electricity, medium voltage [RER]
$FeCl_3$	1.14	$kgCO_2e/kg\ FeCl_3$ (100%)	market for iron (III) chloride, without water, in 40% solution state [GLO]
Polymer	2.26	kg Polymer (100% AS)	market for acrylonitrile [GLO]
NaOH	0.674	kg NaOH (50%)	market for sodium hydroxide, without water, in 50% solution state [GLO]
H_2SO_4	0.059	kg H_2SO_4 (37%)	market for sulphuric acid [GLO]
$(NH_4)_2SO_4$	2	kg N	market for ammonium sulphate, as N [GLO]

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3. Calculations and Results

The following subchapters depict the calculation results of the selected SDE treatement options when implemented at single-stage and two-stage WWTPs. In subchapter 3.1 all relevant calculation inputs and the outputs of the calculation for a single-stage WWTP are exemplary summerized in tables. For the other evaluated scenarios in subschaters 3.2, 3.5. and 3.6 the tables are displaced in the appendix.

3.1. Single-stage WWTP with influent TN/COD ratio of 8/120

3.1.1. Calculation of a single-stage WWTP

The following assumptions (Table 4) were made for the calculation of a single-stage WWTP. The WWTP is designed with two lines except the biological SDE treatment (one single tank). The temperature level for physical SDE treatment (air-stripping and membrane-stripping) is in the range of 60 to 65 °C. The required thermal energy for stripping can be covered from excess heat from CHP. This consideration represents the most energetically and economically case for stripping.

Table 4: Assumptions for calculation of single-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Influent						
Size WWTP (120 PE)	100,000	100,000	100,000	100,000	100,000	PE
specific wastewater production	175.00	175.00	175.00	175.00	175.00	L/PE/d
Temperature (for dimensioning)	12.00	12.00	12.00	12.00	12.00	°C
COD (daily load per PE)	120.00	120.00	120.00	120.00	120.00	g/PE/d
TN (daily load per PE)	8.00	8.00	8.00	8.00	8.00	g/PE/d
P (daily load per PE)	1.80	1.80	1.80	1.80	1.80	g/PE/d
COD-removal WWTP	95.00	95.00	95.00	95.00	95.00	%
TN-removal WWTP	80.00	80.00	80.00	80.00	80.00	%
Primary settling						
COD-removal	30.00	30.00	30.00	30.00	30.00	%
TN/COD in PS	2.50	2.50	2.50	2.50	2.50	%
TSS in PS	30.00	30.00	30.00	30.00	30.00	g/L
COD/VSS in PS	1.75	1.75	1.75	1.75	1.75	-
Bypass	-	-	-	-	-	%
Activated sludge tank 1st stage						
TSS 1st stage	-	-	-	-	-	g/L
COD-removal 1st stage	-	-	-	-	-	%
Percentage of respired COD	-	-	-	-	-	%
COD/VSS in ES 1st stage	-	-	-	-	-	-
Loss of ignition in ES 1st stage	-	-	-	-	-	%

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
DO concentration in 1st stage	-	-	-	-	-	mg/L
SAE aeration system in clear water	-	-	-	-	-	kgO_2/kWh
a-value	-	-	-	-	-	-
Sludge return ratio RS1	-	-	-	-	-	-
TN/COD in ES 1st stage	-	-	-	-	-	%
Mixing energy	-	-	-	-	-	W/m^3
Activated sludge tank 2nd stage						
TSS 2nd stage	3.00	3.00	3.00	3.00	3.00	g/L
Percentage of respired COD	55.00	55.00	55.00	55.00	55.00	%
COD/VSS in ES 2nd stage	1.40	1.40	1.40	1.40	1.40	-
Loss of ignition in ES 2nd stage	72.00	72.00	72.00	72.00	72.00	%
DO concentration in 2nd stage	1.50	1.50	1.50	1.50	1.50	mg/L
SAE aeration system in clear water	3.60	3.60	3.60	3.60	3.60	kgO_2/kWh
a-value	0.50	0.50	0.50	0.50	0.50	-
Sludge return ratio RS2	1.00	1.00	1.00	1.00	1.00	-
TN/COD in ES 2nd stage	6.00	6.00	6.00	6.00	6.00	%
Maximal ratio of $OU_{DN}2/OU_C2$	50.00	50.00	50.00	50.00	50.00	%
Mixing energy	2.00	2.00	2.00	2.00	2.00	W/m^3
Anaerobic sludge treatment						
COD in digested sludge (DS)	30.00	30.00	30.00	30.00	30.00	g/PE/d
Loss of ignition in DS	60.00	60.00	60.00	60.00	60.00	%
COD/VSS in DS	1.40	1.40	1.40	1.40	1.40	-
TSS in raw sludge	60.00	60.00	60.00	60.00	60.00	g/L
TSS in dewatered sludge	300.00	300.00	300.00	300.00	300.00	g/L
$N_{released}/COD_{Biogas}$	3.50	3.50	3.50	3.50	3.50	%
Mixing energy	4.00	4.00	4.00	4.00	4.00	W/m^3
Circulation (pumps) of digester volume	1.00	1.00	1.00	1.00	1.00	1/d
Efficiency of CHP unit (electricity)	35.00	35.00	35.00	35.00	35.00	%
Energy demand for mechanical sludge thickening (MST)	30.00	30.00	30.00	30.00	30.00	Wh/m^3
Polymer dosage for mechancal sludge thickening (MST)	3.00	3.00	3.00	3.00	3.00	gAS/kgTS
Energy demand for dewatering	1.33	1.33	1.33	1.33	1.33	kWh/m^3
Polymer dosage for dewatering	12.00	12.00	12.00	12.00	12.00	gAS/kgTS
Costs for polymer	6.00	6.00	6.00	6.00	6.00	€/kgAS
Co-substrates and external sludge						
Load of CoS/external sludge	-	-	-	-	-	kg/d
TSS CoS/external sludge	-	-	-	-	-	g/L
Loss of ignition CoS/external sludge	-	-	-	-	-	%
COD/VSS CoS/external sludge	-	-	-	-	-	-
VSS degradation	-	-	-	-	-	%
TN/COD CoS/external sludge	-	-	-	-	-	%

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Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Treatment of Sludge dewatering effluent (SDE)						
Without treatment	x					
Nitritation		x				
Anammox			x			
Air-stripping				x		
Membrane-stripping					x	
Temperature in SDE treatment tank	-	25	25	-	-	°C
DO concentration in SDE treatment tank	-	1.50	1.50	-	-	mg/L
SAE aeration system in clear water	-	3.60	3.60	-	-	kgO_2/kWh
a-value	-	0.80	0.80	-	-	-
Mixing energy	-	2.00	2.00	-	-	W/m³
Thermal energy for air-stripping	-	-	-	16.00	-	$kWh_{primary}/kgN$
Thermal energy for membrane-stripping	-	-	-	-	18.00	$kWh_{primary}/kgN$
Electric energy for air-stripping	-	-	-	4.50	-	$kWh_{primary}/kgN$
Electric energy for membrane-stripping	-	-	-	-	6.00	$kWh_{primary}/kgN$
Efficiency of power production	-	-	-	30.00	30.00	%
Demand H_2SO_4 (air- and membrane-stripping)	-	-	-	0.50	0.50	mol/molN
Costs for H_2SO_4 98 %	-	-	-	220.00	220.00	€/m³
Demand NaOH (air- and membrane-stripping)	-	-	-	0.70	0.70	mol/molN
Costs for NaOH 50 %	-	-	-	250.00	250.00	€/m³
Other costs stripping	-	-	-	0.05	0.05	€/kgN
Pumps						
Energy	9.81	9.81	9.81	9.81	9.81	Ws/L/m
Efficiency of pumps	60	60	60	60	60	%
Δh for inflow pump	6.00	6.00	6.00	6.00	6.00	m
Δh for Bypass	-	-	-	-	-	m
Δh for return sludge RS1	-	-	-	-	-	m
Δh for return sludge RS2	2.50	2.50	2.50	2.50	2.50	m
Δh for internal recirculation	0.50	0.50	0.50	0.50	0.50	m
Δh for nitrate recirculation	-	-	-	-	-	m
Δh for digester circulation and heating	3.00	3.00	3.00	3.00	3.00	m
Estimation of plant size						
HRT primary settling tank	1.50	1.50	1.50	1.50	1.50	h
Anoxic respiration	30.00	30.00	30.00	30.00	30.00	$mgO_2/L/h$
SRT 1st stage	-	-	-	-	-	d
P in Biomass (related to COD)	0.50	0.50	0.50	0.50	0.50	%
P in WWTP effluent	1.00	1.00	1.00	1.00	1.00	mg/L
Specific requirement of iron (β=1,5)	2.70	2.70	2.70	2.70	2.70	kgFe/kgP
Sludge from P-precipitation	2.50	2.50	2.50	2.50	2.50	kgTSS/kgFe
Depth of intermediate sedimentation tank	-	-	-	-	-	m

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Surface charging of intermediate sedimentation tank	-	-	-	-	-	m/h
Depth of secondary sedimentation tank	4.50	4.50	4.50	4.50	4.50	m
Surface charging of secondary sedimentation tank	0.60	0.60	0.60	0.60	0.60	m/h
Safety factor for SDE treatment tank	-	1.20	-	-	-	-
HRT Anammox SBR	-	-	2.00	-	-	d
HRT digester	25.00	25.00	25.00	25.00	25.00	d
Estimation of costs for construction						
Costs for infrastructure, design and construction						
Primary sedimentation	650	650	650	650	650	€/m³
Activated sludge tanks	900	900	900	900	900	€/m³
Intermediate and secondary sedimentation	1,200	1,200	1,200	1,200	1,200	€/m³
Digestion	2,500	2,500	2,500	2,500	2,500	€/m³
Fixed costs for electrical engineering	100,000	100,000	100,000	100,000	100,000	€
Fixed costs for measurement technology	75,000	75,000	75,000	75,000	75,000	€/Line
Depreciation period	15	15	15	15	15	a
SDE treatment Nitritation						
Fixed costs for electrical engineering	-	100,000	-	-	-	€
Fixed costs for measurement technology	-	25,000	-	-	-	€/tank
Costs for infrastructure, design and construction	-	2,700	-	-	-	€/kgN
SDE treatment Anammox						
Fixed costs for electrical engineering	-	-	100,000	-	-	€
Fixed costs for measurement technology	-	-	50,000	-	-	€/tank
Costs for infrastructure, design and construction	-	-	2,700	-	-	€/kgN
SDE treatment air-stripping with CO_2-stripping						
Fixed costs for electrical engineering and chemical storage	-	-	-	250,000	-	€
Costs for design and construction	-	-	-	4,100	-	€/kgN
Costs for infrastructure	-	-	-	1,000	-	€/kgN
Depreciation period	-	-	-	10	-	a
SDE treatment membrane-stripping with CO_2-stripping						
Fixed costs for electrical engineering and chemical storage	-	-	-	-	250,000	€
Costs for infrastructure, design and construction	-	-	-	-	4,000	€/kgN
Durability of membranes	-	-	-	-	5	a
Costs for membranes	-	-	-	-	600	€/kgN
Depreciation period	-	-	-	-	10	a

3.1.2. **Calculation results of a single-stage WWTP**

In case of single-stage WWTP the selected SDE treatment option shows only small differences in energy demand. Energy demand of the inlet area (inflow pumps, screens, sand and grease trap) is still the same, independent of selected SDE treatment option. The same can be said for the energy for operating sedimentation tanks, pumping the return sludge, digester circulation, mechanical sludge thickening, sludge dewatering, heating and other infrastructure. Due to reduction of ammonium in sidestream, the pre-treatment of SDE shows lower energy demand for aeration of the AST. The lowest energy demand for aeration is calulated for stripping. However, it must be considered, that this treatment option needs additional energy for operation of the stripping unit. With respect to the additional energy for oxidizing ammonium in sidestream, the biological treatment options Nitritation and Anammox show the lowest overall energy demand. Furthermore, there are slight differences in energy demand regarding stirring units, mainly depending on the required basin volume. The following Table 5 shows in detail the energy demand for the different SDE treatment options.

Table 5: Detailed demand on electrical energy for wastewater treatment of single-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Energy for inflow pumps	477	477	477	477	477	kWh/d
Energy for screens*	205	205	205	205	205	kWh/d
Energy for sand and grease trap*	205	205	205	205	205	kWh/d
Energy for sedimentation tanks*	342	342	342	342	342	kWh/d
Energy for aeration 1st stage	-	-	-	-	-	kWh/d
Energy for aeration 2nd stage	3,706	3,542	3,520	3,582	3,582	kWh/d
Energy for aeration SDE treatment	-	110	110	-	-	kWh/d
Energy for stirring unit 1st stage	-	-	-	-	-	kWh/d
Energy for stirring unit 2nd stage	562	556	541	537	537	kWh/d
Energy for stirring unit SDE treatment	-	6	8	-	-	kWh/d
Energy for stirring unit digester	240	240	240	240	240	kWh/d
Energy for pumps Bypass	-	-	-	-	-	kWh/d
Energy for pumps RS1	-	-	-	-	-	kWh/d
Energy for pumps RS2	205	205	205	205	205	kWh/d
Energy for pumps internal recirculation	83	83	54	50	50	kWh/d
Energy for pumps nitrate recirculation	-	-	-	-	-	kWh/d
Energy for pumps digester circulation	34	34	34	34	34	kWh/d
Energy for air-stripping	-	-	-	175	-	kWh/d
Energy for membrane-stripping	-	-	-	-	233	kWh/d
Energy for MST	20	20	20	20	20	kWh/d
Energy for sludge dewatering	133	133	133	133	133	kWh/d
Energy for heating*	342	342	342	342	342	kWh/d
Energy for other infrastructure*	411	411	411	411	411	kWh/d
Energy for WWTP	6,966	6,913	6,849	6,959	7,017	kWh/d
Energy for WWTP	25.4	25.2	25.0	25.4	25.6	kWh/PE/a

Energy from Biogas utilisation	5,035	5,035	5,035	5,035	5,035	kWh/d
Energy gain/Energy demand	72.27	72.83	73.51	72.35	71.75	%

**Not calculated; assumed values from Austrian Benchmarking for WWTPs (Öffentlicher Bericht ARA 2015).*

Table 6 shows the specific demand on electrical energy for aeration of the AST. In case of SDE stripping, the additional energy demand is added to the energy demand for AST. It can be displayed that the biological pre-treatment of SDE in sidestream leads to a slightly reduction of energy demand of 1.5 % (Nitritation) or 2.1 % (Anammox). In case of SDE stripping, a higher energy demand is to be expected.

Table 6: Energy demand for aeration and stripping with percentage difference for 1-stage WWTP with 8/120

	Energy demand in kWh/PE/a				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
Energy for aeration	13.53	13.33	13.25	13.07	13.07
Energy for stripping	0	0	0	0.64	0.85
Total energy	13.53	13.33	13.25	13.71	13.92
Savings in energy	**0 %**	**- 1.5 %**	**- 2.1 %**	**+ 1.3 %**	**+ 2.9 %**

The results of calculation regarding the energy demand for wastewater treatment with different SDE treatment options (Table 5) are graphically displayed in the following figures. Figure 4 displays the result for single-stage WWTP with mainstream treatment of SDE. In Figure 5 the overall energy demand for SDE Nitritation is shown. Figure 6 displays the required energy for the SDE Anammox option, followed by Figure 7 and Figure 8 for the SDE air-stripping and membrane-stripping option, respectively. The energy demand is calculated as specific energy demand in kWh/PE/a and lies in a narrow range of 25.00 to 25.61 kWh/PE/a. It is shown, that the energetically most advantageous SDE treatment option is sidestream Anammox, the most energy intensive SDE membrane-stripping.

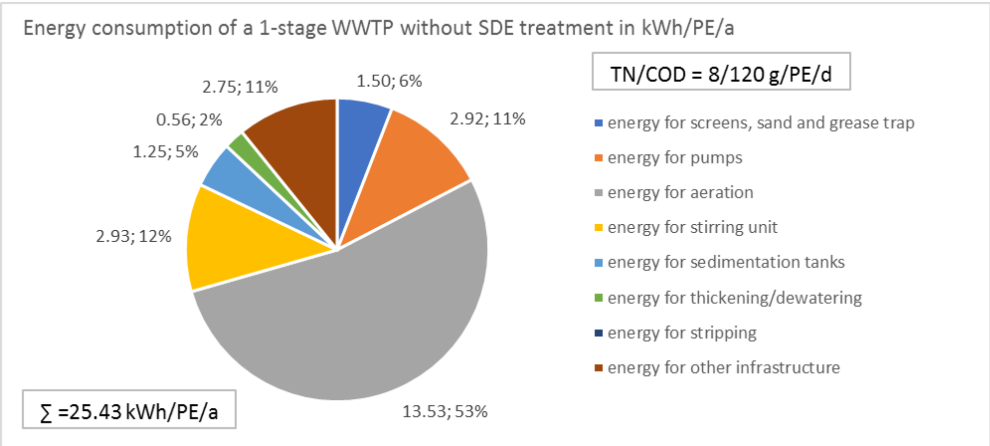

Figure 4: Energy consumption of single-stage WWTP without SDE treatment (8/120)

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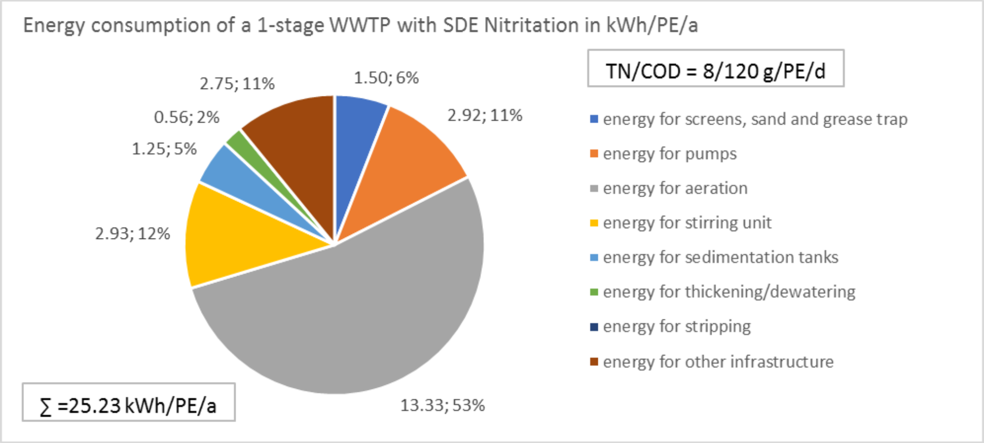

Figure 5: Energy consumption of single-stage WWTP with SDE Nitritation (8/120)

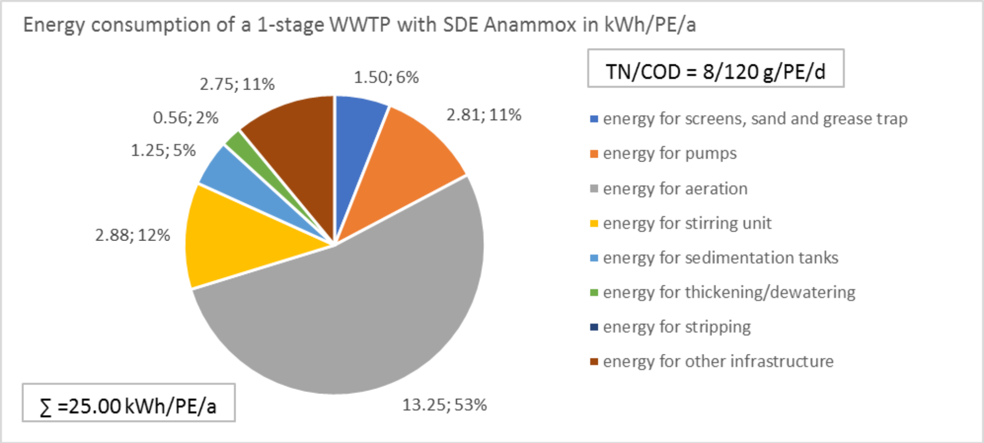

Figure 6: Energy consumption of single-stage WWTP with SDE Anammox (8/120)

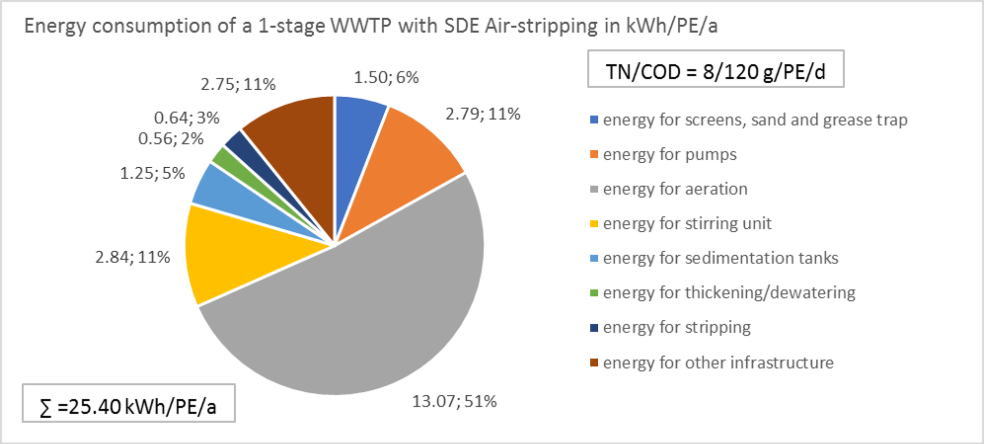

Figure 7: Energy consumption of single-stage WWTP with SDE Air-stripping (8/120)

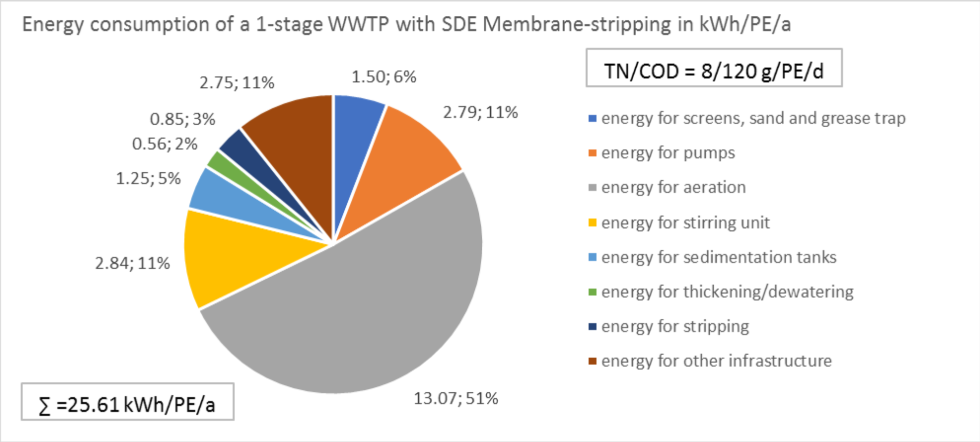

Figure 8: Energy consumption of single-stage WWTP with SDE Membrane-stripping (8/120)

The above calculations of energy demand for wastewater treatment depend on detailed Q-, TN- and COD-balances. These balances (Table 7, Table 8, Table 9) also provide the basis for following estimations of basin volumes (Table 10), building costs (Table 11) and subsequent running costs for operation (Table 12).

Table 7: Detailed Q-balance for single-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Q inflow primary sedimentation	17,500	17,500	17,500	17,500	17,500	m³/d
Q PS	84	84	84	84	84	m³/d
Q outflow primary sedimentation	17,416	17,416	17,416	17,416	17,416	m³/d
Q Bypass	-	-	-	-	-	m³/d
Q ES 1st stage	-	-	-	-	-	m³/d
Q ES 2nd stage	580	580	580	580	580	m³/d
Q inflow MST	664	664	664	664	664	m³/d
Q raw sludge	100	100	100	100	100	m³/d
Q outflow MST to 1st stage	564	564	564	564	564	m³/d
Q inflow digester CoS/external sludge	-	-	-	-	-	m³/d
Q outflow digester	100	100	100	100	100	m³/d
Q dewatered sludge	12	12	12	12	12	m³/d
Q SDE	88	88	88	88	88	m³/d
Q SDE treatment to 1st stage	88	88	88	88	88	m³/d
Q nitrate recirculation	-	-	-	-	-	m³/d
Q inflow 1st stage	-	-	-	-	-	m³/d
Q outflow 1st stage	-	-	-	-	-	m³/d
Q inflow 2nd stage	18,068	18,068	18,068	18,068	18,068	m³/d
Q outflow 2nd stage	17,488	17,488	17,488	17,488	17,488	m³/d
Q RS1	-	-	-	-	-	m³/d
Q RS2	18,068	18,068	18,068	18,068	18,068	m³/d
Q internal recirculation	36,504	36,504	23,858	21,884	21,884	m³/d

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Q total inflow 1st stage	-	-	-	-	-	m³/d
Q inflow intermediate sedimentation	-	-	-	-	-	m³/d
Q outflow intermediate sedimentation	-	-	-	-	-	m³/d
Q total inflow 2nd stage	72,641	72,641	59,995	58,021	58,021	m³/d
Q inflow secondary sedimentation	36,137	36,137	36,137	36,137	36,137	m³/d
Q outflow secondary sedimentation	17,488	17,488	17,488	17,488	17,488	m³/d
Q outflow WWTP	17,488	17,488	17,488	17,488	17,488	m³/d

Table 8: Detailed COD-balance for single-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
COD inflow primary sedimentation	12,000	12,000	12,000	12,000	12,000	kg/d
COD PS	3,600	3,600	3,600	3,600	3,600	kg/d
COD outflow primary sedimentation	8,400	8,400	8,400	8,400	8,400	kg/d
COD Bypass to 2nd stage	-	-	-	-	-	kg/d
COD inflow 1st stage	-	-	-	-	-	kg/d
COD ES 1st stage	-	-	-	-	-	kg/d
COD inflow 2nd stage	8,400	8,400	8,400	8,400	8,400	kg/d
COD ES 2nd stage	3,510	3,510	3,510	3,510	3,510	kg/d
COD outflow WWTP	600	600	600	600	600	kg/d
COD raw sludge	7,110	7,110	7,110	7,110	7,110	kg/d
COD inflow digester CoS/external sludge	-	-	-	-	-	kg/d
COD digested sludge + CoS/external sludge	3,000	3,000	3,000	3,000	3,000	kg/d
COD SDE	0	0	0	0	0	kg/d
COD nitrate recirculation	-	-	-	-	-	kg/d
COD Biogas	4,110	4,110	4,110	4,110	4,110	kg/d
OU_C 1st stage	-	-	-	-	-	kg/d
OU_C 2nd stage	4,290	4,290	4,290	4,290	4,290	kg/d
OU_{DN} 1st stage	-	-	-	-	-	kg/d
OU_{DN} 2nd stage	1,382	1,291	1,062	1,012	1,012	kg/d
$OU_{DN}1/OU_C1$	-	-	-	-	-	%
$OU_{DN}2/OU_C2$	32.22	30.10	24.75	23.59	23.59	%

Table 9: Detailed TN-balance for single-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
TN inflow primary sedimentation	800	800	800	800	800	kg/d
TN PS	90	90	90	90	90	kg/d
TN outflow primary sedimentation	710	710	710	710	710	kg/d
TN Bypass to 2nd stage	-	-	-	-	-	kg/d
TN inflow 1st stage	-	-	-	-	-	kg/d
TN ES 1st stage	-	-	-	-	-	kg/d
TN ES 2nd stage	211	211	211	211	211	kg/d

TN raw sludge	301	301	301	301	301	kg/d
TN inflow digester CoS/external sludge	-	-	-	-	-	kg/d
TN inflow digester	301	301	301	301	301	kg/d
TN SDE	144	144	144	144	144	kg/d
TN digested sludge + CoS/external sludge	157	157	157	157	157	kg/d
TN outflow WWTP	160	160	160	160	160	kg/d
TN total inflow 1st stage	-	-	-	-	-	kg/d
TN denitrified 1st stage	-	-	-	-	-	kg/d
TN outflow 1st stage	-	-	-	-	-	kg/d
TN inflow 2nd stage	854	854	742	724	724	kg/d
TN denitrified 2nd stage	483	483	371	354	354	kg/d
TN outflow 2nd stage	160	160	160	160	160	kg/d
TN nitrate recirculation	-	-	-	-	-	kg/d
TN denitrified + nitrate recirculation 1st stage	-	-	-	-	-	kg/d

Table 10: Calculation of required basin volumes for single-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Basin volume primary sedimentation	1,094	1,094	1,094	1,094	1,094	m³
Basin volume AST 1st stage	-	-	-	-	-	m³
Basin volume intermediate sedimentation	-	-	-	-	-	m³
Basin volume AST 2nd stage	11,710	11,584	11,265	11,196	11,196	m³
Basin volume secondary sedimentation	5,469	5,469	5,469	5,469	5,469	m³
Basin volume SDE treatment	-	127	176	-	-	m³
Volume digester	2,497	2,497	2,497	2,497	2,497	m³

Table 11: Detailed construction costs for single-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Costs primary sedimentation	710,938	710,938	710,938	710,938	710,938	€
Costs AST 1st stage						€
Costs intermediate sedimentation						€
Costs AST 2nd stage	10,538,920	10,425,188	10,138,585	10,076,082	10,076,082	€
Costs secondary sedimentation	6,562,500	6,562,500	6,562,500	6,562,500	6,562,500	€
Costs digester	6,242,560	6,242,560	6,242,560	6,242,560	6,242,560	€
Costs electrical engineering	100,000	100,000	100,000	100,000	100,000	€
Costs measurement technology	150,000	150,000	150,000	150,000	150,000	€
Costs Nitritation electrical engineering		100,000				€
Costs Nitritation measurement technology		25,000				€
Costs Nitritation infrastructure, design, construction		213,617				€
Costs Anammox electrical engineering			100,000			€
Costs Anammox measurement technology			50,000			€

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Costs Anammox infrastructure, design, construction			302,351			€
Costs Air-stripping electrical engineering, chemical storage				250,000		€
Costs Air-stripping design and construction				530,807		€
Costs Air-stripping infrastructure				129,465		€
Costs Membrane-stripping electr. eng., chemical storage					250,000	€
Costs Membrane-stripping design and construction					517,860	€
Costs for membranes					77,679	€
Total costs for WWTP	24,304,917	24,529,803	24,356,933	24,752,351	24,687,619	€
Total costs for WWTP	243.0	245.3	243.6	247.5	246.9	€/PE

Table 12: Running costs for single-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Costs for depreciation WWTP	1,620,328	1,635,320	1,623,796	1,680,499	1,681,794	€/a
Costs for external electricity	84,594	82,254	79,453	84,288	86,840	€/a
Costs for polymer	133,230	133,230	133,230	133,230	133,230	€/a
Costs for H_2SO_4 98%	-	-	-	20,666	20,666	€/a
Costs for NaOH 50%	-	-	-	31,007	31,007	€/a
Other costs stripping	-	-	-	2,363	2,363	€/a
Revenues from sale of N-fertilizer	-	-	-	47,255	47,255	€/a
Overall running costs	1,838,152	1,850,804	1,836,479	1,904,798	1,908,645	€/a
Overall running costs	18.4	18.5	18.4	19.0	19.1	€/PE/a

3.2. Two-stage WWTP with influent TN/COD ratio of 8/120

3.2.1. Calculation for a two-stage WWTP

The assumptions for the calculation of a two-stage WWTP are displayed in detail in appendix 6.1. The WWTP is designed with two lines except the biological SDE treatment (one single tank). The temperature level for physical SDE treatment (air-stripping and membrane-stripping) is in the range of 60 to 65 °C. The required thermal energy for stripping can be covered from excess heat from CHP. This consideration represents the most energetically and economically case for stripping.

The COD load is firstly reduced by the primary settling tank (- 30 %). The efficiency of the 1st stage is assumed to be in a range of 60 %. 30 % of the reduced COD load is converted into CO_2, the remaining 70 % are bound into biomass. In case of insufficient organic carbon for denitrification in the 2nd stage, a part of the outflow from primary sedimentation (bypass) must be dosed to the anoxic zone of the 2nd stage or part of the WWTP effluent must be pumped to the anoxic zone of the 1st stage (nitrate recirculation). The bypass does not increase the hydraulic load on the secondary sedimentation tank, whereas the recirculated effluent (nitrate recirculation) increases the hydraulic load on the intermediate and secondary sedimentation tank. To ensure even in case of stormwater an operation of the plant without any deterioration of wastewater purification the nitrate recirculation is limited by a maximum of 10 % from the WWTP inflow. The remaining amount of missing organic carbon is supplied via bypass.

For 2-stage WWTP without pre-treatment of SDE the required bypass is calculated to 17 % due to the assumption of a maximum of 10 % nitrate recirculation. In case of SDE nitritation in sidestream, approximately 7 % of the inflow is pumped from the WWTP effluent to the anoxic zone of the 1st stage (nitrate recirculation). For all other treatment options (Anammox, air-stripping and membrane-stripping) neither nitrate recirculation nor bypass are required to achieve the goal of 80 % nitrogen removal.

3.2.2. Calculation results for a two-stage WWTP

In case of two-stage WWTP the selected SDE treatment option has a much higher influence on the energy demand compared to single-stage WWTP. Energy demand of the inlet area (inflow pumps, screens, sand and grease trap) is still the same, independent of selected SDE treatment option. Energy for sedimentation tanks, digester circulation, mechanical sludge thickening, sludge dewatering, heating and other infrastructure is not mainly influenced by SDE pre-treatment and therefore almost identical. Small differences occur due to the fact, that bypassing some COD from the effluent of primary settling to the 2nd stage leads to a lower COD load to the 1st stage and corresponding lower production of excess sludge, which will subsequently decrease biogas production and the energy gain from biogas utilization. Depending on the COD load to the 1st and 2nd stages, the energy demand for pumping the return sludge varies in a narrow range.

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Due to reduction of ammonium in sidestream, the pre-treatment of SDE shows lower energy demand for aeration of the AST 2nd stage. The calculation results are compareable to the ones of the single-stage WWTP. The lowest energy demand for aeration is calulated for stripping. However, it must be considered, that this treatment option needs additionally energy for operation of the stripping unit. In term of additional energy demand for the sidestream treatment, the biological treatment options nitritation and Anammox show the lowest overall energy demand. Furthermore, there are slight differences in energy demand regarding stirring units, mainly depending on the required basin volume. Table 27 (Appendix 6.2) shows in detail the energy demand for the different SDE treatment options.

Table 13 shows the specific demand on electrical energy for aeration of the AST. In case of SDE stripping, the energy demand is added to the energy demand for AST. It can be shown that the biological pre-treatment of SDE in sidestream leads to a slightly reduction of energy demand of 5.6 % (nitritation) or 5.4 % (Anammox).

Table 13: Energy demand for aeration and stripping with percentage difference for 2-stage WWTP with 8/120

	Energy demand in kWh/PE/a				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
Energy for aeration	11.21	10.59	10.61	10.44	10.44
Energy for stripping	0	0	0	0.77	1.03
Total Energy	11.21	10.59	10.61	11.21	11.47
Savings in energy	**0 %**	**- 5.6 %**	**- 5.4 %**	**0 %**	**+ 2.3 %**

The bypass of organic carbon from effluent of primary settling tank to the 2nd stage is not necessary due to SDE pre-treatment. This leads as displayed in following table to a higher load of biodegradable organic compounds to the digester, resulting in a higher gain of biogas. The produced electrical energy from CHP unit increases correspondingly and can be assumed to be 6.4 % higher for all SDE treatment options compared to WWTP without SDE pre-treatment.

Table 14: Electric energy from biogas utilization with percentage difference for 2-stage WWTP with 8/120

	Electric energy from CHP in kWh/PE/a				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
	20.87	22.21	22.21	22.21	22.21
Gain of energy	**0 %**	**+ 6.4 %**	**+ 6.4 %**	**+6.4 %**	**+ 6.4 %**

The results of calculation regarding the energy demand for wastewater treatment with different SDE treatment options (Table 27, appendix 6.2) are graphically displayed in the following figures. Figure 9 displays the result for single-stage WWTP with mainstream treatment of SDE. In Figure 10 the overall energy demand for SDE Nitritation is depicted.

Figure 11 displays the required energy for the SDE Anammox option, following Figure 12 and Figure 13 for the SDE air-stripping and membrane-stripping option. The energy demand is calculated as specific energy demand in kWh/PE/a and lies in a narrow range of 22.37 to 23.31 kWh/PE/a. Here it becomes evident, that the energetically most advantageous option is SDE anammox, the most energy intensive treatment option is SDE treatment in mainstream without pre-treatment in sidestream.

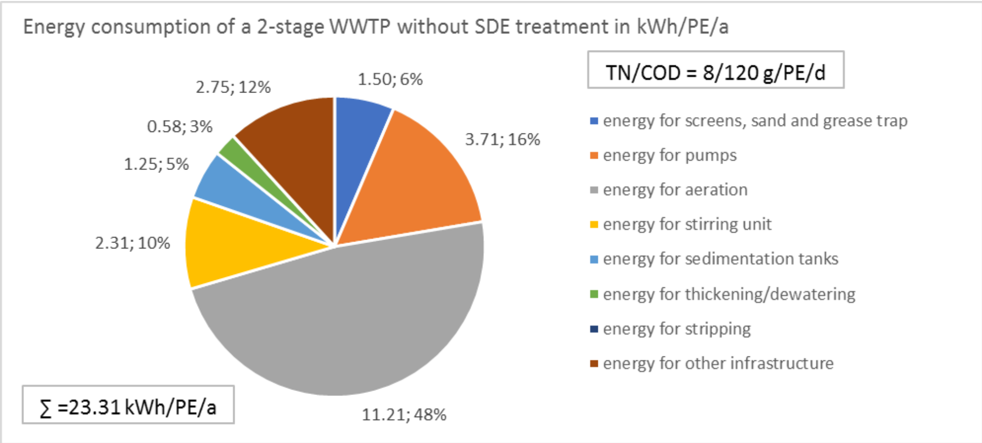

Figure 9: Energy consumption of 2-stage WWTP without SDE treatment (8/120)

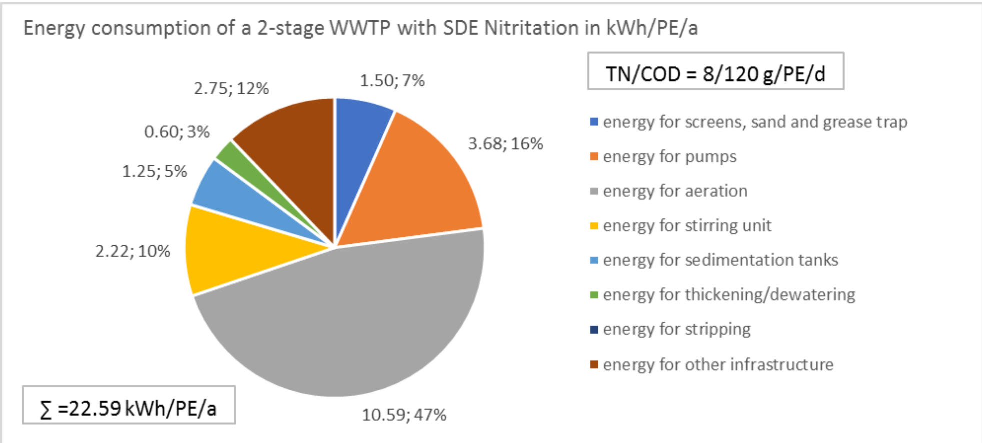

Figure 10: Energy consumption of 2-stage WWTP with SDE Nitritation (8/120)

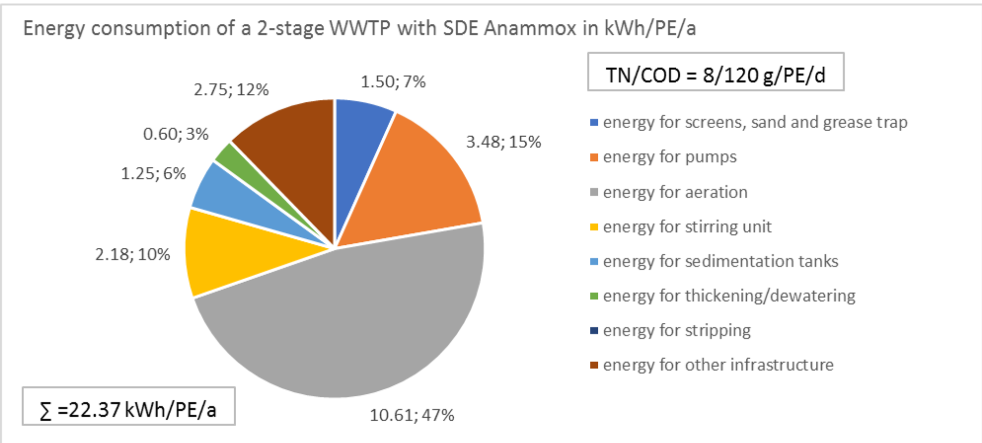

Figure 11: Energy consumption of 2-stage WWTP with SDE Anammox (8/120)

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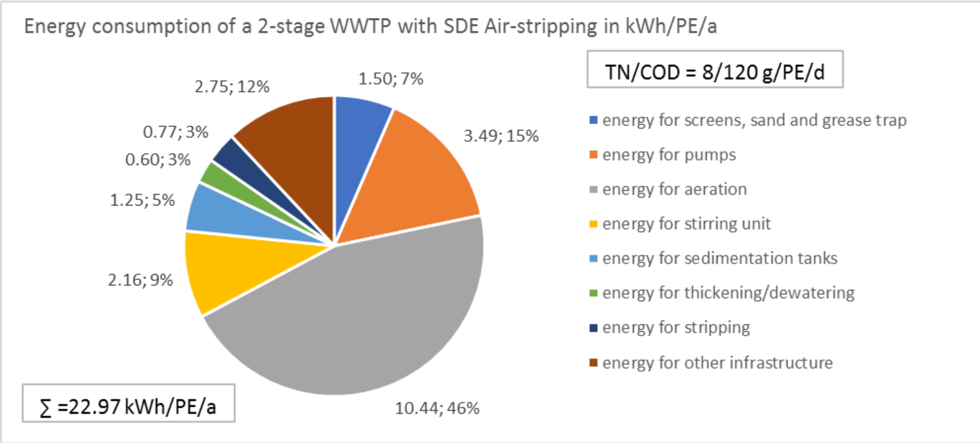

Figure 12: Energy consumption of 2-stage WWTP with SDE Air-stripping (8/120)

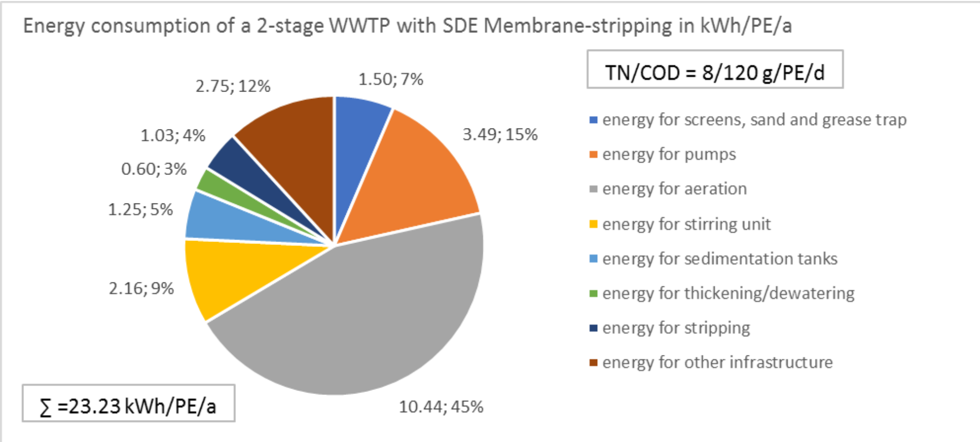

Figure 13: Energy consumption of 2-stage WWTP with SDE Membrane-stripping (8/120)

The above calculations of energy demand for wastewater treatment depend on detailed Q-, TN- and COD-balances. These balances (Table 28, Table 29, Table 30) also provide the basis for following estimations of basin volumes (Table 31), building costs (Table 32) and subsequent running costs for operation (Table 33).

3.3. Comparison of single and 2-stage WWTP with influent TN/COD ratio of 8/120

The comparison of the overall energy demand of single-stage WWTP with an influent ratio of TN/COD = 8/120 g/PE/d shows relatively low savings in energy regarding different SDE treatment options. Without pre-treatment of SDE in sidestream the energy demand is in a range of 25.4 kWh/PE/a. Physical SDE treatment (air-stripping and membrane-stripping) shows the same or a slightly higher energy demand (25.4 or 25.6 kWh/PE/a) due to the high energy demand for the stripping unit (0.64 or 0.85 kWh/PE/a). It must be mentioned, that this energy demand concerns in all scenarios the electric energy demand only due to the assumption, that the energy demand for heat is fully covered by the excess heat from CHP unit. Is this not the case, the energy demand for stripping is in a higher range. The lowest energy demand is calculated for the biological treatment options (25.2 kWh/PE/a for SDE nitritation and 25.0 kWh/PE/a for SDE Anammox).

In case of 2-stage WWTP the overall energy consumption for wastewater treatment is much lower. The biological SDE treatment options show also in this case the lowest energy demand. Compared to single-stage WWTP savings in energy due to the concept of 2-stage WWTP in a range of – 10 % can be expected. This is mainly due to the fact, that the high COD-loaded 1st stage produces energy-rich excess sludge and a lower proportion of COD is aerobically respired to CO_2. The SDE pre-treatment produces nitrite-rich (Nitritation) or nitrate-rich (Anammox) effluent which can be used in the anoxic zone of the 1st stage to cover partially the oxygen demand for carbon respiration (OU_C). This leads due to the poor α-value in the 1st stage compared to the SDE tank to savings in energy demand for aeration. Table 15 and Figure 14 show the calculation results and displays the advantage of the 2-stage WWTP concept.

Table 15: Energy consumption of single and 2-stage WWTP with different SDE treatment options

	Total energy consumption in kWh/PE/a				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
1-stage WWTP	25.4	25.2	25.0	25.4	25.6
2-stage WWTP	23.3	22.6	22.4	23.0	23.2
	- 8.3 %	**- 10.3 %**	**- 10.4 %**	**- 9.4 %**	**- 9.4 %**

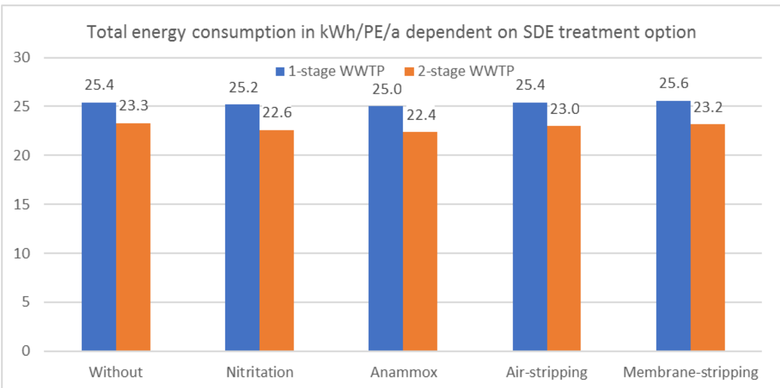

Figure 14: Energy consumption of single and 2-stage WWTP with different SDE treatment options

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The biogas yield depends on the COD load to the digester. In case of 2-stage WWTP the COD in raw sludge is higher compared to single-stage WWTP. This is because of the very low sludge retention time in the 1st stage (about 1 d or slightly higher). The respired amount of COD is only in a range of 30 % which means, that 70% of the reduced COD can be found in the biomass (excess sludge). The proportion of respired COD is in case of single-stage WWTP higher (ca. 50 %) with corresponding lower proportion of COD in excess sludge. Due to pre-treatment of SDE in sidestream, the bypass is reduced mainly or completely unnecessary. This leads to a higher COD load to the 1st stage and to higher COD in raw sludge. This advantage can be seen in Table 16 and Figure 15. The biogas yield for the 2-stage WWTP with SDE treatment is 6.2 % higher compared to SDE mainstream treatment (17 % bypass). Compared to single-stage WWTP the biogas yield or electric energy from biogas utilization is 20.7 % higher compared to single-stage WWTP concept.

Table 16: Electric energy from biogas utilization in CHP of single and 2-stage WWTP with different SDE treatment options

	Electric energy from CHP in kWh/PE/a				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
1-stage WWTP	18.4	18.4	18.4	18.4	18.4
2-stage WWTP	20.9	22.2	22.2	22.2	22.2
	+ 13.6 %	**+ 20.7 %**	**+ 20.7 %**	**+ 20.7 %**	**+ 20.7 %**

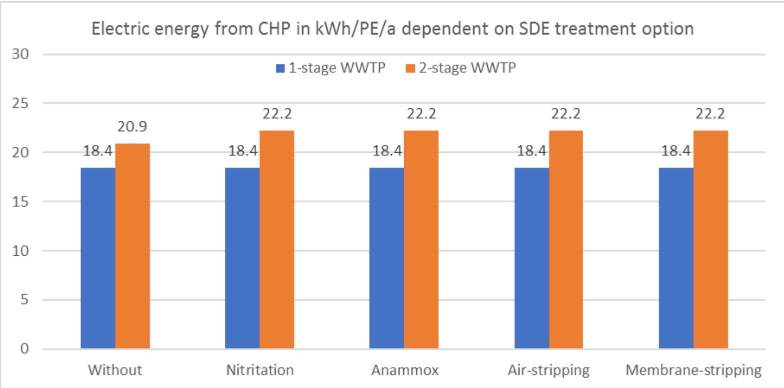

Figure 15: Electric energy from biogas utilization in CHP of single and two-stage WWTP with different SDE treatment options

The costs for construction mainly depend on the size of the required basin volume. For single-stage WWTP the construction costs are in a range of 243.0 (without SDE treatment) to 247.5 €/PE (SDE Air-stripping), depending on the SDE treatment concept. In case of 2-stage WWTP the costs for construction are slightly lower (about 2 to 4 %) and in a range of 235.2 (SDE Anammox) to 241.0 €/PE (Air-stripping), mainly due to savings in required basin volume (Table 17 and Figure 16).

Table 17: Costs for construction of single and 2-stage WWTP with different SDE treatment options

	Costs for construction in €/PE				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
1-stage WWTP	243.0	245.3	243.6	247.5	246.9
2-stage WWTP	237.6	236.1	235.2	241.0	240.2
	- 2.2 %	**- 3.8 %**	**- 3.4 %**	**- 2.6 %**	**- 2.7 %**

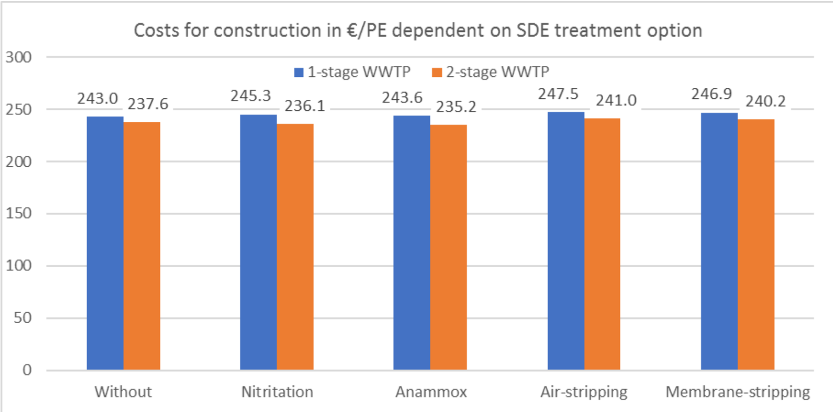

Figure 16: Costs for construction of single and 2-stage WWTP with different SDE treatment options

The calculated running costs for operation mainly depend on depreciation of construction costs, required external electrical energy and materials for operation (e.g. flocculants). These costs are almost in the same range for single-stage WWTP without SDE treatment and biological SDE treatment options. In case of SDE stripping the running costs are in a higher level (+ 3.8 %). The comparison of different SDE treatment options at 2-stage WWTP shows the lowest running costs for biological treatment options (17.1 €/PE/a) and the highest running costs for SDE Membrane-stripping (18.0 €/PE/a). The following Table 18 and Figure 17 display these advantages for biological SDE pre-treatment and show also the advantage of the 2-stage WWTP concept compared to single-stage WWTP concept. Beside savings in energy demand and higher biogas yield the concept of 2-stage WWTP shows benefits in construction costs as well as running costs of operation.

Table 18: Running cost for operation of single and 2-stage WWTP with different SDE treatment options

	Running costs in €/PE/a				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
1-stage WWTP	18.4	18.5	18.4	19.0	19.1
2-stage WWTP	17.5	17.1	17.1	17.9	18.0
	- 4.9 %	**- 7.6 %**	**- 7.1 %**	**- 5.8 %**	**- 5.8 %**

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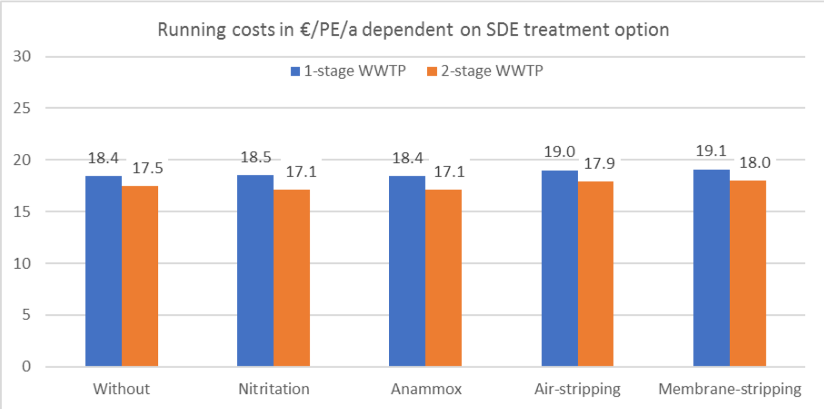

Figure 17. Running cost for operation of 1- and 2-stage WWTP with different SDE treatment options

3.4. Single-stage WWTP with influent TN/COD ratio of 11/120

3.4.1. Calculation of a single-stage WWTP with higher influent nitrogen load

The assumptions for the calculation of a single-stage WWTP with higher influent nitrogen load of TN/COD = 11/120 g/PE/d are displayed in detail in Table 34 (Appendix 6.3). The specific daily nitrogen load in the influent of Austrian WWTP is in a low range of 8 to 9 g/PE/d compared to international standards (11 g/PE/d). To display the differences between low and high nitrogen influent load, the following calculation is based on a nitrogen load of 11 g/PE/d. The WWTP is designed with two lines except the biological SDE treatment (one sigle tank). The temperature level for physical SDE treatment (air-stripping and membrane-stripping) is in the range of 60 to 65 °C. The required thermal energy for stripping can be covered from excess heat from CHP. This consideration represents the most energetically and economically case for stripping. The ratio of TN/COD is 11/120 g/PE/d for this calculation. It is assumed that the higher nitrogen load results from an increased amount of dissolved nitrogen, the amount of particulate nitrogen remains unchanged.

3.4.2. Calculation results of a single-stage WWTP with higher influent nitrogen load

In case of single-stage WWTP with higher influent nitrogen load the selected SDE treatment option shows only small differences in energy demand. Energy demand of the inlet area (inflow pumps, screens, sand and grease trap) is still the same, independent of selected SDE treatment option. Also, energy for sedimentation tanks, pumping the return sludge, digester circulation, mechanical sludge thickening, sludge dewatering, heating and other infrastructure is not influenced by SDE pre-treatment. Due to reduction of ammonium in sidestream, the pre-treatment of SDE shows lower energy demand for aeration of the AST. The lowest energy demand is calulatd for stripping. However, it must be considered, that this treatment option needs additionally energy for operation of the stripping unit. In consideration of the additional energy for oxidizing ammonium in sidestream, the biological treatment options (Nitritation and Anammox) show the lowest overall energy demand. Furthermore, there are slight differences in energy demand regarding the stirring units, mainly depending on the required basin volume. Table 34(Appendix 6.3) shows in detail the energy demand for the different SDE treatment options.

The following table shows the specific demand on electrical energy for aeration of the AST. In case of SDE stripping, the energy demand is added to the energy demand for AST. It can be displayed that the biological pre-treatment of SDE in sidestream leads to a slightly reduction of energy demand of 1.3 % (Nitritation) or 1.9 % (Anammox). SDE stripping results in a higher energy demand.

Table 19: Energy demand for aeration and stripping with percentage difference for single-stage WWTP with 11/120

	Energy demand in kWh/PE/a				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
Energy for aeration	14.98	14.79	14.70	14.53	14.53
Energy for stripping	0	0	0	0.64	0.85
Total energy	14.98	14.79	14.70	15.17	15.38
Savings in energy	**0 %**	**- 1.3 %**	**- 1.9 %**	**+ 1.3 %**	**+ 2.7 %**

The results of calculation regarding the energy demand for wastewater treatment with different SDE treatment options (Table 35, Appendix 6.4) are graphically displayed in the following figures. Figure 18 displays the result for single-stage WWTP with mainstream treatment of SDE. In Figure 19 the overall energy demand for SDE Nitritation is shown. Figure 20 displays the required energy for the SDE Anammox option, following Figure 21 and Figure 22 for the SDE Air-stripping and Membrane-stripping option. The energy demand is calculated as specific energy demand in kWh/PE/a and lies in a narrow range of 26.69 to 27.31 kWh/PE/a. It can be derived, that the energetically most advantageous option is SDE Anammox, the most energy intensive treatment option is SDE membrane-stripping.

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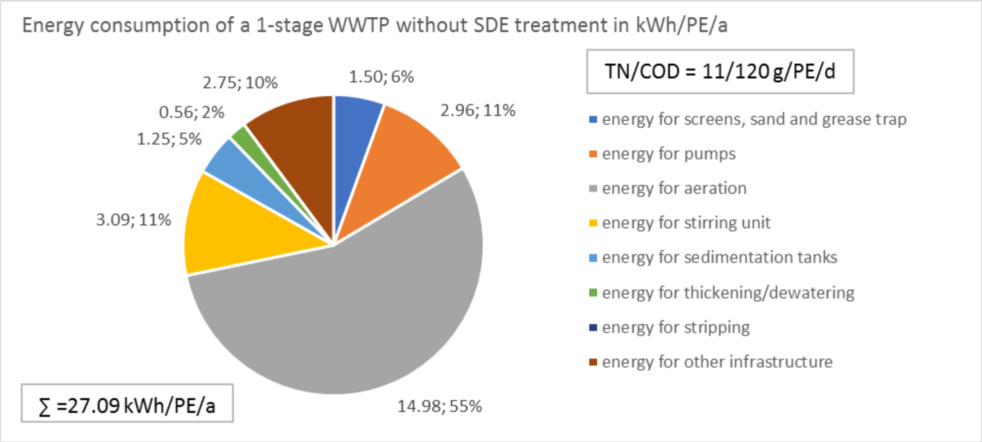

Figure 18: Energy consumption of single-stage WWTP without SDE treatment (11/120)

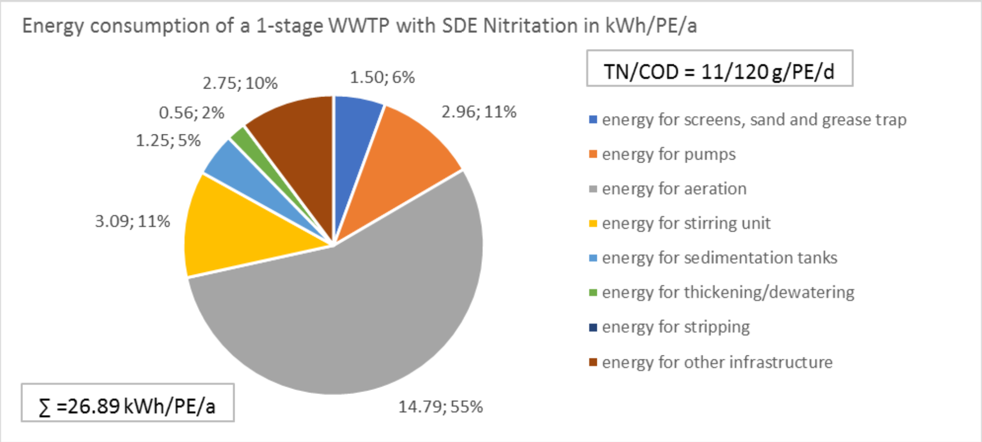

Figure 19: Energy consumption of single-stage WWTP with SDE Nitritation (11/120)

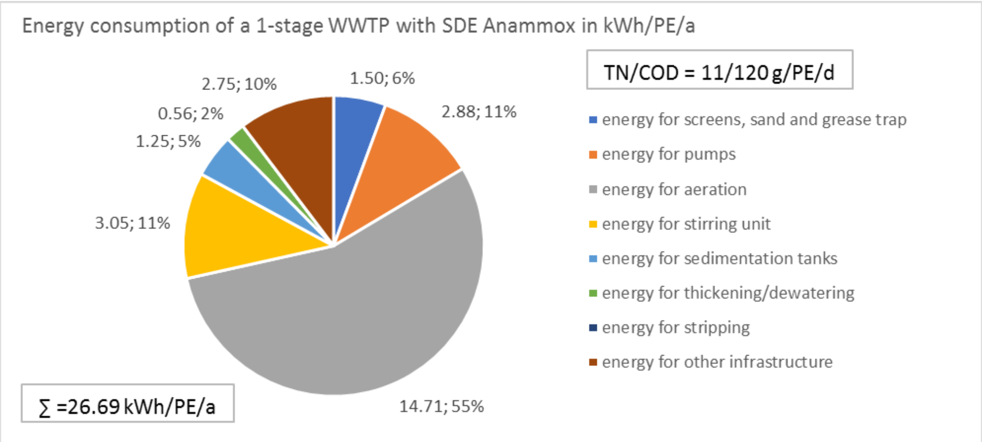

Figure 20: Energy consumption of single-stage WWTP with SDE Anammox (11/120)

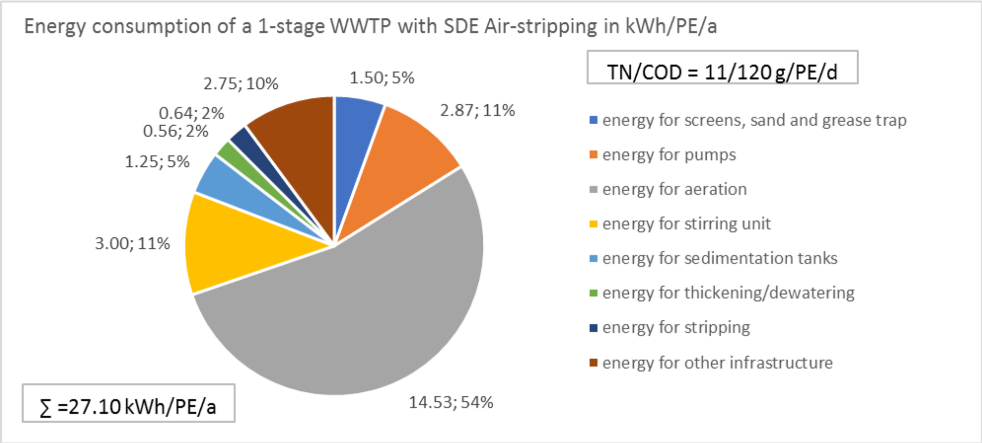

Figure 21: Energy consumption of single-stage WWTP with SDE Air-stripping (11/120)

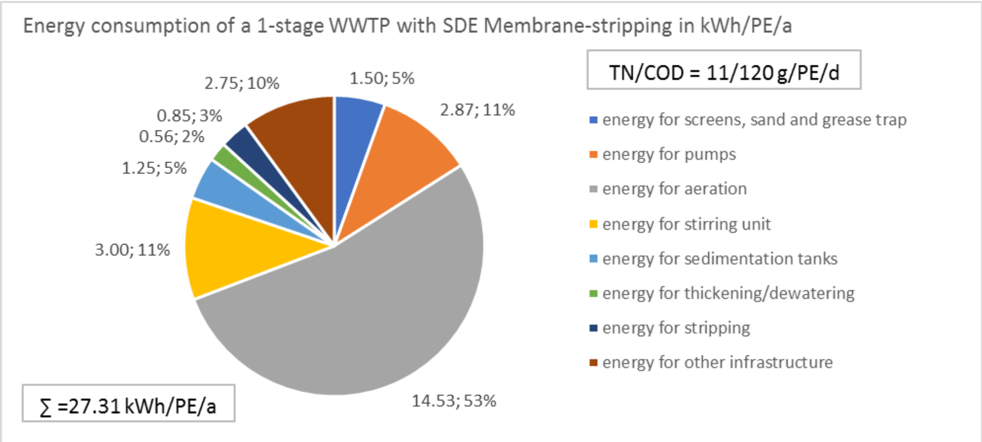

Figure 22: Energy consumption of single-stage WWTP with SDE Membrane-stripping (11/120)

The above calculations of energy demand for wastewater treatment depend on detailed Q-, TN- and COD-balances. These balances (Table 36, Table 37, Table 38 in appendix 6.4) also provide the basis for following estimations of basin volumes (Table 39), building costs (Table 40) and subsequent running costs for operation (Table 41).

3.5. Two-stage WWTP with influent TN/COD ratio of 11/120

3.5.1. Calculation of a two-stage WWTP with higher influent nitrogen load

The assumptions for the calculation of a 2-stage WWTP with higher influent nitrogen load are displayed in detail in Table 42 (appendix 6.5). The WWTP is designed with two lines except the biological SDE treatment (one single tank). The temperature level for physical SDE treatment (air-stripping and membrane-stripping) is in the range of 60 to 65 °C. The required thermal energy for stripping can be covered from excess heat from CHP. This consideration represents the most energetically and economically case for stripping.

The efficiency of the 1st stage is assumed to be in a range of 60 %. 30 % of the reduced COD load is converted into CO_2, the remaining 70 % are bound into biomass. This higher nitrogen load results from an increased amount of dissolved nitrogen, the amount of particulate nitrogen remains unchanged. This assumption leads to insufficient organic carbon for denitrification in the 2nd stage. A part of the outflow from primary sedimentation (bypass) must be dosed to the anoxic zone of the 2nd stage or part of the WWTP effluent must be pumped to the anoxic zone of the 1st stage (nitrate recirculation). Due to the lack of organic carbon, the efficiency of primary sedimentation is reduced to 25 %. The WWTP is hydraulically designed to ensure a nitrate recirculation of a third of the WWTP inflow. The additionally required COD must be added to the 2nd stage via bypass. It has to be stated that the concept of a 2-stage WWTP bases on removing carbon in the high loaded 1st stage. If the TN/COD ratio is 11/120, a substantial removal of carbon in the 1st stage resulting in a lack of carbon in the 2nd stage is counterproductive for the operation of a 2-stage WWTP.

For WWTP without pre-treatment of SDE the required bypass is calculated to 35 % due to the assumption of a maximum of 1/3 nitrate recirculation. In case of SDE Nitritation in sidestream, approximately 20 % of the inflow is pumped from the WWTP effluent to the anoxic zone of the 1st stage (nitrate recirculation) and in case of SDE Anammox 8 %. For the SDE treatment option stripping (air-stripping and membrane-stripping) the bypass is calculated to 10 %.

3.5.2. Calculation results for a two-stage WWTP with higher influent nitrogen load

In case of 2-stage WWTP with higher influent nitrogen load the selected SDE treatment option has a much higher influence on the energy demand compared to single-stage WWTP. Energy demand of the inlet area (inflow pumps, screens, sand and grease trap) is still the same, independent of selected SDE treatment option. The same can be said for sedimentation tanks, digester circulation, mechanical sludge thickening, sludge dewatering, heating and other infrastructure. Small differences occur due to the fact, that bypassing COD from effluent of primary settling to the 2nd stage leads to lower COD load to the 1st stage and consequently to a lower production of excess sludge, which decreases biogas production and the gain of energy from biogas utilization. Depending on the COD load to 1st and 2nd stage, the energy demand for pumping the return sludge varies in a narrow range.

Due to reduction of ammonium in sidestream, the pre-treatment of SDE shows lower energy demand for aeration of the AST 2nd stage. The calculation results are compareable to the results concerning single-stage WWTP. The lowest energy demand is calulated for stripping. However, it must be considered, that this treatment option needs additionally energy for the operation of the stripping unit. In term of additional energy for SDE sidestream treatment, the biological treatment options (nitritation and Anammox) show the lowest overall energy demand. Furthermore, there are slight differences in energy demand regarding stirring units, mainly depending on the required basin volume. The higher the bypass, the lower both, COD load to the 1st stage and basin volume. Lower basin volume leads to less energy for stirring due to the assumption of 2 W/m³. The Table 43 shows in detail the energy demand for the different SDE treatment options.

The following table shows the specific demand on electrical energy for aeration of the AST. In case of SDE stripping, the energy demand is added to the energy demand for AST. It can be displayed that the biological pre-treatment of SDE in sidestream leads to a slightly reduction of energy demand of 4.4 % (nitritation) or 6.6 % (Anammox).

Table 20: Energy demand for aeration and stripping with percentage difference for 2-stage WWTP with 11/120

	Energy demand in kWh/PE/a				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
Energy for aeration	13.19	12.61	12.32	12.21	12.21
Energy for stripping	0	0	0	0.70	0.93
Total energy	13.19	12.61	12.32	12.91	13.14
Savings in energy	**0 %**	**- 4.4 %**	**- 6.6 %**	**- 2.1 %**	**- 0.4 %**

Lowering the bypass of organic carbon from effluent of primary settling tank to the 2nd stage results in a higher gain of biogas from digestion. The highest gas yield respectively gain of electrical energy can be achieved by SDE Anammox. The produced electrical energy is 12.7 % higher compared to WWTP without pre-treatment of SDE.

Table 21: Electric energy from biogas utilization with percentage difference for 2-stage WWTP with 11/120

	Electric energy from CHP in kWh/PE/a				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
	18.07	19.34	20.36	20.19	20.19
Gain of energy	**0 %**	**+ 7.0 %**	**+ 12.7 %**	**+11.7 %**	**+ 11.7 %**

The results of calculation regarding the energy demand for wastewater treatment with different SDE treatment options (Table 43, appendix 6.6) are graphically displayed in the following figures. Figure 23 displays the result for single-stage WWTP with mainstream treatment of SDE. In Figure 24 the overall energy demand for SDE Nitritation is shown. Figure 25 displays the required energy for the SDE Anammox option, following Figure 26 and Figure 27 for the SDE Air-stripping and membrane-stripping option. The energy demand is calculated as specific energy demand in kWh/PE/a and lies in a narrow range of 24.85 to 25.76 kWh/PE/a. The energetically most advantageous option is also in this case SDE Anammox, the most energy intensive treatment option is SDE treatment in mainstream without pre-treatment in sidestream.

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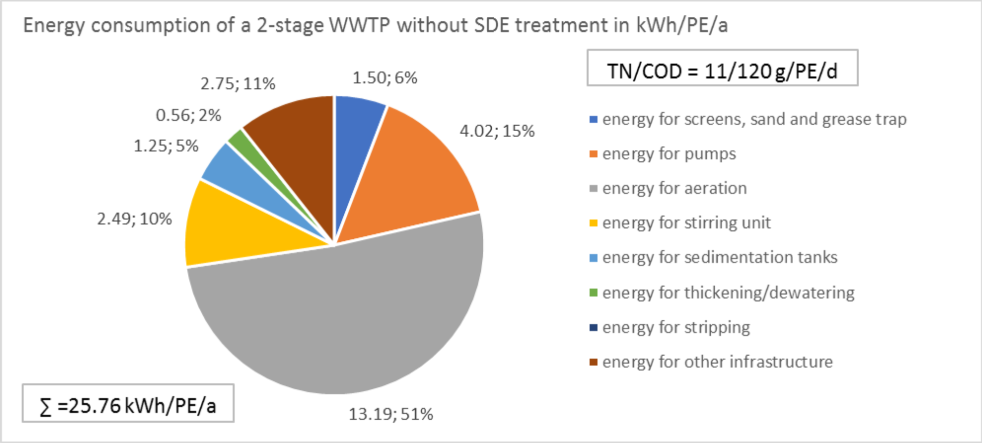

Figure 23: Energy consumption of 2-stage WWTP without SDE treatment (11/120)

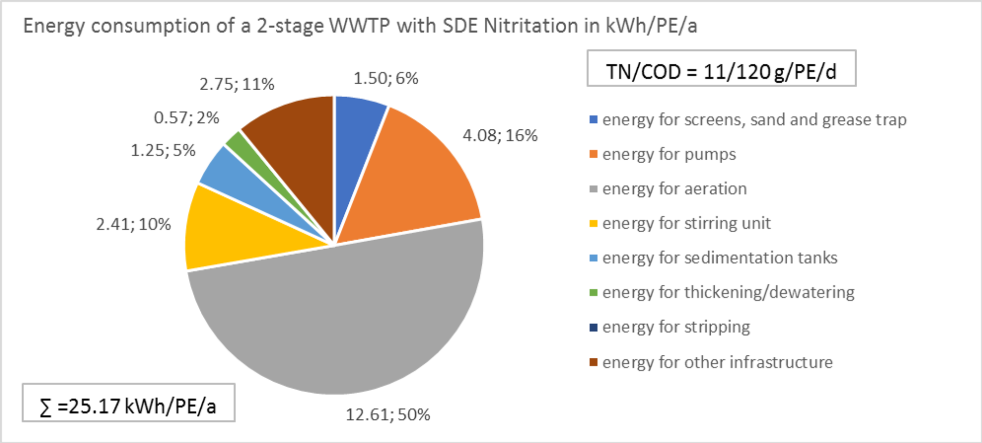

Figure 24: Energy consumption of 2-stage WWTP with SDE Nitritation (11/120)

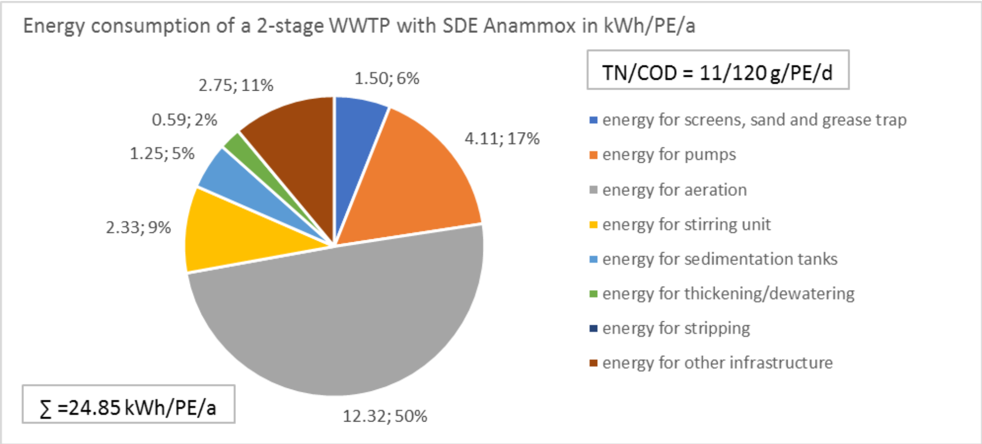

Figure 25: Energy consumption of 2-stage WWTP with SDE Anammox (11/120)

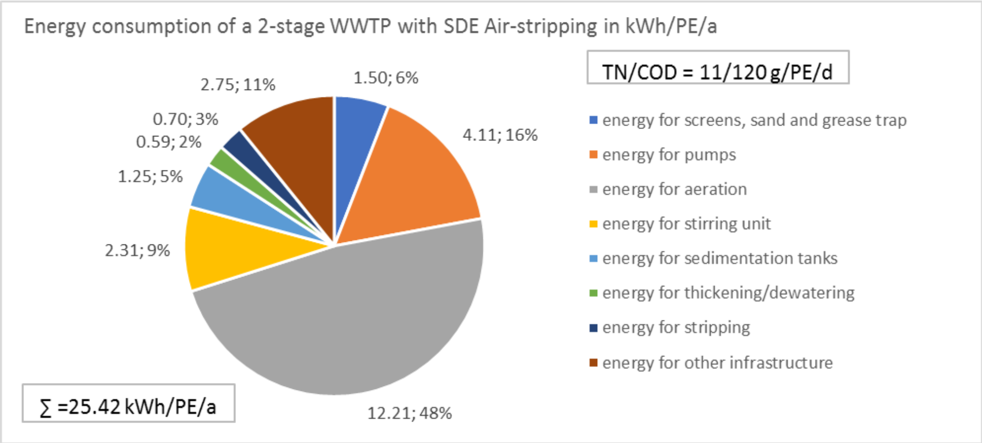

Figure 26: Energy consumption of 2-stage WWTP with SDE Air-stripping (11/120)

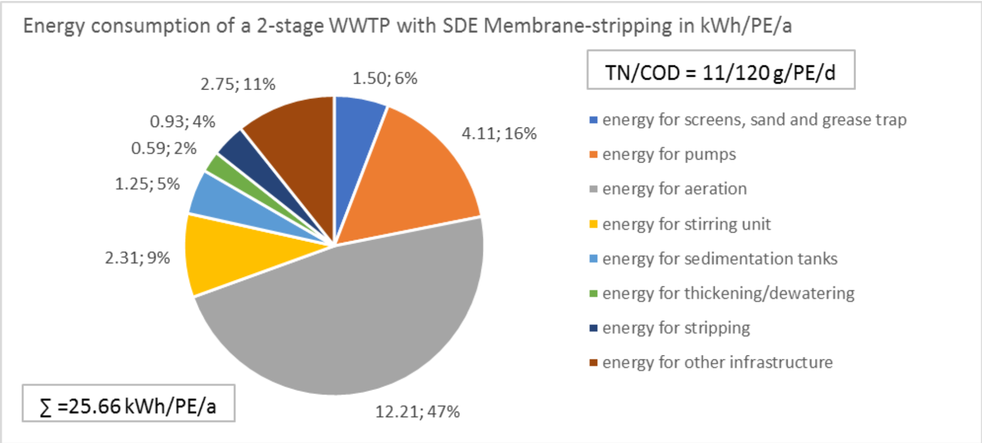

Figure 27. Energy consumption of 2-stage WWTP with SDE Membrane-stripping (11/120)

The above calculations of energy demand for wastewater treatment are based on detailed Q-, TN- and COD-balances. These balances (Table 44, Table 45, Table 46 in appendix 6.6) also provide the basis for following estimations of basin volumes (Table 47), building costs (Table 48) and subsequent running costs for operation (Table 49).

3.6. Comparison of single and 2-stage WWTP with influent TN/COD ratio of 11/120

The comparison of the overall energy demand of single-stage WWTP with an influent ratio of TN/COD = 11/120 g/PE/d shows relatively low savings in energy regarding different SDE treatment options. Without pre-treatment of SDE in sidestream the energy demand is in a range of 27.1 kWh/PE/a. Physical SDE treatment (Air-stripping and membrane-stripping) shows the same or a slightly higher energy demand (27.1 or 27.3 kWh/PE/a) due to the high energy demand for the stripping unit (0.70 or 0.93 kWh/PE/a). It is enphasized, that this calculated energy demand is valid only under the assumption, that the energy demand for heat is fully covered by the excess heat from CHP unit. Is this not the case, the energy demand for stripping is in a higher range.

The lowest energy demand is calculated for the biological treatment options (26.9 kWh/PE/a for SDE Nitritation and 26.7 kWh/PE/a for SDE Anammox).

In case of 2-stage WWTP the overall energy consumption for wastewater treatment is slightly lower. The biological SDE treatment options show also here the lowest energy demand. Compared to single-stage WWTP savings in energy due to the concept of 2-stage WWTP in a range of – 6.3 to – 7.1 % can be calculated. This is mainly due to the fact, that the high COD-loaded 1st stage produces energy-rich excess sludge and a lower proportion of COD is aerobically respired to CO_2. The SDE pre-treatment produces nitrite-rich (Nitritation) or nitrate-rich (Anammox) effluent which can be used in the anoxic zone of the 1st stage to cover partially the oxygen demand for carbon respiration (OU_C). This leads to savings in energy demand for aeration deriving from to the poor α-value in the 1st stage. The following Table 22 and Figure 28 shows the calculation results and displays the advantage of the 2-stage WWTP concept.

Table 22: Energy consumption of 1- and 2-stage WWTP with different SDE treatment options

	Total energy consumption in kWh/PE/a				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
1-stage WWTP	27.1	26.9	26.7	27.1	27.3
2-stage WWTP	25.8	25.2	24.8	25.4	25.7
	- 4.8 %	**- 6.3 %**	**- 7.1 %**	**- 6.3 %**	**- 5.9 %**

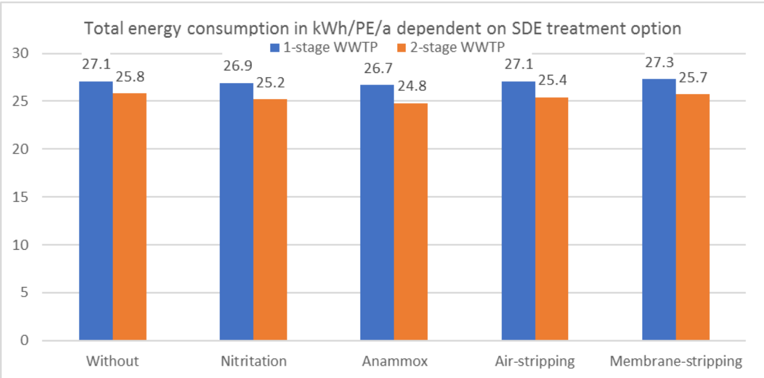

Figure 28: Energy consumption of 1- and 2-stage WWTP with different SDE treatment options

The biogas yield depends on the COD load to the digester. In case of 2-stage WWTP the COD in raw sludge is higher compared to single-stage WWTP. This is because of the very low sludge retention time in the 1st stage (about 1 d or slightly higher). The respired amount of COD is only in a range of 30 % which means, that 70% of the reduced COD can be found in the biomass (excess sludge). The proportion of respired COD is in case of single-stage WWTP higher (ca. 50 %) with corresponding lower proportion of COD in excess sludge. The respired COD in the 2nd stage of a 2-stage WWTP is higher than in AST of single-stage WWTP (ca. 65 %), which leads to lower COD in the excess sludge. The comparison of single-stage WWTP and 2-stage WWTP without SDE pre-treatment in both cases displays in Table 23 an energetical advantage of the single-stage concept. The high amount of COD bypassed to the 2nd stage (35 %) lowers the COD load to the 1st stage and leads to a overall lower biogas yield with corresponding lower gain of energy from biogas utilization. Due to pre-treatment of SDE in sidestream, the bypass is reduced mainly (20 % for SDE Nitritation, 8 % for SDE Anammox and 10 % for both SDE stripping options). This leads to a higher COD load to the 1st stage and to higher COD in raw sludge. This advantage can be seen in Table 23 and Figure 29.

The biogas yield for the 2-stage WWTP with SDE Nitritation is 6.6 % higher, with SDE stripping 11.6 % higher and with SDE Anammox 12.7 % higher compared to SDE mainstream treatment. Compared to single-stage WWTP the biogas yield or electric energy from biogas utilization is in a range of 4.9 to 10.9 % higher compared to single-stage WWTP concept.

Table 23: Electric energy from biogas utilization in CHP of single- and 2-stage WWTP with different SDE treatment options

	Electric energy from CHP in kWh/PE/a				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
1-stage WWTP	18.4	18.4	18.4	18.4	18.4
2-stage WWTP	18.1	19.3	20.4	20.2	20.2
	- 1.6 %	**+ 4.9 %**	**+ 10.9 %**	**+ 9.8 %**	**+ 9.8 %**

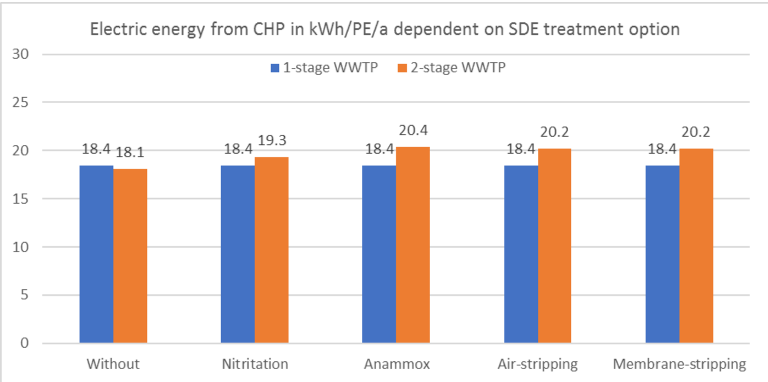

Figure 29: Electric energy from biogas utilization in CHP of single and 2-stage WWTP with different SDE treatment options

The costs for construction mainly depend on the size of the required basin volume. For single-stage WWTP the construction costs are in a range of 251.6 (without SDE treatment) to 256.1 €/PE (SDE Air-stripping), depending on the SDE treatment concept. In case of 2-stage WWTP the costs for construction are slightly lower (about 2 to 4 %) and in a range of 241.8 (SDE Anammox) to 247.4 €/PE (air-stripping), mainly due to savings in required basin volume (Table 24 and Figure 30).

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Table 24: Costs for construction of single- and 2-stage WWTP with different SDE treatment options

	Costs for construction in €/PE				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
1-stage WWTP	251.6	253.8	252.1	256.1	255.4
2-stage WWTP	246.0	244.5	241.8	247.4	246.7
	- 2.2 %	**- 3.7 %**	**- 4.1 %**	**- 3.4 %**	**- 3.4 %**

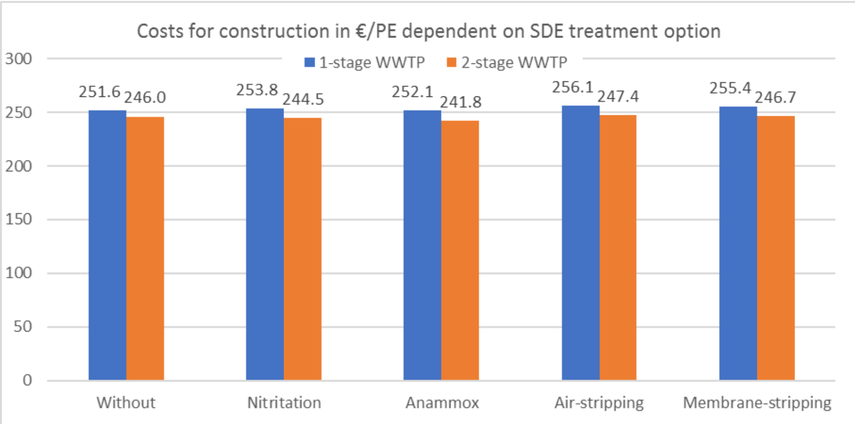

Figure 30: Costs for sonstruction of single- and 2-stage WWTP with different SDE treatment options

The calculated running costs for operation mainly depend on depreciation of construction costs, required external electrical energy and materials for operation (e.g. flocculants). These costs are almost in the same range for single-stage WWTP without SDE treatment and biological SDE treatment options (19.1 to 19.3 €/PE/a). In case of SDE stripping the running costs are in a higher level (+ 4.2 %). The comparison of different SDE treatment options at 2-stage WWTP shows the lowest running costs for biological treatment options (18.0 €/PE/a for SDE Anammox and 18.3€/PE/a for SDE Nitritation) and the highest running costs for SDE stripping options (18.9 €/PE/a). The following Table 25 and Figure 17 display these advantages for biological SDE pre-treatment and show also the advantage of the 2-stage WWTP concept () compared to single-stage WWTP concept. On the contrary, in the scenario without SDE sidestream treatment the high degree of bypass to the 2nd stage required at this higher TN influent load strongly reduces the mentioned advantages. Beside savings in energy demand and higher biogas yield the concept of 2-stage WWTP shows benefits in construction costs as well as running costs of operation.

Table 25: Running cost for operation of single- and 2-stage WWTP with different SDE treatment options

	Running costs in €/PE/a				
	Without	Nitritation	Anammox	Air-stripping	Membrane-stripping
1-stage WWTP	19.2	19.3	19.1	19.8	19.9
2-stage WWTP	18.7	18.3	18.0	18.9	18.9
	- 2.6 %	**- 5.2%**	**- 5.8 %**	**- 4.5 %**	**- 5.0 %**

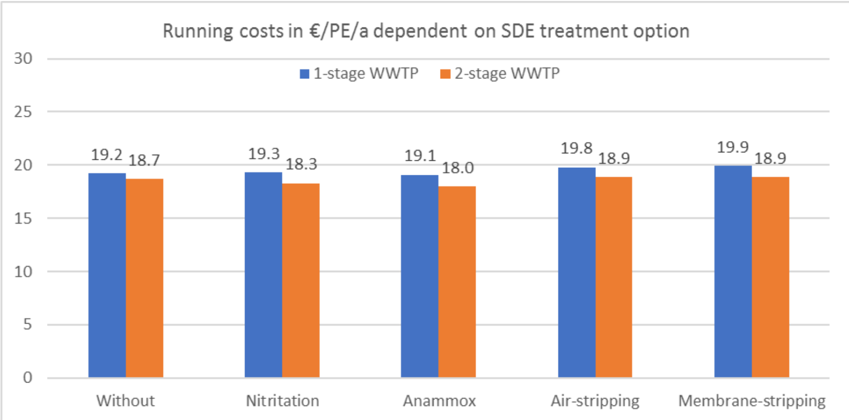

Figure 31: Running cost for operation of single- and 2-stage WWTP with different SDE treatment options

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3.7. Comparison Decision Tool against OCEAN Tool on the basis of a single-stage WWTP

The outcomes of the Decision Tool (WP4) and of the OCEAN Tool (WP5) in term of mass balances for COD and TN as well as in term of energy consumption for operation were compared on the basis of a model single-stage WWTP (500.000 PE) with diluted influent. For this purpose, the input parameters of OCEAN were implemented in the Decision Tool. The comparison shows a good agreement of the data calculated with the two different tools. Small deviations especially in the sludge COD and TN loads derives mainly from the different configuration of the sludge line. On the one end, SDE is returned to influent primary settling in OCEAN, whereas to influent activated sludge tank in Decision Tool. On the other hand COD and TN load in sludge water streams after thickening are neglected in Decision Tool. The energy consumption for infrastructure is differently split in the two models, but total results are comparable.

Input Parameter (values in green are OCEAN parameters)

Influent		
Size WWTP (120 PE)	500,000	PE
specific wastewater production	300	L/PE/d
Temperature (for dimensioning)	12	°C
COD (daily load per PE)	120	g/PE/d
TN (daily load per PE)	11	g/PE/d
P (daily load per PE)	1.8	g/PE/d
COD-removal WWTP	92.0	%
TN-removal WWTP	73.9	%
Primary Settling		
COD-removal	27.9	%
TN/COD in PS	3.2	%
TSS in PS	10.0	g/L
COD/VSS in PS	1.54	-
Activated sludge tank		
TSS	3.67	g/L
Percentage of respired COD	58.9	%
COD/VSS in SAS	1.4	-
Ignition loss SAS	64.8	%
DO	1.5	mg/L
SAE aeration system in clear water	4.27	kgO_2/kWh
a-value	0.55	-
Sludge return ratio RV	1.00	-
TN/COD in SAS	5.33	%
Stirring energy activated sludge tank	1.5	W/m^3
Anaerobic sludge stabilisation		
COD digested sludge (DS)	31.6	g/PE/d
Ignition loss DS	48.7	%
COD/VSS in DS	1.58	-
TSS raw sludge	51.2	g/L
TSS dewatered sludge	250	g/L
$N_{released}/COD_{converted\ to\ biogas}$	2.93	%

Stirring energy digester	7.00	W/m³
Circulation (pumps) of digester volume	1.00	1/d
Efficiency of CHP unit (electricity)	42.00	%
Energy demand mechanical thi-ckening	30.00	Wh/m³
Polymer dosage mechanical thi-ckening	4.8	gAS/kgTS
Energy demand dewatering	2.2	kWh/m³
Polymer dosage dewatering	10.0	gAS/kgTS
CH_4 burned	99.0	%
Pumps		
Pump work	9.81	Ws/L/m
Efficiency of the pumps	62	%
Δh for pumps inflow WWTP	0.0	m
Δh return sludge (RS)	3.0	m
Δh for digester circulation and heating	3	m

Flow-balance

Decision Tool					OCEAN	
Q inflow primary sedimentation	300	L/PE/d	150,000	m³/d	150,000	m³/d
Q PS	3.0	L/PE/d	1,525	m³/d	1,610	m³/d
Q outflow primary sedimentation	297	L/PE/d	148,475	m³/d		
Q SAS	4.8	L/PE/d	2,376	m³/d	2,430	m³/d
Q sludge to thickener	7.8	L/PE/d	3,901	m³/d		
Q raw sludge	1.3	L/PE/d	638	m³/d	635	m³/d
Q outflow digester	1.3	L/PE/d	638	m³/d	623	m³/d
Q digested sludge dewatered	0.2	L/PE/d	82	m³/d	78	m³/d
Q SDE	1.1	L/PE/d	556	m³/d	681	m³/d
Q inflow activated slduge tank	305	L/PE/d	152,294	m³/d		
Q RS	305	L/PE/d	152,294	m³/d		
Q internal recirculation (RV)	368	L/PE/d	184,233	m³/d		
Q inflow + RS + RV	978	L/PE/d	488,822	m³/d		
Q inflow secondary clarifier	609	L/PE/d	304,589	m³/d		
Q outflow secondary clarifier	300	L/PE/d	149,918	m³/d		
Q outflow WWTP	300	L/PE/d	149,918	m³/d	150,104	m³/d

COD-balance

Decision Tool					OCEAN	
COD inflow primary sedimentation	120	g/PE/d	60,000	kg/d	61,277	kg/d
COD PS	33.5	g/PE/d	16,740	kg/d	17,096	kg/d
COD outflow primary sedimentation	86.5	g/PE/d	43,260	kg/d	44,181	kg/d
COD inflow activated sludge tank	86.5	g/PE/d	43,260	kg/d	44,181	kg/d
COD SAS	31.6	g/PE/d	15,808	kg/d	16,186	kg/d
COD raw sludge to digestion	65.1	g/PE/d	32,547	kg/d	33,402	kg/d
COD digested sludge	31.6	g/PE/d	15,798	kg/d	15,798	kg/d
COD SDE	0.0	g/PE/d	0	kg/d	1,397	kg/d
COD Biogas	33.5	g/PE/d	16,749	kg/d	17,604	kg/d

OUC activated sludge tank	45.3	g/PE/d	22,645	kg/d	23,187	kg/d
OUDN activated sludge tank	18.2	g/PE/d	9,079	kg/d	9,586	kg/d
OUDN/OUC	0.40					
COD outflow WWTP	9.6	g/PE/d	4,808	kg/d	4,808	kg/d

TN-balance

Deciosion Tool					OCEAN	
TN inflow primary sedimentation	11	g/PE/d	5,500	kg/d	5,500	kg/d
TN PS	1.1	g/PE/d	537	kg/d	548	kg/d
TN outflow primary sedimentation	9.9	g/PE/d	4,963	kg/d	5,634	kg/d
TN inflow activated sludge tank incl. SDE	10.9	g/PE/d	5,454	kg/d	5,634	kg/d
TN SAS	1.7	g/PE/d	843	kg/d	846	kg/d
TN raw sludge	2.8	g/PE/d	1,380	kg/d	1,394	kg/d
TN raw sludge after thickening (in OCEAN)	2.8	g/PE/d	1,380	kg/d	1,238	kg/d
TN SDE	1.0	g/PE/d	491	kg/d	526	kg/d
TN digested sludge	1.8	g/PE/d	889	kg/d	649	kg/d
TN denitrified activated sludge tank	6.3	g/PE/d	3,175	kg/d	3,352	kg/d
TN outflow WWTP	2.9	g/PE/d	1,437	kg/d	1,437	kg/d
O_2 demand for NH_4 oxidation (OU_N)	39.9	g/PE/d	19,966	kg/d	20,355	kg/d

TSS-balance

Decision Tool					OCEAN	
TSS PS	30.5	g/PE/d	15,248	kg/d	16,097	kg/d
VSS PS	21.8	g/PE/d	10,876	kg/d	11,107	kg/d
ASS PS	8.7	g/PE/d	4,373	kg/d	4,990	kg/d
Ignition Loss			71.3%		69.0%	
TSS SAS	34.9	g/PE/d	17,442	kg/d	17,859	kg/d
VSS SAS	22.6	g/PE/d	11,308	kg/d	11,578	kg/d
ASS SAS	12.3	g/PE/d	6,134	kg/d	6,281	kg/d
Ignition loss			64.8%		64.8%	
TSS raw sludge	65.4	g/PE/d	32,690	kg/d	32,503	kg/d
VSS raw sludge	44.4	g/PE/d	22,183	kg/d	21,995	kg/d
ASS raw sludge	21.0	g/PE/d	10,507	kg/d	10,508	kg/d
Ignition loss raw sludge			67.9%		67.7%	
TSS digested sludge	41.0	g/EW/d	20,478	kg/d	20,478	kg/d
VSS digested sludge	19.9	g/PE/d	9,970	kg/d	9,970	kg/d
ASS digested sludge	21.0	g/PE/d	10,507	kg/d	10,507	kg/d
Ignition Loss			48.7%		48.7%	
VSS degradation digestor			55.1%		54.7%	
COD degradation digestor			51.5%		52.7%	

Chemicals consumption

Decision Tool					OCEAN	
Polymer dosage thickening (PS + SAS)	0.31	gWS/PE/d	157	kgWS/d	86	kgWS/d
Polymer demand dewatering	0.41	gWS/PE/d	205	kgWS/d	205	kgWS/d
$FeCL_3$	3.09	gWS/PE/d	1,547	kgWS/d	1,386	kg/d

Energy demand in operation

Decision Tool					OCEAN	
Energy for aeration activated sludge tank	33.5	Wh/PE/d	16,729	kWh/d	15,749	kWh/d
Energy for stirring unit activated sludge tank	3.8	Wh/PE/d	1,884	kWh/d		
Energy for pumps return sludge	4.0	Wh/PE/d	2,008	kWh/d		
Energy for secondary sedimentation	1.7	Wh/PE/d	855	kWh/d		
Total energy demand AST	**43.0**	**Wh/PE/d**	**21,476**	**kWh/d**	**22,107**	**kWh/d**
Energy for stirring unit in digesters	5.4	Wh/PE/d	2,681	kWh/d		
Energy for pumps digester recirculation	0.4	Wh/PE/d	210	kWh/d		
Total energy sludge digestion	**5.8**	**Wh/PE/d**	**2,891**	**kWh/d**	**2,721**	**kWh/d**
Energy for thickening PS and SAS	0.2	Wh/PE/d	117	kWh/d	615	kWh/d
Energy for digested sludge dewatering	2.8	Wh/PE/d	1,404	kWh/d	1,491	kWh/d
Energy for screens*	1.0	Wh/PE/d	514	kWh/d	411	kWh/d
Energy for sand and grease trap*	1.0	Wh/PE/d	514	kWh/d	481	kWh/d
Energy for primary sedimentation	0.9	Wh/PE/d	428	kWh/d	591	kWh/d
Energy for heating*	3.4	Wh/PE/d	1,712	kWh/d		
Energy for other infrastructure*	4.1	Wh/PE/d	2,055	kWh/d		
Biological odor treatment OCEAN					1,477	kWh/d
Lighting + service water + power losses OCEAN					1,264	kWh/d
Total energy demand WWTP	**62.2**	**Wh/PE/d**	**31,111**	**kWh/d**	**31,157**	**kWh/d**
Total energy gain WWTP	**48.7**	**Wh/PE/d**	**24,375**	**kWh/d**	**24,328**	**kWh/d**
Energy gain/ Energy demand	**0.78**				**0.78**	
Total energy demand WWTP	**22.7**	**Wh/PE/a**			**22.7**	**kWh/PE/a**
Total energy gain WWTP	**17.8**	**Wh/PE/a**			**17.8**	**kWh/PE/a**

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3.8. Calculation results of CO_2-balances

The results of the CO_2-balances based on the assumption of Chapter 2.4 are depicted in the following figures and tables. The calculation was done for all four options single and two stage WWTP as well as influent N/COD of 8/120 and 11/120. Regardless of the scenario, CO_2-balances indicate that the expected main emission sources are the direct N_2O emission of the biological wastewater treatment (main stream/sidestream) and the indirect CO_2 emission of electricity consumption.

The high TN-removal degree of the WWTPs (80%) considerably reduces direct N_2O-emission as compared to other WWTPs with poor TN-removal. Since the N-removal degree was kept constant in all the scenari-os, the emission factor applied for calculation in mainstream is the same. Differencies in the specific N_2O-emissions derive from the varying TN load treated in the activated sludge tank in each scenario, e.g. WWTPs with higher influent TN-load (N/COD=11/120) results in higher specific N_2O-emissions.

N_2O-emissions from sidestream nitritation and anammox are also considerable, the latter being less intensive due to the assumed lower emission factor. N_2O-emissions in sidestream are expected to be higher in the two-stage configuration due to the higher TN-load of the SDE (higher sludge loading to the digester and higher oTS-degradation in the anaerobic digestion). This additional N_2O-emission affect the total netto CO_2-balance of WWTP applying biological SDE sidestream treatment, especially nitritation. In the two-stage configuration, this can be partly counterbalanced by the higher biogas production and lower electricity demand for aeration achievable applying SDE sidestream treatment. The application of alternative aeration technologies (e.g. membrane aerated biofilm reactors) or aeration with pure oxygen could help reducing N_2O-emission through stripping during sidestream nitritation or anammox. Covered SDE treatment tanks and abtmentment of N_2O in the offgas (e.g. combusting air in CHP) would also be a viable option. The calculation of the CO_2e-emissions was peformed under the assumption that the TN-removal efficiency in all the scenarios is 80%. In case the TN-removal at a WWTP is limited by the availability of COD and can be improved by applying nitritration or anammox in sidestream, significantly lower direct N_2O emissions are expected in the AST. Under these operating conditions the carbon footprint of the WWTP can be improved leading to lower CO_2e-emissions comparared to the scenario without side-treatment.

Both air and membrane stripping can improve the CO_2-balance of the plant. Additional indirect CO_2-emissions resulting from higher electricity consumption and chemical consumption are - under the assumption made - lower than the achievable reduction of CO_2-emission in the biological wastewater treatment (lower N-load to be nitrifyed). CO_2-credits of fertiliser are not as relevant as biogas credits. The outcome of the CO_2-balance can be different in case the heat demand for the stripping process cannot be covered by the surplus energy of CHP.

The outcome of the CO_2e-balances is in line with the estimations given within the LCA in WP5. The resulting COe-emissions are somewhat lower in the Decision Tool because CO_2e-emissions of sludge disposal (transport and inceneration) as well as of the infrastructure (building of the WWTP) are not included in the CO_2e-balance, having no impact on the comparision of the different SDE sidestream treatment options.

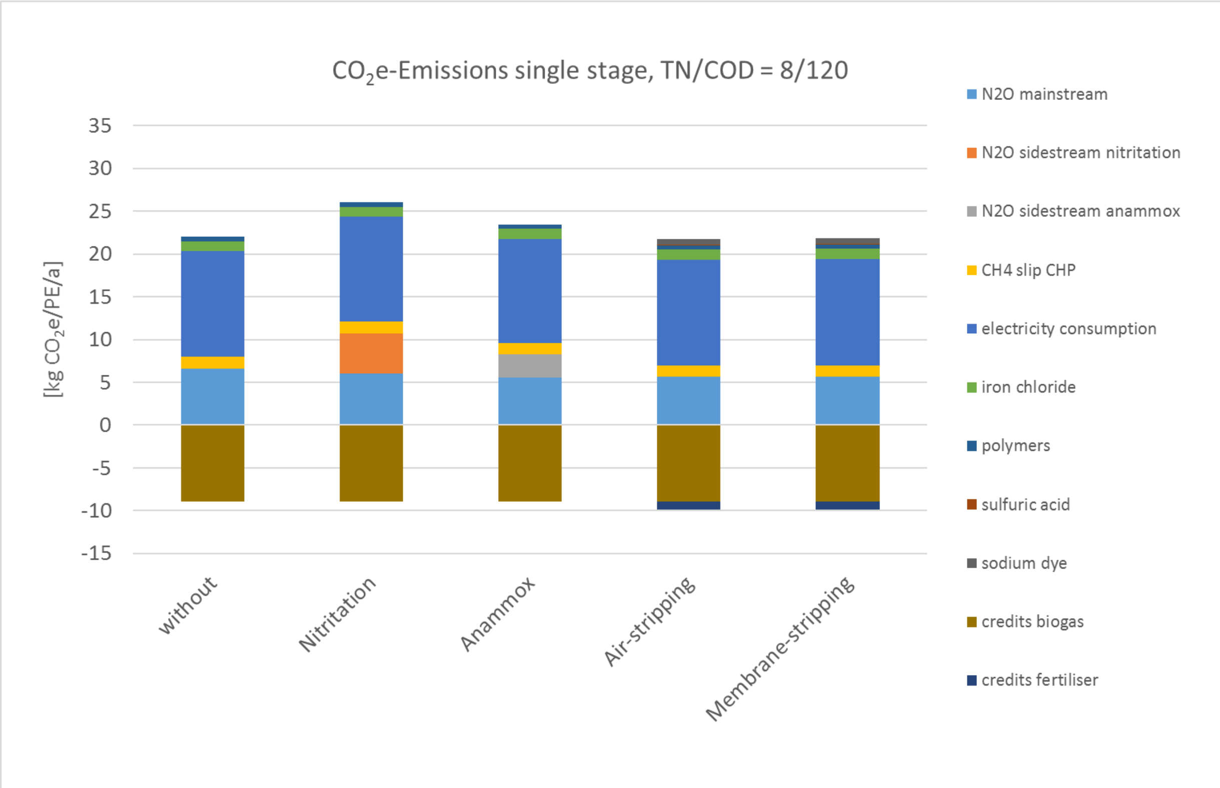

Figure 32: CO_2e-balance of the WWTP single-stage with influent TN/COD = 8/120 and different SDE sidestream treatment options.

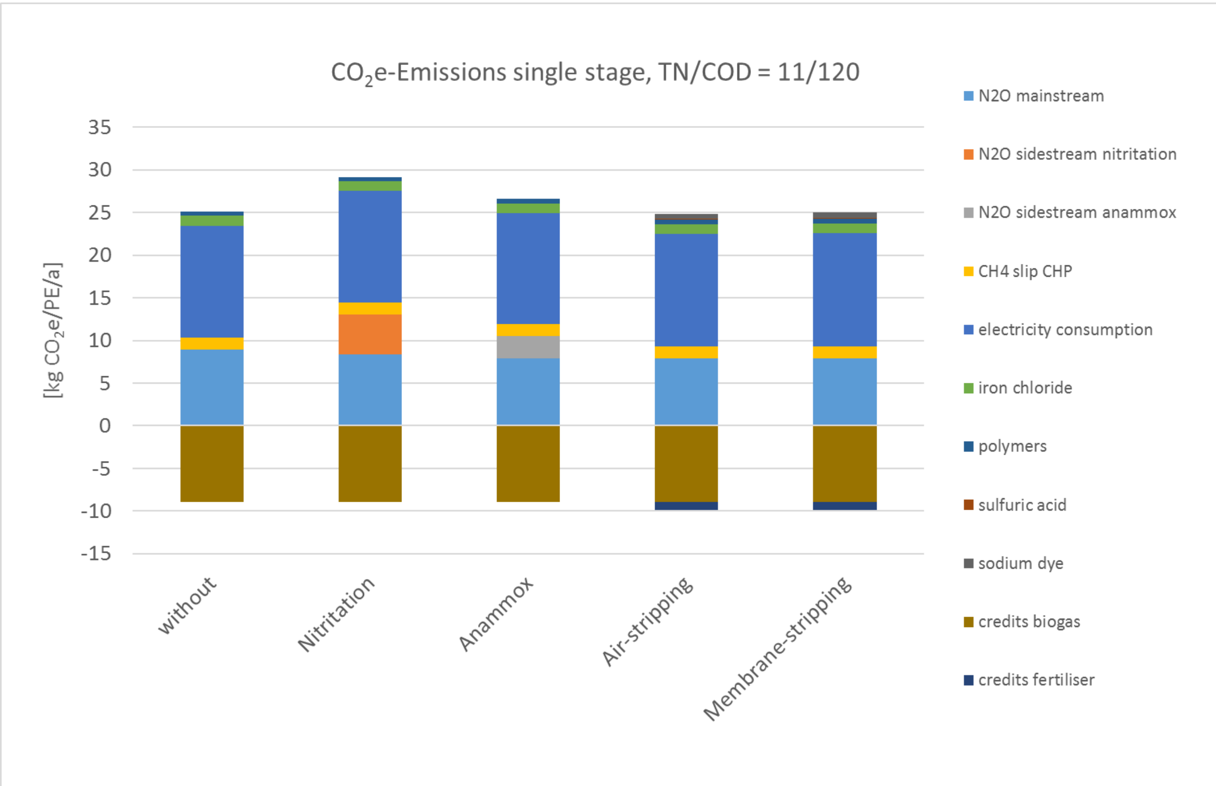

Figure 33: CO_2e-balance of the WWTP single-stage with influent TN/COD = 11/120 and different SDE sidestream treatment options.

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single-stage WWTP with influent N/COD = 8/120	SDE sidestreamt treatment concept without	Nitritation	Anammox	Air-stripping	Membrane-stripping	Unit
CO_2e emissions						
N_2O main stream	6.6	6.0	5.5	5.6	5.6	[kg CO2e/PE/a]
N_2O side stream Nitritation	-	4.7	-	-	-	[kg CO2e/PE/a]
N_2O side stream Anammox	-	-	2.7	-	-	[kg CO2e/PE/a]
CH_4, BHWK slip	1.39	1.39	1.39	1.39	1.39	[kg CO2e/PE/a]
Electricity consumption	12.3	12.24	12.12	12.32	12.42	[kg CO2e/PE/a]
Iron chloride	1.16	1.16	1.16	1.16	1.16	[kg CO2e/PE/a]
Polymers	0.50	0.50	0.50	0.50	0.50	[kg CO2e/PE/a]
Sulfuric acid	-	-	-	0.10	0.10	[kg CO2e/PE/a]
Sodium dye	-	-	-	0.64	0.64	[kg CO2e/PE/a]
CO_2e credits						
Electricity biogas	8.91	8.91	8.91	8.91	8.91	[kg CO2e/PE/a]
Fertiliser $(NH4)2SO_4$	-	-	-	0.95	0.95	[kg CO2e/PE/a]
Total CO_2e emissions	**22.0**	**26.0**	**23.4**	**21.7**	**21.8**	**[kg CO2e/PE/a]**
Total CO_2e credits	**8.9**	**8.9**	**8.9**	**9.9**	**9.9**	**[kg CO2e/PE/a]**
Netto CO_2e emissions	**13.1**	**17.1**	**14.5**	**11.9**	**12.0**	**[kg CO2e/PE/a]**

single-stage WWTP with influent N/COD = 11/120	SDE sidestreamt treatment concept without	Nitritation	Anam-mox	Air-stripping	Membrane-stripping	Unit
CO_2e emissions						
N_2O main stream	8.9	8.3	7.9	7.9	7.9	[kg CO2e/PE/a]
N_2O side stream Nitritation	-	4.7	-	-	-	[kg CO2e/PE/a]
N_2O side stream Anammox	-	-	2.7	-	-	[kg CO2e/PE/a]
CH_4, BHWK slip	1.39	1.39	1.39	1.39	1.39	[kg CO2e/PE/a]
Electricity consumption	13.1	13.04	12.94	13.14	13.24	[kg CO2e/PE/a]
Iron chloride	1.16	1.16	1.16	1.16	1.16	[kg CO2e/PE/a]
Polymers	0.50	0.50	0.50	0.50	0.50	[kg CO2e/PE/a]
Sulfuric acid	-	-	-	0.10	0.10	[kg CO2e/PE/a]
Sodium dye	-	-	-	0.64	0.64	[kg CO2e/PE/a]
CO_2e credits						
Electricity biogas	8.91	8.91	8.91	8.91	8.91	[kg CO2e/PE/a]
Fertiliser $(NH_4)_2SO_4$	-	-	-	0.95	0.95	[kg CO2e/PE/a]
Total CO_2e emissions	**25.1**	**29.2**	**26.6**	**24.9**	**25.0**	**[kg CO2e/PE/a]**
Total CO_2e credits	**8.9**	**8.9**	**8.9**	**9.9**	**9.9**	**[kg CO2e/PE/a]**
Netto CO_2e emissions	**16.2**	**20.3**	**17.7**	**15.0**	**15.1**	**[kg CO2e/PE/a]**

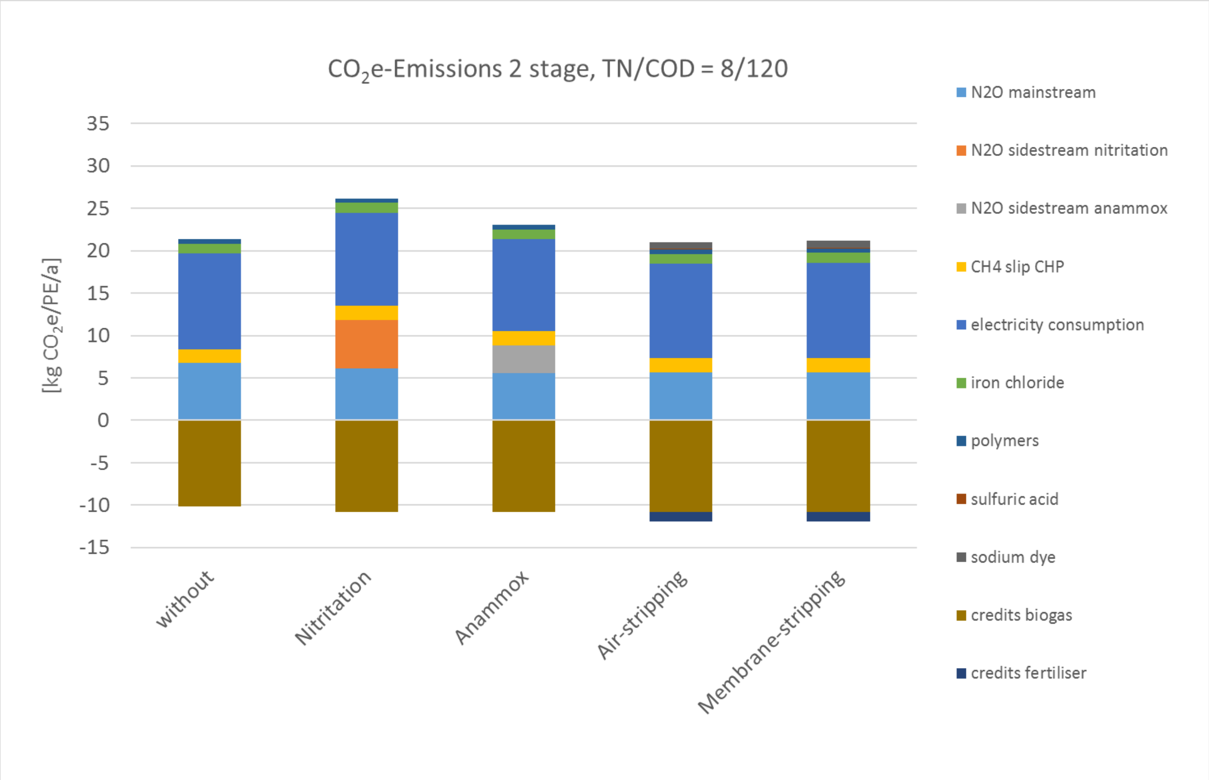

Figure 34: CO_2e-balance of the WWTP 2-stage with influent TN/COD = 8/120 and different SDE sidestream treatment options.

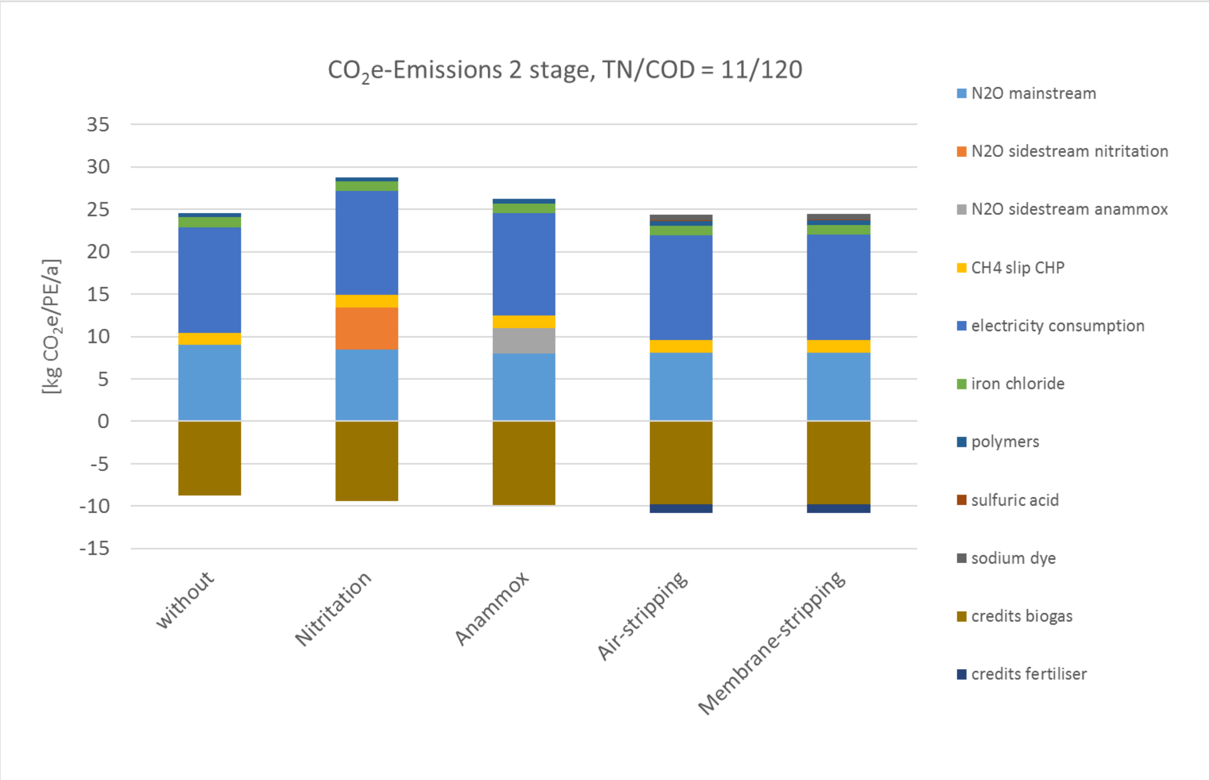

Figure 35: CO_2e-balance of the WWTP 2-stage with influent TN/COD = 11/120 and different SDE sidestream treatment options.

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2-stage WWTP with influent N/COD of 8/120	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
CO_2e emissions						
N_2O main stream	6.8	6.1	5.5	5.6	5.6	[kg CO2e/PE/a]
N_2O side stream Nitritation	-	5.7	-	-	-	[kg CO2e/PE/a]
N_2O side stream Anammox	-	-	3.3	-	-	[kg CO2e/PE/a]
CH_4, BHWK slip	1.58	1.68	1.68	1.68	1.68	[kg CO2e/PE/a]
Electricity consumption	11.3	10.96	10.85	11.14	11.26	[kg CO2e/PE/a]
Iron chloride	1.16	1.16	1.16	1.16	1.16	[kg CO2e/PE/a]
Polymers	0.51	0.51	0.51	0.51	0.51	[kg CO2e/PE/a]
Sulfuric acid	-	-	-	0.12	0.12	[kg CO2e/PE/a]
Sodium dye	-	-	-	0.77	0.77	[kg CO2e/PE/a]
CO_2e credits						
Electricity biogas	10.1	10.8	10.8	10.8	10.8	[kg CO2e/PE/a]
Fertiliser $(NH_4)_2SO_4$	-	-	-	1.14	1.14	[kg CO2e/PE/a]
Total CO_2e emissions	**21.3**	**26.1**	**23.0**	**21.0**	**21.2**	**[kg CO2e/PE/a]**
Total CO_2e credits	**10.1**	**10.8**	**10.8**	**11.9**	**11.9**	**[kg CO2e/PE/a]**
Netto CO_2e emissions	**11.2**	**15.4**	**12.2**	**9.1**	**9.2**	**[kg CO2e/PE/a]**

2-stage WWTP with influent N/COD of 11/120	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
CO_2e emissions						
N_2O main stream	9.0	8.5	8.0	8.1	8.1	[kg CO2e/PE/a]
N_2O side stream Nitritation	-	5.0	-	-	-	[kg CO2e/PE/a]
N_2O side stream Anammox	-	-	3.0	-	-	[kg CO2e/PE/a]
CH_4, BHWK slip	1.37	1.47	1.54	1.53	1.53	[kg CO2e/PE/a]
Electricity consumption	12.5	12.21	12.05	12.33	12.44	[kg CO2e/PE/a]
Iron chloride	1.14	1.14	1.14	1.14	1.14	[kg CO2e/PE/a]
Polymers	0.50	0.50	0.51	0.51	0.51	[kg CO2e/PE/a]
Sulfuric acid	-	-	-	0.11	0.11	[kg CO2e/PE/a]
Sodium dye	-	-	-	0.70	0.70	[kg CO2e/PE/a]
CO_2e credits						
Electricity biogas	8.8	9.4	9.9	9.8	9.8	[kg CO2e/PE/a]
Fertiliser $(NH_4)_2SO_4$	-	-	-	1.04	1.04	[kg CO2e/PE/a]
Total CO_2e emissions	**24.5**	**28.8**	**26.2**	**24.4**	**24.5**	**[kg CO2e/PE/a]**
Total CO_2e credits	**8.8**	**9.4**	**9.9**	**10.8**	**10.8**	**[kg CO2e/PE/a]**
Netto CO_2e emissions	**15.8**	**19.4**	**16.3**	**13.5**	**13.7**	**[kg CO2e/PE/a]**

4. Summary and Conclusions

The comparison of 1single and 2-stage WWTPs shows in all considered scenarios a lower energy consumption for wastewater treatment with a 2-stage WWTP. In addition the biogas yield and corresponding gain of energy from biogas utilization in a CHP unit is higher. The reason for this energetic advantage is the concept of this 2-stage process with a high COD-loaded 1st treatment stage, which reflects the basic idea of the PowerStep concept.

At single-stage WWTPs with an influent load of 120 gCOD/PE/d approximately 36 gCOD/PE/d are removed as primary sludge and transfered to the anaerobic stabilization. The remaining 84 gCOD/PE/d must be removed in the AST. The removed COD is partially respired (about 55 %) and bound into biomass (35.1 gCOD/PE/d). Beside primary sludge, only the degradable COD in the biomass serves as energy source during anaerobic stabilization. The amount of COD that must be anaerobically stabilized equates to 71.1 gCOD/PE/d. The 1st stage of a 2-stage WWTP is highly loaded with COD and characterized by a low sludge retention time (about 1 d), resulting in a correspondingly high sludge production. The proportion of respired COD in the 1st stage is in the range of about 30 % of the removed COD, whereby the COD in the produced sludge is correspondingly high (32.8 gCOD/PE/d). The proportion of respired COD in the 2nd stage is considerably higher (65 %) than in the 1st stage of a 2-stage WWTP or the AST of a single-stage WWTP. This results in a lower amount of COD in the excess sludge (10.9 gCOD/PE/d). The amount of COD for anaerobic stabilization equates to 79.7 gCOD/PE/d, which is 8.6 gCOD/PE/d higher compared to single-stage WWTP. This leads to a higher biogas yield and a higher gain of energy from biogas utilization.

A higher proportion of COD in biomass also means that less COD is degraded aerobically in the AST. The total oxygen demand for carbon removal (OU_C) is calculated to 42.9 gO_2/PE/d for single-stage WWTP and to 34.3 gO_2/PE/d for 2-stage WWTP. The oxygen demand for the oxidation of nitrogen decreases as the amount of COD in the biomass increases. This leads to the fact that in single-stage WWTP a higher demand of oxygen for oxidation of nitrogen is necessary (27.9 gO_2/PE/d) compared to 2-stage WWTP (26.9 gO_2/PE/d). Therefore, the overall oxygen demand for wastewater treatment at single-stage WWTP is 14 % higher compared to 2-stage WWTP.

The comparison of the calculated single and 2-stage WWTP confirms these energetic advantages of the 2-stage WWTP. Depending on the SDE treatment option the comparison of the calculations presented in chapter 3.3 show, that 2-stage WWTP can be expected to need about 10 % less electrical energy. The electrical energy from biogas utilization is about 20 % higher than in case of single-stage WWTP. The construction costs for 2-stage WWTP are about 3 % below the costs for a single-stage WWTP and the operating costs in a range of 5 to 8 % according to the SDE treatment option.

While the concept of 2-stage WWTP shows clear advantages with influent composition of TN/COD = 8/120 regarding energy demand, gain of energy, construction costs and running costs, these benfits are not noticeable to this extent in case of higher nitrogen influent load. The main reason is the concept of the 2-stage WWTP with high COD-removal of the AST 1st stage. This implies an appropriate COD influent load and the desired goal of reducing COD before nitrification and denitrification in the 2nd stage. It

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is important to provide sufficient COD for denitrification. If the TN/COD ratio is unfavorable, the removed COD in 1st stage leads to a lack of organic carbon for denitrification in the 2nd stage. There are mainly two options (bypass or nitrate recirculation) to solve this problem. If an appropriate amount of COD is dosed via bypass to the anoxic zone of the 2nd stage, the COD load to the 1st stage decreases with the consequence of lower sludge production and thus also a lower energy content in the excess sludge. This results in a lower biogas yield and a lower energy gain from biogas utilization. The second option is to charge back an appropriate amount of nitrate from WWTP effluent to the anoxic zone of the 1st stage using the largely unused denitrification capacity of the high COD loaded AST. For this measure a large volume of water must be pumped back to the 1st stage, leading to correspondingly high energy costs. As shown in chapter 3.6, for an influent ratio of TN/COD = 11/120 the advantage of a 2-stage WWTP is comparingly lower. Nevertheless, the 2-stage WWTP is even in the case of a high nitrogen load advantageous compared to single-stage WWTP concepts concerning energy demand (approx. - 6 %), energy gain from biogas utilization (+ 5 to + 10 %), construction costs (- 3 %) and operating costs (- 5 %).

The SDE treatment option influences the energy balance of the WWTP. Therefore, the whole WWTP must be considered for evaluation of the most advantageous SDE treatment option. Comparison of the different SDE treatment options has shown, that especially at single-stage WWTP (chapter 3.1.2) a rather small impact on energy and costs can be expected. The total required energy for the WWTP varies in a range of 25.0 to 25.6 kWh/PE/a. Achievable savings in energy regarding the energetically most favorable process of SDE treatment (Anammox) and the energetically most unfavorable treatment option (Membrane-stripping) are only 2.4 %. Even the operating costs including depreciation of construction costs show only a small cost advantage for Anammox of about 3.8 % compared to Membrane-stripping. The calculation of a single-stage WWTP with higher nitrogen influent load shows very similar results (chapter 3.4.2). The most energy-efficient SDE treatment option is also Anammox, however, the energy demand for the energetically most unfavorable treatment option (Membrane-stripping) is only 2.2 % higher. There is also only a small difference (4.2 %) regarding the operating costs between the cheapest (Anammox) and the most expensive (Membrane-stripping) treatment option. For the concept of single-stage WWTP the energy demand as well as the operating costs for the different SDE treatment options are almost equivalent.

Even at 2-stage WWTP a similar result is calculated (chapter 3.2.2). The most energy-efficient SDE treatment option is also Anammox, however, the energy demand for the energetically most unfavorable treatment option (Membrane-stripping) is only 3.6 % higher. Regarding the operating costs the most expensive treatment (Membrane-stripping) is 5.3 % more expensive than the cheapest SDE treatment options (Nitritation and Anammox). With higher nitrogen load (chapter 3.5.2) the advantage in energy demand (Anammox vs. Membrane-stripping) results to – 3.5 %. The operating costs for Membrane-stripping are 5 % higher than the operating costs for Anammox.

Additional costs for the different SDE treatment options could not be considerd in these comparisons. Beside costs for energy and operating costs (mainly depreciation, operating materials such as flocculants) other operating costs result from e. g.

additional maintenance, price fluctuations of chemicals, durability of measurement systems and probes, costs for highly qualified personnel, etc.

SDE Nitritation: The additional costs for SDE nitritation are manageable. For the control of the aeration system it is sufficient to use a pH probe. The pH value to be measured is in a range of 7.0 to 7.5. Experiences from full-scale Nitritation at WWTP Kirchbichl have shown, that even a failure of the aeration system over several days with correspondingly high ammonium concentrations (up to 1,400 mg/L) and a high pH value of 8.5 (due to high ammonia concentration) in the SDE treatment tank results in no irreversible damage of bacteria. Also long term temperature fluctuations in a range of 15 to 39 °C (tested in lab-scale) lead to no problems with nitritaion process. A disturbance of the nitritation process was not determined during the entire testing phase in full-scale. Therefore, it can be assumed that no relevant additional costs for the operation of nitritation must be expected.

SDE Anammox: The operation of a SDE Anammox treatment is more challenging. It is reported in literature (e.g. Lackner *et al*., 2014) that the Anammox process is prone to interferences, which inevitably requires a high level of maintenance and thus additional costs. Even in case of operation without any disturbances higher costs due to the accuracy of the measurement (control of the Anammox process in a very narrow pH range) and the corresponding calibration and technical requirements for the probes can be expected. Specially qualified and trained personnel can additionally increase the operating costs.

SDE Stripping: For calculating the costs for stripping, several assumptions were made. Some of these assumptions can increase the costs for this treatment option significantly. The high demand for chemicals and strong fluctuation in prizes are unpredictable costs factors. It is also assumed, that the resulting procuct from stripping can be sold as a nitrogen fertilizer (1 €/kgN). This assumption strongly depends on whether this sales market is available, and the product can be sold at this price. It was further assumed that the excess heat from the CHP unit is sufficient to cover the heat demand for stripping. If this is not the case for example due to lower biogas yield or higher electrical efficiency of the CHP unit, external energy must be supplied with corresponding negatively impact of operating costs. I also has to be mentioned, that specially trained and qualified personnel must be provided for operation due to the complexity of the system. This will further increase the personnel costs.

Concerning all these uncertainties of operation and the fact, that SDE Nitritation is nearly energetically equivalent to SDE Anammox, Nitritation is more stable and most probably the less costly solution. Compared to a 2-stage WWTP without pre-treatment of SDE, the SDE Nitritation in sidestream leads to savings in energy demand of 5.6 % and to a higher gain of energy from biogas utilization in a CHP unit of 6.4 %. The construction costs of a 2-stage WWTP with SDE Nitritation is slightly cheaper (- 0.6 %) compared to SDE treatment in mainstream. Additinally, the operating costs are in a lower range (- 2.3 %). Thus, the SDE Nitritation in sidestream leads beside savings in energy to savings in costs.

The results of the CO_2-balance show, that, with the assumptions made, the biological SDE treatment options produce additional N_2O emissions in the sidestream, which negatively influence the CO_2 footprint of the WWTP. The nitritation produces higher emissions compared to the Anammox process. In case of 2-stage WWTP, the higher N_2O emissions can be partially compensated by both, the higher biogas yield from anaerobic digestion and the lower energy demand for aeration. Innovative technical solutions (e.g. bubble-free aeration or treatment of N_2O-rich off-gas) may contribute to improve the CO_2 footprint of WWTP with biological SDE pre-treatment (especially in case of nitritation). If the biological TN-removal in mainstream is limited by the availability of COD and can be improved by applying nitritration or anammox in sidestream, the carbon footprint of the WWTP can be improved leading to lower or comparable CO_2e-emissions referred to the scenario without side-treatment.

With the assumptions made, the physical SDE treatment options (stripping) lead to a significant reduction of CO_2 emissions of the WWTP. These assumptions depend on many boundary conditions (e. g. sufficient excess heat from CHP unit) and can therefore vary. It must be emphasized, that the CO_2 footprint is not an appropriate basis of decision-making in the field of urban water management. Thus, this aspect is supplemented in WP5 by an ecological assessment (LCA) for selected SDE pre-treatment options in sidestream.

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6. Appendix

6.1. Calculation of a 2-stage WWTP with TN/COD = 8/120

Table 26: Assumptions for calculation of 2-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Influent						
Size WWTP (120 PE)	100,000	100,000	100,000	100,000	100,000	PE
specific wastewater production	175	175	175	175	175.00	L/PE/d
Temperature (for dimensioning)	12.00	12.00	12.00	12.00	12.00	°C
COD (daily load per PE)	120.00	120.00	120.00	120.00	120.00	g/PE/d
TN (daily load per PE)	8.00	8.00	8.00	8.00	8.00	g/PE/d
P (daily load per PE)	1.80	1.80	1.80	1.80	1.80	g/PE/d
COD-removal WWTP	95.00	95.00	95.00	95.00	95.00	%
TN-removal WWTP	80.00	80.00	80.00	80.00	80.00	%
Primary settling						
COD-removal	30.00	30.00	30.00	30.00	30.00	%
TN/COD in PS	2.50	2.50	2.50	2.50	2.50	%
TSS in PS	30.00	30.00	30.00	30.00	30.00	g/L
COD/VSS in PS	1.75	1.75	1.75	1.75	1.75	-
Bypass	17.00	0.00	0.00	0.00	0.00	%
Activated sludge tank 1st stage						
TSS 1st stage	3.00	3.00	3.00	3.00	3.00	g/L
COD-removal 1st stage	60.00	60.00	60.00	60.00	60.00	%
Percentage of respired COD	30.00	30.00	30.00	30.00	30.00	%
COD/VSS in ES 1st stage	1.50	1.50	1.50	1.50	1.50	-
Loss of ignition in ES 1st stage	77.00	77.00	77.00	77.00	77.00	%
DO concentration in 1st stage	1.50	1.50	1.50	1.50	1.50	mg/L
SAE aeration system in clear water	3.60	3.60	3.60	3.60	3.60	kgO_2/kWh
a-value	0.40	0.40	0.40	0.40	0.40	-
Sludge return ratio RS1	1.00	1.00	1.00	1.00	1.00	-
TN/COD in ES 1st stage	6.00	6.00	6.00	6.00	6.00	%
Mixing energy	2.00	2.00	2.00	2.00	2.00	W/m^3
Activated sludge tank 2nd stage						
TSS 2nd stage	3.00	3.00	3.00	3.00	3.00	g/L
Percentage of respired COD	65.00	65.00	65.00	65.00	65.00	%
COD/VSS in ES 2nd stage	1.40	1.40	1.40	1.40	1.40	-
Loss of ignition in ES 2nd stage	72.00	72.00	72.00	72.00	72.00	%
DO concentration in 2nd stage	1.50	1.50	1.50	1.50	1.50	mg/L
SAE aeration system in clear water	3.60	3.60	3.60	3.60	3.60	kgO_2/kWh

a-value	0.60	0.60	0.60	0.60	0.60	-
Sludge return ratio RS2	1.00	1.00	1.00	1.00	1.00	-
TN/COD in ES 2nd stage	6.00	6.00	6.00	6.00	6.00	%
Maximal ratio of $OU_{DN}2/OU_C2$	50.00	50.00	50.00	50.00	50.00	%
Mixing energy	2.00	2.00	2.00	2.00	2.00	W/m³
Anaerobic sludge treatment						
COD in digested sludge (DS)	30.00	30.00	30.00	30.00	30.00	g/PE/d
Loss of ignition in DS	60.00	60.00	60.00	60.00	60.00	%
COD/VSS in DS	1.40	1.40	1.40	1.40	1.40	-
TSS in raw sludge	60.00	60.00	60.00	60.00	60.00	g/L
TSS in dewatered sludge	300.00	300.00	300.00	300.00	300.00	g/L
$N_{released}/COD_{Biogas}$	3.50	3.50	3.50	3.50	3.50	%
Mixing energy	4.00	4.00	4.00	4.00	4.00	W/m³
Circulation (pumps) of digester volume	1.00	1.00	1.00	1.00	1.00	1/d
Efficiency of CHP unit (electricity)	35.00	35.00	35.00	35.00	35.00	%
Energy demand for mechanical sludge thickening (MST)	30.00	30.00	30.00	30.00	30.00	Wh/m³
Polymer dosage for mechancal sludge thickening (MST)	3.00	3.00	3.00	3.00	3.00	gAS/kgTS
Energy demand for dewatering	1.33	1.33	1.33	1.33	1.33	kWh/m³
Polymer dosage for dewatering	12.00	12.00	12.00	12.00	12.00	gAS/kgTS
Costs for polymer	6.00	6.00	6.00	6.00	6.00	€/kgAS
Co-substrates and external sludge						
Load of CoS/external sludge	-	-	-	-	-	kg/d
TSS CoS/external sludge	-	-	-	-	-	g/L
Loss of ignition CoS/external sludge	-	-	-	-	-	%
COD/VSS CoS/external sludge	-	-	-	-	-	-
VSS degradation	-	-	-	-	-	%
TN/COD CoS/external sludge	-	-	-	-	-	%
Treatment of Sludge dewatering effluent (SDE)						
Without treatment	x					
Nitritation		x				
Anammox			x			
Air-stripping				x		
Membrane-stripping					x	
Temperature in SDE treatment tank	-	25	25	-	-	°C
DO concentration in SDE treatment tank	-	1.50	1.50	-	-	mg/L
SAE aeration system in clear water	-	3.60	3.60	-	-	kgO_2/kWh
a-value	-	0.80	0.80	-	-	-
Mixing energy	-	2.00	2.00	-	-	W/m³
Thermal energy for air-stripping	-	-	-	16.00	-	$kWh_{primary}/kg$
Thermal energy for membrane-stripping	-	-	-	-	18.00	$kWh_{primary}/kg$
Electric energy for air-stripping	-	-	-	4.50	-	$kWh_{primary}/kg$
Electric energy for membrane-stripping	-	-	-	-	6.00	$kWh_{primary}/kg$
Efficiency of power production	-	-	-	30.00	30.00	%

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Demand H_2SO_4 (air- and membrane-stripping)	-	-	-	0.50	0.50	mol/molN
Costs for H_2SO_4 98 %	-	-	-	220.00	220.00	€/m³
Demand NaOH (air- and membrane-stripping)	-	-	-	0.70	0.70	mol/molN
Costs for NaOH 50 %	-	-	-	250.00	250.00	€/m³
Other costs stripping	-	-	-	0.05	0.05	€/kgN
Pumps						
Energy	9.81	9.81	9.81	9.81	9.81	Ws/L/m
Efficiency of pumps	60	60	60	60	60	%
Δh for inflow pump	6.00	6.00	6.00	6.00	6.00	m
Δh for Bypass	0.00	0.00	0.00	0.00	0.00	m
Δh for return sludge RS1	2.50	2.50	2.50	2.50	2.50	m
Δh for return sludge RS2	2.50	2.50	2.50	2.50	2.50	m
Δh for internal recirculation	0.50	0.50	0.50	0.50	0.50	m
Δh for nitrate recirculation	3.00	3.00	3.00	3.00	3.00	m
Δh for digester circulation and heating	3.00	3.00	3.00	3.00	3.00	m
Estimation of plant size						
HRT primary settling tank	1.50	1.50	1.50	1.50	1.50	h
Anoxic respiration	30.00	30.00	30.00	30.00	30.00	$mgO_2/L/h$
SRT 1st stage	1.50	1.50	1.50	1.50	1.50	d
P in Biomass (related to COD)	0.50	0.50	0.50	0.50	0.50	%
P in WWTP effluent	1.00	1.00	1.00	1.00	1.00	mg/L
Specific requirement of iron (β=1,5)	2.70	2.70	2.70	2.70	2.70	kgFe/kgP
Sludge from P-precipitation	2.50	2.50	2.50	2.50	2.50	kgTSS/kgFe
Depth of intermediate sedimentation tank	3.50	3.50	3.50	3.50	3.50	m
Surface charging of intermediate sedimentation tank	1.20	1.20	1.20	1.20	1.20	m/h
Depth of secondary sedimentation tank	4.50	4.50	4.50	4.50	4.50	m
Surface charging of secondary sedimentation tank	0.60	0.60	0.60	0.60	0.60	m/h
Safety factor for SDE treatment tank	-	1.20	-	-	-	-
HRT Anammox SBR	-	-	2.00	-	-	d
HRT digester	25.00	25.00	25.00	25.00	25.00	d
Estimation of costs for construction						
Costs for infrastructure, design and construction						
Primary sedimentation	650	650	650	650	650	€/m³
Activated sludge tanks	900	900	900	900	900	€/m³
Intermediate and secondary sedimentation	1,200	1,200	1,200	1,200	1,200	€/m³
Digestion	2,500	2,500	2,500	2,500	2,500	€/m³
Fixed costs for electrical engineering	100,000	100,000	100,000	100,000	100,000	€
Fixed costs for measurement technology	75,000	75,000	75,000	75,000	75,000	€/Line
Depreciation period	15	15	15	15	15	a
SDE treatment Nitritation						
Fixed costs for electrical engineering	-	100,000	-	-	-	€
Fixed costs for measurement technology	-	25,000	-	-	-	€/tank

Costs for infrastructure, design and construction	-	2,700	-	-	-	€/kgN
SDE treatment Anammox						
Fixed costs for electrical engineering	-	-	100,000	-	-	€
Fixed costs for measurement technology	-	-	50,000	-	-	€/tank
Costs for infrastructure, design and construction	-	-	2,700	-	-	€/kgN
SDE treatment air-stripping with CO_2-stripping						
Fixed costs for electrical engineering and chemical storage	-	-	-	250,000	-	€
Costs for design and construction	-	-	-	4,100	-	€/kgN
Costs for infrastructure	-	-	-	1,000	-	€/kgN
Depreciation period	-	-	-	10	-	a
SDE treatment membrane-stripping with CO_2-stripping						
Fixed costs for electrical engineering and chemical storage	-	-	-	-	250,000	€
Costs for infrastructure, design and construction	-	-	-	-	4,000	€/kgN
Durability of membranes	-	-	-	-	5	a
Costs for membranes	-	-	-	-	600	€/kgN
Depreciation period	-	-	-	-	10	a

6.2. Calculation results for a 2-stage WWTP with TN/COD = 8/120

Table 27: Detailed demand on electrical energy for wastewater treatment of single stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Energy for inflow pumps	477	477	477	477	477	kWh/d
Energy for screens*	205	205	205	205	205	kWh/d
Energy for sand and grease trap*	205	205	205	205	205	kWh/d
Energy for sedimentation tanks*	342	342	342	342	342	kWh/d
Energy for aeration 1st stage	893	982	1,064	1,142	1,142	kWh/d
Energy for aeration 2nd stage	2,179	1,786	1,709	1,719	1,719	kWh/d
Energy for aeration SDE treatment	0	133	133	0	0	kWh/d
Energy for stirring unit 1st stage	56	68	68	68	68	kWh/d
Energy for stirring unit 2nd stage	326	275	263	265	265	kWh/d
Energy for stirring unit SDE treatment	0	7	9	0	0	kWh/d
Energy for stirring unit digester	251	258	258	258	258	kWh/d
Energy for pumps Bypass	0	0	0	0	0	kWh/d
Energy for pumps RS1	191	219	206	206	206	kWh/d
Energy for pumps RS2	221	214	201	201	201	kWh/d
Energy for pumps internal recirculation	68	46	33	36	36	kWh/d
Energy for pumps nitrate recirculation	23	16	0	0	0	kWh/d
Energy for pumps digester circulation	36	37	37	37	37	kWh/d
Energy for air-stripping	0	0	0	211	0	kWh/d

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Energy for membrane-stripping	0	0	0	0	282	kWh/d
Energy for MST	21	22	22	22	22	kWh/d
Energy for sludge dewatering	139	143	143	143	143	kWh/d
Energy for heating*	342	342	342	342	342	kWh/d
Energy for other infrastructure*	411	411	411	411	411	kWh/d
Energy for WWTP	6,387	6,190	6,130	6,293	6,363	kWh/d
Energy for WWTP	23.3	22.6	22.4	23.0	23.2	kWh/PE/a
Energy from Biogas utilisation	5,718	6,086	6,086	6,086	6,086	kWh/d
Energy gain/Energy demand	89.53	98.32	99.28	96.71	95.64	%

** Not calculated, but assumed values from benchmarking report Austrian WWTP 2015*

Table 28: Detailed Q-balance for 2-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Q inflow primary sedimentation	17,500	17,500	17,500	17,500	17,500	m³/d
Q PS	86	84	84	84	84	m³/d
Q outflow primary sedimentation	17,414	17,416	17,416	17,416	17,416	m³/d
Q Bypass	2,960	0	0	0	0	m³/d
Q ES 1st stage	386	473	473	473	473	m³/d
Q ES 2nd stage	230	181	181	181	181	m³/d
Q inflow MST	702	738	738	738	738	m³/d
Q raw sludge	104	107	107	107	107	m³/d
Q outflow MST to 1st stage	597	630	630	630	630	m³/d
Q inflow digester CoS/external sludge	0	0	0	0	0	m³/d
Q outflow digester	104	107	107	107	107	m³/d
Q dewatered sludge	12	12	12	12	12	m³/d
Q SDE	92	96	96	96	96	m³/d
Q SDE treatment to 1st stage	92	96	96	96	96	m³/d
Q nitrate recirculation	1,714	1,184	0	0	0	m³/d
Q inflow 1st stage	16,858	19,326	18,141	18,141	18,141	m³/d
Q outflow 1st stage	16,472	18,853	17,669	17,669	17,669	m³/d
Q inflow 2nd stage	19,432	18,853	17,669	17,669	17,669	m³/d
Q outflow 2nd stage	19,202	18,672	17,488	17,488	17,488	m³/d
Q RS1	16,858	19,326	18,141	18,141	18,141	m³/d
Q RS2	19,432	18,853	17,669	17,669	17,669	m³/d
Q internal recirculation	30,073	20,095	14,643	16,046	16,046	m³/d
Q total inflow 1st stage	33,716	38,651	36,283	36,283	36,283	m³/d
Q inflow intermediate sedimentation	33,716	38,651	36,283	36,283	36,283	m³/d
Q outflow intermediate sedimentation	16,472	18,853	17,669	17,669	17,669	m³/d
Q total inflow 2nd stage	68,938	57,800	49,980	51,384	51,384	m³/d
Q inflow secondary sedimentation	38,865	37,706	35,337	35,337	35,337	m³/d
Q outflow secondary sedimentation	19,202	18,672	17,488	17,488	17,488	m³/d
Q outflow WWTP	17,488	17,488	17,488	17,488	17,488	m³/d

Table 29: Detailed COD-balance for 2-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
COD inflow primary sedimentation	12,000	12,000	12,000	12,000	12,000	kg/d
COD PS	3,600	3,600	3,600	3,600	3,600	kg/d
COD outflow primary sedimentation	8,400	8,400	8,400	8,400	8,400	kg/d
COD Bypass to 2nd stage	1,428	0	0	0	0	kg/d
COD inflow 1st stage	6,972	8,400	8,400	8,400	8,400	kg/d
COD ES 1st stage	2,676	3,276	3,276	3,276	3,276	kg/d
COD inflow 2nd stage	4,577	3,720	3,720	3,720	3,720	kg/d
COD ES 2nd stage	1,392	1,092	1,092	1,092	1,092	kg/d
COD outflow WWTP	600	600	600	600	600	kg/d
COD raw sludge	7,668	7,968	7,968	7,968	7,968	kg/d
COD inflow digester CoS/external sludge	0	0	0	0	0	kg/d
COD digested sludge + CoS/external sludge	3,000	3,000	3,000	3,000	3,000	kg/d
COD SDE	0	0	0	0	0	kg/d
COD nitrate recirculation	0	0	0	0	0	kg/d
COD Biogas	4,668	4,968	4,968	4,968	4,968	kg/d
OU_C 1st stage	1,147	1,404	1,404	1,404	1,404	kg/d
OU_C 2nd stage	2,585	2,028	2,028	2,028	2,028	kg/d
OU_{DN} 1st stage	50	197	97	0	0	kg/d
OU_{DN} 2nd stage	1,292	1,014	837	873	873	kg/d
$OU_{DN}1/OU_C1$	4.34	14.01	6.89	0.00	0.00	%
$OU_{DN}2/OU_C2$	50.00	50.00	41.26	43.06	43.06	%

Table 30: Detailed TN-balance for 2-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
TN inflow primary sedimentation	800	800	800	800	800	kg/d
TN PS	90	90	90	90	90	kg/d
TN outflow primary sedimentation	710	710	710	710	710	kg/d
TN Bypass to 2nd stage	121	0	0	0	0	kg/d
TN inflow 1st stage	589	710	710	710	710	kg/d
TN ES 1st stage	161	197	197	197	197	kg/d
TN ES 2nd stage	84	66	66	66	66	kg/d
TN raw sludge	334	352	352	352	352	kg/d
TN inflow digester CoS/external sludge	0	0	0	0	0	kg/d
TN inflow digester	334	352	352	352	352	kg/d
TN SDE	163	174	174	174	174	kg/d
TN digested sludge + CoS/external sludge	171	178	178	178	178	kg/d
TN outflow WWTP	160	160	160	160	160	kg/d
TN total inflow 1st stage	753	884	749	727	727	kg/d
TN denitrified 1st stage	0	96	34	0	0	kg/d

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TN outflow 1st stage	592	592	518	531	531	kg/d
TN inflow 2nd stage	713	592	518	531	531	kg/d
TN denitrified 2nd stage	452	355	293	305	305	kg/d
TN outflow 2nd stage	177	172	160	160	160	kg/d
TN nitrate recirculation	17	12	0	0	0	kg/d
TN denitrified + nitrate recirculation 1st stage	17	107	34	0	0	kg/d

Table 31: Calculation of required basin volumes for 2-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Basin volume primary sedimentation	1,094	1,094	1,094	1,094	1,094	m³
Basin volume AST 1st stage	1,159	1,418	1,418	1,418	1,418	m³
Basin volume intermediate sedimentation	2,127	2,127	2,127	2,127	2,127	m³
Basin volume AST 2nd stage	6,792	5,726	5,480	5,531	5,531	m³
Basin volume secondary sedimentation	5,469	5,469	5,469	5,469	5,469	m³
Basin volume SDE treatment	0	138	191	0	0	m³
Volume digester	2,610	2,687	2,687	2,687	2,687	m³

Table 32: Detailed construction costs for 2-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Costs primary sedimentation	710,938	710,938	710,938	710,938	710,938	€
Costs AST 1st stage	1,042,691	1,276,364	1,276,364	1,276,364	1,276,364	€
Costs intermediate sedimentation	2,552,083	2,552,083	2,552,083	2,552,083	2,552,083	€
Costs AST 2nd stage	6,112,423	5,153,655	4,932,205	4,977,631	4,977,631	€
Costs secondary sedimentation	6,562,500	6,562,500	6,562,500	6,562,500	6,562,500	€
Costs digester	6,525,077	6,718,452	6,718,452	6,718,452	6,718,452	€
Costs electrical engineering	100,000	100,000	100,000	100,000	100,000	€
Costs measurement technology	150,000	150,000	150,000	150,000	150,000	€
Costs Nitritation electrical engineering	-	100,000	-	-	-	€
Costs Nitritation measurement technology	-	25,000	-	-	-	€
Costs Nitritation infrastructure, design, construction	-	258,212	-	-	-	€
Costs Anammox electrical engineering	-	-	100,000	-	-	€
Costs Anammox measurement technology	-	-	50,000	-	-	€
Costs Anammox infrastructure, design, construction	-	-	365,469	-	-	€
Costs Air-stripping electrical engineering, chemical storage	-	-	-	250,000	-	€
Costs Air-stripping design and construction	-	-	-	641,617	-	€
Costs Air-stripping infrastructure	-	-	-	156,492	-	€
Costs Membrane-stripping electr. eng., chemical storage	-	-	-	-	250,000	€
Costs Membrane-stripping design and construction	-	-	-	-	625,968	€

Costs for membranes	-	-	-	-	93,895	€
Total costs for WWTP	23,755,712	23,607,203	23,518,010	24,096,077	24,017,831	€
Total costs for WWTP	237.6	236.1	235.2	241.0	240.2	€/PE

Table 33: Running costs for 2-stage WWTP with influent ratio TN/COD = 8/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Costs for depreciation WWTP	1,583,714	1,573,814	1,567,867	1,641,342	1,642,907	€/a
Costs for external electricity	29,279	4,549	1,922	9,071	12,156	€/a
Costs for polymer	135,012	136,232	136,232	136,232	136,232	€/a
Costs for H_2SO_4 98%	-	-	-	24,980	24,980	€/a
Costs for NaOH 50%	-	-	-	37,480	37,480	€/a
Other costs stripping	-	-	-	2,856	2,856	€/a
Revenues from sale of N-fertilizer	-	-	-	57,120	57,120	€/a
Overall running costs	1,748,005	1,714,595	1,706,021	1,794,842	1,799,491	€/a
Overall running costs	17.5	17.1	17.1	17.9	18.0	€/PE/a

6.3. Calculation of a single-stage WWTP with TN/COD = 11/120

Table 34: Assumptions for calculation of single-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Influent						
Size WWTP (120 PE)	100,000	100,000	100,000	100,000	100,000	PE
specific wastewater production	175.00	175.00	175.00	175.00	175.00	L/PE/d
Temperature (for dimensioning)	12.00	12.00	12.00	12.00	12.00	°C
COD (daily load per PE)	120.00	120.00	120.00	120.00	120.00	g/PE/d
TN (daily load per PE)	11.00	11.00	11.00	11.00	11.00	g/PE/d
P (daily load per PE)	1.80	1.80	1.80	1.80	1.80	g/PE/d
COD-removal WWTP	95.00	95.00	95.00	95.00	95.00	%
TN-removal WWTP	80.00	80.00	80.00	80.00	80.00	%
Primary settling						
COD-removal	30.00	30.00	30.00	30.00	30.00	%
TN/COD in PS	2.50	2.50	2.50	2.50	2.50	%
TSS in PS	30.00	30.00	30.00	30.00	30.00	g/L
COD/VSS in PS	1.75	1.75	1.75	1.75	1.75	-
Bypass	-	-	-	-	-	%
Activated sludge tank 1st stage						
TSS 1st stage	-	-	-	-	-	g/L

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Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
COD-removal 1st stage	-	-	-	-	-	%
Percentage of respired COD	-	-	-	-	-	%
COD/VSS in ES 1st stage	-	-	-	-	-	-
Loss of ignition in ES 1st stage	-	-	-	-	-	%
DO concentration in 1st stage	-	-	-	-	-	mg/L
SAE aeration system in clear water	-	-	-	-	-	kgO_2/kWh
a-value	-	-	-	-	-	-
Sludge return ratio RS1	-	-	-	-	-	-
TN/COD in ES 1st stage	-	-	-	-	-	%
Mixing energy	-	-	-	-	-	W/m³
Activated sludge tank 2nd stage						
TSS 2nd stage	3.00	3.00	3.00	3.00	3.00	g/L
Percentage of respired COD	55.00	55.00	55.00	55.00	55.00	%
COD/VSS in ES 2nd stage	1.40	1.40	1.40	1.40	1.40	-
Loss of ignition in ES 2nd stage	72.00	72.00	72.00	72.00	72.00	%
DO concentration in 2nd stage	1.50	1.50	1.50	1.50	1.50	mg/L
SAE aeration system in clear water	3.60	3.60	3.60	3.60	3.60	kgO_2/kWh
a-value	0.50	0.50	0.50	0.50	0.50	-
Sludge return ratio RS2	1.00	1.00	1.00	1.00	1.00	-
TN/COD in ES 2nd stage	6.00	6.00	6.00	6.00	6.00	%
Maximal ratio of $OU_{DN}2/OU_C2$	50.00	50.00	50.00	50.00	50.00	%
Mixing energy	2.00	2.00	2.00	2.00	2.00	W/m³
Anaerobic sludge treatment						
COD in digested sludge (DS)	30.00	30.00	30.00	30.00	30.00	g/PE/d
Loss of ignition in DS	60.00	60.00	60.00	60.00	60.00	%
COD/VSS in DS	1.40	1.40	1.40	1.40	1.40	-
TSS in raw sludge	60.00	60.00	60.00	60.00	60.00	g/L
TSS in dewatered sludge	300.00	300.00	300.00	300.00	300.00	g/L
$N_{released}/COD_{Biogas}$	3.50	3.50	3.50	3.50	3.50	%
Mixing energy	4.00	4.00	4.00	4.00	4.00	W/m³
Circulation (pumps) of digester volume	1.00	1.00	1.00	1.00	1.00	1/d
Efficiency of CHP unit (electricity)	35.00	35.00	35.00	35.00	35.00	%
Energy demand for mechanical sludge thickening (MST)	30.00	30.00	30.00	30.00	30.00	Wh/m³
Polymer dosage for mechancal sludge thickening (MST)	3.00	3.00	3.00	3.00	3.00	gAS/kgTS
Energy demand for dewatering	1.33	1.33	1.33	1.33	1.33	kWh/m³
Polymer dosage for dewatering	12.00	12.00	12.00	12.00	12.00	gAS/kgTS
Costs for polymer	6.00	6.00	6.00	6.00	6.00	€/kgAS
Co-substrates and external sludge						
Load of CoS/external sludge	-	-	-	-	-	kg/d
TSS CoS/external sludge	-	-	-	-	-	g/L

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Loss of ignition CoS/external sludge	-	-	-	-	-	%
COD/VSS CoS/external sludge	-	-	-	-	-	-
VSS degradation	-	-	-	-	-	%
TN/COD CoS/external sludge	-	-	-	-	-	%
Treatment of Sludge dewatering effluent (SDE)						
Without treatment	x					
Nitritation		x				
Anammox			x			
Air-stripping				x		
Membrane-stripping					x	
Temperature in SDE treatment tank	-	25	25	-	-	°C
DO concentration in SDE treatment tank	-	1.50	1.50	-	-	mg/L
SAE aeration system in clear water	-	3.60	3.60	-	-	kgO_2/kWh
a-value	-	0.80	0.80	-	-	-
Mixing energy	-	2.00	2.00	-	-	W/m³
Thermal energy for air-stripping	-	-	-	16.00	-	$kWh_{primary}$/k
Thermal energy for membrane-stripping	-	-	-	-	18.00	$kWh_{primary}$/k
Electric energy for air-stripping	-	-	-	4.50	-	$kWh_{primary}$/kN
Electric energy for membrane-stripping	-	-	-	-	6.00	$kWh_{primary}$/k
Efficiency of power production	-	-	-	30.00	30.00	%
Demand H_2SO_4 (air- and membrane-stripping)	-	-	-	0.50	0.50	mol/mol N
Costs for H_2SO_4 98 %	-	-	-	220.00	220.00	€/m³
Demand NaOH (air- and membrane-stripping)	-	-	-	0.70	0.70	mol/mol N
Costs for NaOH 50 %	-	-	-	250.00	250.00	€/m³
Other costs stripping	-	-	-	0.05	0.05	€/kgN
Pumps						
Energy	9.81	9.81	9.81	9.81	9.81	Ws/L/m
Efficiency of pumps	60	60	60	60	60	%
Δh for inflow pump	6.00	6.00	6.00	6.00	6.00	m
Δh for Bypass	-	-	-	-	-	m
Δh for return sludge RS1	-	-	-	-	-	m
Δh for return sludge RS2	2.50	2.50	2.50	2.50	2.50	m
Δh for internal recirculation	0.50	0.50	0.50	0.50	0.50	m
Δh for nitrate recirculation	-	-	-	-	-	m
Δh for digester circulation and heating	3.00	3.00	3.00	3.00	3.00	m
Estimation of plant size						
HRT primary settling tank	1.50	1.50	1.50	1.50	1.50	h
Anoxic respiration	30.00	30.00	30.00	30.00	30.00	$mgO_2/L/h$
SRT 1st stage	-	-	-	-	-	d

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Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
P in Biomass (related to COD)	0.50	0.50	0.50	0.50	0.50	%
P in WWTP effluent	1.00	1.00	1.00	1.00	1.00	mg/L
Specific requirement of iron (β=1,5)	2.70	2.70	2.70	2.70	2.70	kgFe/kgP
Sludge from P-precipitation	2.50	2.50	2.50	2.50	2.50	kgTSS/kg Fe
Depth of intermediate sedimentation tank	-	-	-	-	-	m
Surface charging of intermediate sedimentation tank	-	-	-	-	-	m/h
Depth of secondary sedimentation tank	4.50	4.50	4.50	4.50	4.50	m
Surface charging of secondary sedimentation tank	0.60	0.60	0.60	0.60	0.60	m/h
Safety factor for SDE treatment tank	-	1.20	-	-	-	-
HRT Anammox SBR	-	-	2.00	-	-	d
HRT digester	25.00	25.00	25.00	25.00	25.00	d
Estimation of costs for construction						
Costs for infrastructure, design and construction						
Primary sedimentation	650	650	650	650	650	€/m³
Activated sludge tanks	900	900	900	900	900	€/m³
Intermediate and secondary sedimentation	1,200	1,200	1,200	1,200	1,200	€/m³
Digestion	2,500	2,500	2,500	2,500	2,500	€/m³
Fixed costs for electrical engineering	100,000	100,000	100,000	100,000	100,000	€
Fixed costs for measurement technology	75,000	75,000	75,000	75,000	75,000	€/Line
Depreciation period	15	15	15	15	15	a
SDE treatment Nitritation						
Fixed costs for electrical engineering	-	100,000	-	-	-	€
Fixed costs for measurement technology	-	25,000	-	-	-	€/tank
Costs for infrastructure, design and construction	-	2,700	-	-	-	€/kgN
SDE treatment Anammox						
Fixed costs for electrical engineering	-	-	100,000	-	-	€
Fixed costs for measurement technology	-	-	50,000	-	-	€/tank
Costs for infrastructure, design and construction	-	-	2,700	-	-	€/kgN
SDE treatment air-stripping with CO_2-stripping						
Fixed costs for electrical engineering and chemical storage	-	-	-	250,000	-	€
Costs for design and construction	-	-	-	4,100	-	€/kgN
Costs for infrastructure	-	-	-	1,000	-	€/kgN
Depreciation period	-	-	-	10	-	a
SDE treatment membrane-stripping with CO_2-stripping						
Fixed costs for electrical engineering and chemical storage	-	-	-	-	250,000	€
Costs for infrastructure, design and construction	-	-	-	-	4,000	€/kgN
Durability of membranes	-	-	-	-	5	a
Costs for membranes	-	-	-	-	600	€/kgN
Depreciation period	-	-	-	-	10	a

6.4. Calculation results for a single-stage WWTP with TN/COD = 11/120

Table 35: Detailed demand on electrical energy for wastewater treatment of single-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Energy for inflow pumps	477	477	477	477	477	kWh/d
Energy for screens*	205	205	205	205	205	kWh/d
Energy for sand and grease trap*	205	205	205	205	205	kWh/d
Energy for sedimentation tanks*	342	342	342	342	342	kWh/d
Energy for aeration 1st stage	-	-	-	-	-	kWh/d
Energy for aeration 2nd stage	4,105	3,941	3,918	3,981	3,981	kWh/d
Energy for aeration SDE treatment	-	110	110	-	-	kWh/d
Energy for stirring unit 1st stage	-	-	-	-	-	kWh/d
Energy for stirring unit 2nd stage	608	602	586	583	583	kWh/d
Energy for stirring unit SDE treatment	-	6	8	-	-	kWh/d
Energy for stirring unit digester	240	240	240	240	240	kWh/d
Energy for pumps Bypass	-	-	-	-	-	kWh/d
Energy for pumps RS1	-	-	-	-	-	kWh/d
Energy for pumps RS2	205	205	205	205	205	kWh/d
Energy for pumps internal recirculation	94	94	73	70	70	kWh/d
Energy for pumps nitrate recirculation	-	-	-	-	-	kWh/d
Energy for pumps digester circulation	34	34	34	34	34	kWh/d
Energy for air-stripping	-	-	-	175	-	kWh/d
Energy for membrane-stripping	-	-	-	-	233	kWh/d
Energy for MST	20	20	20	20	20	kWh/d
Energy for sludge dewatering	133	133	133	133	133	kWh/d
Energy for heating*	342	342	342	342	342	kWh/d
Energy for other infrastructure*	411	411	411	411	411	kWh/d
Energy for WWTP	7,422	7,368	7,312	7,424	7,482	kWh/d
Energy for WWTP	27.1	26.9	26.7	27.1	27.3	kWh/PE/a
Energy from Biogas utilisation	5,035	5,035	5,035	5,035	5,035	kWh/d
Energy gain/Energy demand	67.84	68.33	68.86	67.82	67.29	%

** Not calculated, but assumed values from benchmarking report Austrian WWTP 2015*

Table 36: Detailed Q-balance for single-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Q inflow primary sedimentation	17,500	17,500	17,500	17,500	17,500	m³/d
Q PS	84	84	84	84	84	m³/d
Q outflow primary sedimentation	17,416	17,416	17,416	17,416	17,416	m³/d
Q Bypass	-	-	-	-	-	m³/d
Q ES 1st stage	-	-	-	-	-	m³/d

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Q ES 2nd stage	580	580	580	580	580	m³/d
Q inflow MST	664	664	664	664	664	m³/d
Q raw sludge	100	100	100	100	100	m³/d
Q outflow MST to 1st stage	564	564	564	564	564	m³/d
Q inflow digester CoS/external sludge	-	-	-	-	-	m³/d
Q outflow digester	100	100	100	100	100	m³/d
Q dewatered sludge	12	12	12	12	12	m³/d
Q SDE	88	88	88	88	88	m³/d
Q SDE treatment to 1st stage	88	88	88	88	88	m³/d
Q nitrate recirculation	-	-	-	-	-	m³/d
Q inflow 1st stage	-	-	-	-	-	m³/d
Q outflow 1st stage	-	-	-	-	-	m³/d
Q inflow 2nd stage	18,068	18,068	18,068	18,068	18,068	m³/d
Q outflow 2nd stage	17,488	17,488	17,488	17,488	17,488	m³/d
Q RS1	-	-	-	-	-	m³/d
Q RS2	18,068	18,068	18,068	18,068	18,068	m³/d
Q internal recirculation	41,332	41,332	32,135	30,699	30,699	m³/d
Q total inflow 1st stage	-	-	-	-	-	m³/d
Q inflow intermediate sedimentation	-	-	-	-	-	m³/d
Q outflow intermediate sedimentation	-	-	-	-	-	m³/d
Q total inflow 2nd stage	77,468	77,468	68,272	66,836	66,836	m³/d
Q inflow secondary sedimentation	36,137	36,137	36,137	36,137	36,137	m³/d
Q outflow secondary sedimentation	17,488	17,488	17,488	17,488	17,488	m³/d
Q outflow WWTP	17,488	17,488	17,488	17,488	17,488	m³/d

Table 37: Detailed COD-balance for single-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
COD inflow primary sedimentation	12,000	12,000	12,000	12,000	12,000	kg/d
COD PS	3,600	3,600	3,600	3,600	3,600	kg/d
COD outflow primary sedimentation	8,400	8,400	8,400	8,400	8,400	kg/d
COD Bypass to 2nd stage	-	-	-	-	-	kg/d
COD inflow 1st stage	-	-	-	-	-	kg/d
COD ES 1st stage	-	-	-	-	-	kg/d
COD inflow 2nd stage	8,400	8,400	8,400	8,400	8,400	kg/d
COD ES 2nd stage	3,510	3,510	3,510	3,510	3,510	kg/d
COD outflow WWTP	600	600	600	600	600	kg/d
COD raw sludge	7,110	7,110	7,110	7,110	7,110	kg/d
COD inflow digester CoS/external sludge	-	-	-	-	-	kg/d
COD digested sludge + CoS/external sludge	3,000	3,000	3,000	3,000	3,000	kg/d
COD SDE	0	0	0	0	0	kg/d
COD nitrate recirculation	-	-	-	-	-	kg/d
COD Biogas	4,110	4,110	4,110	4,110	4,110	kg/d
OU_C 1st stage	-	-	-	-	-	kg/d

OU_C 2nd stage	4,290	4,290	4,290	4,290	4,290	kg/d
OU_{DN} 1st stage	-	-	-	-	-	kg/d
OU_{DN} 2nd stage	2,068	1,978	1,748	1,698	1,698	kg/d
$OU_{DN}1/OU_C1$	-	-	-	-	-	%
$OU_{DN}2/OU_C2$	48.22	46.10	40.75	39.59	39.59	%

Table 38: Detailed TN-balance for single-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
TN inflow primary sedimentation	1,100	1,100	1,100	1,100	1,100	kg/d
TN PS	90	90	90	90	90	kg/d
TN outflow primary sedimentation	1,010	1,010	1,010	1,010	1,010	kg/d
TN Bypass to 2nd stage	-	-	-	-	-	kg/d
TN inflow 1st stage	-	-	-	-	-	kg/d
TN ES 1st stage	-	-	-	-	-	kg/d
TN ES 2nd stage	211	211	211	211	211	kg/d
TN raw sludge	301	301	301	301	301	kg/d
TN inflow digester CoS/external sludge	-	-	-	-	-	kg/d
TN inflow digester	301	301	301	301	301	kg/d
TN SDE	144	144	144	144	144	kg/d
TN digested sludge + CoS/external sludge	157	157	157	157	157	kg/d
TN outflow WWTP	220	220	220	220	220	kg/d
TN total inflow 1st stage	-	-	-	-	-	kg/d
TN denitrified 1st stage	-	-	-	-	-	kg/d
TN outflow 1st stage	-	-	-	-	-	kg/d
TN inflow 2nd stage	1,154	1,154	1,042	1,024	1,024	kg/d
TN denitrified 2nd stage	723	723	611	594	594	kg/d
TN outflow 2nd stage	220	220	220	220	220	kg/d
TN nitrate recirculation	-	-	-	-	-	kg/d
TN denitrified + nitrate recirculation 1st stage	-	-	-	-	-	kg/d

Table 39: Calculation of required basin volumes for single-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Basin volume primary sedimentation	1,094	1,094	1,094	1,094	1,094	m³
Basin volume AST 1st stage	-	-	-	-	-	m³
Basin volume intermediate sedimentation	-	-	-	-	-	m³
Basin volume AST 2nd stage	12,663	12,537	12,218	12,149	12,149	m³
Basin volume secondary sedimentation	5,465	5,465	5,465	5,465	5,465	m³
Basin volume SDE treatment	-	127	176	-	-	m³
Volume digester	2,497	2,497	2,497	2,497	2,497	m³

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Table 40: Detailed construction costs for single-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Costs primary sedimentation	710,938	710,938	710,938	710,938	710,938	€
Costs AST 1st stage						€
Costs intermediate sedimentation						€
Costs AST 2nd stage	11,396,920	11,283,188	10,996,585	10,934,082	10,934,082	€
Costs secondary sedimentation	6,558,036	6,558,036	6,558,036	6,558,036	6,558,036	€
Costs digester	6,242,560	6,242,560	6,242,560	6,242,560	6,242,560	€
Costs electrical engineering	100,000	100,000	100,000	100,000	100,000	€
Costs measurement technology	150,000	150,000	150,000	150,000	150,000	€
Costs Nitritation electrical engineering		100,000				€
Costs Nitritation measurement technology		25,000				€
Costs Nitritation infrastructure, design, construction		213,617				€
Costs Anammox electrical engineering			100,000			€
Costs Anammox measurement technology			50,000			€
Costs Anammox infrastructure, design, construction			302,351			€
Costs Air-stripping electrical engineering, chemical storage				250,000		€
Costs Air-stripping design and construction				530,807		€
Costs Air-stripping infrastructure				129,465		€
Costs Membrane-stripping electr. eng., chemical storage					250,000	€
Costs Membrane-stripping design and construction					517,860	€
Costs for membranes					77,679	€
Total costs for WWTP	25,158,453	25,383,338	25,210,469	25,605,887	25,541,154	€
Total costs for WWTP	251.6	253.8	252.1	256.1	255.4	€/PE

Table 41: Running costs for single-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Costs for depreciation WWTP	1,677,230	1,692,223	1,680,698	1,737,401	1,738,696	€/a
Costs for external electricity	104,544	102,204	99,746	104,634	107,186	€/a
Costs for polymer	133,230	133,230	133,230	133,230	133,230	€/a
Costs for H_2SO_4 98%	-	-	-	20,666	20,666	€/a
Costs for NaOH 50%	-	-	-	31,007	31,007	€/a
Other costs stripping	-	-	-	2,363	2,363	€/a
Revenues from sale of N-fertilizer	-	-	-	47,255	47,255	€/a
Overall running costs	1,915,004	1,927,656	1,913,674	1,982,047	1,985,893	€/a
Overall running costs	19.2	19.3	19.1	19.8	19.9	€/PE/a

6.5. Calculation of a 2-stage WWTP with TN/COD = 11/120

Table 42: Assumptions for calculation of 2-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Influent						
Size WWTP (120 PE)	100,000	100,000	100,000	100,000	100,000	PE
specific wastewater production	175	175	175	175	175.00	L/PE/d
Temperature (for dimensioning)	12.00	12.00	12.00	12.00	12.00	°C
COD (daily load per PE)	120.00	120.00	120.00	120.00	120.00	g/PE/d
TN (daily load per PE)	11.00	11.00	11.00	11.00	11.00	g/PE/d
P (daily load per PE)	1.80	1.80	1.80	1.80	1.80	g/PE/d
COD-removal WWTP	95.00	95.00	95.00	95.00	95.00	%
TN-removal WWTP	80.00	80.00	80.00	80.00	80.00	%
Primary settling						
COD-removal	25.00	25.00	25.00	25.00	25.00	%
TN/COD in PS	2.50	2.50	2.50	2.50	2.50	%
TSS in PS	30.00	30.00	30.00	30.00	30.00	g/L
COD/VSS in PS	1.75	1.75	1.75	1.75	1.75	-
Bypass	35.00	20.00	8.00	10.00	10.00	%
Activated sludge tank 1st stage						
TSS 1st stage	3.00	3.00	3.00	3.00	3.00	g/L
COD-removal 1st stage	60.00	60.00	60.00	60.00	60.00	%
Percentage of respired COD	30.00	30.00	30.00	30.00	30.00	%
COD/VSS in ES 1st stage	1.50	1.50	1.50	1.50	1.50	-
Loss of ignition in ES 1st stage	77.00	77.00	77.00	77.00	77.00	%
DO concentration in 1st stage	1.50	1.50	1.50	1.50	1.50	mg/L
SAE aeration system in clear water	3.60	3.60	3.60	3.60	3.60	kgO_2/kWh
a-value	0.40	0.40	0.40	0.40	0.40	-
Sludge return ratio RS1	1.00	1.00	1.00	1.00	1.00	-
TN/COD in ES 1st stage	6.00	6.00	6.00	6.00	6.00	%
Mixing energy	2.00	2.00	2.00	2.00	2.00	W/m^3
Activated sludge tank 2nd stage						
TSS 2nd stage	3.00	3.00	3.00	3.00	3.00	g/L
Percentage of respired COD	65.00	65.00	65.00	65.00	65.00	%
COD/VSS in ES 2nd stage	1.40	1.40	1.40	1.40	1.40	-
Loss of ignition in ES 2nd stage	72.00	72.00	72.00	72.00	72.00	%
DO concentration in 2nd stage	1.50	1.50	1.50	1.50	1.50	mg/L
SAE aeration system in clear water	3.60	3.60	3.60	3.60	3.60	kgO_2/kWh
a-value	0.60	0.60	0.60	0.60	0.60	-
Sludge return ratio RS2	1.00	1.00	1.00	1.00	1.00	-

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TN/COD in ES 2nd stage	6.00	6.00	6.00	6.00	6.00	%
Maximal ratio of $OU_{DN}2/OU_{C}2$	50.00	50.00	50.00	50.00	50.00	%
Mixing energy	2.00	2.00	2.00	2.00	2.00	W/m³
Anaerobic sludge treatment						
COD in digested sludge (DS)	30.00	30.00	30.00	30.00	30.00	g/PE/d
Loss of ignition in DS	60.00	60.00	60.00	60.00	60.00	%
COD/VSS in DS	1.40	1.40	1.40	1.40	1.40	-
TSS in raw sludge	60.00	60.00	60.00	60.00	60.00	g/L
TSS in dewatered sludge	300.00	300.00	300.00	300.00	300.00	g/L
$N_{released}/COD_{Biogas}$	3.50	3.50	3.50	3.50	3.50	%
Mixing energy	4.00	4.00	4.00	4.00	4.00	W/m³
Circulation (pumps) of digester volume	1.00	1.00	1.00	1.00	1.00	1/d
Efficiency of CHP unit (electricity)	35.00	35.00	35.00	35.00	35.00	%
Energy demand for mechanical sludge thickening (MST)	30.00	30.00	30.00	30.00	30.00	Wh/m³
Polymer dosage for mechancal sludge thickening (MST)	3.00	3.00	3.00	3.00	3.00	gAS/kgTS
Energy demand for dewatering	1.33	1.33	1.33	1.33	1.33	kWh/m³
Polymer dosage for dewatering	12.00	12.00	12.00	12.00	12.00	gAS/kgTS
Costs for polymer	6.00	6.00	6.00	6.00	6.00	€/kgAS
Co-substrates and external sludge						
Load of CoS/external sludge	-	-	-	-	-	kg/d
TSS CoS/external sludge	-	-	-	-	-	g/L
Loss of ignition CoS/external sludge	-	-	-	-	-	%
COD/VSS CoS/external sludge	-	-	-	-	-	-
VSS degradation	-	-	-	-	-	%
TN/COD CoS/external sludge	-	-	-	-	-	%
Treatment of Sludge dewatering effluent (SDE)						
Without treatment	x					
Nitritation		x				
Anammox			x			
Air-stripping				x		
Membrane-stripping					x	
Temperature in SDE treatment tank	-	25	25	-	-	°C
DO concentration in SDE treatment tank	-	1.50	1.50	-	-	mg/L
SAE aeration system in clear water	-	3.60	3.60	-	-	kgO_2/kWh
a-value	-	0.80	0.80	-	-	-
Mixing energy	-	2.00	2.00	-	-	W/m³
Thermal energy for air-stripping	-	-	-	16.00	-	$kWh_{primary}$/kg
Thermal energy for membrane-stripping	-	-	-	-	18.00	$kWh_{primary}$/kg
Electric energy for air-stripping	-	-	-	4.50	-	$kWh_{primary}$/kg
Electric energy for membrane-stripping	-	-	-	-	6.00	$kWh_{primary}$/kg
Efficiency of power production	-	-	-	30.00	30.00	%
Demand H_2SO_4 (air- and membrane-stripping)	-	-	-	0.50	0.50	mol/molN
Costs for H_2SO_4 98 %	-	-	-	220.00	220.00	€/m³

Demand NaOH (air- and membrane-stripping)	-	-	-	0.70	0.70	mol/molN
Costs for NaOH 50 %	-	-	-	250.00	250.00	€/m³
Other costs stripping	-	-	-	0.05	0.05	€/kgN
Pumps						
Energy	9.81	9.81	9.81	9.81	9.81	Ws/L/m
Efficiency of pumps	60	60	60	60	60	%
Δh for inflow pump	6.00	6.00	6.00	6.00	6.00	m
Δh for Bypass	0.00	0.00	0.00	0.00	0.00	m
Δh for return sludge RS1	2.50	2.50	2.50	2.50	2.50	m
Δh for return sludge RS2	2.50	2.50	2.50	2.50	2.50	m
Δh for internal recirculation	0.50	0.50	0.50	0.50	0.50	m
Δh for nitrate recirculation	3.00	3.00	3.00	3.00	3.00	m
Δh for digester circulation and heating	3.00	3.00	3.00	3.00	3.00	m
Estimation of plant size						
HRT primary settling tank	1.50	1.50	1.50	1.50	1.50	h
Anoxic respiration	30.00	30.00	30.00	30.00	30.00	$mgO_2/L/h$
SRT 1st stage	1.50	1.50	1.50	1.50	1.50	d
P in Biomass (related to COD)	0.50	0.50	0.50	0.50	0.50	%
P in WWTP effluent	1.00	1.00	1.00	1.00	1.00	mg/L
Specific requirement of iron (β=1,5)	2.70	2.70	2.70	2.70	2.70	kgFe/kgP
Sludge from P-precipitation	2.50	2.50	2.50	2.50	2.50	kgTSS/kgFe
Depth of intermediate sedimentation tank	3.50	3.50	3.50	3.50	3.50	m
Surface charging of intermediate sedimentation tank	1.20	1.20	1.20	1.20	1.20	m/h
Depth of secondary sedimentation tank	4.50	4.50	4.50	4.50	4.50	m
Surface charging of secondary sedimentation tank	0.60	0.60	0.60	0.60	0.60	m/h
Safety factor for SDE treatment tank	-	1.20	-	-	-	-
HRT Anammox SBR	-	-	2.00	-	-	d
HRT digester	25.00	25.00	25.00	25.00	25.00	d
Estimation of costs for construction						
Costs for infrastructure, design and construction						
Primary sedimentation	650	650	650	650	650	€/m³
Activated sludge tanks	900	900	900	900	900	€/m³
Intermediate and secondary sedimentation	1,200	1,200	1,200	1,200	1,200	€/m³
Digestion	2,500	2,500	2,500	2,500	2,500	€/m³
Fixed costs for electrical engineering	100,000	100,000	100,000	100,000	100,000	€
Fixed costs for measurement technology	75,000	75,000	75,000	75,000	75,000	€/Line
Depreciation period	15	15	15	15	15	a
SDE treatment Nitritation						
Fixed costs for electrical engineering	-	100,000	-	-	-	€
Fixed costs for measurement technology	-	25,000	-	-	-	€/tank
Costs for infrastructure, design and construction	-	2,700	-	-	-	€/kgN

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SDE treatment Anammox						
Fixed costs for electrical engineering	-	-	100,000	-	-	€
Fixed costs for measurement technology	-	-	50,000	-	-	€/tank
Costs for infrastructure, design and construction	-	-	2,700	-	-	€/kgN
SDE treatment air-stripping with CO_2-stripping						
Fixed costs for electrical engineering and chemical storage	-	-	-	250,000	-	€
Costs for design and construction	-	-	-	4,100	-	€/kgN
Costs for infrastructure	-	-	-	1,000	-	€/kgN
Depreciation period	-	-	-	10	-	a
SDE treatment membrane-stripping with CO_2-stripping						
Fixed costs for electrical engineering and chemical storage	-	-	-	-	250,000	€
Costs for infrastructure, design and construction	-	-	-	-	4,000	€/kgN
Durability of membranes	-	-	-	-	5	a
Costs for membranes	-	-	-	-	600	€/kgN
Depreciation period	-	-	-	-	10	a

6.6. Calculation results for a 2-stage WWTP with TN/COD = 11/120

Table 43: Detailed demand on electrical energy for wastewater treatment of 2-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Energy for inflow pumps	477	477	477	477	477	kWh/d
Energy for screens*	205	205	205	205	205	kWh/d
Energy for sand and grease trap*	205	205	205	205	205	kWh/d
Energy for sedimentation tanks*	342	342	342	342	342	kWh/d
Energy for aeration 1st stage	519	597	808	850	850	kWh/d
Energy for aeration 2nd stage	3,096	2,741	2,444	2,496	2,496	kWh/d
Energy for aeration SDE treatment	0	116	122	0	0	kWh/d
Energy for stirring unit 1st stage	46	58	67	65	65	kWh/d
Energy for stirring unit 2nd stage	400	352	313	319	319	kWh/d
Energy for stirring unit SDE treatment	0	6	9	0	0	kWh/d
Energy for stirring unit digester	237	244	250	249	249	kWh/d
Energy for pumps Bypass	0	0	0	0	0	kWh/d
Energy for pumps RS1	201	232	255	251	251	kWh/d
Energy for pumps RS2	267	267	265	266	266	kWh/d
Energy for pumps internal recirculation	44	29	17	19	19	kWh/d
Energy for pumps nitrate recirculation	78	79	77	78	78	kWh/d
Energy for pumps digester circulation	34	35	35	35	35	kWh/d
Energy for air-stripping	0	0	0	192	0	kWh/d
Energy for membrane-stripping	0	0	0	0	256	kWh/d
Energy for MST	21	22	23	23	23	kWh/d

Energy for sludge dewatering	131	135	138	138	138	kWh/d
Energy for heating*	342	342	342	342	342	kWh/d
Energy for other infrastructure*	411	411	411	411	411	kWh/d
Energy for WWTP	7,058	6,896	6,807	6,965	7,029	kWh/d
Energy for WWTP	25.8	25.2	24.8	25.4	25.7	kWh/PE/a
Energy from Biogas utilisation	4,952	5,299	5,577	5,531	5,531	kWh/d
Energy gain/Energy demand	70.17	76.85	81.93	79.41	78.69	%

** Not calculated, but assumed values from benchmarking report Austrian WWTP 2015*

Table 44: Detailed Q-balance for 2-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Q inflow primary sedimentation	17,500	17,500	17,500	17,500	17,500	m³/d
Q PS	73	72	71	71	71	m³/d
Q outflow primary sedimentation	17,427	17,428	17,429	17,429	17,429	m³/d
Q Bypass	6,099	3,486	1,394	1,743	1,743	m³/d
Q ES 1st stage	318	400	465	455	455	m³/d
Q ES 2nd stage	304	257	219	226	226	m³/d
Q inflow MST	695	729	756	751	751	m³/d
Q raw sludge	99	102	104	104	104	m³/d
Q outflow MST to 1st stage	596	627	652	648	648	m³/d
Q inflow digester CoS/external sludge	0	0	0	0	0	m³/d
Q outflow digester	99	102	104	104	104	m³/d
Q dewatered sludge	12	12	12	12	12	m³/d
Q SDE	87	90	92	92	92	m³/d
Q SDE treatment to 1st stage	87	90	92	92	92	m³/d
Q nitrate recirculation	5,735	5,795	5,658	5,712	5,712	m³/d
Q inflow 1st stage	17,746	20,454	22,436	22,138	22,138	m³/d
Q outflow 1st stage	17,427	20,054	21,971	21,683	21,683	m³/d
Q inflow 2nd stage	23,527	23,540	23,365	23,426	23,426	m³/d
Q outflow 2nd stage	23,223	23,283	23,146	23,200	23,200	m³/d
Q RS1	17,746	20,454	22,436	22,138	22,138	m³/d
Q RS2	23,527	23,540	23,365	23,426	23,426	m³/d
Q internal recirculation	19,351	12,557	7,594	8,350	8,350	m³/d
Q total inflow 1st stage	35,491	40,909	44,873	44,276	44,276	m³/d
Q inflow intermediate sedimentation	35,491	40,909	44,873	44,276	44,276	m³/d
Q outflow intermediate sedimentation	17,427	20,054	21,971	21,683	21,683	m³/d
Q total inflow 2nd stage	66,404	59,637	54,324	55,203	55,203	m³/d
Q inflow secondary sedimentation	47,054	47,080	46,731	46,852	46,852	m³/d
Q outflow secondary sedimentation	23,223	23,283	23,146	23,200	23,200	m³/d
Q outflow WWTP	17,488	17,488	17,488	17,488	17,488	m³/d

Table 45: Detailed COD-balance for 2-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
COD inflow primary sedimentation	12,000	12,000	12,000	12,000	12,000	kg/d
COD PS	3,000	3,000	3,000	3,000	3,000	kg/d
COD outflow primary sedimentation	9,000	9,000	9,000	9,000	9,000	kg/d
COD Bypass to 2nd stage	3,150	1,800	720	900	900	kg/d
COD inflow 1st stage	5,850	7,200	8,280	8,100	8,100	kg/d
COD ES 1st stage	2,205	2,772	3,226	3,150	3,150	kg/d
COD inflow 2nd stage	5,850	5,040	4,392	4,500	4,500	kg/d
COD ES 2nd stage	1,838	1,554	1,327	1,365	1,365	kg/d
COD outflow WWTP	600	600	600	600	600	kg/d
COD raw sludge	7,043	7,326	7,553	7,515	7,515	kg/d
COD inflow digester CoS/external sludge	0	0	0	0	0	kg/d
COD digested sludge + CoS/external sludge	3,000	3,000	3,000	3,000	3,000	kg/d
COD SDE	0	0	0	0	0	kg/d
COD nitrate recirculation	0	0	0	0	0	kg/d
COD Biogas	4,043	4,326	4,553	4,515	4,515	kg/d
OU_C 1st stage	945	1,188	1,382	1,350	1,350	kg/d
OU_C 2nd stage	3,413	2,886	2,465	2,535	2,535	kg/d
OU_{DN} 1st stage	307	454	390	305	305	kg/d
OU_{DN} 2nd stage	1,706	1,443	1,232	1,268	1,268	kg/d
$OU_{DN}1/OU_C1$	32.49	38.23	28.18	22.61	22.61	%
$OU_{DN}2/OU_C2$	50.00	50.00	50.00	50.00	50.00	%

Table 46: Detailed TN-balance for 2-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
TN inflow primary sedimentation	1,100	1,100	1,100	1,100	1,100	kg/d
TN PS	75	75	75	75	75	kg/d
TN outflow primary sedimentation	1,025	1,025	1,025	1,025	1,025	kg/d
TN Bypass to 2nd stage	359	205	82	103	103	kg/d
TN inflow 1st stage	666	820	943	923	923	kg/d
TN ES 1st stage	132	166	194	189	189	kg/d
TN ES 2nd stage	110	93	80	82	82	kg/d
TN raw sludge	318	335	348	346	346	kg/d
TN inflow digester CoS/external sludge	0	0	0	0	0	kg/d
TN inflow digester	318	335	348	346	346	kg/d
TN SDE	141	151	159	158	158	kg/d
TN digested sludge + CoS/external sludge	176	183	189	188	188	kg/d
TN outflow WWTP	220	220	220	220	220	kg/d
TN total inflow 1st stage	808	971	978	938	938	kg/d
TN denitrified 1st stage	0	83	31	0	0	kg/d

TN outflow 1st stage	675	722	754	749	749	kg/d
TN inflow 2nd stage	1,034	927	836	852	852	kg/d
TN denitrified 2nd stage	597	505	431	443	443	kg/d
TN outflow 2nd stage	327	329	325	327	327	kg/d
TN nitrate recirculation	107	109	105	107	107	kg/d
TN denitrified + nitrate recirculation 1st stage	107	192	136	107	107	kg/d

Table 47: Calculation of required basin volumes for 2-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Basin volume primary sedimentation	1,094	1,094	1,094	1,094	1,094	m³
Basin volume AST 1st stage	955	1,200	1,396	1,364	1,364	m³
Basin volume intermediate sedimentation	2,127	2,127	2,127	2,127	2,127	m³
Basin volume AST 2nd stage	8,330	7,323	6,517	6,652	6,652	m³
Basin volume secondary sedimentation	5,469	5,469	5,469	5,469	5,469	m³
Basin volume SDE treatment	0	130	184	0	0	m³
Volume digester	2,469	2,542	2,601	2,591	2,591	m³

Table 48: Detailed construction costs for 2-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Costs primary sedimentation	710,938	710,938	710,938	710,938	710,938	€
Costs AST 1st stage	859,091	1,080,000	1,256,727	1,227,273	1,227,273	€
Costs intermediate sedimentation	2,552,083	2,552,083	2,552,083	2,552,083	2,552,083	€
Costs AST 2nd stage	7,497,102	6,590,700	5,865,579	5,986,433	5,986,433	€
Costs secondary sedimentation	6,562,500	6,562,500	6,562,500	6,562,500	6,562,500	€
Costs digester	6,172,247	6,355,060	6,501,310	6,476,935	6,476,935	€
Costs electrical engineering	100,000	100,000	100,000	100,000	100,000	€
Costs measurement technology	150,000	150,000	150,000	150,000	150,000	€
Costs Nitritation electrical engineering	-	100,000	-	-	-	€
Costs Nitritation measurement technology	-	25,000	-	-	-	€
Costs Nitritation infrastructure, design, construction	-	224,844	-	-	-	€
Costs Anammox electrical engineering	-	-	100,000	-	-	€
Costs Anammox measurement technology	-	-	50,000	-	-	€
Costs Anammox infrastructure, design, construction	-	-	334,925	-	-	€
Costs Air-stripping electrical engineering, chemical storage	-	-	-	250,000	-	€
Costs Air-stripping design and construction	-	-	-	583,112	-	€
Costs Air-stripping infrastructure	-	-	-	142,223	-	€
Costs Membrane-stripping electr. eng., chemical storage	-	-	-	-	250,000	€
Costs Membrane-stripping design and construction	-	-	-	-	568,890	€

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

Costs for membranes	-	-	-	-	85,334	€
Total costs for WWTP	24,603,961	24,451,125	24,184,062	24,741,496	24,670,384	€
Total costs for WWTP	246.0	244.5	241.8	247.4	246.7	€/PE

Table 49: Running costs for 2-stage WWTP with influent ratio TN/COD = 11/120 and different SDE sidestream treatment options

Parameters	SDE sidestreamt treatment concept					Unit
	without	Nitritation	Anammox	Air-stripping	Membrane-stripping	
Costs for depreciation WWTP	1,640,264	1,630,075	1,612,271	1,681,944	1,683,366	€/a
Costs for external electricity	92,223	69,912	53,879	62,809	65,612	€/a
Costs for polymer	132,787	133,940	134,862	134,708	134,708	€/a
Costs for H_2SO_4 98%	-	-	-	22,703	22,703	€/a
Costs for NaOH 50%	-	-	-	34,062	34,062	€/a
Other costs stripping	-	-	-	2,596	2,596	€/a
Revenues from sale of N-fertilizer	-	-	-	51,911	51,911	€/a
Overall running costs	1,865,274	1,833,926	1,801,012	1,886,911	1,891,136	€/a
Overall running costs	18.7	18.3	18.0	18.9	18.9	€/PE/a