#

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

D 5.6: Market validation for new concepts

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

Deliverable 5.6	*Market validation for new concepts*
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Deliverable lead:	Veolia Germany
Author(s):	Damien Cazalet
Contact for queries	Damien Cazalet (damien.cazalet@veolia.com)
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Abstract	Results of energy audits performed in twenty wastewater treatment plants in Europe are presented in this report. The energy-efficiency has been assessed using the modified Veolia software OCEAN as well as several benchmarks published by the German water association (DWA). As a result of the current situation analysis, concrete actions, which aim upgrading the plants to the state-of-the-art, have been proposed and assessed with costs/benefits analysis. In a second step, POWERSTEP concepts have been defined and assessed regarding the energy-efficiency and the operating costs (except maintenance & staff). Investment, maintenance and staff costs have been calculated for three plants capacities in the frame of a life cycle assessment and costing whose results are available in the deliverable D5.5 (Remy & Cazalet, 2018).

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)

Versioning and Contribution History

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	2018-06-07	Christian Loderer (KWB)	1st Review
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v.04	2018-06-28	Damien Cazalet (Veolia Germany)	Actualisation of the results with the last missing audits
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Table of Content

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

List of figures

Glossary

AOB	Ammonia-oxidising bacteria
BOD	Biochemical oxygen demand
CAPEX	Capital expenditure
COD	Chemical oxygen demand
IFAS	Integrated fixed-film activated sludge
KPI	Key performance indicator
N	Nitrogen
NOB	Nitrite-oxidising bacteria
OPEX	Operating expenditure
P	Phosphorus
PE	Population equivalents
SBR	Sequencing batch reactor
TSS	Total suspended solids
WWTP	Wastewater treatment plant

Executive summary

This report summarizes the results of energy audits performed in twenty wastewater treatment plants in Europe. The energy-efficiency of the plant has been assessed using Veolia software OCEAN as well as several benchmarks published by the German water association (DWA). As a result of the current situation analysis, concrete actions, which aim upgrading the plants to the state-of-the-art, have been proposed and assessed with costs/benefits analysis. In a second step, POWERSTEP concepts have been defined and assessed regarding the energy-efficiency and the operating costs (except maintenance & staff). Investment, maintenance and staff costs have been calculated for three different plants capacities (5.000 PE, 50.000 PE, 500.000 PE) in the frame of a life cycle assessment and costing whose results are available in the deliverable D5.5 (Remy & Cazalet, 2018).

The assessment of the selected WWTP has showed that:

- Large plants (> 100.000 PE) usually have lower specific electricity consumptions to medium and small plants
- Big discrepancies could be observed concerning the specific electricity consumption of medium plants (10.001 to 100.000 PE) which are partly due to different level of discharge requirements, post-treatment being required in some plants, and to staff skills
- Three of the plants already produce more energy than they consume, but only one of them exclusively uses the energy production potential of the wastewater.
- Operating data are available but often not used at their maximal potential to assess the performances of the plants and in this study inconsistent data could be found out in a lot of plants.

The implementation step by step of the proposed state-of-the-art measures is the first step to extend energy self-sufficiency to more plants because consequent energy savings could be reached. Due to the lower level of energy-efficiency, savings potential are higher for medium plants. Most of them can be reached without CAPEX or with short-term payback increasing the interest of the implementation. At large WWTP, most savings can be achieved only with CAPEX. Measures with longer payback time often concern equipment renewal and should be performed by technical renewal. In addition to the energy savings, the implementation of sludge digestion at WWTP, which do not have any yet, represents a non-negligible potential to increase the energy production.

One of the proposed and assessed POWERSTEP technology (mainstream Anammox) is not yet mature enough to be implemented but it represents a very interesting option for the future. The energy production could be drastically increased thanks to higher sludge production with a higher biogas potential and lead to new levels of energy-efficiency.

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1. Introduction

Within the H2020 innovation project POWERSTEP (www.POWERSTEP.eu), a selection of innovative processes is demonstrated in pilot or full-scale which should significantly improve the energy balance of a municipal wastewater treatment plant (WWTP), finally enabling the operation of energy-positive treatment schemes.

Currently, municipal wastewater treatment in Europe requires a significant amount of energy to eliminate organic matter and nutrients (i.e. nitrogen and phosphorus) from the sewage prior to its discharge. In Germany for example, an average amount of electricity of 32 kWh per capita per year is required to treat wastewater. Overall, the municipal wastewater sector in Europe is estimated to consume the annual electricity generation of two large (1.000 MW) power plants [source: H2020 Project POWERSTEP; Grant Agreement No. 641661].

At the same time, calculations show that organic matter contained in municipal wastewater accounts for a chemical energy potential of 175 kWh per capita and year, or 87.500 GWh per year for entire Europe which is equivalent to 12 large power stations. This relation shows that it should be possible to design and operate energy-positive WWTPs by reducing energy demand for water treatment and exploiting the energy potential of the organic matter in raw wastewater.

Today, improving energy efficiency of WWTPs typically addresses only marginal improvements like more efficient aggregates (aerators and pumps) or anaerobic sludge treatment in a digester to produce biogas. The realisation of an energy-positive WWTP requires a combination of new concepts for wastewater treatment together with an optimised integration of existing technologies in all side aspects.

POWERSTEP uses concepts and technologies that have been successfully tested in pilot scale plants. Their full-scale commercial references with a reliable assessment of process efficiencies under realistic conditions remain at stake. POWERSTEP aims to demonstrate their viability to ensure a successful market deployment of the new technologies.

Within POWERSTEP there are four distinct interconnected steps to make the wastewater treatment plants energy-positive (Figure 1):

- Carbon extraction for enhanced energy recovery into biogas
- Nitrogen removal with low carbon requirements in the main stream
- Biogas valorisation and efficient energy management
- Nitrogen management in side stream

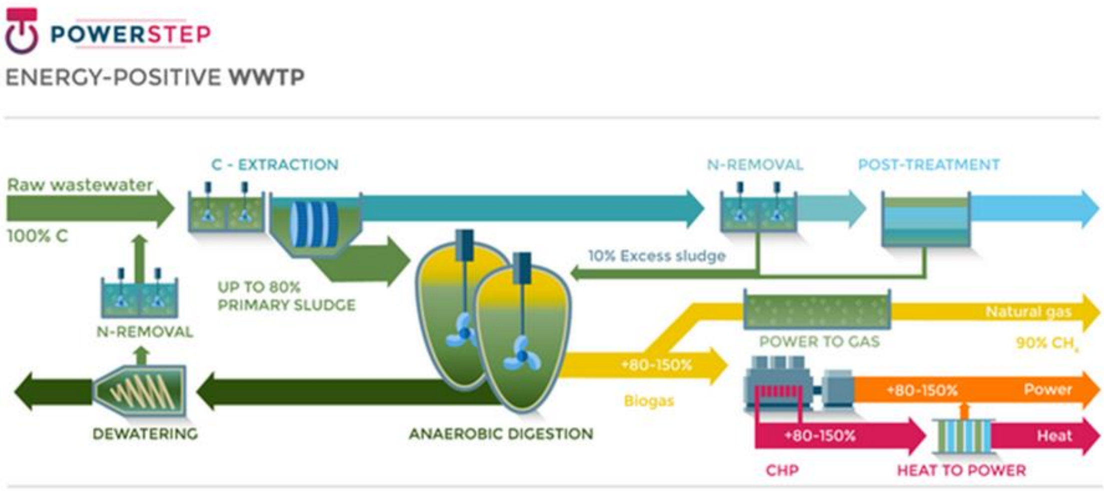

Figure 1: POWERSTEP concept of energy-positive wastewater treatment plant

The work package 5 aims to propose innovative treatment schemes based on these four steps which could enable WWTP to become energy self-sufficient and to evaluate the replication potential in Europe.

Within the work package 5, free energy audits have been performed in twenty WWTP in Europe in order to evaluate the current situation and the potential for implementing POWERSTEP concepts in existing WWTP.

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2. POWERSTEP energy audit

2.1. Concept

Conventional energy audits consist of:

1. Evaluation of the current situation
2. Investigation of optimisation potentials and proposition of correspondent measures to reach the state-of-the-art

A POWERSTEP energy audit is actually a conventional energy audit extended with an evaluation of the implementation of POWERSTEP concept at the WWTP. By this way, the effect of the implementation of POWERSTEP technologies can be evaluated separately from the effect of the "state-of-the-art" measures.

The proposed POWERSTEP treatment schemes have been selected according to:

- Capacity and actual inlet loads of the WWTP
- Current treatment scheme
- Results of the treatment schemes comparison (Remy & Cazalet, 2018) which was also performed using the OCEAN software

2.2. OCEAN software

The OCEAN software is the main tool used to perform the energy audits. The tool has been developed since 2009 by Veolia to enable:

- Predictive comparison of the energy-efficiency of different treatment schemes in pre-project
- Evaluation of the energy-efficiency of existing WWTP & calculation of optimisation measures

OCEAN is able to calculate the mass and energy balances as well as the chemicals consumptions of municipal WWTP. Since OCEAN has been developed to perform predictive comparison, the software is very flexible regarding the input data. Except the "construction" of the treatment schemes and the selection of equipment technologies, the tool is able either to assume or to calculate all other parameters in a consistent way. It enables performing energy audits in WWTP which have low quality of operating data:

- Inconsistencies between the operating data can be easily traced as well as the reason and corrections can be proposed to the plant operator.
- Missing data can be assumed in function of the available data. This is mostly the case in small WWTP since they do not have to measure and report as many parameters as large WWTP or with a lower frequency.

However it usually prevails: the higher the quality of the data, the higher the accuracy of the calculations. All data which can be available at a WWTP are useful to assess the performance of the plant:

- Plant data: process flow diagram, process description, tank dimensions …

- Equipment data: technology, nominal characteristics, nominal efficiency, manufacturer …
- Outlet discharge requirements: concentration limits and period (spot sample, 24h-composite, monthly or annual average) …
- Operating data:
  - Online data: flows, oxygen concentration in aeration tanks, ammonium, nitrate and phosphate measurements, redox potential …
  - Lab data: water composition, sludge composition, biogas composition, TSS content in activated sludge tank, sludge volume index …
  - Energy measurements: meters for consumed & produced energy (electricity and heat), sub meters …

Figure 2 summarizes the input and output data of the OCEAN software.

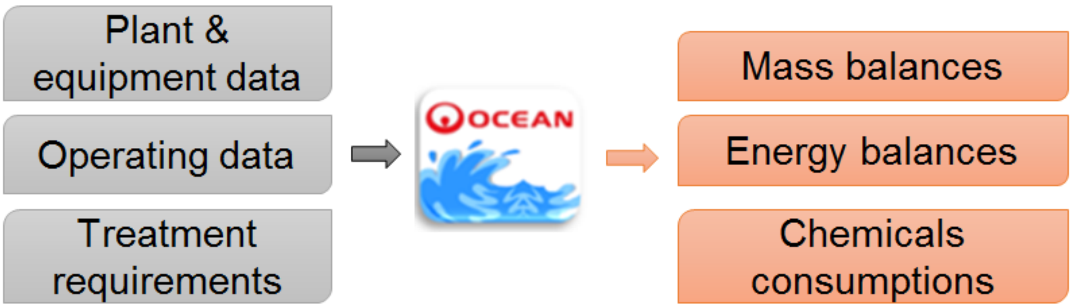

Figure 2: Input and output data of the OCEAN software

Figure 3 shows a screenshot of the OCEAN software.

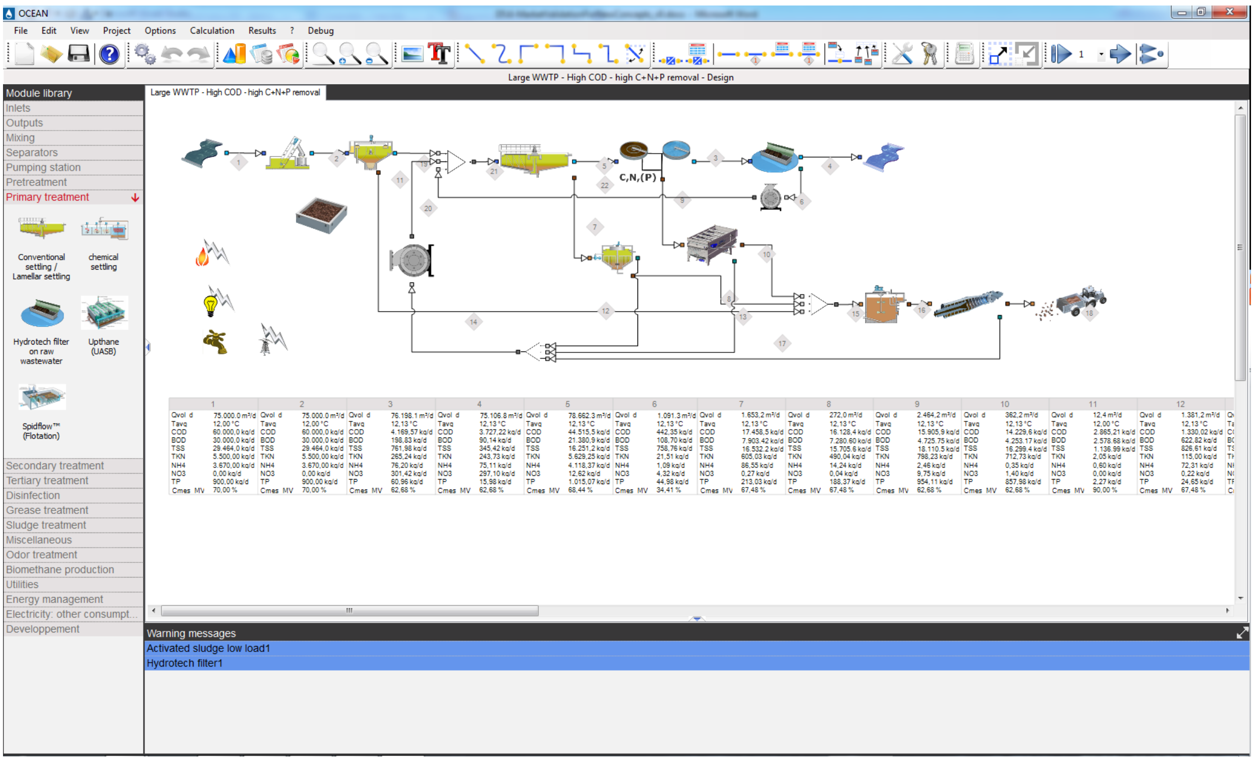

Figure 3: Screenshot of the OCEAN software

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The WWTP can be built by drag & drop actions using the available process modules listed on the left side. Process module calculations are based on literature and Veolia experience as plant provider and operator. During the POWERSTEP project, further development has been done in the OCEAN software:

- To improve the accuracy of some main modules using new calculation models (e.g. activated sludge model from the DWA-A 131 worksheet (DWA, 2016))
- To implement calculations models for the POWERSTEP technologies in collaboration with the project partners

2.3. Methodology & working steps

The energy audit is performed in five steps:

1. Data collection
2. Plausibility check & first assessment
3. Visit of the WWTP
4. Scenarios calculation using OCEAN software
5. Audit report delivery

An energy audit can usually be performed within one month if the timeline can be planned in an optimal way.

2.3.1. Data collection:

A questionnaire as Excel-file is sent to the WWTP operator where we ask for all data which can be available at a WWTP:

- Plant & equipment data
- Operating data in annual average of the last three years
- Energy and consumables buying and selling (if relevant) prices
- Sludge disposal costs

Filling the questionnaire represents a time expenditure of approx. one day for the operator, depending on the complexity of the plant, the amount of data and the quality of their management.

2.3.2. Plausibility check & first assessment

First the data from the last three years are compared in order to choose the most appropriate year. As far as possible, the most recent data are used for the assessment but some years are not representative of normal operation (e.g. implementation of measures which can lead to transitional conditions). The comparison of the operating data of the three years also shows if measures, which have a relevant effect on the performances, have been implemented.

A first calculation of the "current situation" is done with OCEAN using the selected annual data. The available data can be checked for consistency and a comparison between the calculated and actual values highlight the points which have to be discussed with the operator during the plant visit.

In parallel, some KPI are calculated and compared with literature:

- Specific electricity consumption and production (if appropriate) are calculated in kWh/(PE(COD)·a) and compared to the benchmark of the German water association performed every two years (DWA, 2016)
- The specific coagulant consumption is calculated in mol_{Me}/kgP and compared with guide values from the DWA-A 202 worksheet (DWA, 2011)
- The performance of the sludge thickening is assessed comparing the specific polymer consumption (if so) and reached DM content to ranges given by the DWA-M 381 information sheet (DWA, 2007)
- The performance of the sludge dewatering is assessed comparing the specific polymer consumption and reached DM content to ranges given by the DWA-M 366 information sheet (DWA, 2013)

The use of KPI is complementary to the first calculation of the "current situation" scenario with OCEAN and can help to solve inconsistencies. In some plants the disposed sludge amount (considering dry matter) is high compared to the inlet loads of the plant. In one of the plants, the analysis of the KPI argued for an overestimation of the disposed sludge amount:

- High DM content are reached in the sludge dewatering while the specific polymer consumption is lower than the minimal value given by the DWA-M 366 information sheet (DWA, 2013) → quite probable that the sludge amount are too high
- Specific electricity consumption and production are comparable to the 15 – 20% best plants in the DWA benchmark (DWA, 2016) → quite improbable that the inlet loads are underestimated

In case of inconsistencies, corrections have been proposed to correct the operating data:

- Assessment with KPI is adjusted to the corrected values.
- "Current situation" scenario is calculated taking into account these corrections.

2.3.3. Visit of the WWTP

The visit of the WWTP is a very important step in the audit process:

- Questions from the first assessment can be answered
- Check of inconsistent data: the operator usually has an opinion about the accuracy of the several data which can help to identify problematic data
- Visual assessment of the plant & equipment
- Additional important information can be collected about
    - Operating issues
    - Way of operating the plant (monitoring using KPI and/or targets)
    - Local context (legislation, prices, …)
    - Plant specificities and constraints
    - Staff skills regarding operational optimisation (process engineering skills)
    - Engagement / interest for optimising the energy efficiency & costs balances of the plant

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- Implemented, ongoing and planned projects
- Exchange with the operator concerning potential optimisation measures

To take maximum advantage of the visit, it is necessary that the contact person on site knows very well the plant but also the context and constraints.

2.3.4. Scenarios calculation using OCEAN software

Figure 4 gives a short overview of the methodology used to perform the POWERSTEP energy audits:

1. Calibration of the "current situation" scenario
2. Calculation step by step of state-of-the-art measures to reach a "state-of-the-art" scenario taking into account all measures
3. Calculation of POWERSTEP scenarios

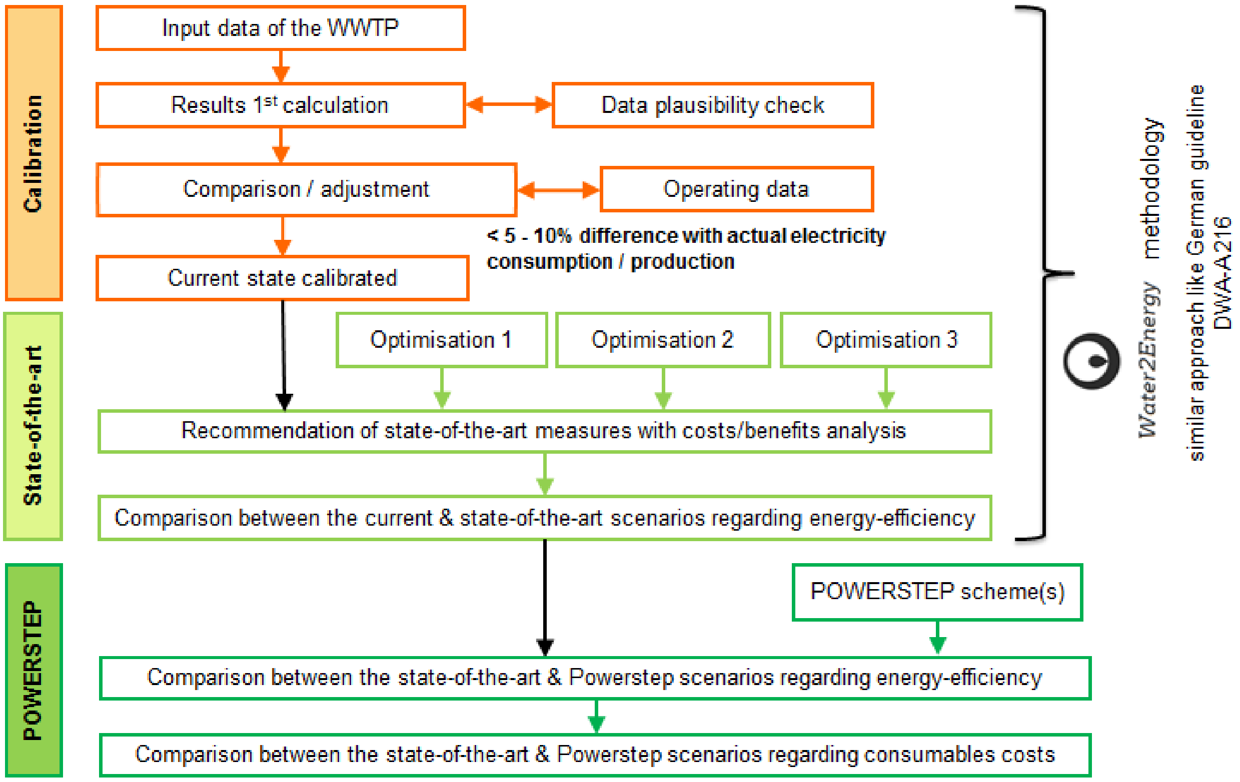

Figure 4: Overview of the POWERSTEP audit methodology

Calibration of the "current situation" scenario

This scenario is calculated based on all the collected data (questionnaire and visit) and the corrections performed during the consistency check.

The tool is considered as calibrated if the calculated electricity consumptions and productions are close enough to the actual values. The difference between the calculated and actual values is usually lower than 5% which is very satisfying.

In some plants, electricity sub meters are available and used during the calibration to check the electricity consumption calculated for the measured consumers. It gives more substance to the OCEAN calibration.

Figure 5 shows that calibration results were satisfying for most of the plants:

- Concerning the WWTP 6 and 12, the total electricity consumption was not consistent with the sub meters.
- WWTP 8 has a complicated treatment schemes with several treatment lines using different processes. Moreover pumps, blowers as well as other equipment are quite old and not as efficient as they should be. The deviation can be partly explained by the fact that only few pumps have the measurement required to assess their energy efficiency. For other equipment, the assumed energy efficiency probably does not fit with the actual one.
- The mass balances of the WWTP 17 were not fitting leading to higher uncertainty of the calculations
- For all other plants, the actual electricity consumption and production could be calculated with acceptable deviation.

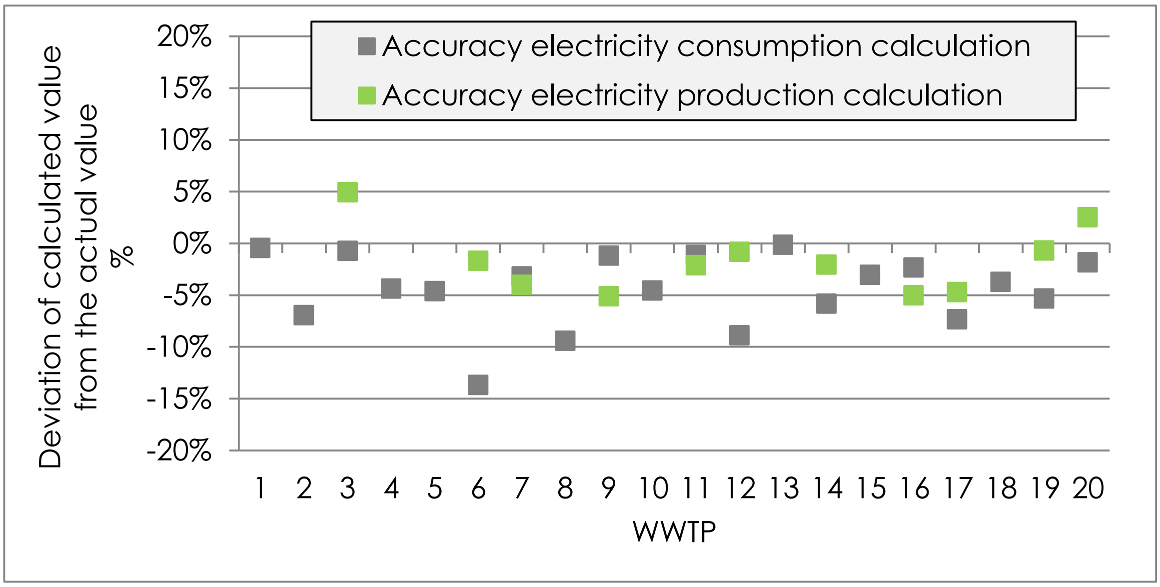

Figure 5: Accuracy of OCEAN tool calculations

For the few WWTP which buy and/or sell other energy sources (gas or heat), the deviation between sold and bought quantities has been calculated and is lower than 10% except for natural gas consumption in one plant. However the natural gas consumption represents for this plant only 2% of the energy contained in the biogas.

Calculation of the state-of-the-art scenario

Once the "current situation" scenario is calibrated, the next step is to propose and evaluate state-of-the-art measures. Issues and saving potentials are pointed out during the current situation assessment and the WWTP visit:

- Non-compliance with the discharge requirements

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- Operating issues or unstable operating conditions (e.g. bulking, foaming in the digestion, …)
- Non-optimal way of operation of certain processes
- Outdated equipment technologies
- Oversized equipment and/or tanks
- Lack of energy recovery using digestion process for medium and large plants

A "state-of-the-art scenario" is calculated with OCEAN starting from the calibrated "current situation" scenario, all proposed measures being implemented step by step. The order of the calculation is quite important since several measures can have an impact on the same consumers. Following aspects are taken into account:

- The benefit: priority for the measures to make the plant compliant with legislation and to reach stable operation
- The implementation costs and efforts: priority for the measures without CAPEX
- The synergies: e.g. measures to improve air diffusion system should be calculated and implemented before measures to renew outdated blowers since the efficiency of the air diffusion system has an effect on the required air flow.

The use of the OCEAN software gives the advantage that the effects of the proposed measures on the whole WWTP operation are taken into account.

For each state-of-the-art measure, an "optimisation summary sheet" compiles (examples in annex 0):

- A description of the measure: objective(s), benefit, points to be taken carefully, recommendations
- Cost-benefit analysis:
  - The order of magnitude of the investment costs has been estimated according to former projects implemented in WWTP operated by Veolia.
  - Savings and additional operating costs (e.g. to make the plant compliant) calculated according to OCEAN results and the prices given by the operator.
- Key values: relevant parameters for the savings calculation, assumptions, results

The optimisation sheet enables the WWTP manager to evaluate the pertinence, the priority and the convenient time to implement each measure and to make decision. For example, some equipment renewal measures have a quite long payback time which makes sense to implement them at a time of technological renewal.

Figure 6 shows the large panel of state-of-the-art measures which have been proposed in the POWERSTEP audits. "Energy audits" should not be limited to an analysis of the energy-efficiency of the equipment. High energy and more generally costs savings can be reached optimising the operating conditions of the different processes. To take maximum advantage of an energy audit, the auditor should have skills and experience in all these fields. The OCEAN tool allows performing a global assessment of the plant operation in a limited time. However it is not possible to give treatment guarantees using OCEAN tool. For measures affecting the treatment performance, further investigations/calculations are required to ensure that the measures do not negatively impact treatment performance.

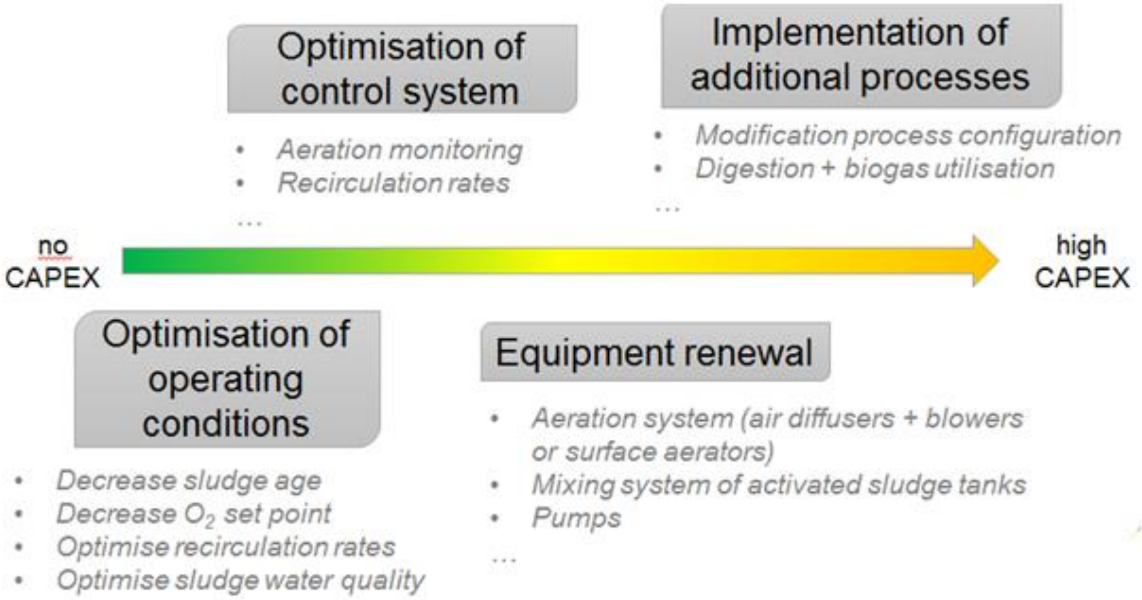

Figure 6: Type of state-of-the-art measures proposed in the frame of POWERSTEP audits

Calculation of the POWERSTEP scenario(s)

The third step of the calculation process is to evaluate the effect of the implementation of POWERSTEP technologies. The calculation of the POWERSTEP scenarios are based on the state-of-the-art scenario so it has been assumed that all proposed state-of-the-art measures will be implemented before the POWERSTEP concept(s). By this way, the "real" effect of POWERSTEP concepts can be assessed, additional effect due to "non-optimised" current situation being excluded.

Following scenarios have been considered and calculated:

1. Main scenario with the objective to increase at a maximum the carbon extraction without use of external carbon needs
2. Only for plants with biomethane injection: evaluation of the implementation of a Power-To-Gas technology to convert electricity in synthetic methane through transformation of the CO_2 extracted from the biogas, combined with the implementation of the POWERSTEP scenario 1

For the "POWERSTEP 1" scenario, tailor-made treatment schemes have been defined for each WWTP according to:

- Results of the treatment schemes comparison (Remy & Cazalet, 2018)
- Capacity and loading of the WWTP
- Current treatment scheme

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The results of "POWERSTEP 1" scenario are compared to the state-of-the-art scenario regarding:

- Energy balances
- Operating costs excluding maintenance and staff: energy, consumables and sludge disposal costs

If so, the POWERSTEP 2 scenario is compared with "POWERSTEP 1" results. Since the main goal of this process is to enable the conversion of electricity into gas which can be stored, this scenario has only been considered as an "add-on" in the audits assessment.

The investment costs have not been calculated for the POWERSTEP scenario(s) because they were not yet available. In the meantime, they have been calculated for three plant capacities as new plants (no retrofitting) in the frame of a life cycle costing. Results are available in the deliverable 5.5 (Remy & Cazalet, 2018).

2.3.5. Audit deliverable

For each assessed WWTP, a report or a presentation was delivered to the plant manager including:

1. Results summary:
    - Summary of electricity balances (e.g. in annex 0)
    - Evolution of the position in the DWA benchmarks for electricity consumption and production (DWA, 2016) (representation of all scenarios in the diagrams, e.g. in annex 0)
    - Global energy balances considering electricity, gas and heat
2. Context:
    - Description of WWTP including treatment schemes and dimensioning loads
    - Discharge requirement
3. Description of the audit methodology
4. Overview of operating data
    - Actual inlet loads (average values and if available 85%ile values) and determination of the loading rate (comparison with the dimensioning loads)
    - Comparison of the actual outlet concentration in annual average with the discharge limits
    - Argumentations about inconsistent and implausible data with proposition of corrections
5. Assessment of the WWTP performance using KPI
    - Assessment of the current "way of operation": use of KPI? Targets?
    - if necessary, proposition of some KPI to be followed in operation
    - results of the comparison with several DWA benchmarks (chapter 2.3.2, annex **Fehler! Verweisquelle konnte nicht gefunden werden.**)
6. Results of the assessment based on OCEAN calculations (chapter 2.3.4)

- Calibration of the "current situation" scenario (annex **Fehler! Verweisquelle konnte nicht gefunden werden.**)
- Optimisation sheets for each proposed state-of-the-art measure and comparison of the energy balances of the "state-of-the-art" to the "current situation" scenario (annex 0)
- Description of the POWERSTEP scenario(s) and comparison with the state-of-the-art scenario regarding energy balances and operating costs (except staff and maintenance costs)

2.4. Time expenditure

The time expenditure of an audit varies from 5 to 8 working days depending on the complexity of the treatment scheme, the quality of the data and the number of proposed measures:

- approx. 1 day to perform the first assessment and consistency check (chapter 2.3.2)
- 0,5 to 1,5 days for the visit (travel is not included) (chapter 2.3.3)
- 2 to 3 days to perform the calculations (chapter 2.3.4)
- 1,5 to 2,5 days to write the audit report (chapter 2.3.5)

3. Selection of the wastewater treatment plants

3.1. Selection process

At the beginning of the POWERSTEP project, the scope, methodology and deliverable of the POWERSTEP audits were defined.

Then the organisation of the audit campaign started in January 2016 with the preparation of the audit campaign. Together with B.&S.U. (Beratungs- und Service-Gesellschaft Umwelt mbH) and KWB (Kompetenzzentrum Wasser Berlin gGmbH), following steps were defined and scheduled:

1. Audit promotion from April 2016 to December 2016
2. Call for candidatures from October 2016 to December 2016
3. Selection of the candidatures in January 2017

From January 2016 to April 2016, a Powerpoint presentation describing the audit timeline, the methodology and audit deliverables was prepared as well as a cooperation agreement establishing the roles and duties of each partner. Data confidentiality and anonymised publication of the results were important points of the cooperation agreement. Both documents were uploaded on the POWERSTEP website in April 2016 in order to promote the audits. Moreover a communication was done by B.&S.U. within the European Energy Awards network and by KWB within other European projects in order to reach the maximal amount of municipalities.

In October 2016, the call for candidatures started. Interested municipalities had to fill a questionnaire asking for some key data:

- Plant capacity
- Loading rate
- Information concerning the treatment scheme
- Electricity price
- Discharge limits

The questionnaire was established according to selection criteria that were defined upstream in order to ensure a large panel of conditions.

Thirty-eight candidatures were received until the deadline and twenty plants were selected under these conditions:

- 6 tickets were reserved for the three project partner which operate WWTP
- Get a panel as representative as possible of the variabilities within Europe
  - Geographic location
  - From small to large WWTP
  - From low to high specific electricity consumption
  - From standard to advanced discharge requirements
  - From low to high electricity price

A cooperation agreement was signed with all the selected WWTP.

3.2. A WWTP panel representing various conditions

3.2.1. Location

The twenty WWTP are located in nine different countries (Figure 7). Germany is the most represented country because most of candidatures came from German WWTP.

Figure 7: Location of the selected WWTP

3.2.2. Treatment capacity

The WWTP selection covers a large range of plant capacities from 2.000 PE to 2.000.000 PE (Figure 8):

- 1 WWTP in the size range 1.000 to 5.000 PE (German size range GK 2)
- 6 WWTPs in the size range 10.001 to 100.000 PE (German size range GK 4)
- 13 WWTPs in the size range higher than 100.000 PE (German size range GK 5)

Large plants were favoured in the selection because they have the highest potential for POWERSTEP concept implementation (greater technical and economic viability + relatively greatest impact on a regional energy balance). As a consequence, 15 WWTPs are equipped with sludge digestion producing biogas.

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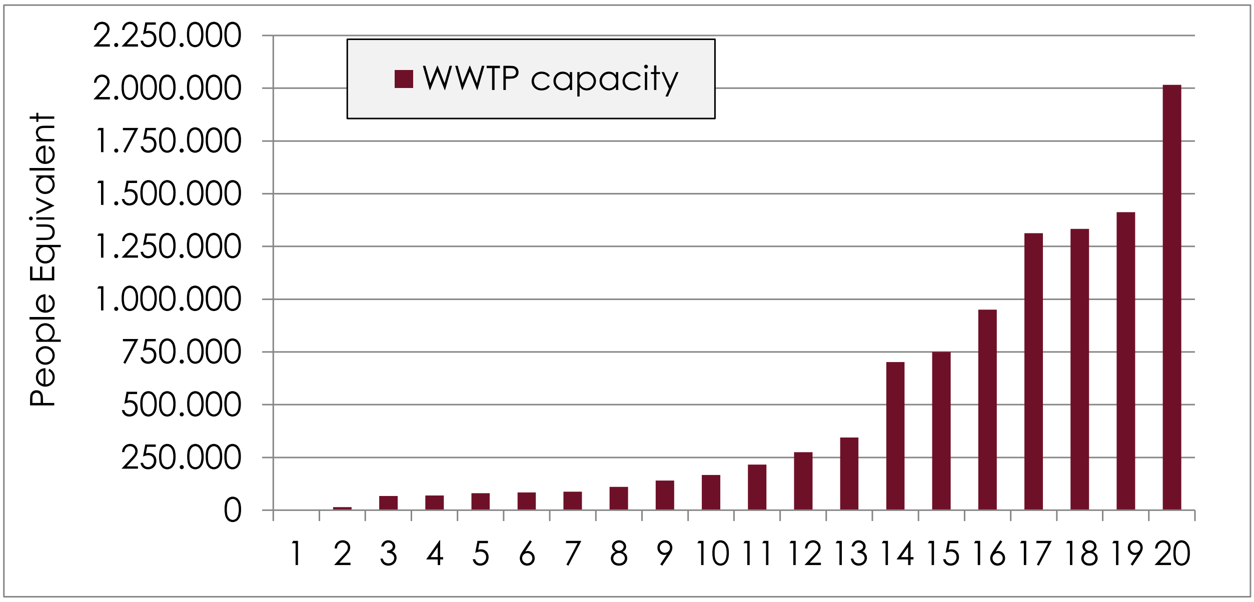

Figure 8: Capacity of the selected WWTP

3.2.3. Discharge requirements & treatment scheme

The analysis of the discharge requirements shows relatively high discrepancies between the twenty WWTP:

- Compliance determination:
  - Based on raw analysis results from grab or 24 h-composite sample or based on calculated periodic average (monthly or annual)
  - Limit for N depending on the wastewater temperature or not (no limit below 12°C wastewater temperature in most of the plants)
- COD discharge limit from 40 mg/l to 125 mg/l without correlation with the capacity of the WWTP (Figure 9)
- Plant 8 has no COD discharge limit but limits for BOD and TSS
- N discharge limit decreases with the capacity of the plant, the values being usually in a range from 8 mg/l to 18 mg/l (Figure 10)
  - N discharge limits are not exactly comparable: in Germany the "Nges" limit actually corresponds to a limit for inorganic nitrogen (NH_4-N + NO_x-N) while limits are usually expressed in total nitrogen (inorganic + organic), organic nitrogen outlet concentration representing up to 2 mg/l
  - Plant 4 had until 2015 very strict discharge limits (for all parameters) but they are now discharging in other river for which the requirements are much lower
  - Plant 16 has to treat carbon pollution only. However phosphorus removal is being implemented in 2018 and nitrogen removal has to be implemented in the coming years (project start in 2018).
- P discharge limits are for most WWTP between 1 mg/l and 2 mg/l (Figure 11)
- Plant 4 has a requirement on Escherichia coli (5.000 UFC/100ml)

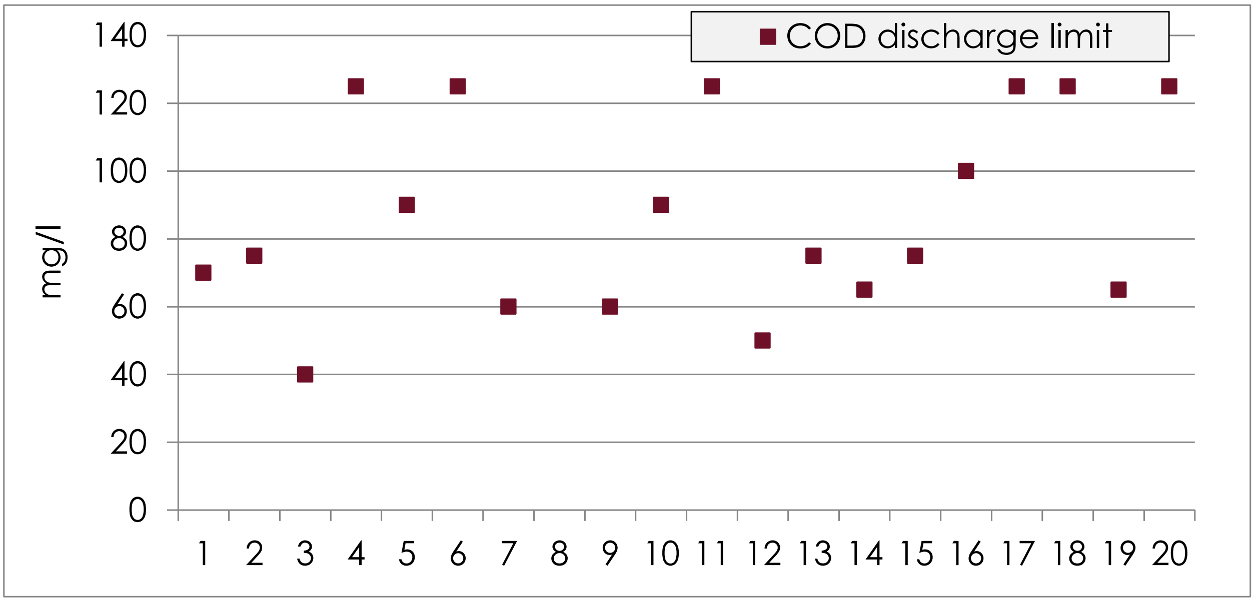

Figure 9: COD discharge limit at selected WWTP

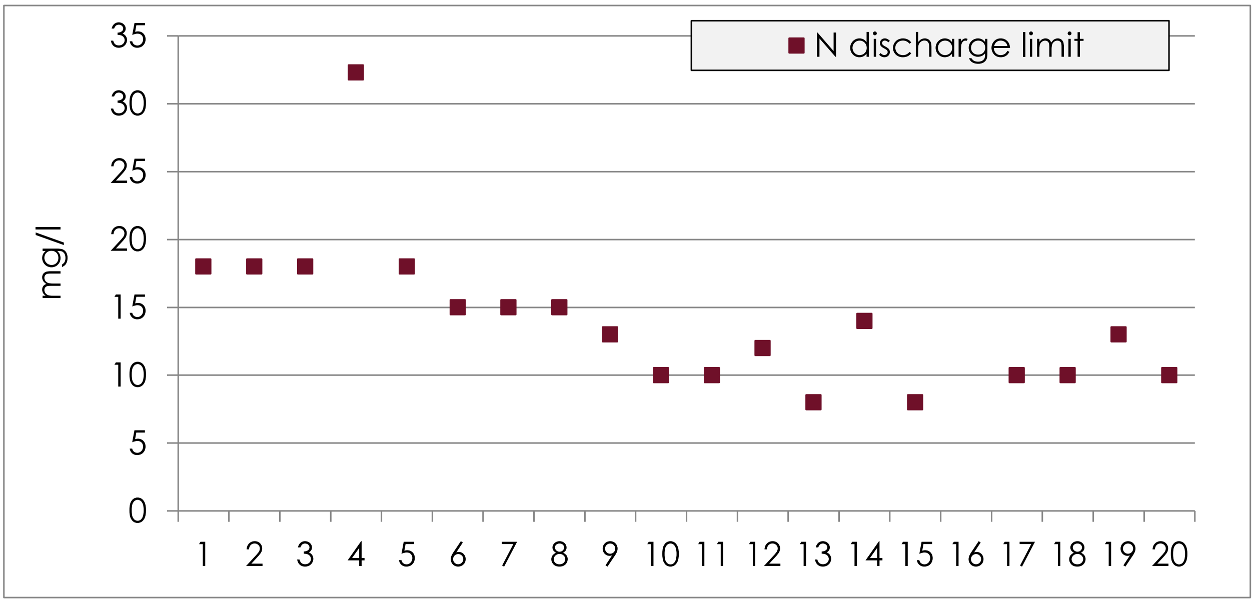

Figure 10: N discharge limit at selected WWTP

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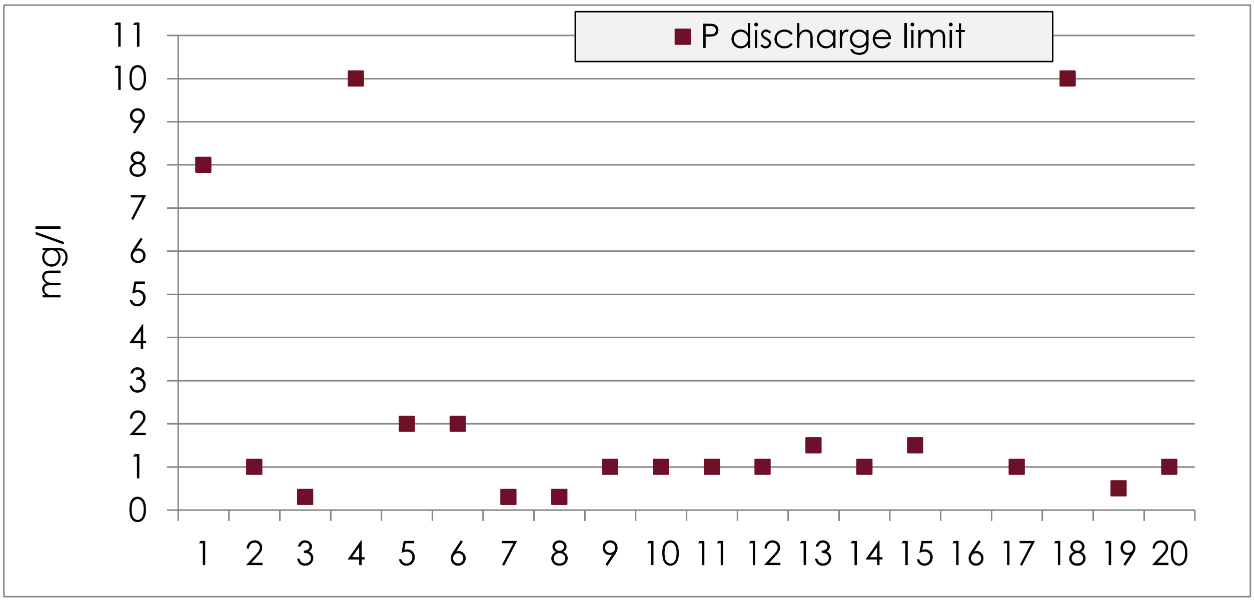

Figure 11: P discharge limit at selected WWTP

Concerning the treatment schemes, all plants are equipped with activated sludge process as main biological treatment, one of them using SBR configuration. For plants with low P discharge requirement (< 1 mg/l), a post treatment with coagulation or coagulation/flocculation is used (filtration or settling). Fifteen plants are equipped with conventional primary settling tanks in order to recover COD for the digestion. One plant is drying the sludge up to 90% DM content and two other plants are incinerating it.

3.2.4. Electricity consumption & electricity price

The WWTP were selected in order to have large panels of specific electricity consumption. Figure 12 shows that the specific electricity consumption of the selected medium WWTP (10.001 to 100.000 PE) is quite variable. Discrepancies are lower for large WWTP (> 100.000 PE) since half of the plants are closed to the 15%ile value of DWA benchmark (DWA, 2016) while other half are near the median value.

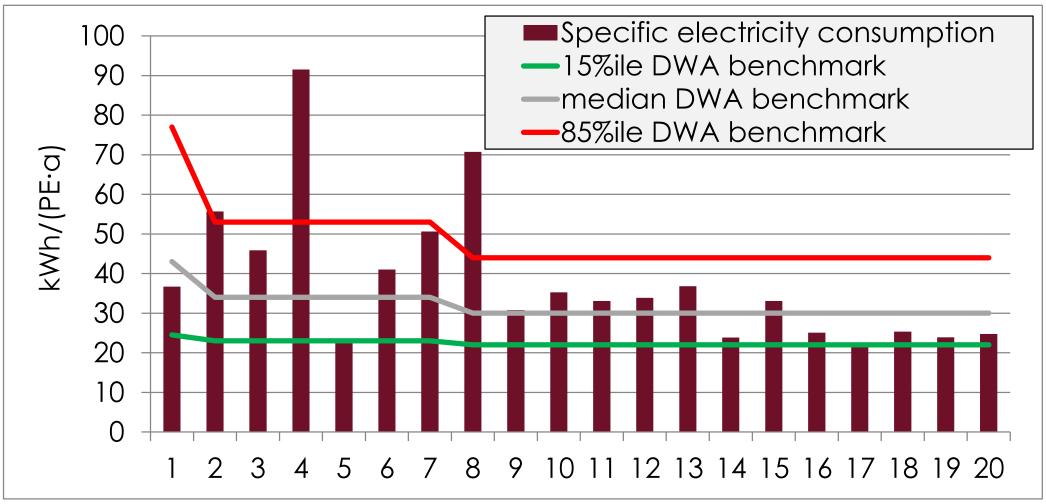

Figure 12: Comparison of the specific electricity consumption of the selected WWTP with the 15%ile, median and 85%ile values of the DWA benchmark (DWA, 2016)

Figure 13 shows that electricity buying prices strongly depends on the national context (way to produce electricity, taxes). As a result there is a factor five between the lowest and highest price.

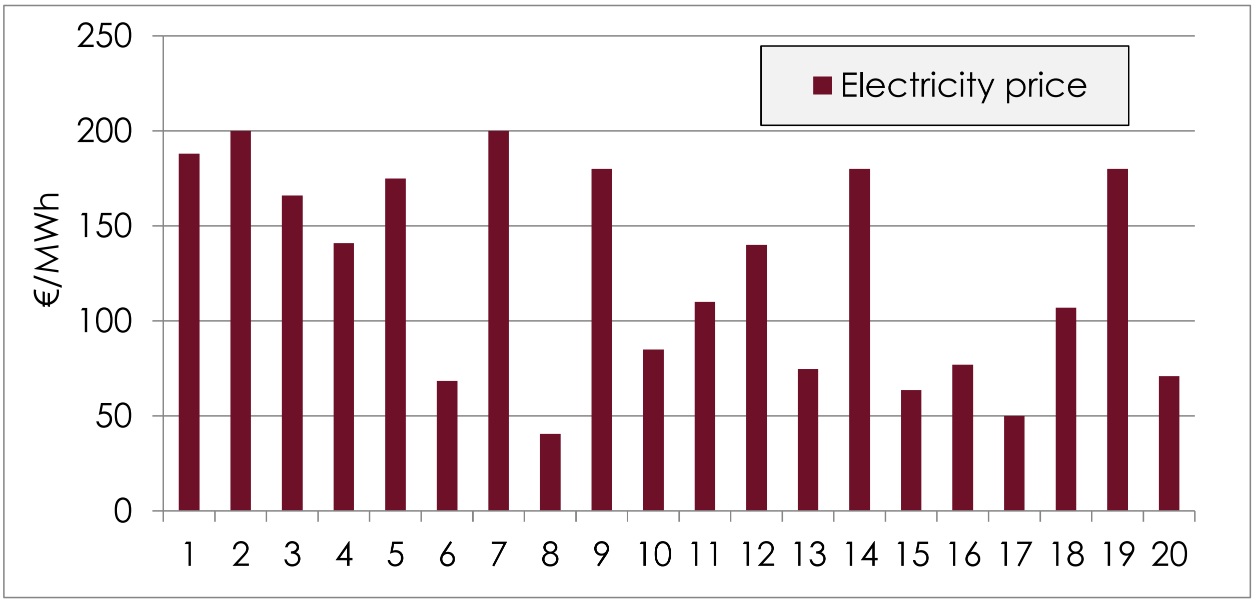

Figure 13: Electricity buying price at selected WWTP

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4. Assessment of the selected plants

4.1. Operation and treatment performances

4.1.1. Actual average loading rates

For the plants where the data were available, the actual loading rate has been determined considering the 85%ile of the daily COD inlet loads according to ATV-DVWK-A198 (ATV-DVWK, 2003)

However, for many plants the 85%ile loads were not available. For this reason, a comparison was done using the average load (Figure 14). Taking into account that the ratio between 85%ile and average loads amounts to 1,2 to 1,3 (observed when 85%ile loads are available), an average loading rate of 80% would approximately correspond to a loading rate of 100%. Figure 14 shows:

- The loading rates are very variable (from 40% to 140%)
- Four (large) plants are overloaded by at least 20% in average
- Four plants are loaded at approx. 80% in average corresponding to a loading rate of approx. 100%
- Twelve plants are strongly underloaded, of which five plants treat in average less than 50% of the dimensioning load

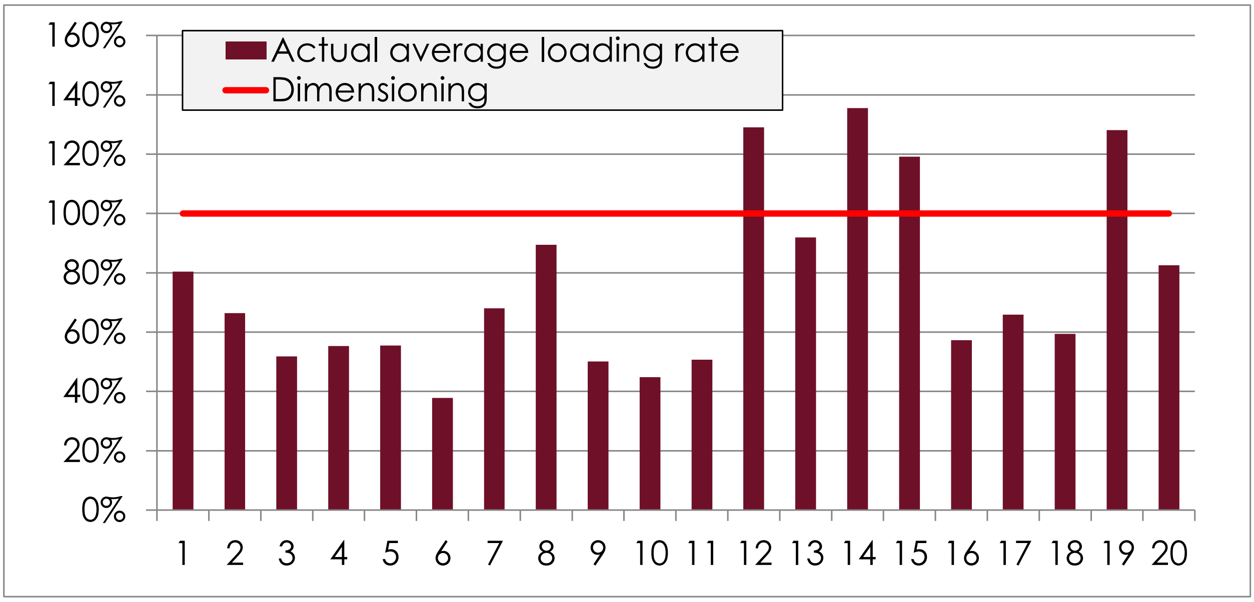

Figure 14: Actual average loading rates of the WWTP

4.1.2. Compliance with the discharge requirements

At seventeen plants, all annual average concentrations are lower than the discharge limits. Nevertheless, it does not mean that the effluent quality complies with the discharge requirements since some of the plant are evaluated in shorter period of time (spot sample, 24h-composite, monthly average, …). At the other three WWTP, the issue always concerns the nitrogen:

- At one plant, the configuration of the biological treatment does not enable to reach better effluent quality
- At the two other plants, the operating conditions could be optimised to meet the requirements

Local water authorities have different approaches concerning the outlet quality which the operators more or less encourage to meet the discharge requirements:

- at one of the non-compliant plants, there was no real inconvenient (no monetary penalties, no citation before the court)
- at other plants, the plant manager could be cited before the court in case of recurrent non-compliance
- in several countries, WWTP have to pay fees for the actual amount of pollutant they discharge respectively the amount they are allowed to discharge, the specific costs increasing in case of non-compliance

4.1.3. Operation monitoring

Operating data quality

In all WWTP, data are collected according to the requirements from the local water authorities. In most of the plants, no cross-checking of the data is performed to ensure consistency between parameters which are dependent. At large WWTP, the skills level of the “numerous” staff make that most of the collected data are consistent. At medium WWTP, it is more often the case that the data are not consistent and nobody is able to detect implausible values. The worst case scenario is that the calculated and assessed KPIs are impacted. The plant manager could for example think that the performance of the plant is better than it actually is.

Monitoring

Most of the plants are using KPIs linked to the operating costs (specific energy consumption, specific chemicals consumptions, DM content of the disposed sludge …):

- Monthly or yearly comparison of values
- Comparison with values from the literature or from benchmarks
- Comparison with targeted values

This level of monitoring enables detecting anomalies and deviation but is not really adapted to find out optimization potentials and assess the implementation of measures. An extension of the followed KPI should be considered:

- Operating conditions (e.g. sludge age in the activated sludge process)
- Set points (e.g. dissolved oxygen in the aeration tanks)
- Performance of key equipment (e.g. specific energy consumption of inlet pumps, pressure difference of the blowers to assess the state of the air diffusers)

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4.2. Energy efficiency

4.2.1. Energy balances

Beside electricity which can be produced at WWTP equipped with cogeneration unit of the biogas produced in the sludge digestion, combustible (natural gas or fuel oil) and heat are imported and/or exported at some WWTP (

Figure 15):

- Combustible:
  - Import is usually negligible compared to the electricity import: two WWTPs had high natural gas and oil consumptions due to:
    - Total Sludge drying (> 90% DM content)
    - Oversized CHP due to very low loading rate of the WWTP
  - Export is quite usual in northern Europe since the biogas produced in the digestion is commonly upgraded to biomethane in order to be used as combustible (e.g. combustible for cars or busses).
- Heat:
  - Heat is usually produced in excess at WWTP but most of the time, the excess is lost due to the location of the WWTPs which are usually too far away from potential external consumers
  - Only three plants (8, 13, 15) are connected to district heating network. Two are equipped with sludge drying and incineration which are big heat consumer respectively producer. The third one is buying heat from the network and can by this way upgrade a higher amount of biogas, biomethane being sold as vehicle gas.

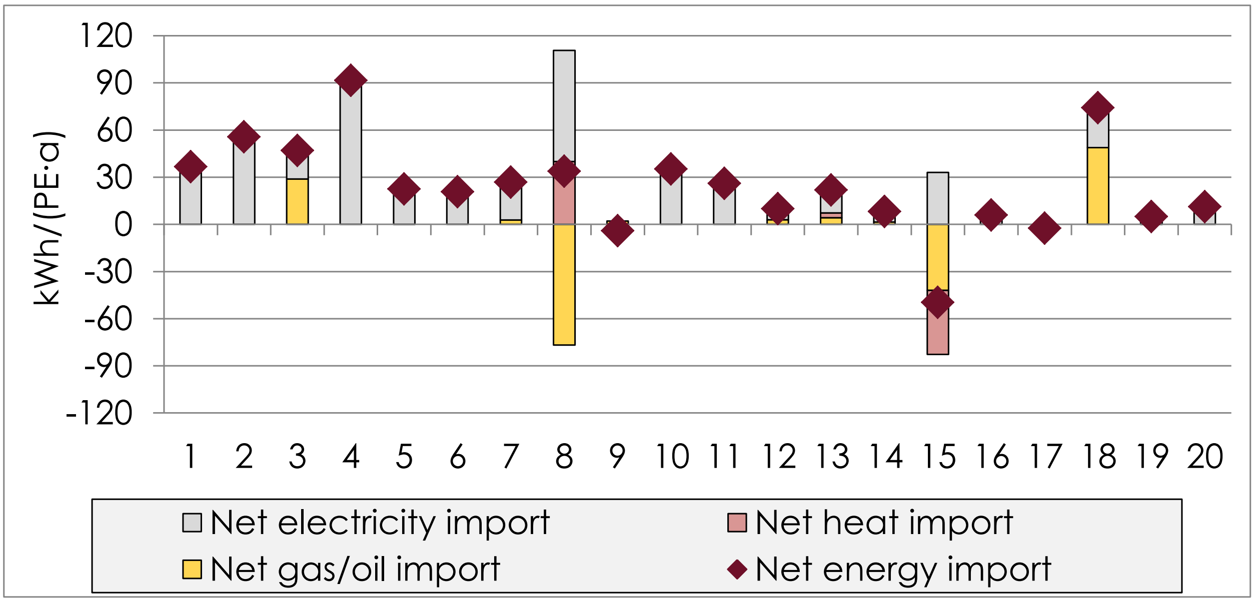

Figure 15: Overview of the current energy import and export at the assessed WWTP

Figure 15 shows that three plants (9, 15, 17) export more energy than they import so they have positive energy balances:

- Plant 9 and 17 are producing more electricity than they consume:
  - One of the plant is only using the wastewater as energy source
  - The other one is digesting co-substrates in the digestion which enhances the biogas production and as a consequence the electricity production
- Plant 15 is not producing electricity but exporting raw biogas
  - It has the advantage that a lower energy amount is lost while a huge part of heat produced by the cogeneration is lost.
- Plant 14 is producing a large amount of electricity from wind turbine (approx. 17 kWh/(PE·a)).

4.2.2. Relation between electricity consumption and other parameters

Next step was to try to find out correlations between specific electricity consumption and capacity, discharge requirement, electricity price and inlet concentration (dilution effect) since these parameters could affect it even if **the number of WWTP participating to the audits is too low to get representative results.** Further assessment with more representative sample of WWTP should be performed to confirm following results.

Specific electricity consumption versus WWTP capacity

First the specific electricity consumption was represented in function of the WWTP capacity (Figure 16):

- For medium WWTP (10.001 to 100.000 PE), it seems that the specific electricity consumption is independent from the capacity:
  - Three plants are equipped with tertiary treatment and one of them also with disinfection. It leads to higher electricity consumption.
  - For this size range, discrepancies were noticed concerning staff skills which make that some WWTP are not operated in an efficient way but focusing on security margin to avoid non-compliance.
- For large WWTP (> 100.000 PE), the range of specific electricity is relatively constant (approx. 35 kWh/(PE·a) if the capacity is lower than 300.000 PE and approx. 25 kWh/(PE·a) if the capacity is higher than 700.000 PE)
  - The pressure to improve energy efficiency is higher than for medium plants

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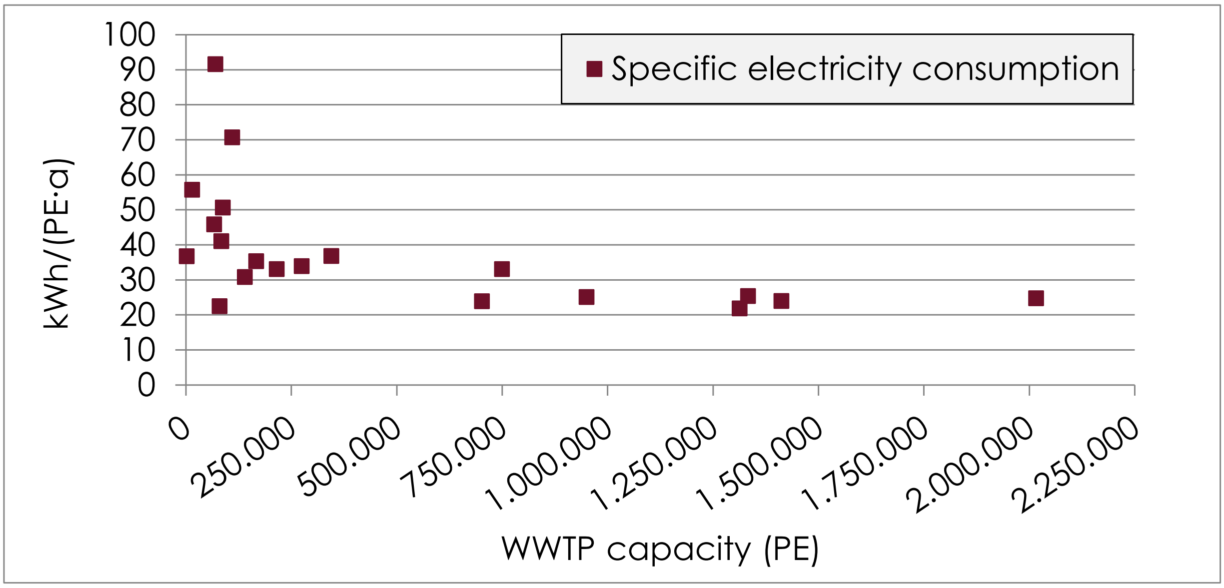

Figure 16: Specific electricity consumption versus WWTP capacity

Specific electricity consumption versus electricity price

Figure 17 shows that the electricity price has apparently no impact on the specific electricity consumption.

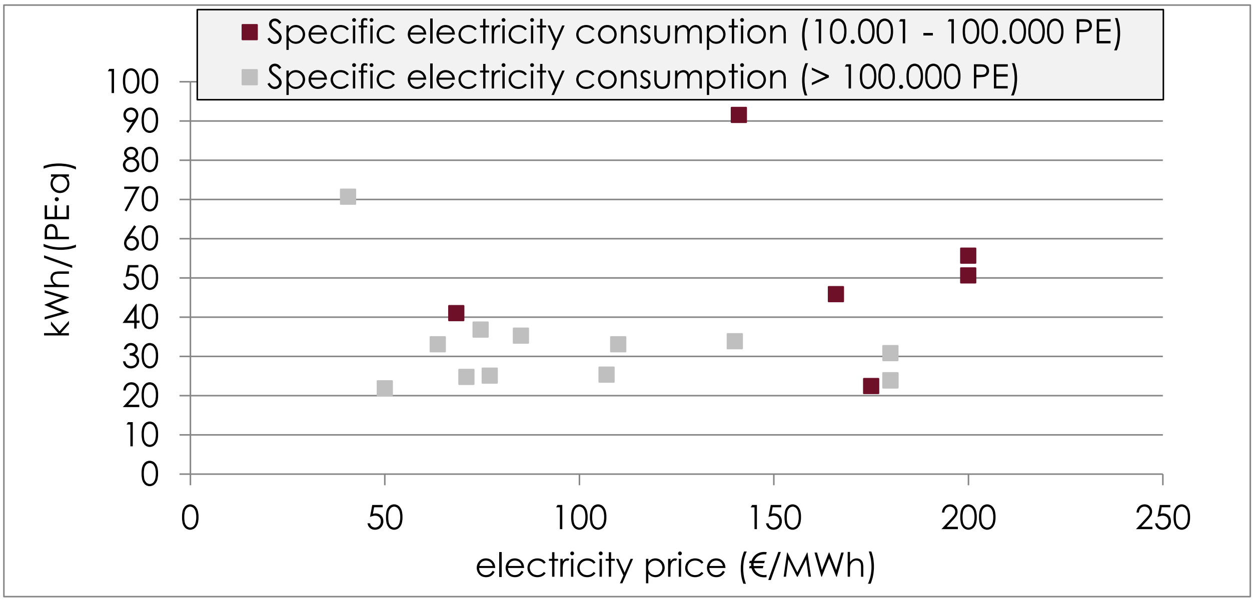

Figure 17: Specific electricity consumption versus plant capacity

Specific electricity consumption versus inlet COD concentration

Figure 18 shows that the concentration of the wastewater does not really have an impact on the specific electricity consumption. The WWTP whose inlet COD concentration is higher than 2.000 mg/l is not representative because a large part of the load proceeds from industries.

The higher the concentration of the wastewater, the higher the required removal to comply with the discharge requirements but the lower the electricity consumption for pumping in the water line (e.g. wastewater pumping, return activated sludge pumps)

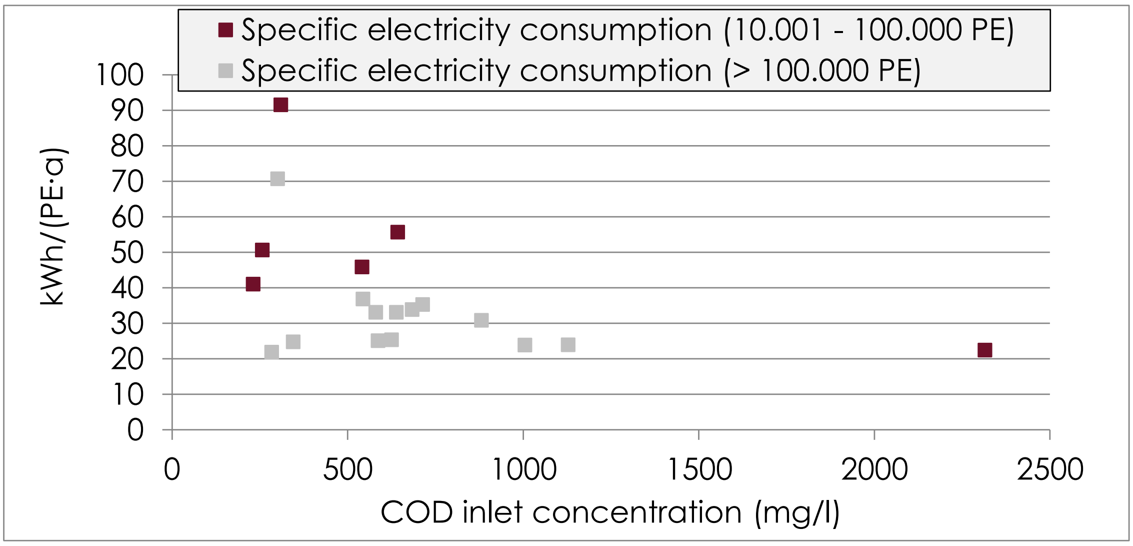

Figure 18: Specific electricity consumption versus inlet COD concentration

Specific electricity consumption versus discharge requirement

No correlation could be found out. However it is obvious that plants with very low phosphorus discharge limit (≤ 0,3 mg/l) have higher specific electricity consumption due to the post-treatment to ensure to comply with the guarantee regarding phosphorus. A pumping station is required to feed the filtration or settling plant and some electricity is consumed for coagulation (and flocculation if so) and for filter washing.

Concerning the nitrogen discharge limit (if required), the impact on the specific electricity consumption is quite limited. Outlet nitrogen concentrations are usually in the same range (NH_4-N < 3 mg/l and TN< 10 mg/l) whatever the discharge limit of the plant.

COD discharge limit has no impact on the specific electricity consumption.

Specific electricity consumption versus WWTP loading rate

No correlation could be found out. Nevertheless the loading rate has an impact on the specific electricity consumption of the plants since some fixed consumers are running whatever the load (e.g. tanks mixing). Depending on the loading rate and configuration of the process, some tanks can be stopped, reducing the fixed electricity consumption. In this case, the impact is reduced.

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5. Results of the assessment performed with OCEAN

5.1. Proposed state-of-the-art measures

Figure 6 (chapter 2.3.4) shows the large panel of proposed state-of-the-art measures from no CAPEX (optimisation of operating parameters) up to heavy CAPEX actions (implementation of digestion plant). In this chapter, the proposed measures (except implementation of sludge digestion which concerns three WWTP) have been assessed more in details. Some examples are available in annex 0.

The proposed measures have been classified per main purpose, some of them having several levers of optimisation:

- Avoid operating issues (e.g. bulking, foaming in digester, …)
- Improve treated water quality: it only concerns two large plants which are not complying with the discharge requirements
- Energy savings
- Other costs savings (e.g. chemicals, sludge disposal, …)

For each type of measure and each WWTP capacity range, an average number of proposed measures has been calculated dividing the related total number of proposed measures by the related total number of WWTP. Figure 19 shows that the average number of proposed measures for medium WWTP is about 40% higher than for large WWTP. The difference comes from measures aiming to reduce energy and more generally operating costs (other costs corresponding to chemicals and sludge disposal costs) (Figure 19):

- Medium WWTP have a lower monitoring level and have to be operated with more “safety”
- Process skills are often missing at medium WWTP. Plant operators are usually not open to change operating conditions because they do not know what the limits for the process are and they are afraid of “loosing” their operation stability.

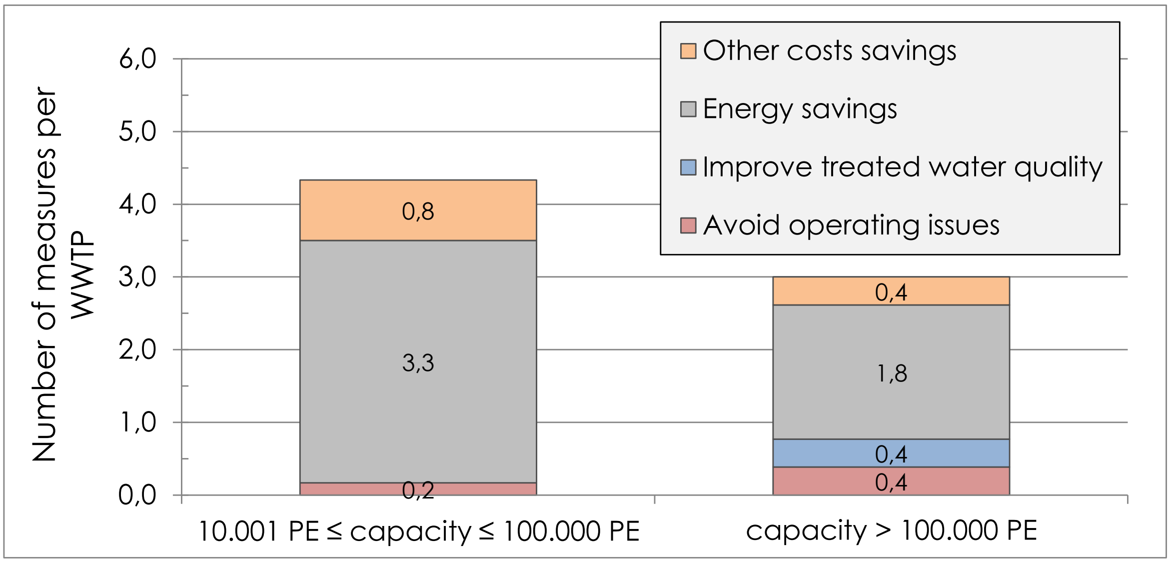

Figure 19: Repartition of the proposed state-of-the-art measures per main purpose and plant capacity

For each measure (except the ones to improve treated water quality which lead to higher operating costs), a payback time has been calculated without taking into account the cost of capital. The measures have been classified in three categories:

- Immediate measures (no investment costs): the measure should be immediately implemented
- Short-term measures (payback time is shorter than three years): the measure should be implemented soon
- Medium- and long-term measures (payback time is longer than three years): these measures often concern the replacement of equipment through more efficient ones. They should be implemented at time of technical renewal, when investment is anyway necessary. The payback time of the additional investment cost is then considerably shorter.

For each category of measure and each WWTP capacity range, an average number of proposed measures has been calculated dividing the related total number of proposed measures by the related total number of WWTP. Figure 20 shows similar repartition of the measures per plant capacity range:

- 35 to 40% of immediate measures
- 25 to 30% of short-term measures
- Approx. 35% for medium- and long-term measures.

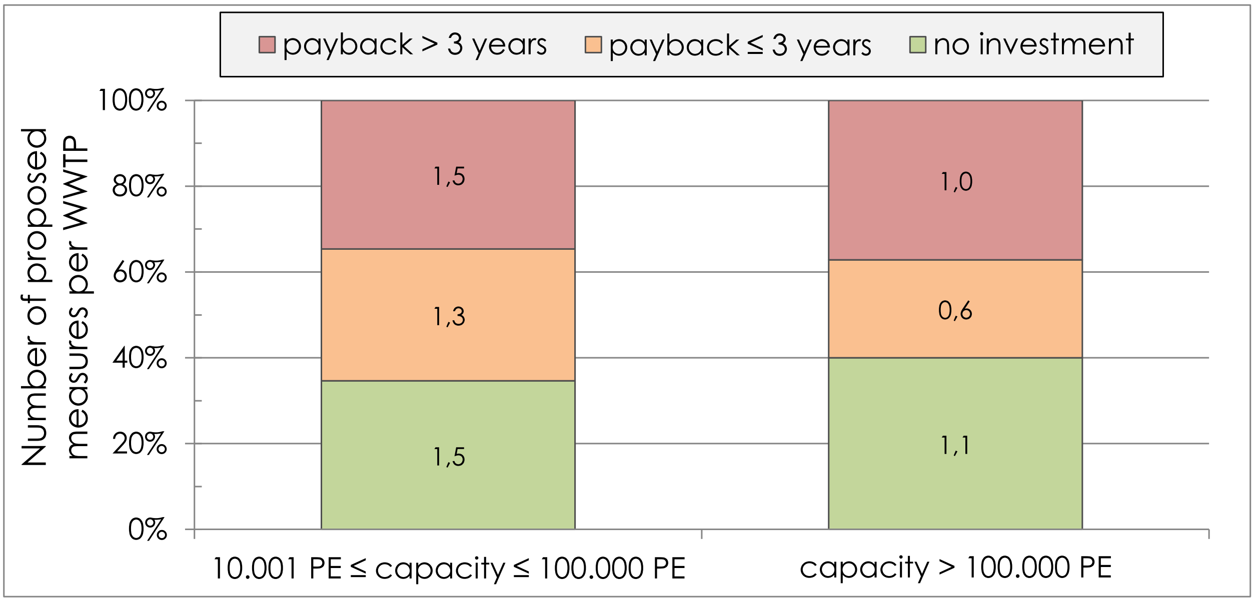

Figure 20: Number and part of proposed measures (except measures to improve the outlet quality) per range of payback time and plant capacity range

For each payback time and plant capacity ranges, average specific costs savings have been calculated per measure (Figure 21):

- In both WWTP capacity ranges, immediate measures lead to lower costs savings than measures with CAPEX.
- In both WWTP capacity ranges, measures with CAPEX lead to same order of magnitude of operating costs savings.

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- The level of specific operating costs savings per measure is higher for medium WWTP compared to large plants.

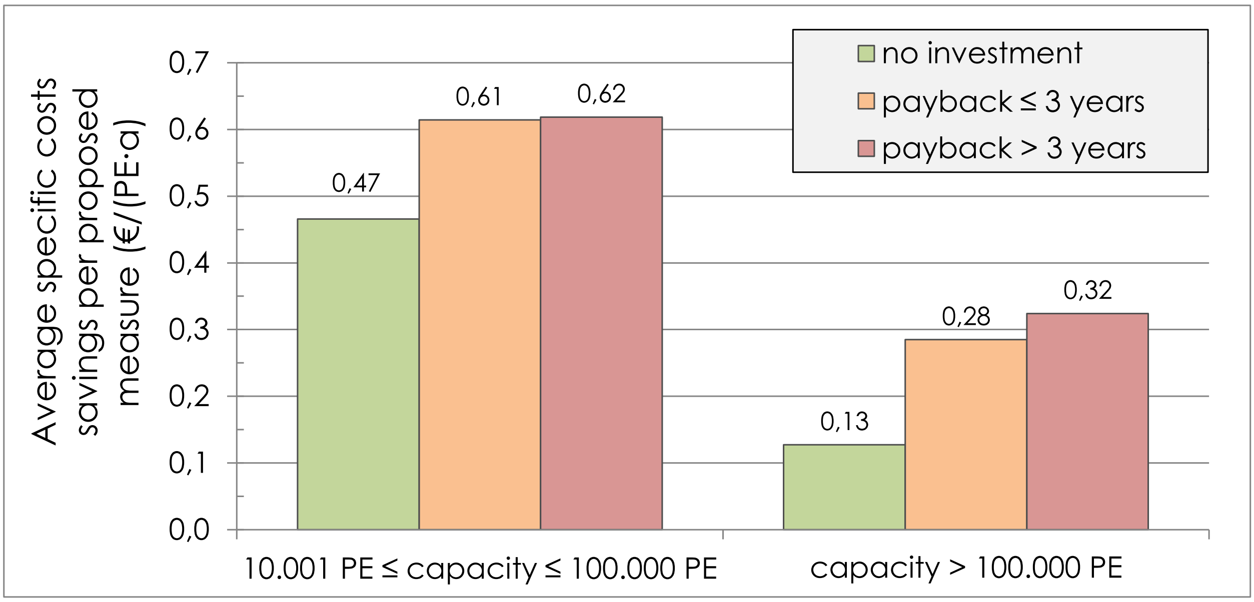

Figure 21: Average specific costs savings per measure (except measures to improve the outlet quality) per payback time range and plant capacity range

5.2. Proposed POWERSTEP treatment schemes

5.2.1. Proposed schemes for WWTP < 50.000 PE

Two plants had a capacity lower than 50.000 PE. Both have no sludge digestion because it is not economic. Therefore they also do not have primary treatment. For both WWTPs, no digestion has been proposed as state-of-the-art measure because their capacity is too low, the largest one being able to treat the wastewater of 15.000 PE.

Figure 22 shows the treatment scheme which has been proposed:

- Chemically enhanced microfiltration as primary treatment:
  - This process has been demonstrated at a small plant (Olsson & Pellicer-Nàcher, 2018)
  - Results of the treatment schemes comparison (Remy & Cazalet, 2018) show that treatment schemes with chemically enhanced microfiltration have similar economic feasibility and energy balances like chemically enhanced settling
  - Microfiltration offers a very flexible operation due to the short retention time and the variation of the performance depending on the use or not of chemicals. It is very useful for small plants in order to avoid issues regarding nitrogen removal
  - Microfiltration is very compact and is well adapted to small plants
- Biological treatment does not change, mainstream Anammox being not adapted for small WWTP:

- High monitoring level required in order to ensure optimal conditions for AOB establishment avoiding NOB growth.

Figure 22: Proposed POWERSTEP treatment scheme for WWTP < 50.000 PE

Following aspects make POWERSTEP concept interesting for small WWTP, especially in water association which have several small WWTP and a larger plant equipped with digestion:

- Electricity can be saved for aeration
- The primary sludge has a quite high biogas potential and could be digested in the larger WWTP

The benefits at the water association level are non-negligible and regional concepts could be by the way developed to make digestion economic in smaller associations.

5.2.2. Proposed schemes for WWTP ≥ 50.000 PE

Fifteen of the eighteen medium and large WWTP, whose capacity is higher than 50.000 PE, are equipped with digestion. For the three other plants, a digestion was proposed as state-of-the-art measure.

Figure 23 shows the proposed treatment schemes:

- Chemically enhanced primary treatment
  - Enhancement of existing primary settling tanks through coagulation and flocculation
  - Chemically enhanced microfiltration (coagulation/flocculation) in WWTP which have no primary treatment: this process was chosen according to the results of the treatment schemes comparison (Remy & Cazalet, 2018)
- Mainstream Anammox as one-stage IFAS process
  - The process needs further development and trials before it can be implemented at full scale in a WWTP (Stefansdottir, Christensson, & Piculell, 2018). However it was included in the POWERSTEP scheme because it represents high potential for improving the energy balance in the future (Remy & Cazalet, 2018).
  - Mainstream Anammox is very interesting because a very low amount of COD is required for the nitrogen treatment: in one-stage IFAS configuration, a small amount of nitrogen is still removed by nitrification/denitrification (assumed to be 5% according to pilot trials performed by Veolia in France). Higher COD amounts can (have to) be extracted in the primary treatment which actions both levers of energy-efficiency:
    - Produce more: higher primary sludge amount means higher biogas production. Moreover, shorter sludge age is required to avoid NOB

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growth so the surplus activated sludge has higher biogas potential than conventional activated sludge process.

- Consume less: lower COD amount at the inlet of the biological treatment means lower electricity consumption for the aeration

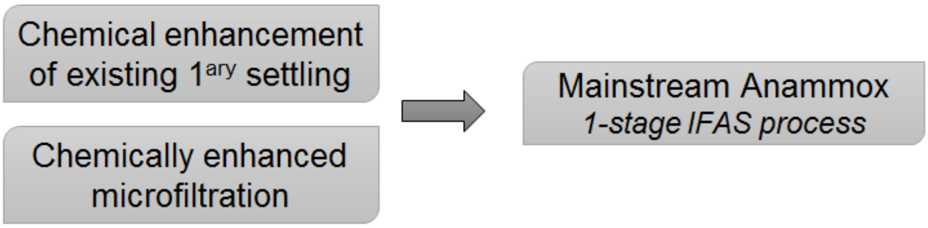

Figure 23: Proposed POWERSTEP treatment scheme for WWTP ≥ 50.000 PE

For the WWTP which only has discharge limits for carbon pollution, the proposed scenarios are slightly different:

- POWERSTEP scenario: chemical enhancement of the existing primary settling combined to the existing activated sludge process with short sludge age (high load)
- Two additional scenarios to evaluate the advantages of POWERSTEP concept by upgrading the plant with nitrogen and phosphorus removal (anaerobic tanks combined with co-precipitation):
  - Upgraded state-of-the-art scenario: in the state-of-the-art scenario, the existing activated sludge process is adapted to remove nitrogen by nitrification / denitrification
  - Upgraded POWERSTEP scenario: in the POWERSTEP scenario, the existing activated sludge process is reconstructed in mainstream Anammox in IFAS configuration.

5.2.3. Add-on for WWTP with biogas upgrading

For the few WWTP with biogas upgrading, Power-To-Gas technology has been proposed as an add-on to the POWERSTEP treatment schemes. Principle of Power-To-Gas is to convert electricity into synthetic methane. By this way, excess green electricity could be stored as synthetic methane in the gas grid. Power-To-Gas consists in two steps:

1. Electrolyser: electricity is consumed to produce dihydrogen from water
2. Methanation: bacteria consume the dihydrogen produced by the electrolyser and carbon dioxide proceeding from the biogas upgrading plant to produce methane.

Trials have demonstrated that the Power-To-Gas technology is very flexible in operation and suits very well in WWTP with biogas upgrading (Lardon, Thornberg, & Krosgaard, 2018):

- CO_2 is a reagent of the biological reaction of Power-To-Gas and is available from the biogas upgrading
- Existing connection to the gas grid

- The heat recovered from Power-To-Gas can be used to heat the digester: a lower part of the biogas has to be utilized in a boiler to produce heat so higher part can be upgraded and injected in the grid
- Oxygen is a sub-product of the electrolysis used in Power-To-Gas and could be used for aeration of the biological treatment
- The excess sludge produced by Power-To-Gas (small amount) can be treated in the digestion

5.3. Effect on the energy balances

For all assessed WWTP, the specific energy production has been represented in function of the specific energy consumption for each scenario (Figure 24):

- Reference scenario (red points)
- State-of-the-art scenario (light green points)
- POWERSTEP scenario (dark green points)

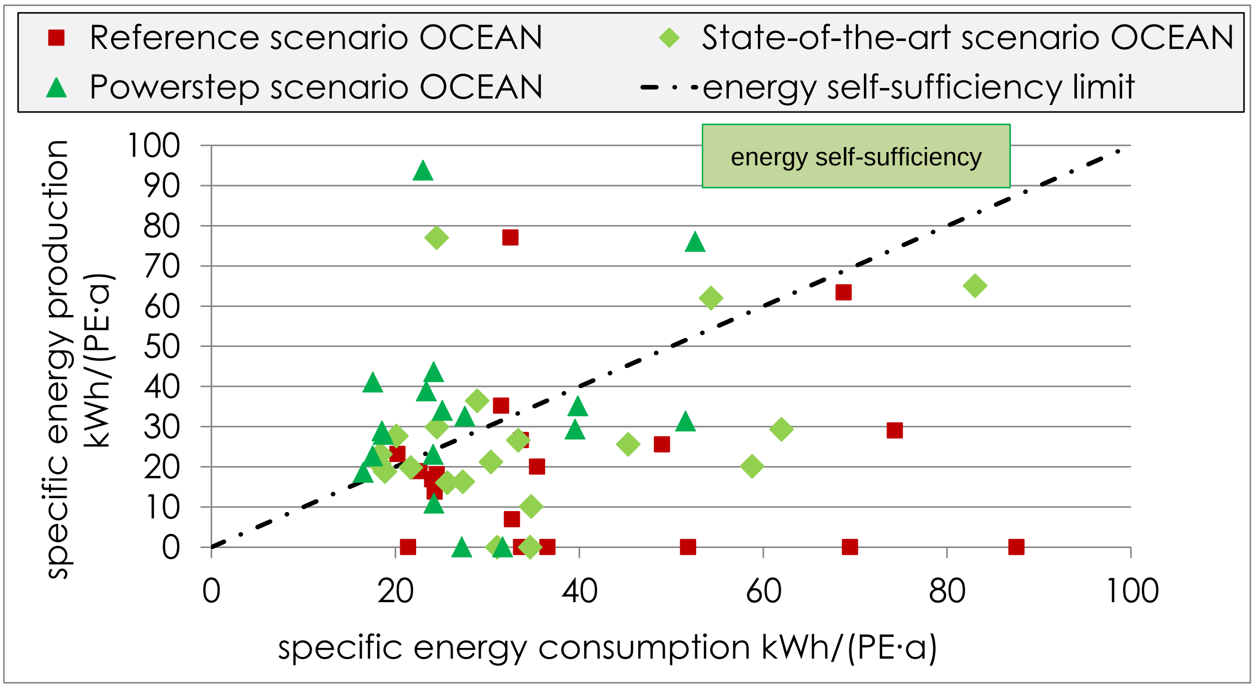

Figure 24: Specific energy production vs consumption for reference and state-of-the-art scenarios at each WWTP

Figure 24 shows that state-of-the-art measures mostly impact the energy consumption (most of light green points are at same ordinate like red points but closer to the ordinate axis). An increase of the energy production could be reached in some plants, sludge digestion having been proposed in three of which. POWERSTEP concepts have higher lever to increase the energy production and lead at the same time to further energy savings.

For both state-of-the-art and POWERSTEP scenario, these affirmations seem to be valid:

- The higher the energy consumption, the higher the saving potential
- The lower the energy production, the higher the potential for increasing it.

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Figure 25 shows:

- The impact of state-of-the-art measures on the net energy needs:
  - Approx. 40% of the large plants (numbers 8 to 20) can reach energy self-sufficiency implementing state-of-the-art measures.
  - Only one of the small and medium plants could reach similar results but the energy balance benefits from the relatively high part of very organic industrial wastewater treated by this plant.
- The impact of Powerstep concepts on the net energy needs:
  - Only one of the large plants (numbers 8 to 20) cannot reach energy self-sufficiency. The reason is the sludge drying which requires a lot of energy. For the plant 14, the higher energy demand for sludge drying is compensated by the electricity produced by the wind turbines.
  - Only two (5 and 6) of the medium plants with digestion (3 to 7) can reach energy self-sufficiency. The plants 3, 4 and 7 have unfavourable conditions:
    - High part of electricity consumption for wastewater pumping
    - Presence of post-treatment which require an intermediate pumping station
    - Oversized plant and especially digester and biogas cogeneration which requires natural gas consumption to provide enough heat to maintain optimal temperature (high losses compared to the biogas production) and make the operation of the cogeneration economic.
- For the plants 1 and 2 which are too small to have their own sludge digestion, the impact of the Powerstep scenario on the energy demand (actually electricity) is very low, the energetic valorisation of the sludge taking place in the sludge disposal facility (digestion or incineration plant).

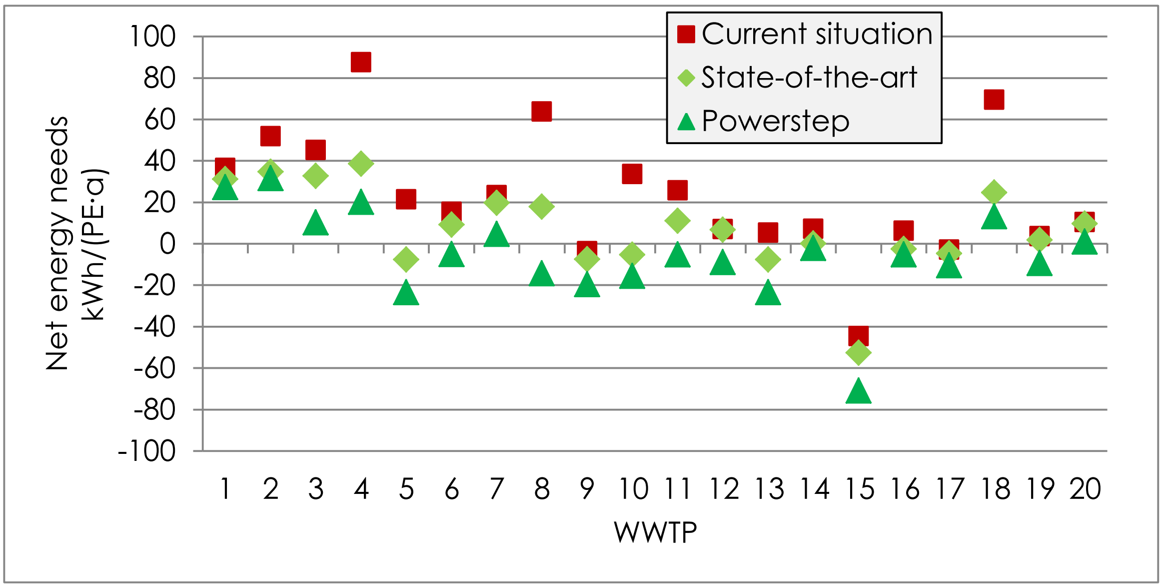

Figure 25: Net specific energy needs for reference and state-of-the-art scenarios at each WWTP

Figure 26 shows the benefit of POWERSTEP for upgrading a plant to nitrogen and phosphorus removal:

- "OCEAN 2016" represents the current electricity balance (only carbon removal)
- "OCEAN upgraded state-of-the-art" represents the state-of-the-art scenario upgraded to remove nitrogen and phosphorus
- "OCEAN upgraded POWERSTEP" represents the POWERSTEP scenario upgraded to remove nitrogen and phosphorus using Anammox bacteria

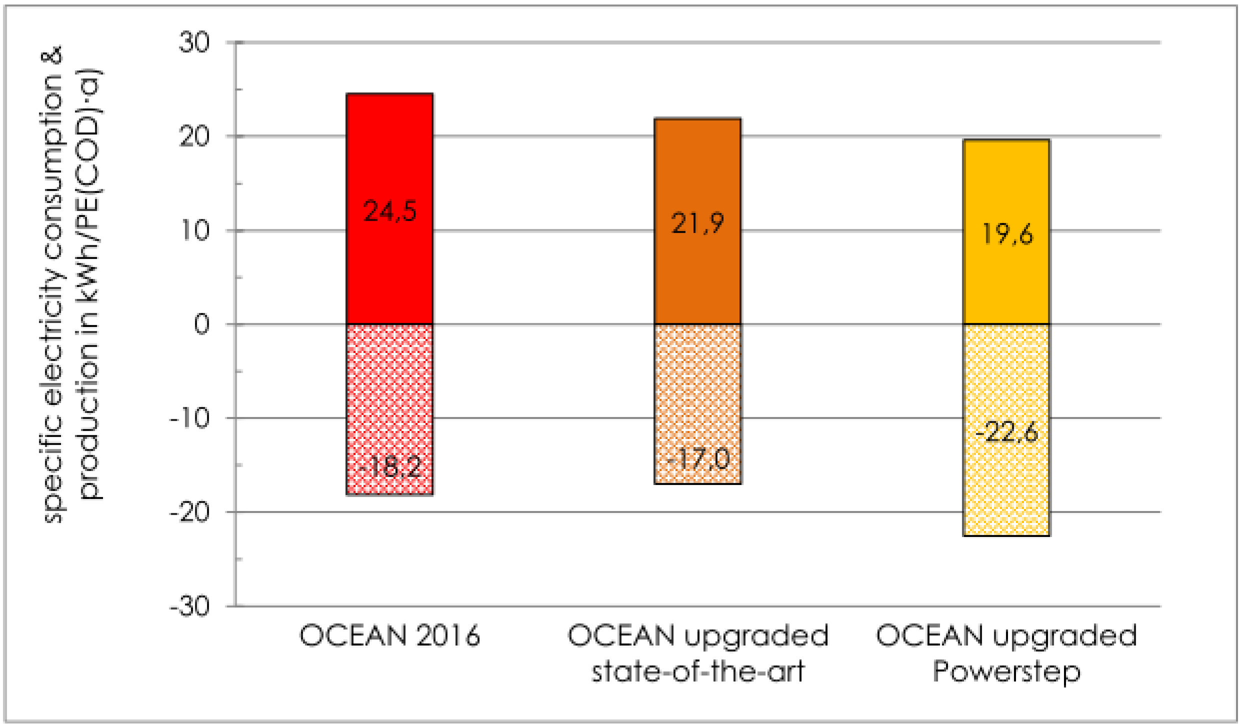

Figure 26: Comparison of current and targeted electricity balances at a WWTP with only carbon removal after upgrading to nitrogen removal according to state-of-the-art and using POWERSTEP concepts

The implementation of state-of-the-art measures would compensate the effect of the additional nitrogen and phosphorus treatment resulting in equivalent electricity balances. POWERSTEP concept could even lead to improve the energy balance while removing nitrogen and phosphorus.

6. Summary and conclusions

6.1. Current energy-efficiency and perspectives

The assessment of the selected plants (chapter 4) has shown that the energy-efficiency level mostly depends on:

- Plant capacity: bigger plants have better energy balances
  - Staff is more aware of energy-efficiency and usually disposes of a larger panel of skills to optimise the plant
  - Equipment are more efficient
- Staff (at medium plants): in several medium plants, the operators are focused on maintaining stable operating conditions so they are not really open to change operating parameters in order to reach costs savings. Most of the time, it is due either to a lack of skills or to an apprehension to do something wrong which could negatively impact the treatment performances.

Figure 27 summarizes the cumulative optimisation potentials for energy consumption and production through implementation of state-of-the-art measures and POWERSTEP scenarios:

- State-of-the-art measures mostly lead to reducing the energy consumption. In some of the assessed WWTP, and especially plants which are not yet equipped with digestion, the energy production could also be increased.
  - An analysis of the proposed measures has highlighted the lower level of energy-efficiency of the medium plants compared to the large ones.
  - For medium plants, big costs savings could be reached through immediate and short-term measures while investments are required at large plants, the operating conditions having usually already been optimised in the past.
- POWERSTEP scenarios also use both lever (save and produce more energy) but the highest potential remains in the increase of the energy production resulting from higher sludge production with higher biogas potential.

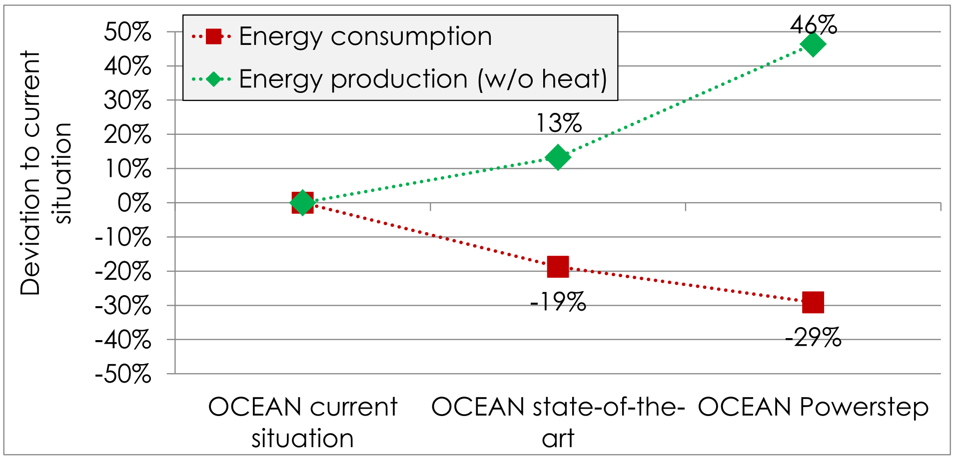

Figure 27: Cumulative optimisation potentials for energy consumption and production through state-of-the-art measures and POWERSTEP concept

Balances of cumulative net energy consumptions (Figure 28) show the benefit to the group of assessed WWTP:

- State-of-the-art measures could lead to produce more energy than the consumption for the assessed WWTP
- POWERSTEP concepts enable doubling the "energy savings" which could be reached implementing state-of-the-art measures.

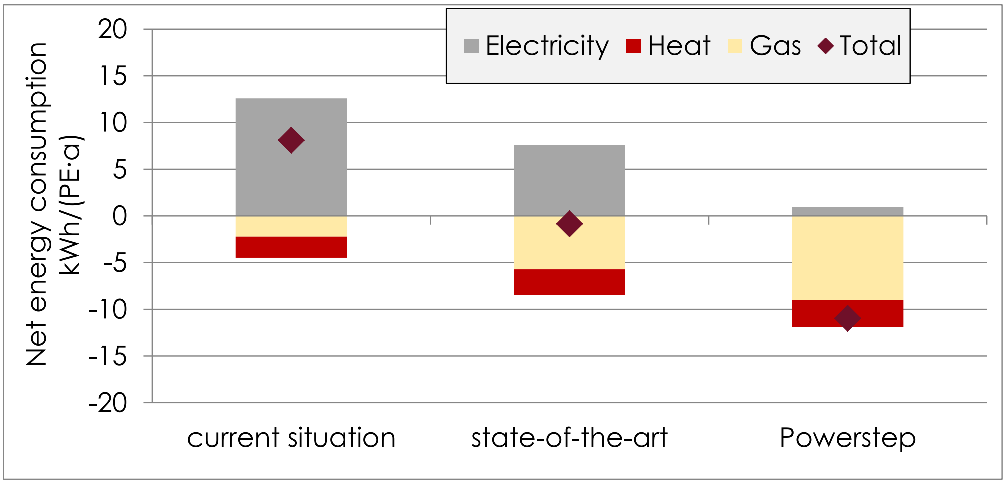

Figure 28: Cumulative net specific energy consumptions per energy vector

6.2. Challenges

First challenge is to improve the utilisation of the available data in order to improve the assessment of the performances of the plants:

- A lot of data are available (at least at large WWTP) but they are not really used at their full potential
- WWTP have to report a lot of operating data but the experience shows that most data are cross checked and inconsistencies could be found during the audits. The use of tools like OCEAN should be recommended because they offer the possibility to check the data and assess the plant at the same time.

Second challenge is to further educate staff at medium plants regarding process optimisation and energy optimisation. Both are very complementary to maximise the improvement of the energy balances and the costs savings. By this way, it would be easier to make that the operators give higher importance to plant optimisation and not stay focused on the stability of the treatment performances taking too high safety margin.

Third challenge is the implementation of the proposed state-of-the-art measures:

- Immediate measures without CAPEX have to be implemented as soon as possible
- Short-term measures (payback shorter than three years) should be implemented just after the immediate measures
- Medium- and long-term measures mostly concern equipment and should be implemented at time of technological renewal

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In order to assess the effect of each optimisation comparing with the prevision, the measures have to be implemented step by step.

6.3. Conclusion

Energy self-sufficient plant is no longer a dream. Some plants are already producing more energy than they consume:

- Using only the energy potential of the wastewater if the conditions are favourable
- Using other energy sources (co-digestion, green energy production, …)

Nevertheless significant optimisation potentials exist (especially in medium WWTP) and could be reached upgrading existing plants to state-of-the-art. An important lever for it is the education of the staff in order to give them enough confidence to implement optimisation measures. The implementation of state-of-the-art measures should be the next step to extend energy self-sufficiency to more and more plants.

POWERSTEP concepts are not yet mature enough to be implemented but they could significantly increase the energy production and reach further savings which would lead to new levels of energy-efficiency at WWTPs.

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Annex I: Example of audits results summary

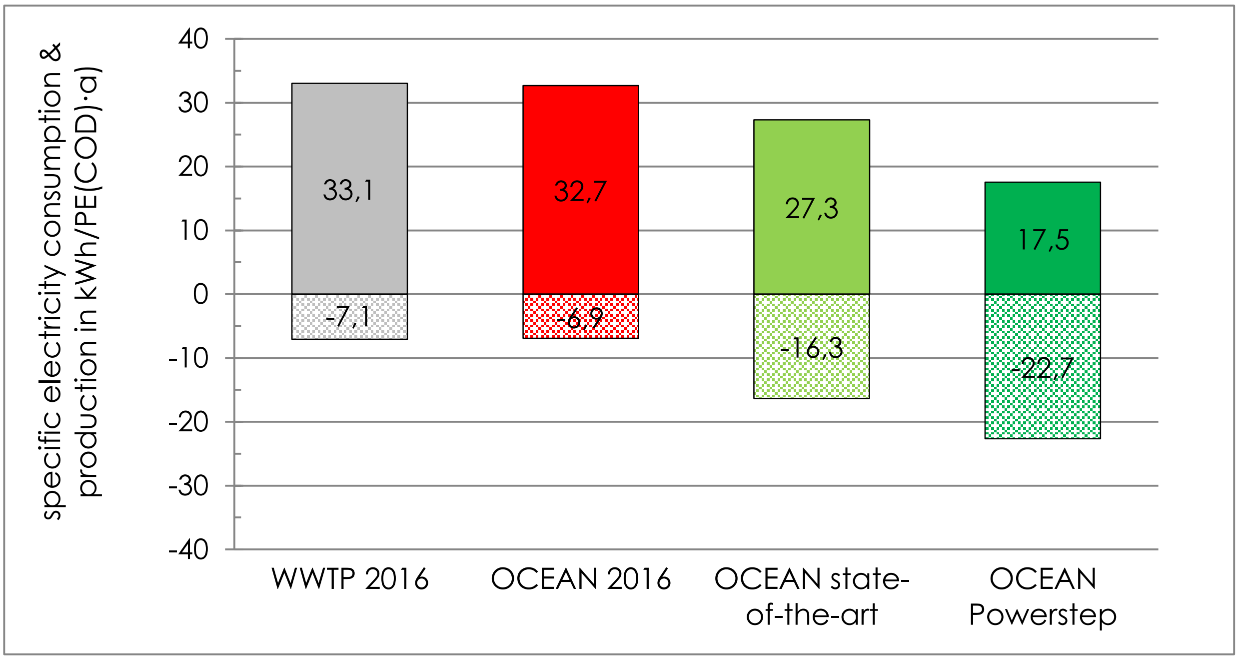

Figure 29: Electricity balances

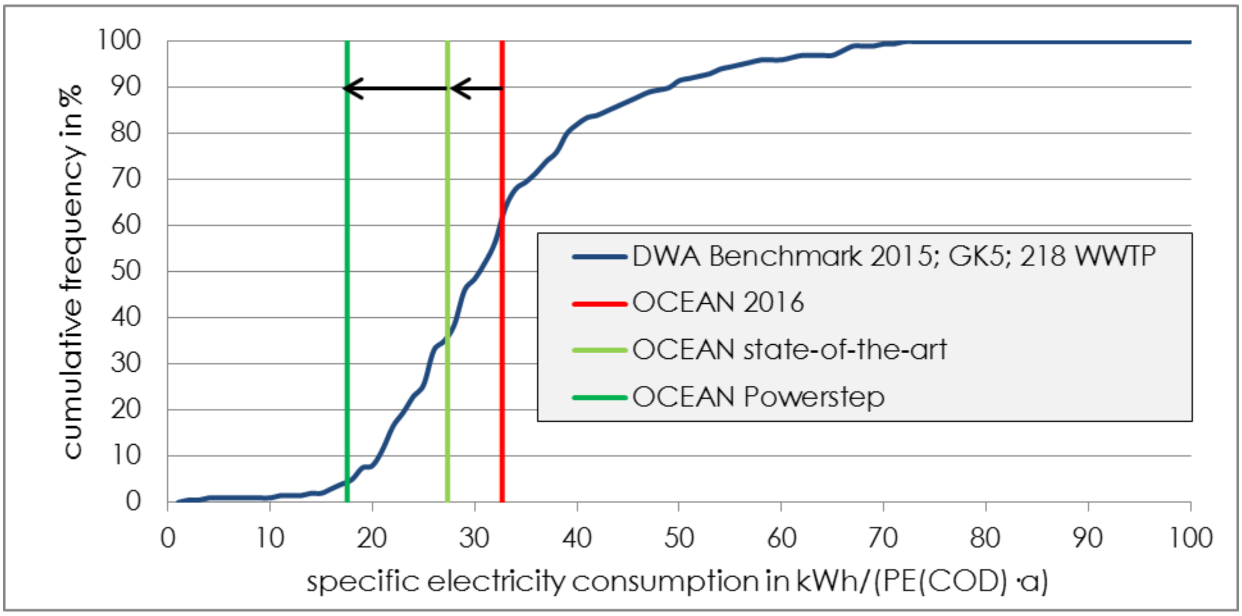

Figure 30: Evolution in the DWA benchmark for electricity consumption

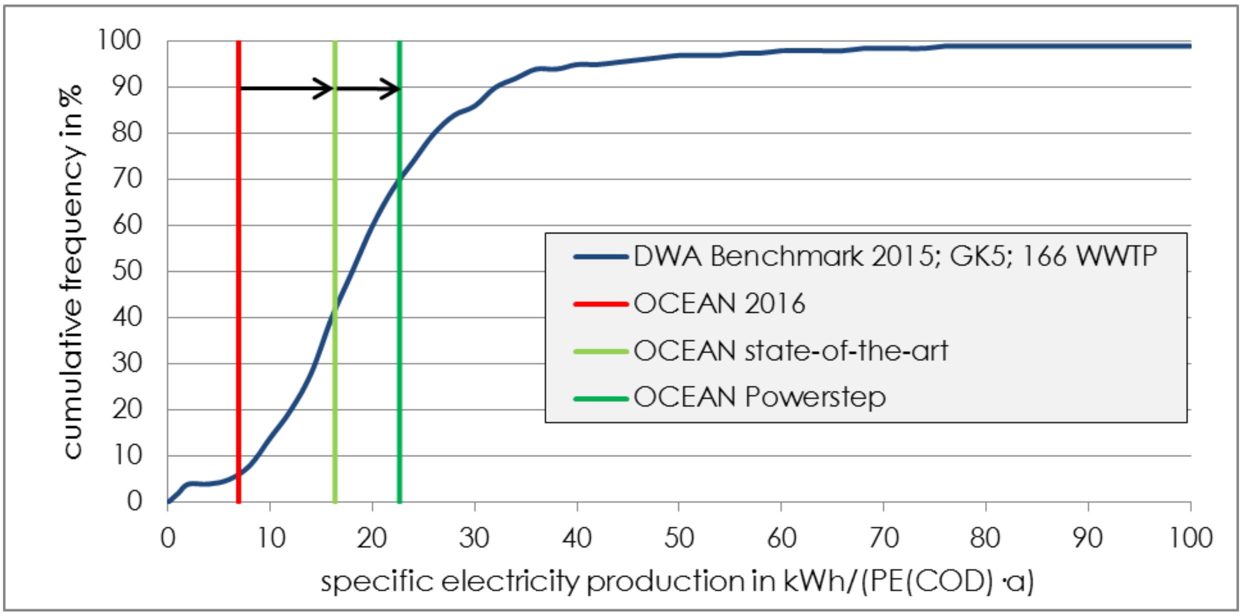

Figure 31: Evolution in the DWA benchmark for electricity production

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Annex II: Example of assessment with benchmark

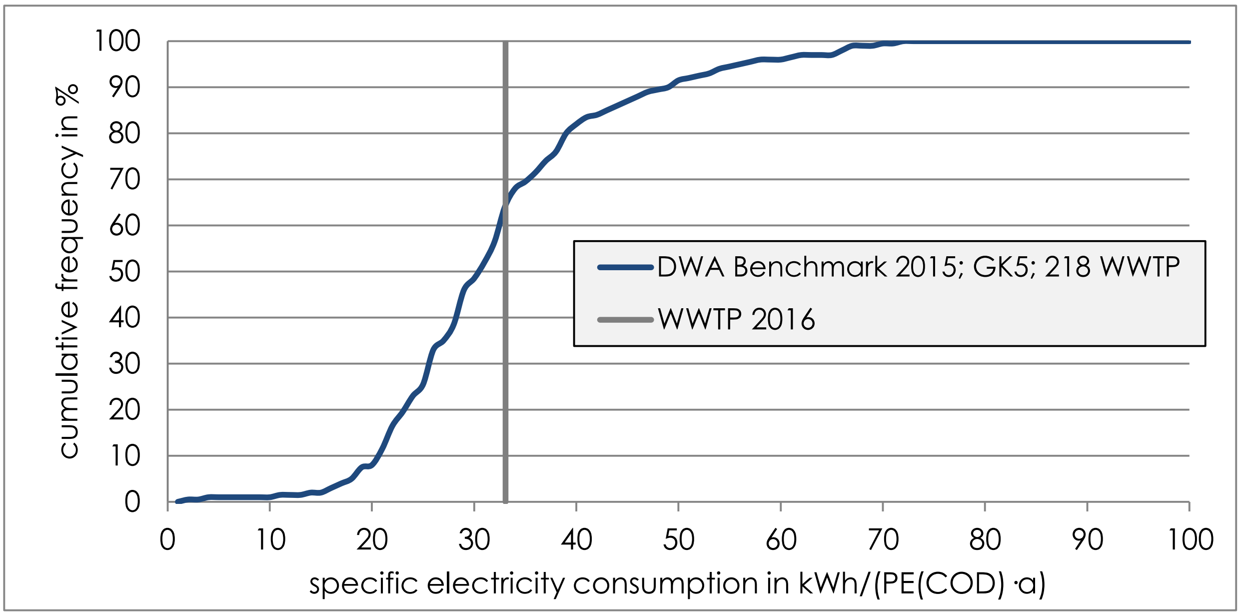

Figure 32: Example of assessment of the electricity consumption

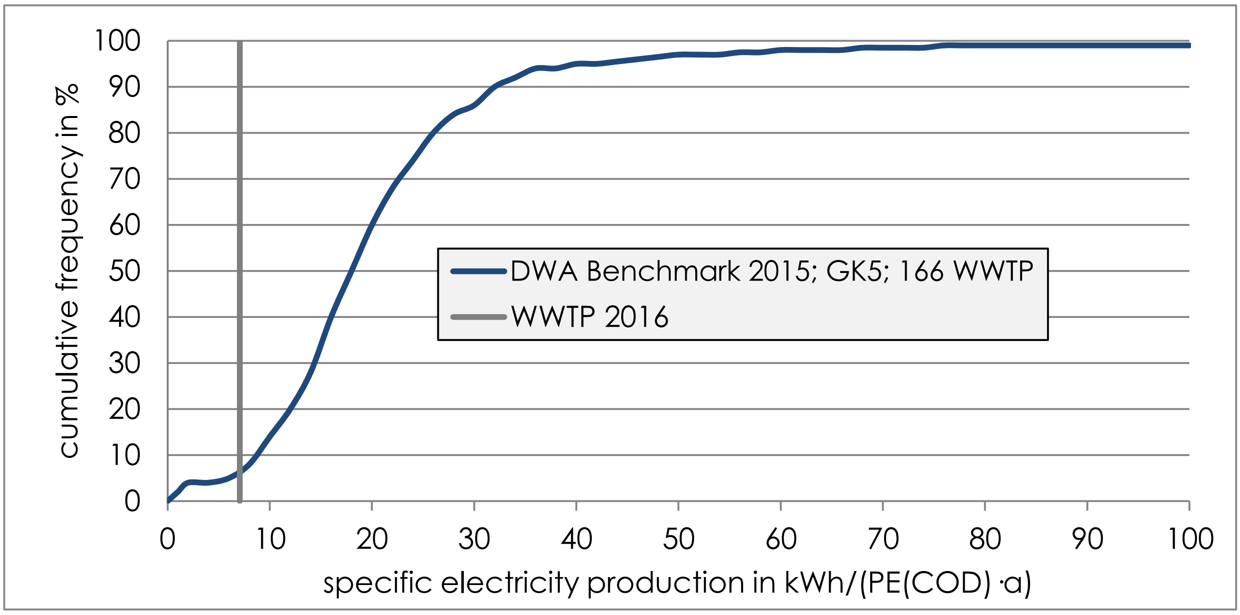

Figure 33: Example of assessment of the electricity production

Parameter	Unit	Co-precipitation
Coagulant	**-**	**$FeCl_3$**
Dosing point	-	Aeration tank
Coagulant consumption	m³/a	2.125
	t/a	3.008
	kg/d	8.241
Daily metal (Fe) consumption	kg Fe /d	1.187
	mol Fe /d	21.267
P inlet load WWTP	kg P /d	1.241
Specific coagulant consumption	mol Fe/kg P	**17,1**
Guide value from German water association (DWA-A 202)	mol Fe/kg P	11 for WWTP with Bio-P 23 for WWTP without Bio-P

Figure 34: Example of assessment of the coagulant consumption

	Unit	2016 Primary sludge thickening	2016 Surplus activated sludge thickening	2016 dewatering
Technology	-	Gravity thickening	drum	Band filter press
Yearly polymer consumption	t/a	0	37,6	43,4
Active matter content	%	-	~ 50	~ 100
Sludge quantity	tDM/a	31.175	6.886	10.031
Specific polymer consumption	**kg a.m. / tDM**	**0**	**2,7**	**4,3**
Reached sludge DM content	**%**	**4,7**	**3,5**	**18**
DM capture rate	**%**	**37**	**76**	**97**

Figure 35: Example of assessment of the thickening & dewatering

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Annex III: Example of results of OCEAN calibration

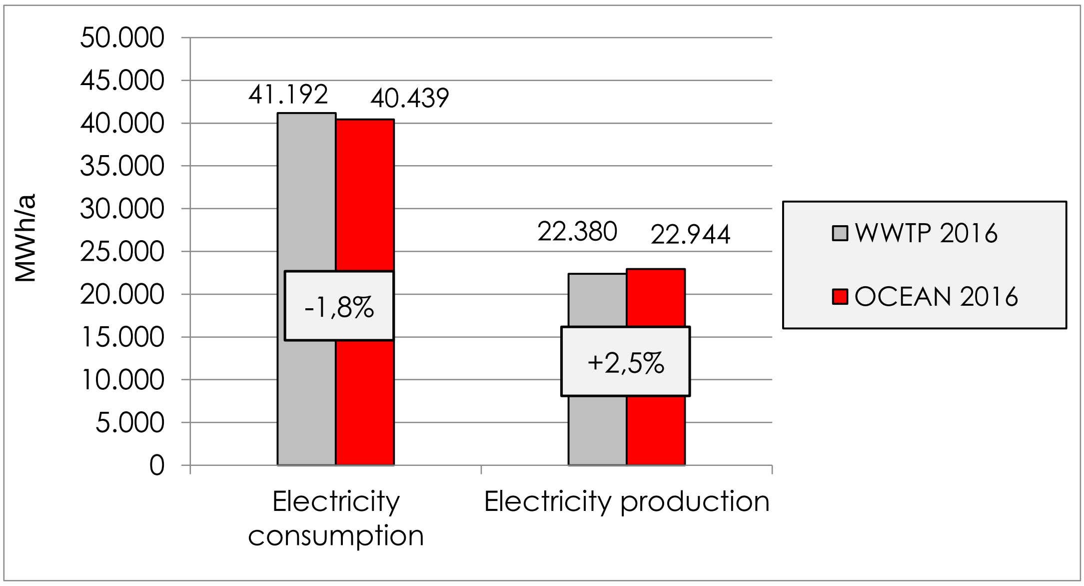

Figure 36: Accuracy of the electricity consumption & production calculations

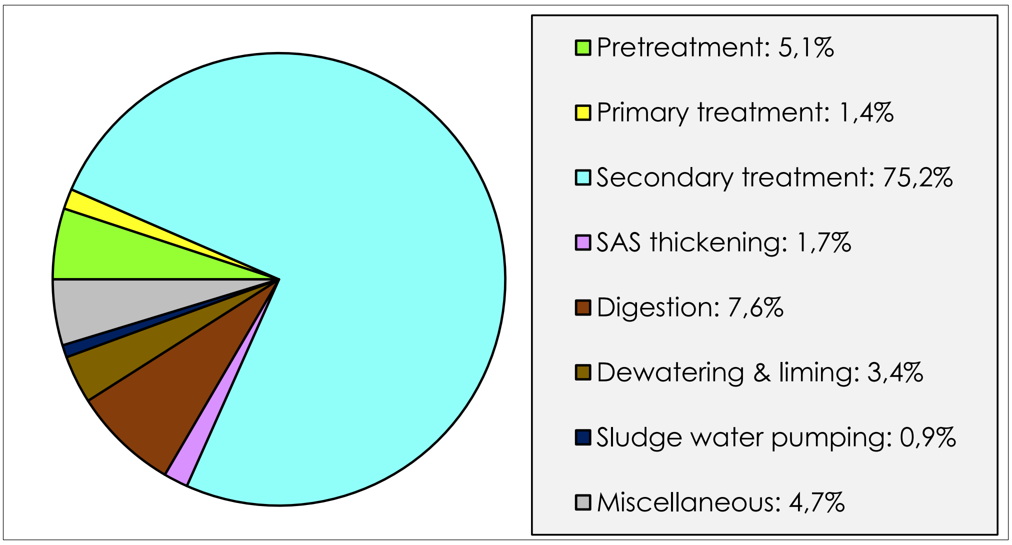

Figure 37: Repartition of the electricity consumption

Annex IV: Examples of state-of-the-art measures

Action GI-2. Optimisation of the return activated sludge

Technical Issues

According to the chapter 4.3.2, the data relative to the return activated sludge (RAS) rate are not consistent. All calculations made in this measure are based on a current RAS rate of 135%.

The implementation of the Action GI-1 and especially the improvement of the SAS thickening should reduce the inlet load of the activated sludge process. For this reason, a decrease of the TSS content up to 1,1 g/l is expected by maintaining the sludge age constant. Since no mixers are installed in the aeration tanks, the stop of additional aeration tanks could be contra-productive. No mixing energy would be saved and the reduction of the number of air diffusers could lead to an increase of the electricity consumption for aeration. Less tanks in operation means less diffusers in operation and as a consequence a higher specific air flow. The higher the specific air flow, the lower the oxygen transfer efficiency and the higher the pressure difference. For this reason, we do not necessarily recommend stopping additional tanks.

However electricity savings could be reached by optimising the RAS rate. According to the German norm DWA-A 131, the maximal recommended TSS concentration of the RAS rate can be calculated depending on the sludge volume index (SVI) considering a maximal thickening time in the clarifier of 2h. Taking into account a SVI of 140 ml/g, the RAS rate could be decreased in order to reach TSS concentrations up to 4,5 g/l. By this way, the electricity consumption of the RAS and SAS pumps could be decreased.

For this reason, we recommend to decrease the RAS rate to reach 4,5 g/l TSS concentration in the RAS. According to the DWA-A 131, it corresponds to a RAS rate of 30 - 35%.

Key parameters and assumptions

- Situation after implementation of the Action GI-1:
  - TSS content in aeration tanks: 1,1 g/l
  - RAS rate: 135%
    - approx. 150.000 m³/d
  - Surplus activated sludge:
    - 8.500 m³/d
    - 0,19% DM
    - 16.200 kgDM/d
- After implementation of the measure:
  - TSS content in the RAS/SAS ("set point"): 4,5 g/l
  - RAS rate: 32%
    - 36.000 m³/d
  - Surplus activated sludge:
    - 3.600 m³/d
    - 0,45% DM
    - 16.200 kgDM/d
- **Electricity savings calculated with OCEAN:** 822 MWh/a → **63.300 €/a**

Cost Benefits Analysis

Investment Cost	**0 €**
Electricity savings	**822 MWh/a**
Consumables costs savings (€/a)	**63.300 €/a**

Figure 38: Process optimisation

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Action GI-4. Implementation of a more efficient air diffusion system

Technical Issues

The plant is equipped with disc diffusers in EPDM. According to the data from the dimensioning and the OCEAN calibration, the oxygen transfer efficiency was estimated to amount approx. 5,1%/$m_{immersion}$ which corresponds to approx. 15,3 $gO_2/(m_{immersion} \cdot Nm^3)$.

With the increase of the energy price, more efficient systems have been developed and the dimensioning with older membrane diffuser technologies is done with a higher focus on the oxygen transfer efficiency.

We recommend to consider the **installation of plate diffusers**:

- The whole depth is used to transfer oxygen since they are fixed at the bottom;
- According to several references, the life time seems to be longer (> 10 a), polyurethane is used as material;
- The oxygen transfer is higher than with tube diffuser (7 - 8 %/m according to manufacturer guarantees)

The estimated invest costs are higher than disc diffusers renewal. However the higher oxygen transfer and longer life time should allow making the additional invest costs economic.

In order to optimise the invest costs, we recommend to proceed to **a new dimensioning of the aeration system** using the actual loads instead of the capacity calculated during the dimensioning and to compare several manufacturers.

Key parameters and assumptions

- Situation after implementation of the previous actions:
  - Oxygen needs: 6.847 kgO_2/d
  - Oxygen transfer efficiency: 15,3 $gO_2/(Nm^3 \cdot m)$
  - Air flow: 48,9 M Nm^3/a
  - Pressure difference: 700 mbar
  - Blower specific electricity consumption: 4,3 $Wh/(Nm^3 \cdot 100mbar)$
- Situation after implementation of plate air diffusers:
  - Oxygen transfer efficiency: 21,0 $gO_2/(Nm^3 \cdot m)$
  - Air flow: 35,6 M Nm^3/a
  - Pressure difference: 720 mbar
- **Electricity savings:** 380 MWh/a → **41.800 €/a**

Cost Benefits Analysis

Investment Cost	250.000 € (rough estimation)
Electricity savings	380 MWh/a
Costs savings	41.800 €/a

Figure 39: Optimisation through equipment renewal

Action GI-1. Implementation of a mechanical thickening for the SAS

Technical Issues

The SAS (Surplus Activated Sludge) is thickened per gravity in a tank near the digestion. Gravity thickening does not allow reaching so high DM content as mechanical thickening (approx. 2 - 3% vs 5 - 7%). The consequence is that the SAS flow to the digester is approx. twice higher than it would be with a mechanical thickening.

For the WWTP it is not a big issue because the digestion volume is sufficient but it leads to a higher heat consumption (approx. twice higher).

To date the heat for the digestion has been provided by the gas motor. With the building of the biogas upgrading plant, the goal would be to upgrade the whole produced biogas. A reduction of the heat consumption for the digesters would allow limiting heat consumption from the district heating. **The calculated heat saving is a maximal value since the lower heat recovery from the centrate (lower flow) was not taken into account.**

Moreover the increase of DM content induces an increase of the sludge retention time in the digestion. Considering that 20 d are sufficient for mesophilic digestion, two digesters could be stopped (savings for mixing and recirculation pumps).

Several mechanical thickening technologies are on the market. Gravity belt thickeners, drum thickeners, disc thickeners, centrifuge decanters are the most common. Performances are quite similar except for the centrifuge decanters which usually allow reaching higher DM content consuming less polymer but more electricity. Since the residence time in the digester is not a problem, the calculation has been done with gravity belt thickening.

Key parameters and assumptions

- SAS characteristics (estimated with OCEAN):
  - SAS production: 3.312 tDM/a
  - Current SAS flow: 128.000 m³/a
  - SAS flow after optimisation: 71.400 m³/a
- Shutdown of 2 digesters
  - 26 d sludge retention time instead of 39 d: small digestion performance decrease
  - **Decrease biomethane production:** 453 MWh/a → **27.900 €/a**
  - **Heat saving drying/incineration** (higher oDM content): 150 MWh/a → **8.800 €/a**
  - Increase
- Energy savings:
  - Heat saving: max. 3.311 MWh/a
  - **Heat saving: max. 196.500 €/a**
- Liquid polymer consumption (50% active matter):
  - Specific consumption : 4,7 kg a.m./tDM
  - Polymer consumption: 31,2 t/a
  - **Polymer costs: 71.900 €/a**
- Effect on electricity consumption (considering saving and additional consumptions):
  - Savings: 1.113 MWh/a
  - **Electricity savings: 83.100 €/a**

Cost Benefits Analysis

Investment Cost	**250.000 €**
Energy savings	**1.113 MWh/a electricity & max. 3.461 MWh/a heat**
Energy production decrease	**453 MWh/a biomethane**
Additional polymer consumption	**31,2 t/a**
Savings/revenue	**188.600 €/a**

Figure 40: Optimisation through implementation of additional process

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Annex V: Example of POWERSTEP concept effect on energy balance & consumables costs

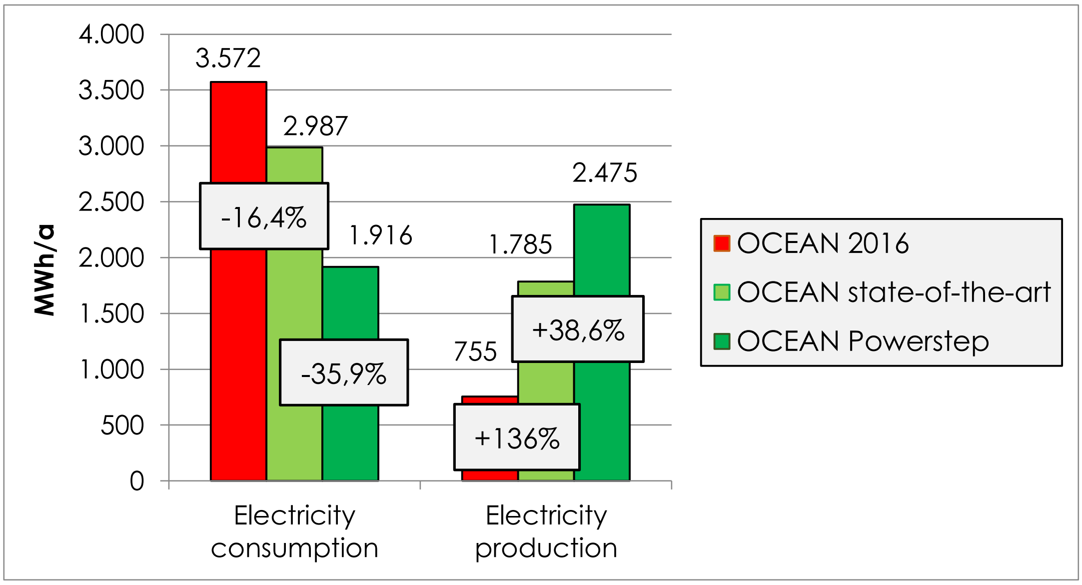

Figure 41: Effect of main POWERSTEP concept on electricity balance at one of the plant

	OCEAN Powerstep vs OCEAN state-of-the-art	OCEAN Powerstep vs OCEAN state-of-the-art (€/a)
CONSUMABLE COSTS (€/a)		**- 97.300**
Costs for energy buying		**- 121.700**
• Electricity	- 1.106 MWh/a	- 121.700
Costs for chemicals		**+ 16.800**
• Coagulant	± 0 t/a	± 0
• powder polymer (primary settling)	+ 8,6 t/a	+ 19.800
• powder polymer (thickening)	- 1,9 t/a	- 4.400
• powder polymer (dewatering)	+ 0,6 t/a	+ 1.400
Savings for sludge disposal	**+ 694 t/a**	**+7.600**
REVENUES (€/a)		**+26.200**
Revenues from energy selling		**+ 26.200**
• Electricity	+ 655 MWh/a	+ 26.200
RESULTING CONSUMABLES COSTS SAVINGS/REVENUES (€/a)		**+ 123.500**

Figure 42: Effect of main POWERSTEP concept on consumables and sludge disposal costs at one of the plant

Parameter	Unit	Powerstep 2
CO2 available from biogas upgrading plant	Nm³/a	246.600
Assumed running time	h/d h/a	8 2.900
ADDITIONAL REVENUES	**€/a**	**388.500**
Synthetic methane production (from the reaction between CO_2 & H_2) CH4 content Synthetic methane energy content	Nm³/a % MWh/a	251.600 98 2.500
Synthetic methane revenue (assumption: same price as biomethane)	€/a	262.500
Heat recovery Heat exchange power Heat consumption for digestion Part of the heat needs covered through heat recovery (assumption: digester is heated only 8h/d or heat storage is installed) Higher biomethane production due to lower biogas utilisation in boiler	MWh/a kW MWh/a % MWh/a	1.500 510 1.200 100 1.200
Biomethane revenue increase thanks to heat recovery	€/a	126.000
ADDITIONAL CONSUMABLES COSTS	**€/a**	**278.900**
Electricity consumption Average Power Electricity buying price during off-peak hours (assumption)	MWh/a MW €/MWh	4.960 1,7 MW 60
Additional electricity costs for the electrolyser	€/a	+ 297.600
Oxygen available Corresponding part of the oxygen needs in biological treatment (in the Powerstep 2 scenario) Max. Electricity saving potential for aeration (100% oxygen utilisation)	Nm³/a kg/a % MWh/a	493.200 704.200 47 220
Additional electricity costs for the WWTP operation	€/a	- 18.700
Water consumption in the electrolyser	m³/a	55
RESULTING CONSUMABLES SAVINGS & REVENUES	**€/a**	**109.600**

Figure 43: Example of effect of Power-To-Gas technology on consumables costs

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