KEY FIGURE DATA FOR ENERGY EFFICIENCY

Benchmarking the Baltic Sea Region in the project IWAMA – Interactive Water Management

IWAMA Interactive Water Management

Interreg Baltic Sea Region

EUROPEAN UNION
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EU STRATEGY FOR THE BALTIC SEA REGION FLAGSHIP

EVALUATING ENERGY EFFICIENCY OF WASTEWATER TREATMENT

Collecting key figure data from the wastewater treatment plants in the Baltic Sea Region

As a part of the Interreg BSR co-funded IWAMA project, data from 66 wastewater treatment plants (WWTPs) could be assessed for evaluation of the energy consumption related to nutrient removal. The information was provided from Sweden, Finland, Russia, Estonia, Latvia, Lithuania, Poland, Belarus and Germany.

The data presented in this report gives information about the current energy demand of variously scaled and equipped wastewater treatment plants (WWTPs) in the Baltic sea region (BSR) which are operated under different legal requirements and diverse restrictions regarding nutrient effluent values (mostly according HELCOM). In the framework of Interreg BSR project Interactive Water Management (IWAMA), key figure data has been collected with a questionnaire addressing WWTP in the region. A total number of 66 responses (reference year 2015) could be assessed for evaluation of the energy consumption related to nutrient removal. This report contains general information about the loads to be treated and the treatment efficiency. A unified comparative benchmark of the energy efficiency in relation to nutrient removal has been developed, which shall be applicable in different countries. Therefore, this report contains a description of the methodology applied.

The data collected revealed that different technologies are applied with varying success in high treatment efficiency combined with low energy consumption. However, there is no clear region based dependency. Speculative influencing factors are the age of WWTP and installed equipment, motivated and well-trained staff in combination with the availability of financial resources devoted to upgrading of WWTPs. Innovation and resource efficiency is also driven by legal requirements or financial benefits offered.

The challenges that WWT operators all around BSR are facing in increasing energy efficiency while up keeping or improving nutrient removal efficiency, are similar across borders. With the help of benchmarking it is possible to detect possible performance gaps. Therefore, all participating WWTP received an individual feedback including suggestions what measures could lead to better results in future benchmarking.

Half of the WWTPs considered in the evaluation are operated using less than 37 kWh/($PE_{COD,120}$·a). But only 20 % consume less than 23 kWh/($PE_{COD,120}$·a). This benchmark is proposed to be aimed by all plants in the region, still considering that the main task of a WWTP is treating wastewater in a proper way.

It is recommended to continue and extend the key figure comparison in the Baltic region as a motivation for optimized WWTP operation.

The information collected is available for all stakeholders in the region. The benchmark can be used as a soft goal to encourage higher efficiency in WWTP. Main key figures are displayed in user-friendly graphs, offering other WWTPs in the region opportunities to calculate their respective value and compare. Large deviations from the suggested benchmark indicate a demand for detailed energy audit of a plant.

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Editor's note: In this report, a comma is used as decimal marker.

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SYMBOLS AND ABBREVIATIONS

Symbols	Unit	Explanation
$B_{d,BOD5}$	[kg/d]	Daily BOD_5 load
C_{XXX}	[mg/l]	Concentration of the parameter XXX in the homogenized sample
$MLSS_{AT}$	[g/l]	Mixed liquor suspended solids in the aeration tank
OU_c	[mg/l]	Oxygen uptake during carbon elimination
PE	[PE]	Population Equivalent
$PE_{COD,120}$	[PE]	PE based on a load of 120 g COD/(PE·d)
$PE_{N,11}$	[PE]	PE based on a load of 11 g N/(PE·d)
PE_{dim}	[PE]	PE based on dimensioned values
S_{XXX}	[mg/l]	Concentration of the parameter XXX in the filtered sample/ soluble fraction of the concentration
T_{AT}	[°C]	Temperature in the aeration tank
V_{aer}	[m³]	Volume of aerated tank
V_{anox}	[m³]	Volume of anoxic tank
X_{XXX}	[mg/l]	Concentration of the parameter XXX of the filter residue / particular fraction of the concentration

Abbreviations	Explanation
CHP	Combined heat and power plant
SBR	Sequencing Batch Reactor
WWTP	Wastewater Treatment Plant

Indices	Explanation
aer	aeration
AT	aeration tank
BM	biomass
degrad	degradable
eff	effluent of the wastewater treatment plant
inB	inflow to the biological stage
inf	inflow to the wastewater treatment plant
SS	surplus sludge
Tot	total
TSS	total suspended solids

1 INTRODUCTION

The wastewater treatment sector has a large energy consumption in comparison to other municipal consumers and smart energy management is not commonly applied in the Baltic Sea region (BSR). The innovative approach pursued by IWAMA project entails reducing nutrient impact on the Baltic Sea at low energy level since there is a nexus between efficient nutrient removal and sustainable use of energy in the treatment process.

Key figure data is essential to evaluate the general situation and to develop a benchmark. It provides information about the current situation of different scaled wastewater treatment plants (WWTPs) in the BSR, which are operated under different legal requirements and different restrictions for nutrient effluent values (mostly according to HELCOM). While country-based key figure comparison is an accepted and widely applied method, this novel approach combines transnational information from different legal backgrounds and technological levels.

To collect the data, uniform questionnaires have been developed, asking for relevant process data both related to energy management and sludge handling. Key figure data has been provided on a voluntary base from almost 70 WWTPs in nine different countries: Estonia, Lithuania, Latvia, Poland, Germany, Finland, Sweden, Belarus and Russia. The data was evaluated and used to develop a suggestion for a unified comparative benchmark of the energy consumption in relation to nutrient removal. Due to extensive lack of data, some datasets had to be excluded from further analysis. The final database contains information from 66 WWTPs. To develop the complex benchmark representing efficient nutrient removal at lowest possible energy consumption, the focus had to be narrowed to fewer datasets providing all necessary information. For further use, the questionnaire might be revised to collect only information mandatory for calculation. To ensure anonymous data processing, all results were shown by assigning contributing WWTPs to four regions:

- Baltic region (Estonia, Lithuania and Latvia)
- South-Baltic region (Poland and Germany)
- Nordic region (Finland and Sweden)
- Slavic region (Belarus, Russia including Kaliningrad)

While the total number of feedback is sufficient, it needs to be mentioned that both from regional and technological aspects certain imbalances can be recognized. As depicted in Figure 1, the distribution among the regions is unequal. The South-Baltic region is represented by a major share of 28 contributing WWTPs, which amounts to nearly half of the WWTPs. Almost a third belong to the Baltic region. The Nordic region is represented by 10 WWTPs and the remaining 7 WWTPs are located within the Slavic region.

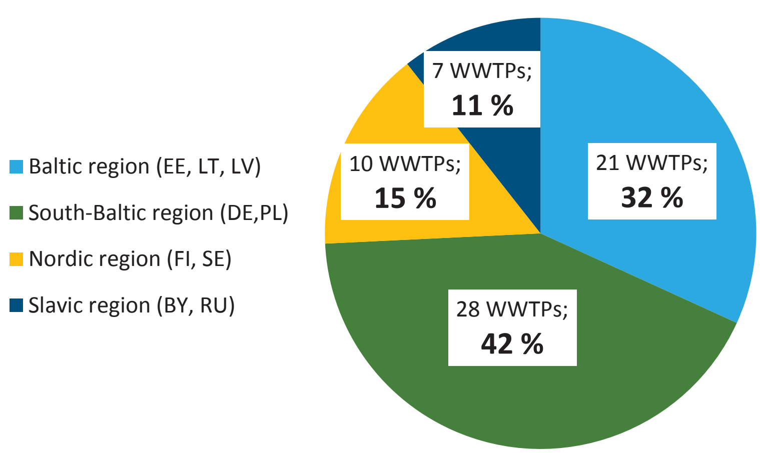


Figure 1 – Distribution of 66 contributing WWTPs into four regions

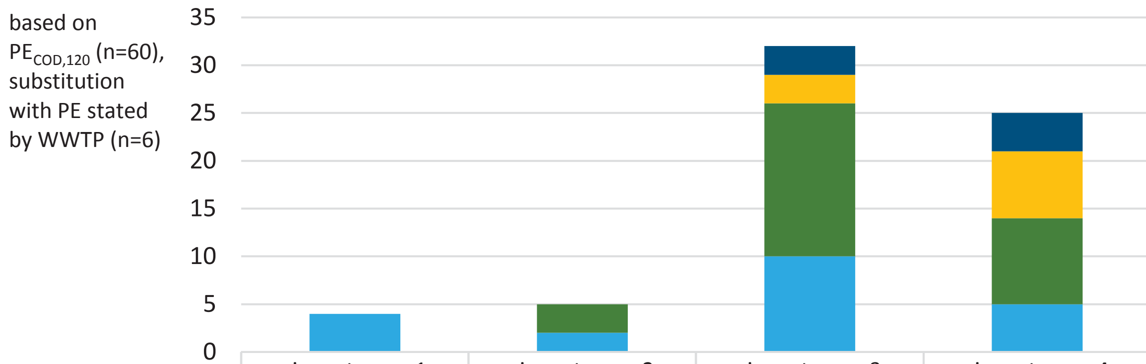
2 QUALITY ASSESSMENT AND DATA VALIDATION

A total of 66 data sets have been accepted for the evaluation procedure where the vast difference of data completeness and consistency had to be considered. As an initial and fundamental step, nutrient data was examined and crosschecked with simple load calculations and mass balances. In doing so, obvious faults in mathematical conversions and mistakes in units could be detected. Imprecise data marked with mathematical operators like "less than" (e.g. "< 3 mg/l") or ranges (e.g. "85-95 %" removal efficiency) were not taken into account. Furthermore, missing data was amended or substituted whenever possible. Sometimes either concentrations or loads were missing, while the real average flow rate was given. Thus, with the help of basic conversions, the missing value could easily be amended. Substitutions were many times implemented for concentrations and loads entering the biological reactor. Since proper measurement data was often missing at that point, they were replaced by reduced inflow concentrations or loads. The reduction ratios through primary clarification were adopted from DWA-A 131 (2016). They depend on the retention time of the wastewater in the primary clarifiers but since this time was not inquired, the general assumption of 0,75 – 1 h was made. In most cases, the real reduction achieved by primary clarification and calculated by the available data corresponds well to the assumed reduction ratio.

3 BASIC WWTP CHARACTERISTICS

3.1. Population Equivalent

The population equivalent (PE) is an inevitable basis in any calculation of specific key figures and development of benchmarks dealing with WWTPs. In the context of this report, PE refers to a basic load of 120 g COD/(PE·d). Figure 2 shows the size distribution of 66 WWTPs, mainly based on $PE_{COD,120}$. When the influent COD was not available, the value was substituted by the PE stated by the WWTP. In the region, different size classifications are used. The grouping in this report follows the size groups established in HELCOM recommendation 28E/5 (2007). Besides earlier mentioned regional imbalances, there are as well inequalities in size expressed in Figure 2. In general, there is a clear focus on the bigger WWTPs handling more than 10.000 PE. Both smaller size categories (< 10.000 PE) involve just 14 % of the overall number of WWTPs and are mainly represented by the Baltic region. Almost half of all WWTPs are assigned to size category 3 (10.001 – 100.000 PE) which includes WWTPs of all regions, the South-Baltic being the most prominent. The remaining 38 % of the WWTPs belong to size category 4 with a well-balanced regional distribution.



	size category 1 300 - 2.000 PE	size category 2 2.001 - 10.000 PE	size category 3 10.001 - 100.000 PE	size category 4 > 100.000 PE
Slavic region	0	0	3	4
Nordic region	0	0	3	7
South-Baltic region	0	3	16	9
Baltic region	4	2	10	5

Figure 2 – WWTPs grouped by size according to HELCOM recommendation 28E/5 (2007) and region

3.2. Influent parameters

The specific daily wastewater flow in the regions differ, with lowest median value in the South-Baltic region (see Table 1). The differences have not been investigated further. Also, COD concentrations at the inlet show a large variation (see Table 2). It can be concluded that the specific flow rates do have an impact on energy-nutrient-nexus since WWTP in the different regions are facing partly high organic concentrations in the wastewater inflow, while others receive low concentrations in the inlet. The wastewater of the South-Baltic region for example, is so little diluted that there is almost double COD load at the inflow to the WWTP when compared to the same amount of wastewater in the Nordic region.

Table 1 – Specific wastewater flow rate (mainly based on $PE_{COD,120}$)

	min	max	median
	[l / ($PE_{COD,120}$·d)]		
Baltic region	60	385	165
South-Baltic region	46	241	120
Nordic region	134	294	218
Slavic region	148	303	171

Table 2 – COD concentration at the inlet

	min	max	median
	[mg COD / l]		
Baltic region	320	1.573	741
South-Baltic region	498	2.637	1.002
Nordic region	416	896	557
Slavic region	396	813	704

The ratio of COD and BOD_5 is an indicator of the biodegradability of the incoming sewage. A short summary is presented in Table 3. More than 80 % of WWTPs stated industrial influence, but this is not necessarily reflected in high COD/BOD_5 ratios.

Table 3 – COD/BOD_5 ratios at the influent of WWTPs

COD/BOD_5	Baltic region [n]	South-Baltic region [n]	Nordic region [n]	Slavic region [n]
<2	*2*	*7*	*0*	*3*
2-4	*14*	*21*	*9*	*4*

The COD/N ratio is defined by the incoming sewage. If the COD/N ratio is below 10, substrate might be missing and limiting the denitrification process. About 30 % of the WWTPs in all regions go below this value (see Table 4). A common method is to add C-source to the process, e.g. methanol. Of course, this implies additional costs.

Table 4 – COD/N ratios at the influent of WWTPs

COD/N	Baltic region [n]	South-Baltic region [n]	Nordic region [n]	Slavic region [n]
<10	*8*	*8*	*1*	*2*
>= 10	*8*	*18*	*8*	*5*

3.3. Treatment processes

Various specifications on treatment steps and processes were inquired and analysed. Figure 3 illustrates the applied treatment technologies. In all regions, the activated sludge system including nitrification and denitrification could be ascertained as the predominant or even exclusively applied technology. A considerable share performs this treatment within a Sequencing Batch Reactor (SBR), which are mostly used in the Baltic region. The majority in all regions though uses conventional multistage flow-through systems. More detailed specifications were only given by two South-Baltic WWTPs. One of them uses the activated sludge system in combination with downstream trickling filters, a sludge blanket reactor and two-stage biofiltration. The other one applies a Cyclic Activated Sludge Technology (CAST). Since this technology can be understood as a sort of SBR, it was numbered among the SBRs in Figure 3. An activated sludge system with merely carbon removal was determined in almost half of the Slavic WWTPs and in only very few WWTPs in the Baltic and South-Baltic region.

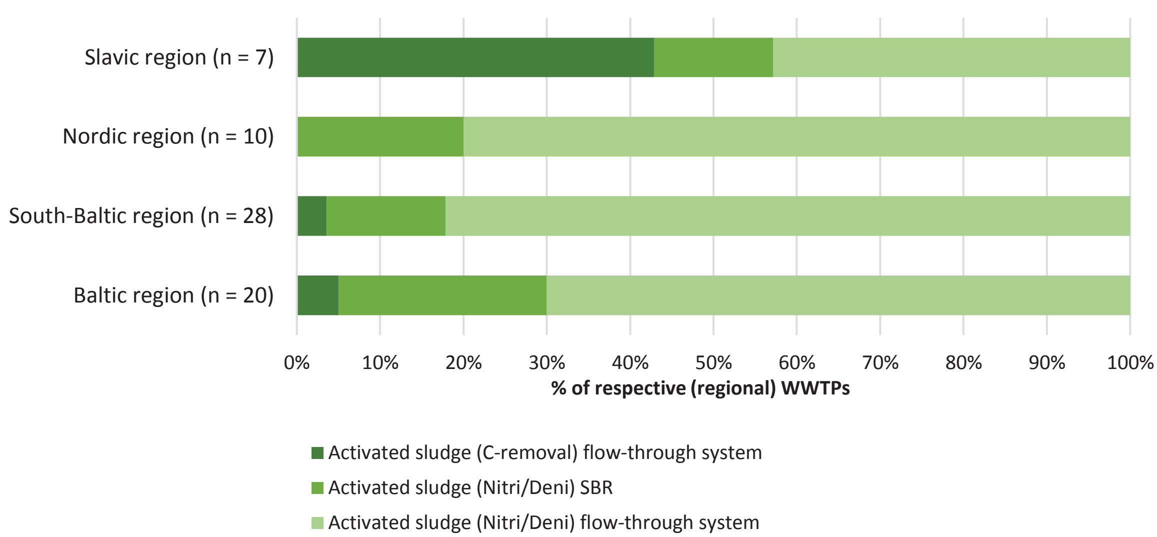


Figure 3 – Applied wastewater treatment technologies

Figure 4 displays the use of primary clarification among the WWTPs. In general, about 65 % of all contributing plants use primary clarification. All contributing Nordic plants use primary clarification. In the Slavic region, this applies to more than 80 % and in the South-Baltic region to around 70 %. Least use at about 33% was ascertained in the Baltic region. WWTPS, that are not applying primary clarification, were in most cases rather small or medium-sized plants serving less than 100.000 $PE_{COD,120}$ and treating less than 20.000 m³/d. An exception was a South-Baltic WWTP, which is a big plant dealing with large proportions of industrial wastewater. Therefore, various pre-treatment steps are applied instead of primary clarification. Remarkably, 8 out of 9 Estonian plants and all 3 contributing Latvian WWTPs do not apply primary clarification.

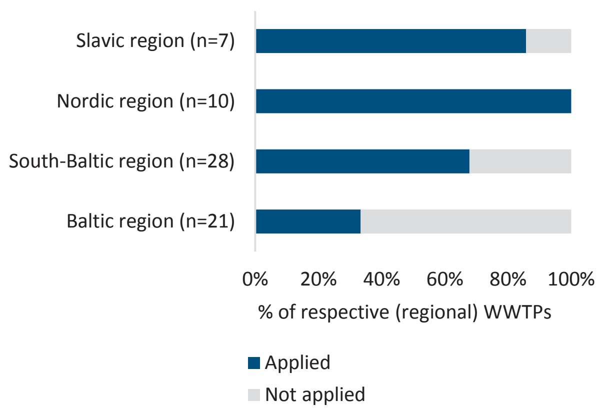


Figure 4 – Use of primary clarification

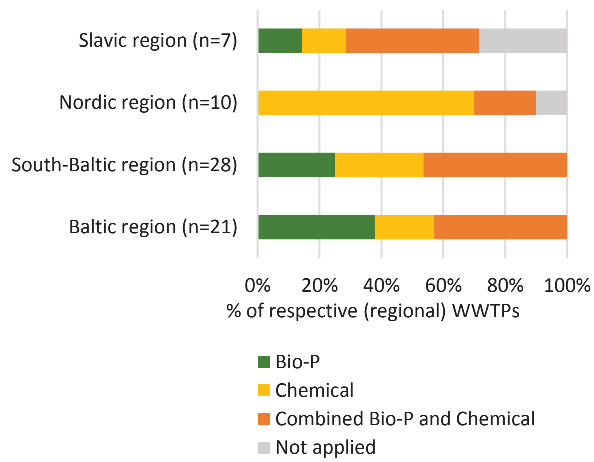


Figure 5 – Phosphorus removal processes

Figure 5 demonstrates the utilisation of different phosphorous removal processes. Only very few contributing WWTPs in the Slavic and Nordic region do not remove phosphorous. Apart from that, the application of Bio-P, chemical or combined removal processes is quite balanced. Among the Nordic plants however, there is a clear focus on chemical phosphorous removal whereas none of them uses exclusive Bio-P treatment.

Figure 6 and Figure 7 give an overview of the barely applied disinfection methods and the use of effluent filtration. Chemical disinfection was only found in the Baltic and Slavic region on one WWTP each. UV-light was likewise just applied on one plant each in the Slavic, Nordic and South-Baltic region. All remaining plants do not use any disinfection methods.

Effluent filtration is percentagewise mostly applied in the Nordic region, followed by the Slavic region. Just about 10 % of the Baltic and South-Baltic WWTPs use this treatment step.

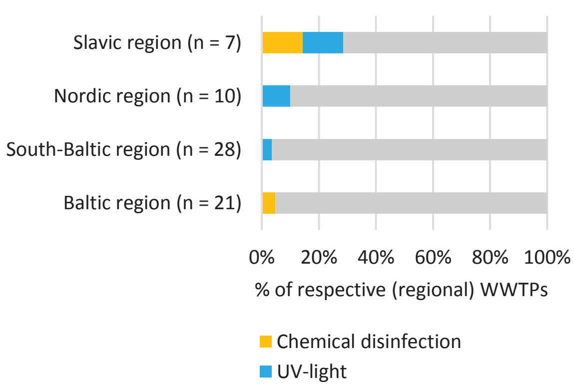


Figure 6 – Applied disinfection methods

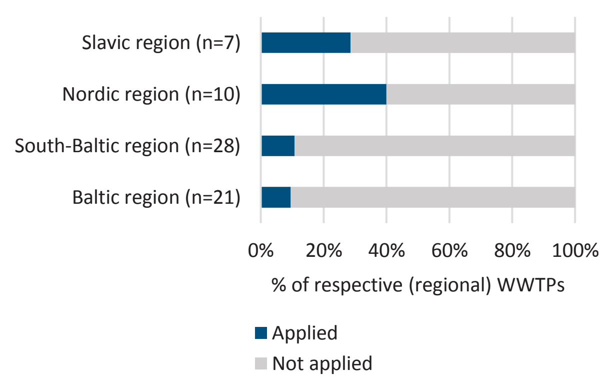


Figure 7 – Use of effluent filtration

3.4. Degree of utilization

The degree of utilization (DU) expresses how much of the available capacity of a WWTP is actually used or, in other words, describes how well the dimensioning of a plant matches real conditions, which can have significant impact on the energetical performance of a WWTP. The ratio was determined by relating the actual $PE_{COD,120}$ as described above to the dimensioned PE. Figure 8 and Figure 9 display the DU of the contributing plants in an overall and regional manner. A large range between 20 - 170 % was detected with a median DU at about 80%. According to DWA-A 131 (2016), WWTPs should be designed based on 85% of the actual load. Regionalized there are just minor differences. In general, almost all Baltic plants are underloaded whereas in the other regions 10 - 30 % of the WWTPs are overloaded. When relating the DU to nitrogen ($PE_{N,11}$ / PE_{dim}), the median loading rate diminishes to about 70 %, 65 % with respect to phosphorus.

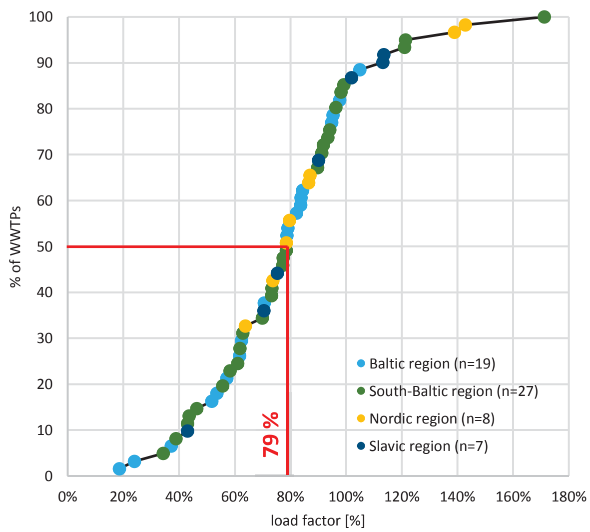


Figure 8 – Degree of utilization based on COD, accumulative

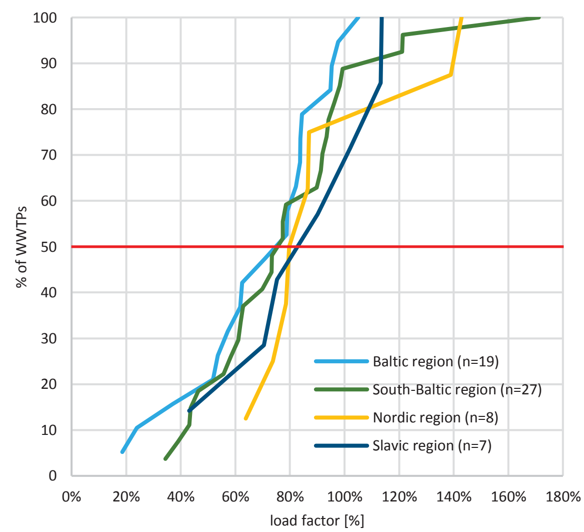


Figure 9 – Degree of utilization based on COD, regionalized

3.5. Sludge age

The sludge age describes the average retention time of sludge in the biological stage. Figure 10 illustrates the calculated sludge ages based on BOD_5 both in a regional and overall manner. The overall sludge age ranges between 5 and 71 days. Regional differences are quite evident. While 50 % of the Slavic plants have a sludge age lower than 12 days, the sludge age of the same share of the Baltic plants is less than 32 days, which accounts to a tremendous difference of 20 days. Nordic and South-Baltic region take an intermediate position with a mean sludge age of around 17 days that corresponds to the overall mean sludge age of about 18 days. Further details on the calculation of the sludge age are given in the attachment.

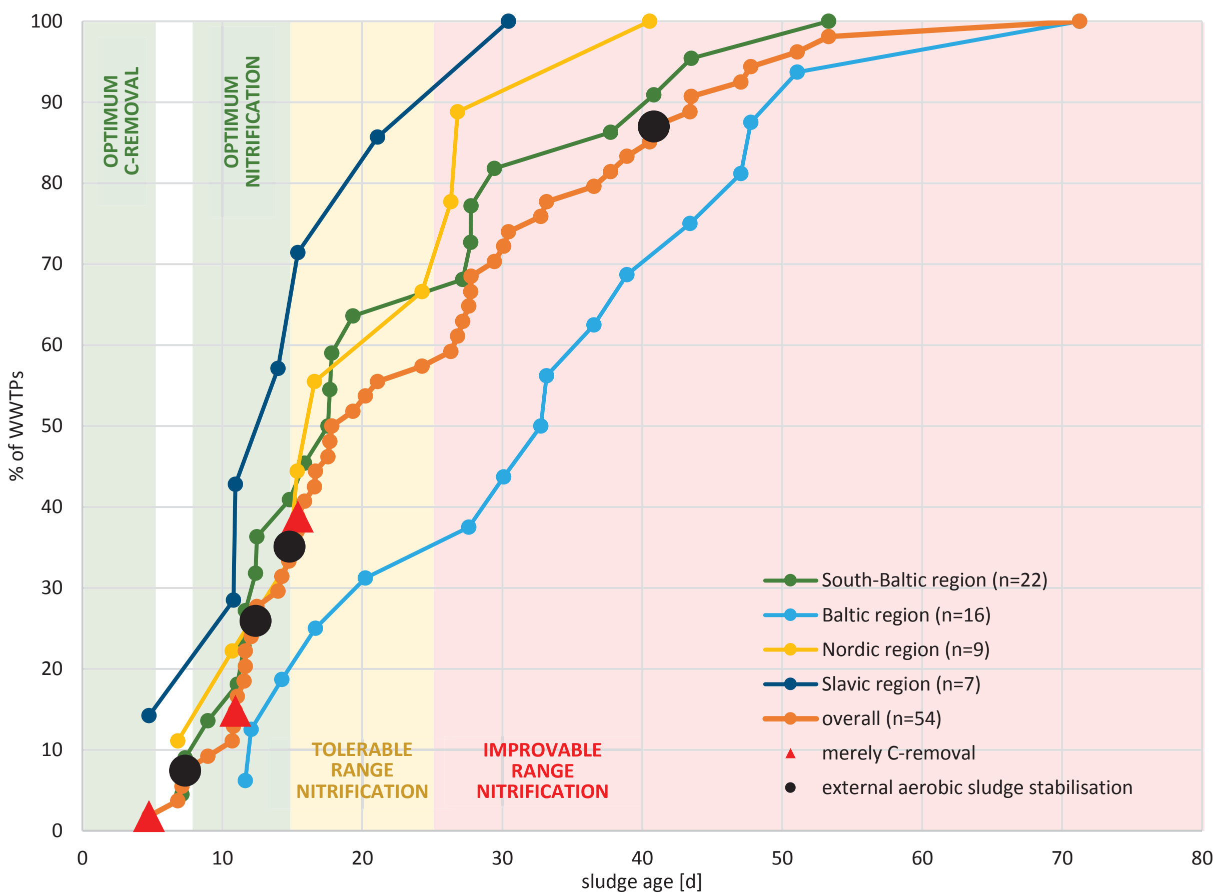


Figure 10 – Sludge age based on BOD_5 as overall and regional display

Too high sludge age is linked to less biogas production in a following anaerobic step and may have a negative effect on the sludge settling quality as well. Lower sludge age is linked to bigger biogas production, while in a colder climate and season, a problem of biological nitrogen removal is created. Very low or very high sludge age values can show either problems in the biological treatment or problems with the related data.

4 REMOVAL EFFICIENCIES

Nutrient removal is the main objective of a WWTP and is subject to legal regulations. Removal rates are linked to energy consumption as well as energy production. In Figure 11, removal efficiencies of various characteristic wastewater parameters are illustrated with varying amount of available data. The graphs' lines match typical removal rates of WWTPs with BOD_5 being best degradable, a median removal of around 99 % is achieved. Regarding suspended solids, a removal rate with a median at about 98 % is achieved. COD and phosphorous have a median removal efficiency of about 96 %. For nitrogen, the lowest removal rates can be observed at a median of 86 %.

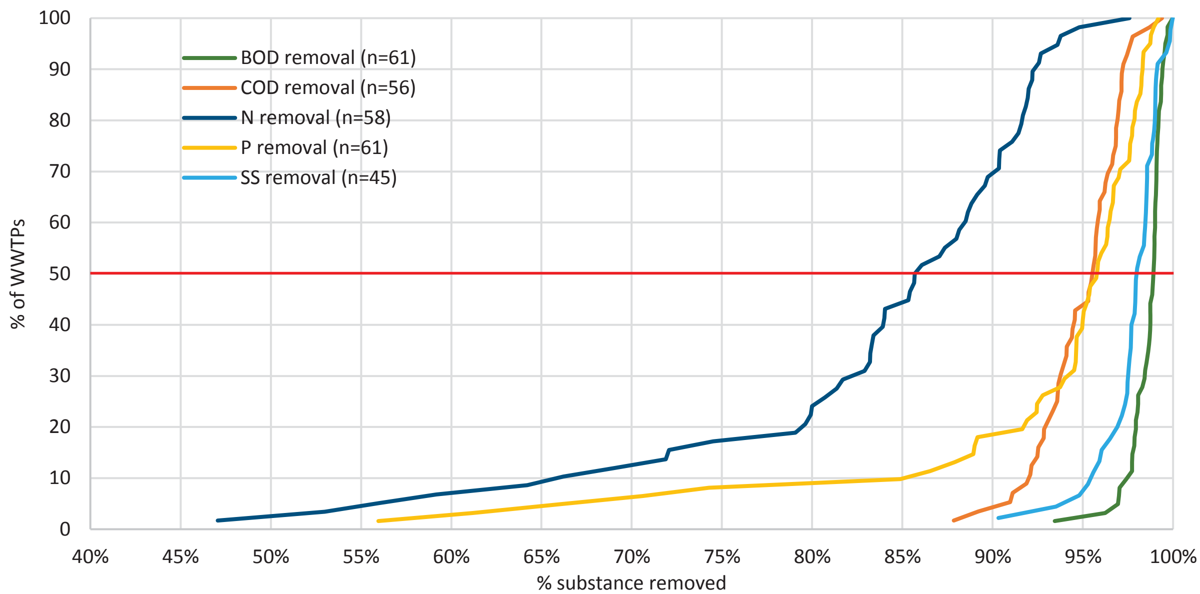


Figure 11 – Nutrient removal efficiency

Legal regulations concerning limited nutrient effluent concentrations or required percentage reduction differ in the countries. As a cross-national commission, HELCOM unites almost all contributing countries, Belarus being the only non-member state. HELCOM recommendation 28E/5 (2007), summarized in Table 5, just refers to the elimination of BOD_5, N_{tot} and P_{tot}. An older version from 1999 (HELCOM recommendation 20E/6) referred to COD and recommended a minimum reduction of 80 %. HELCOM recommendations were taken here as reference since their limitations for effluent concentrations are in most cases stricter than country-specific legislations.

Table 5 – Nutrient removal regulations according to HELCOM recommendations 28E/5 (2007)

	BOD_5		N_{tot}		P_{tot}	
	reduction [%]	limit effluent [mg/l]	reduction [%]	limit effluent [mg/l]	reduction [%]	limit effluent [mg/l]
group 1 (300 - 2.000 PE)	80	25	30	35	70	2
group 2 (2.000 - 10.000 PE)	80	15	30		80	1
group 3 (10.001 - 100.000 PE)	80	15	70 - 80	15	90	0,5
group 4 (> 100.000 PE)	80	15	70 - 80	10	90	0,5

4.1. COD removal

In Figure 12 and Figure 13 COD removal efficiency calculated on the influent/ effluent data provided is displayed in an overall and regional manner. The overall median COD removal efficiency is set at about 96 %, which almost equals the median of the South-Baltic region being the most influential one in terms of data availability. In the Baltic region, median removal efficiency accounts to about 95 % whereas Nordic and Slavic region reach a median COD removal of around 93 %. The Slavic region is showing the biggest variations from 88 - 99 % of COD elimination. Effluent COD concentrations of all regions are summarised in Table 6.

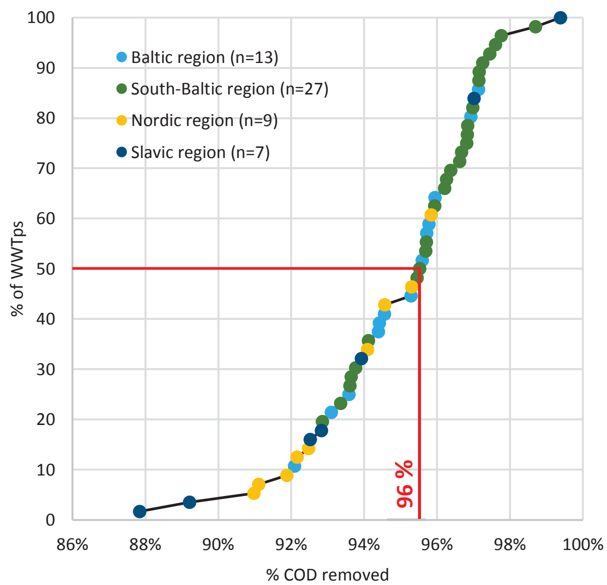


Figure 12 – Overall COD removal efficiency

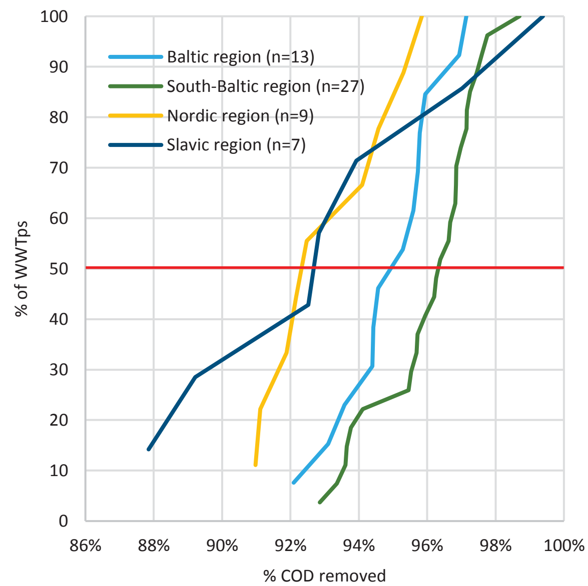


Figure 13 – Regional COD removal efficiency

Table 6 – Summarised effluent COD concentrations

	n	min	max	median
		[mg/l]		
Baltic region	13	29	61	41
South-Baltic region	27	19	164	34
Nordic region	9	30	52	41
Slavic region	7	5	86	34

A minimum COD reduction of 80 % is fulfilled in all plants. The same applies for BOD_5 (not shown) except for one WWTP in the Slavic region, which does not fulfil the criteria of the required BOD_5 effluent concentration.

4.2. Nitrogen removal

In Figure 14 and Figure 15, nitrogen removal efficiency is displayed in an overall and regional manner. The overall median nitrogen removal efficiency is set about 86 %. Looking at the defined regions, South-Baltic and Baltic region show best results in nitrogen removal with a median about 90 and 87 %. Nordic and Slavic region have a median nitrogen reduction of about 75 %. Plants with an activated sludge technology but without a nitri-/ denitrification process (merely C-removal) are on inferior positions, as it was expected.

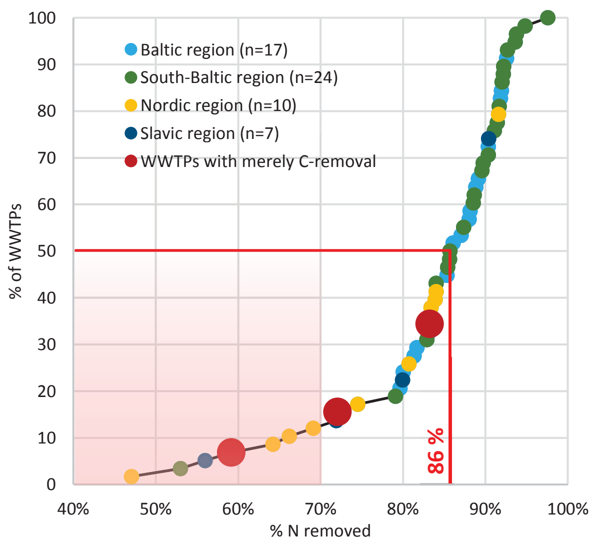


Figure 14 – Overall N removal efficiency

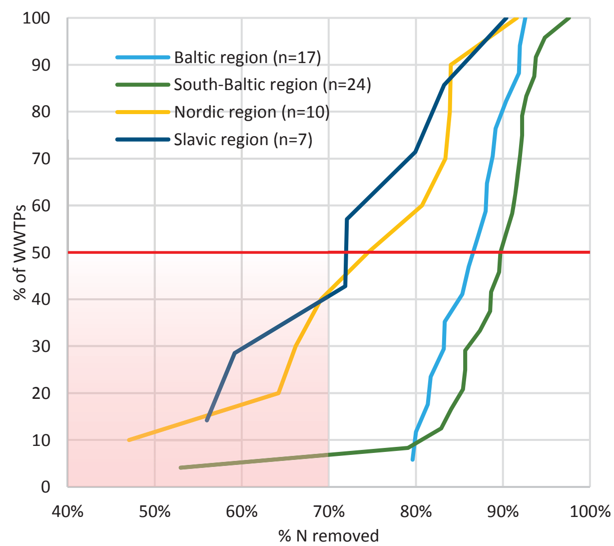


Figure 15 – Regional N removal efficiency

In the figures above, there is also the HELCOM recommendation displayed in red showing minimum nitrogen reduction of 70 % for larger WWTP size groups as they are mainly represented here. In Figure 14, it can be seen that about 12 % do not fulfil the percentage reduction rate. Together with the second criteria of limited effluent concentrations (see Table 7) non-fulfilling WWTPs sum up to 20%.

Table 7 – Summarised effluent N concentrations

	n	min	max	median
		[mg/l]		
Baltic region	17	5	17	9
South-Baltic region	24	2	32	8
Nordic region	10	4	18	13
Slavic region	7	7	28	14

4.3. Phosphorous removal

Figure 16 and Figure 17 show the phosphorous removal rate in an overall and regional manner. The overall median is set at around 96 %. Regionalized, it can be seen that the Nordic region, despite to its other nutrient removal rates, has a forerunner position with a median at about 97 %, followed by the Baltic and South-Baltic region at about 96 and 95 %. The least P removal efficiency was determined in the Slavic region having a mean P removal of about 80 %.

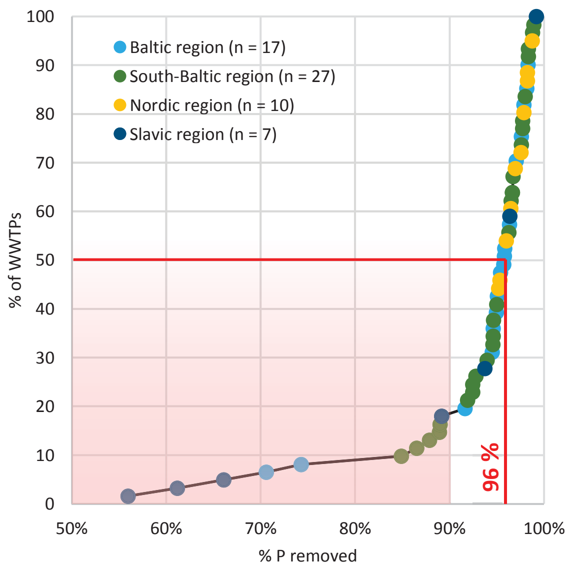


Figure 16 – Overall P removal efficiency

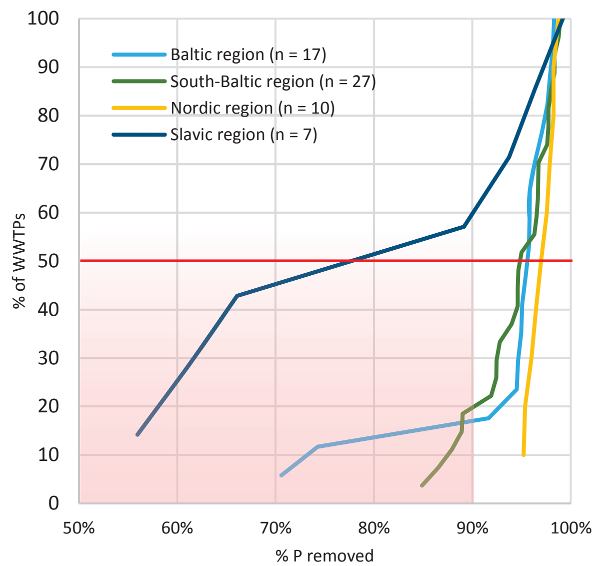


Figure 17 – Regional P removal efficiency

In terms of applied P removal processes there were no indications that one process results in better removal rates than another. Regarding HELCOM recommendations, P removal for larger plants should at least be 90 %. In the above figures, this limit is displayed in red. Taking both HELCOM criteria (reduction rate and limited effluent concentration) into account, there are almost 40 % of the contributing WWTPs not fulfilling the recommendations. Effluent P concentrations of all regions are summarised in Table 8.

Table 8 – Summarised effluent P concentrations

	n	min	max	median
		[mg/l]		
Baltic region	20	0,2	2,6	0,4
South-Baltic region	27	0,2	2,6	0,5
Nordic region	10	0,1	0,3	0,2
Slavic region	7	0,1	2,9	0,9

5 ENERGY CONSUMPTION

The total energy demand of a wastewater treatment plant is influenced by various factors. If the activated sludge process is applied, the largest part of electrical energy is used to supply oxygen for the aeration system. In addition, other treatment steps and especially pumping and mixing of wastewater do influence the total energy demand. Furthermore, the energy demand depends on the electrical efficiency of the installed equipment. To analyse all influencing factors, a detailed energy audit of a WWTP is needed. With the help of user-friendly key figures and benchmarks, hints for the demand of energy optimization and a detailed energy audit can be obtained.

While energy efficient wastewater treatment has been promoted in the recent years, different ratios to be used as key figures have been presented in literature (see Table 9). This report presents the most commonly used and adds a new suggestion [kWh/kgO_2] which should reflect the energy efficiency in relation to the nutrient removal efficiency.

Table 9 – Overview and valuation of analysed key figures

Key figure	Energy is related to	Evaluation
kWh_{tot}/m^3	1 parameter: m^3	Since the concentration of pollutants in the wastewater vary significantly in the regions (shown in Table 2 for COD), kWh/m³ becomes meaningless when exclusively considered and rather makes sense when comparing only hydraulic based equipment. Besides, there is no reference to the cleaning efficiency. Because of these reasons, we do not recommend this key figure for general benchmarking.
$kWh_{tot}/(PE{\cdot}a)$	2 parameters: $C_{COD,inf}$, m^3	This key figure is widely accepted and can be determined easily. However, it does not refer to the cleaning efficiency.
$kWh_{tot}/kgCOD_{rem}$	3 parameters: $C_{COD,inf}$, $C_{COD,eff}$, m^3	This key figure is also easy to determine and takes into account at least COD removal efficiency. However, if COD removal efficiency in the dataset is in a similar range, results correspond to $kWh_{tot}/(PE{\cdot}a)$, which is why this key figure does not provide an added value.
kWh_{tot}/kgO_2	12 parameters: $C_{COD,inf}$, $C_{COD,eff}$, $C_{N,inf}$, $S_{orgN,eff}$, $S_{NH4\text{-}N,eff}$, $S_{NO3\text{-}N,eff}$, $X_{SS,inf}$, V_{aer}, V_{anox}, $MLSS_{AT}$, $B_{BOD5,inf}$, T_{AT}	This newly applied key figure involves several parameters and takes cleaning efficiency not only of COD but also of nitrogen into account. Disadvantage of having this amount of reference is the aspect that the determination of the key figure takes a lot of time and cannot be estimated in a simplified manner.

The oxygen demand as a reference value has been selected to better represent nutrient removal efficiency. Details of the calculation method suggested are presented in the attachment. In the following sub-sections the respective key figures will be outlined in detail. The key figure [kWh/m³] however, even though it was analysed, will not be presented here due to the reasons mentioned above.

5.1. Specific energy consumption kWh/($PE_{COD,120}$·a)

A widely accepted and often used ratio is based on the total energy demand of a plant in relation to the connected $PE_{COD,120}$. This is displayed in Figure 18 and Figure 19 in an overall and regional manner. The overall median is set at around 37 kWh/($PE_{COD,120}$·a), which corresponds to the median of Baltic, South-Baltic and Nordic region. Slavic region in fact, shows best results having a median of just 22 kWh/($PE_{COD,120}$·a). However only 5 WWTPs are included, which is considered as a reason for a non-representative result.

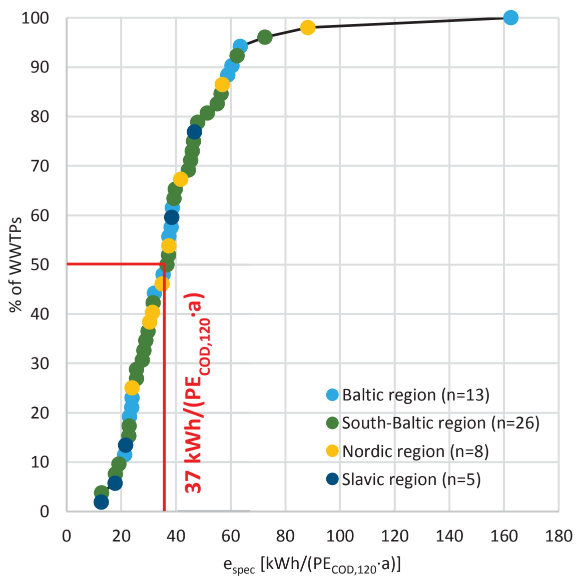


Figure 18 – Specific energy consumption [kWh/($PE_{COD,120}$·a)], accumulative

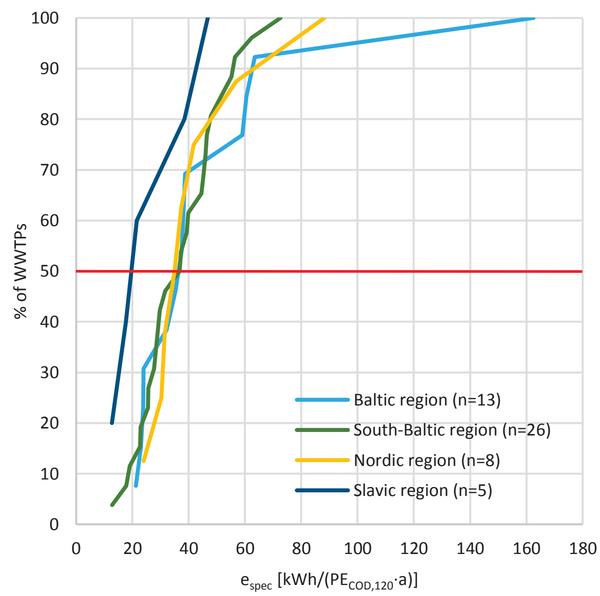


Figure 19 – Specific energy consumption [kWh/($PE_{COD,120}$·a)], regionalised

In Figure 20, kWh/($PE_{COD,120}$ ·a) is shown in relation to the connected PE. A dependency of large WWTPs being more energy efficient than smaller plants is indicated, but a fitted power function reveals a low correlation coefficient only. Moreover, larger plants might exploit economies of scale since they use large and generally more efficient equipment, especially larger pumps and generators.

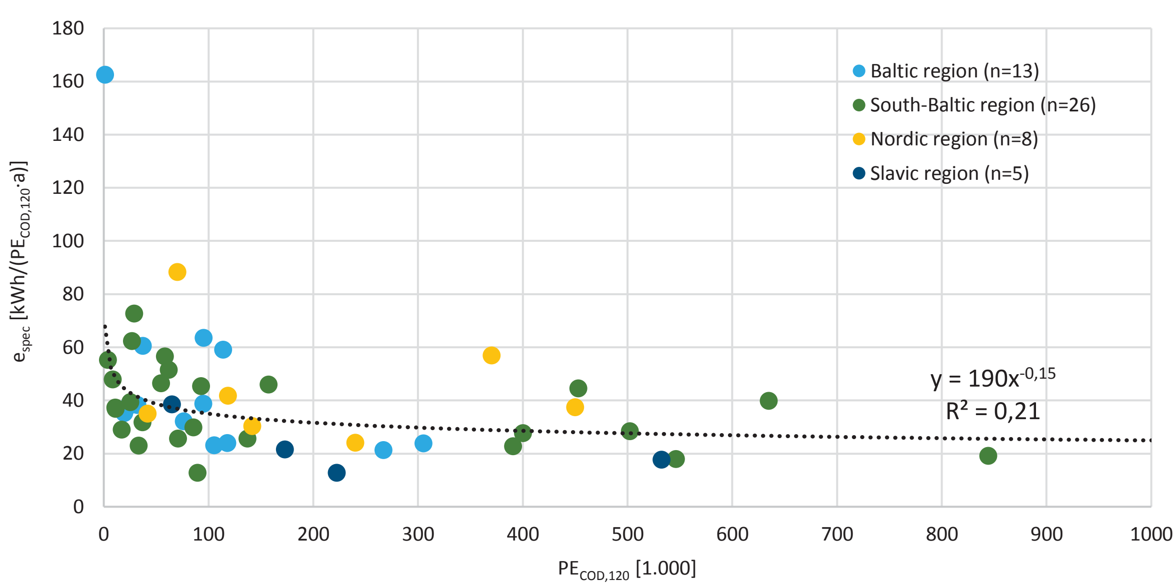


Figure 20 – Specific energy consumption [kWh/($PE_{COD,120}$·a)] in relation to connected PE [$PE_{COD,120}$]

Furthermore, the degree of utilization can have significant impact on the performance of a WWTP as illustrated in Figure 21. Lowest specific energy consumption can be found within the section of 90-100% used capacity. Heavy underloading is linked to worse energy performances. Partly, this can also be perceived for overloaded WWTPs although for that case, there is not enough data available.

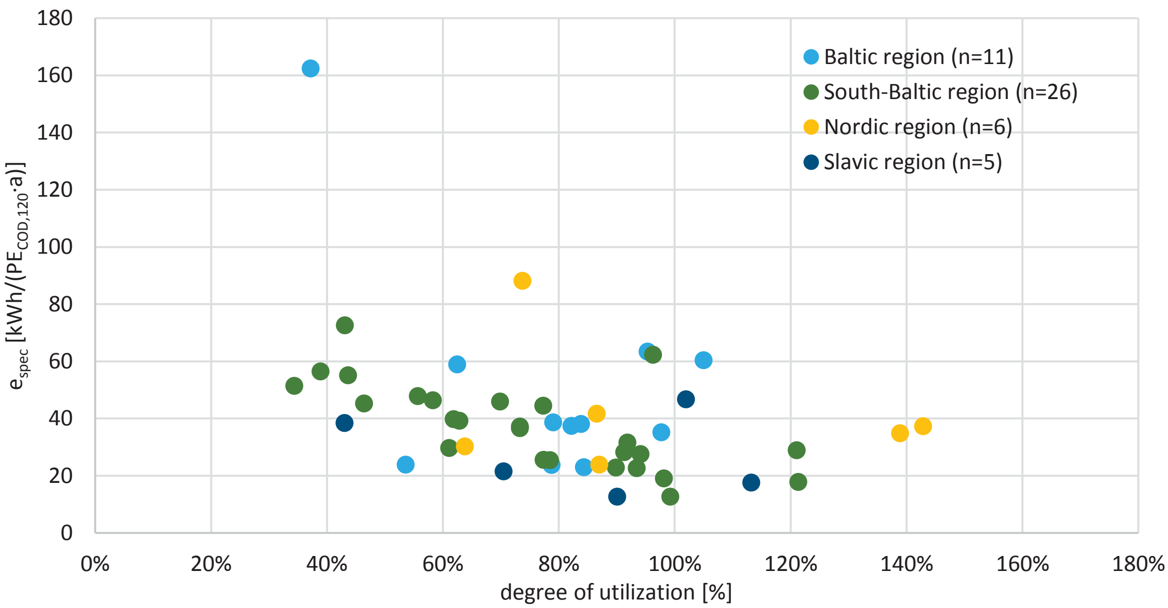


Figure 21 – Specific energy consumption [kWh/(PE$_{COD,120}$·a)] in relation to degree of utilization

5.2. Specific energy consumption kWh/kgCOD$_{rem}$

Another approach is to describe the ratio of total energy consumption divided by COD removed (Figure 22 and Figure 23). However, since almost all treatment plants achieve similar COD-removal efficiencies > 90%, there is no significant difference to the specific energy consumption related to COD-load based PE ratio.

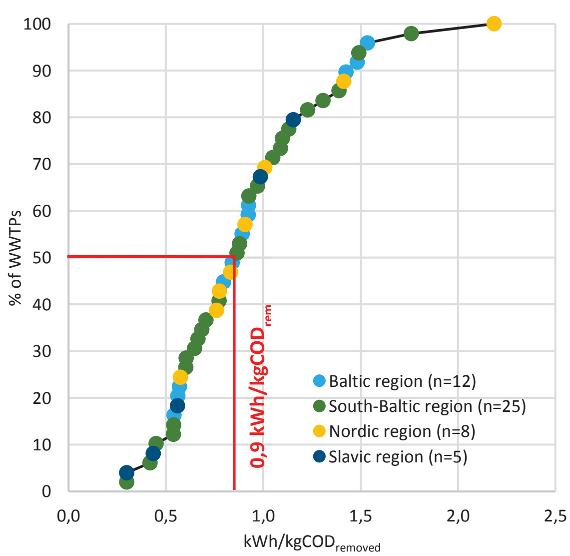


Figure 22 – Specific energy consumption [kWh/kgCODrem], accumulative

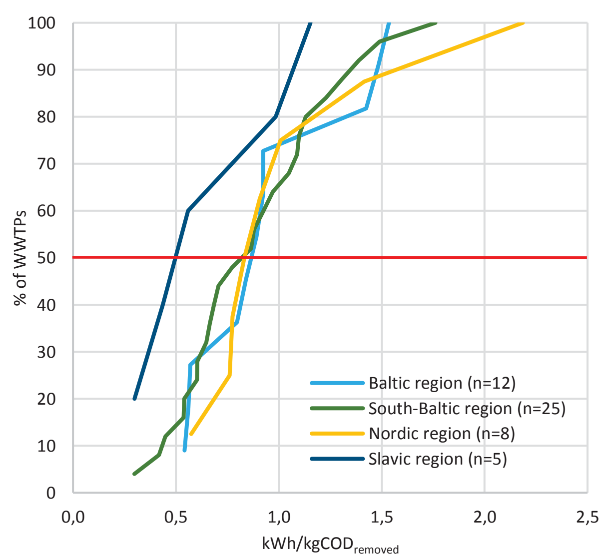


Figure 23 – Specific energy consumption [kWh/kgCOD$_{rem}$], regionalised

5.3. Specific energy consumption kWh/kgO$_2$

Oxygen is a main influencer concerning nutrient removal efficiency as well as energy consumption. Thus, the specific energy consumption related to oxygen demand [kWh/kgO$_2$] is deemed to display exactly the nexus of nutrient removal and energy use. So far, this key figure is not commonly used while its applicability has been tested for this report.

Due to the large amount of required data, the ratio could be determined only from 31 WWTPs (Baltic n=9, South-Baltic n=15, Nordic n=2, Slavic n=5). Often effluent nitrogen components such as ammonium or nitrate were not stated or volumes for estimating the sludge age were missing in the data input.

The following parameters have been analysed to check their influence and thus plausibility of the newly applied ratio [kWh/kgO$_2$]. In the following, some examples of the checks are shown.

- Year of construction
- Sludge age
- Temperature in aeration tank
- COD-fractionation
- Treatment steps
- Share of municipal/ industrial wastewater
- Use of primary clarification
- COD/BOD ratio

Year of construction:
For this analysis, the year of construction/ reconstruction of the biological treatment ranges from 1984 until 2015. From all regions, older and newer plants are included. Even though the newest plant features the best kWh/kgO$_2$ ratio, it was also assessed that the oldest plant is among the top ten (rank 7). In general, it was found out that for the scope of this benchmark the year of construction/ reconstruction is not showing any influence on the performance assessed by kWh/kgO$_2$. Same perception was made when relating the year of construction to kWh/($PE_{COD,120}$·a).

Sludge age:
The sludge age is regarded here merely as an influencing variable for the oxygen demand and not directly for the electricity consumption, which is kept steady for better comparison. It was found that the sludge age has a rather weak influence on the oxygen demand. In Figure 24, the impact of drastically increasing and decreasing the sludge age is illustrated. As expected, the oxygen demand decreases when sludge age decreases. Consequently, the ratio kWh/kgO$_2$ increases. Contrary observation was made for decreasing the sludge age, although changes show effects more rapidly. In the end, it seems as if WWTPs with higher sludge age are more energy efficient. However, this conclusion should not be drawn because the depicted variations cannot be regarded as realistic condititions since electricity consumption would also increase when oxygen demand rises.

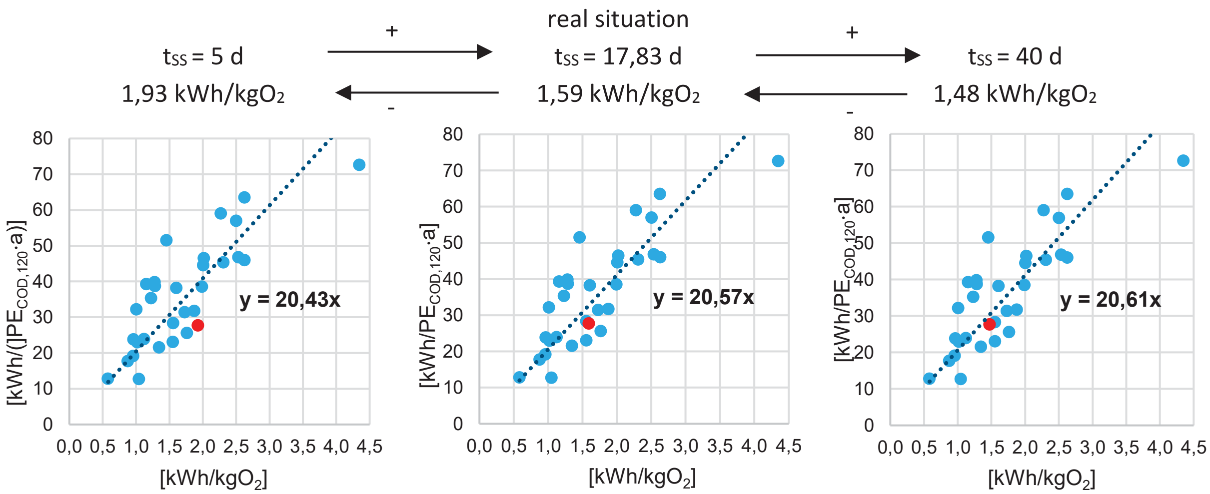


Figure 24 – Impact of sludge age on kWh/kgO₂

A relation between kWh/($PE_{COD,120}$·a) and kWh/kgO_2 (see Figure 25) was recognizable and can be described with a linear function but reveals only a minor correlation coefficient. Both key figures, the established [kWh/($PE_{COD,120}$·a)] as well as the new approach [kWh/kgO_2], often show similar results in assessing the energy performance of a WWTP. However, since kWh/($PE_{COD,120}$·a) does not include any cleaning efficiency, kWh/kgO_2 is considered as providing a more realistic picture of the plants energy performance. Nonetheless, the determination of the new key figure [kWh/kgO_2] is very elaborate and might not be applicable for plants having little possibilities to collect all necessary data.

When comparing the WWTPs ranking results of both key figures, deviations in a range of 10-20 % were detected, both in a negative and positive way, which almost counterbalance in the overall situation.

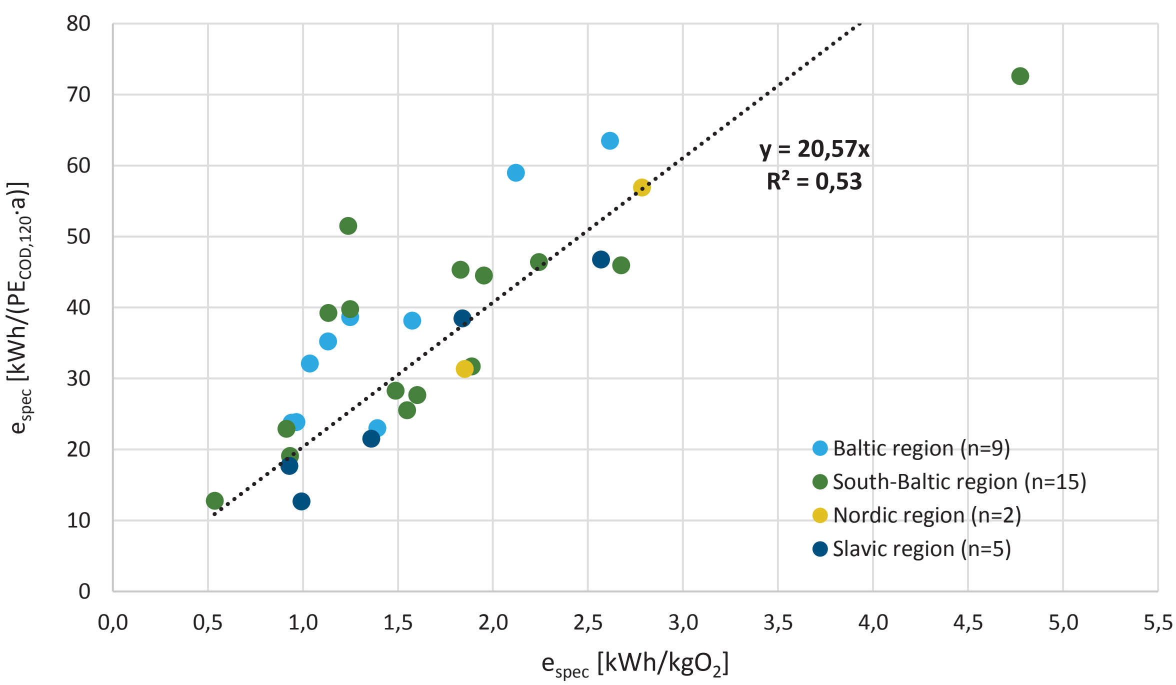


Figure 25 – Specific energy consumption kWh/kgO₂ in relation to kWh/($PE_{COD,120}$·a)

6 ENERGY PRODUCTION

The demand for (electrical) energy even for those plants with very energy efficient treatment process and equipment is still in a considerable range. Therefore, the use of renewable energy sources is recommended to lower the environmental impact. Anaerobic treatment of sludge is a commonly applied process to produce biogas, which in terms can be processed by a combined heat and power plant to gain heat and electrical energy. According to the replies, a total of 23 WWTPs does make use of the biogas produced, while 27 stated that digestion is applied at their treatment facility. The feasibility of anaerobic digestion is usually linked to the size of a treatment plant, lowest value stated is 29.000 $PE_{COD,120}$. Other, rather process independent options like wind (0), solar (2) and hydropower (1) are not yet commonly applied.

A simple approach to compare different WWTPs with anaerobic sludge treatment is to calculate the specific biogas production in relation to the connected PE. 50% of the plants produce more than 27 l/($PE_{COD,120}$·d) (Figure 26). The database includes WWTPs treating only their own sludge as well as WWTPs who accept external sludge and/or co-ferments. Looking at gas production yield in relation to the fed VSS, 50% of the plants achieve more than 400 l/kg VSS (Figure 27), but only about 20% of the plants achieve values higher than 500 l/kg VSS.

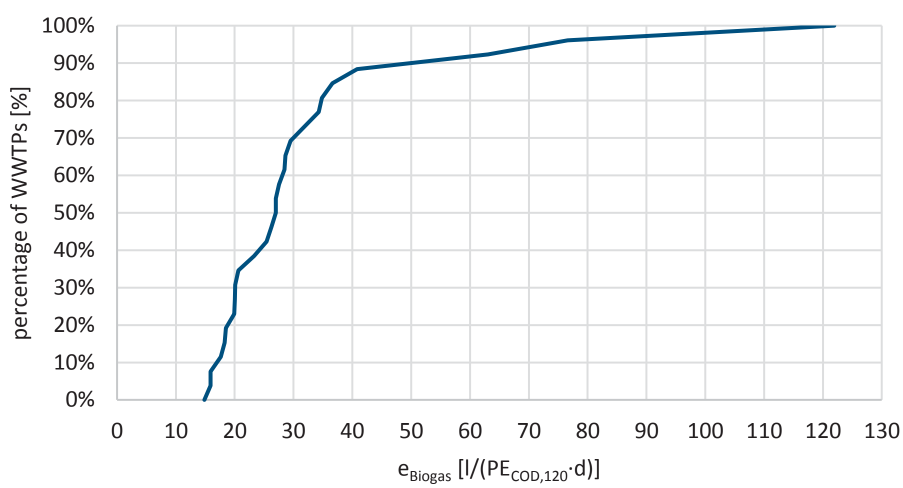


Figure 26 – Specific biogas production [l/($PE_{COD,120}$·d)], n=27

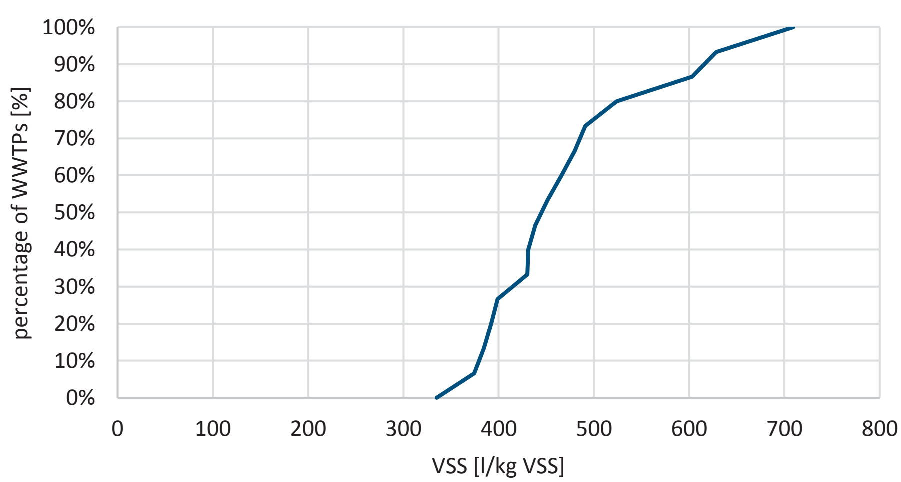


Figure 27 – Specific biogas production in relation to fed VSS [l/kg VSS], n=16

The detailed analysis of the specific biogas production in relation to PE and fed VSS did not reveal any specific trends regarding used substrates. Nevertheless, the plot of the average daily biogas production vs. the connected inhabitants based on the COD-load demonstrates a higher potential of plants utilizing both external sludge and co-ferments, especially considering WWTPs below 150.000 $PE_{COD,120}$ (Figure 28). In fact, the biogas production is on a similar level as plants with 2-3 times larger $PE_{COD,120}$.

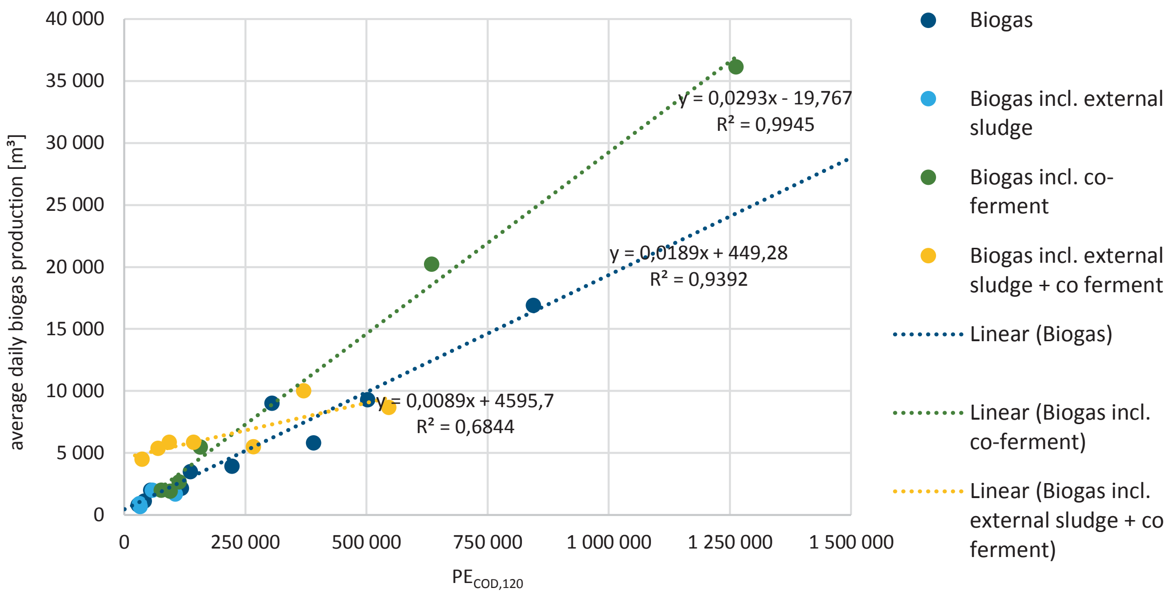


Figure 28 – Average daily biogas production [m³] vs. $PE_{COD,120}$, n=27

The biogas obtained is used in most cases to produce electrical energy and heat. Other options applied in the meantime like upgrading the biogas to operate vehicles or feeding into the local gas grid have not been mentioned with respect to the reference year.

To evaluate the efficiency of the CHP, the rate of digester gas conversion is a useful key figure. Based on the average methane content in the biogas (54-67 %), this value describes how much of the theoretical potential is transferred into electrical energy. It is assumed that the total amount of biogas is used. The rate of digester gas conversion is above 26% regarding the 50% percentile (Figure 29). 20 % of the plants reported values indicating a very efficient digester gas conversion rate above 35 %. The influence of external sludge and/or co-ferments has been checked but revealed no significant impact.

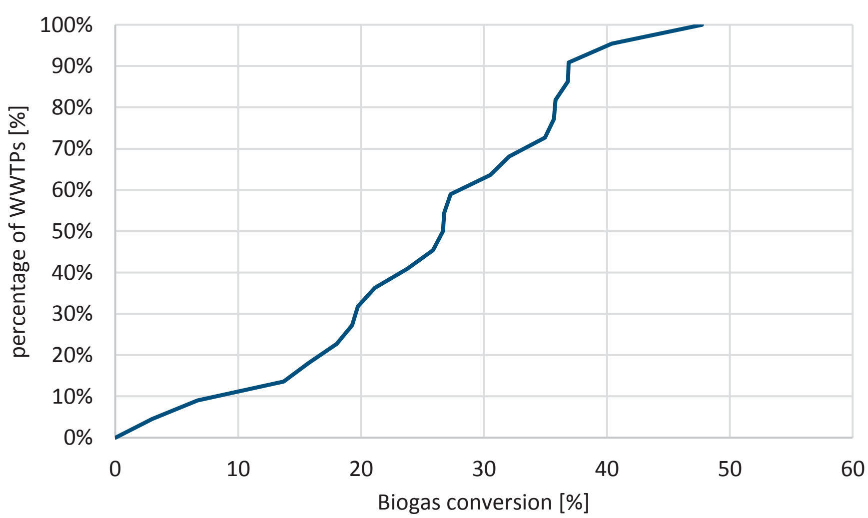


Figure 29 – Rate of biogas conversion into electrical energy, n=23

With provided data of total electrical energy demand and total energy production per year the degree of self-supply in terms of electrical energy is calculated and plotted in Figure 30. 50 % of the considered WWTP achieve 45 % of self-supply in terms of electrical energy. 4 WWTP achieve values higher than 80 %. Compared to the electrical energy obtained from biogas, the few other sources of electrical energy contributed so little to the total energy production that these values have been neglected in the evaluation.

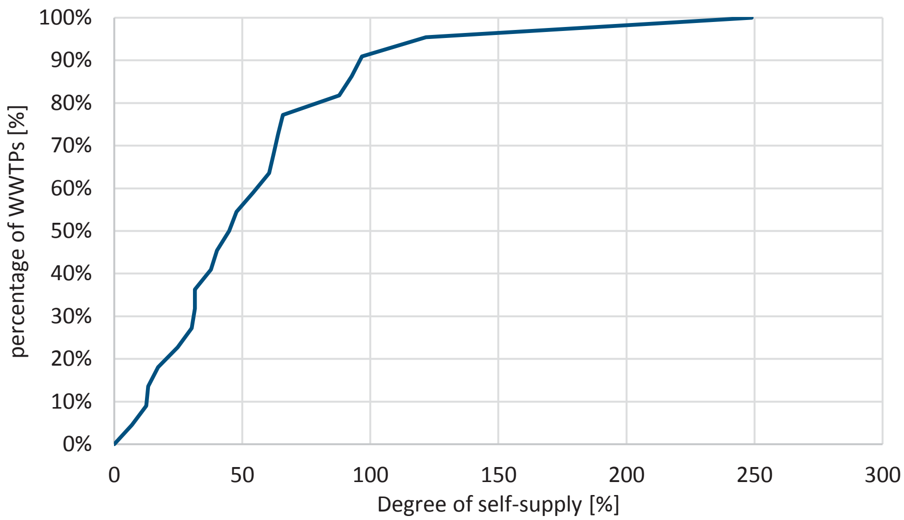


Figure 30 – Degree of self-supply of electrical energy, n=23

Based on 20 replies from the Baltic and South-Baltic sub-region, where most of the information has been provided, 40 % of WWTP do have a demand for an external heat while already 35 % are able to cover energy demand for anaerobic treatment plus building heating and/or other treatment steps like drying.

7 CONCLUSION

The report provides an overview both on treatment efficiency and energetic issues related to 66 WWTP in the Baltic Sea Region. Contributing to the Interreg BSR co-funded IWAMA project information was provided from Sweden, Finland, Russia, Estonia, Latvia, Lithuania, Poland, Belarus and Germany.

Most of the calculations in the report are based on 120 g COD/(PE·d), especially the classification of WWTP. The evaluation revealed differences in inlet concentration depending on the sub-region selected up to factor 2. Removal efficiencies achieved meet HELCOM 28/E5 requirements in almost presented figures.

The data collected revealed that different technologies are applied with varying success in high treatment efficiency combined with low energy consumption. But there is no clear region-based dependency.

Different approaches to calculate key figures for energy consumption have been adopted to the data and compared to an extensive calculation based on the oxygen consumption in the treatment process. The efforts of calculating a key figure based on kg O_2 seem to prevail the benefits of receiving more information. Almost equal results are obtained using a PE based key figure.

Half of the WWTPs considered in the evaluation are operated using less than 37 kWh/($PE_{COD,120}$·d). But only 20 % consume less than 23 kWh/($PE_{COD,120}$·d). This benchmark is proposed to be aimed by all plants in the region, still considering that the main task of a WWTP is treating wastewater in a proper way.

The production of energy from biogas has also been evaluated. The specific biogas production in the region achieved by 50 % of the WWTPs is greater than 27 l/($PE_{COD,120}$·d) while 20 % achieve more than 34 l/($PE_{COD,120}$·d)

The challenges that WWT operators all around BSR are facing in increasing energy efficiency while up keeping or improving nutrient removal efficiency, are similar across borders. With the help of benchmarking it is possible to detect possible performance gaps.

It is recommendable to continue and extend the key figure comparison in the Baltic region as a motivation for optimized WWTP operation.

The information collected is available for all stakeholders in the region. The benchmark can be used as a soft goal to encourage higher efficiency in WWTP. Main key figures are displayed in user-friendly graphs, offering other WWTP in the region opportunities to calculate their respective value and compare. Large deviations from the suggested benchmark indicate a demand for detailed energy audit of a plant.

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HELCOM (1999)	HELCOM Recommendation 20E/6 (1999)
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ATTACHMENTS

A.1 – Calculation of the oxygen demand

Oxygen is an inevitable requirement to ensure an effective biological treatment and can be regarded as a key influencer in concerns of nutrient removal efficiency as well as energy consumption. Blowers usually are the main energy consumers in a WWTP. Their consumption can be estimated to about 44% of the total energy consumption of a WWTP using activated sludge technology with nitri- and denitrification [LfU, 1998]. Due to its important role, a new key figure based on the oxygen demand is suggested. The determination of the oxygen demand will be outlined in the following. Later, these results will be crucial for the specific energy consumption [kWh/kgO_2] of which it is expected to serve as a key performance indicator assessing the energy efficiency in relation to nutrient removal of a WWTP.

When considering an activated sludge process (including nitri- and denitrification) with separate sludge stabilization, as it applies to all contributing plants, there is a demand of free dissolved oxygen in the aerated/ aerobic zones of the biological reactor in order to perform carbon elimination and nitrification. In the anoxic zone however, which is used for denitrification, required oxygen is already available in an undissolved bound matter as NO_3^-. As a result, there is an oxygen output in the form of CO_2 and H_2O. For the determination of the overall oxygen uptake (OU) this means the following:

$$OU = OU_{C-elimination} + OU_{Nitrification} - OU_{Denitrification}$$

1. C-elimination: Demand of dissolved oxygen to ensure aerobic conditions for the growth of heterotrophic microorganisms which transform dissolved organic wastewater constituents to solid inorganic end-products
   Oxygen uptake: 1,2 kgO_2/ kgBOD_5 [ATV-DVWK-A 131, 2000]

$$OU_{d,C} = Q \cdot OU_c \ / 1000 \quad \left[\frac{kgO_2}{d}\right]$$

$$OU_C = C_{COD,degrad,inB} + C_{COD,dos} - X_{COD,BM} - X_{COD,inert,BM} \quad \left[\frac{mg}{l}\right]$$

2. Nitrification: $NH_4{}^+ + 2O_2 + 2HCO_3 \rightarrow NO_3{}^- + 2CO_2 + H_2O$

   Demand of dissolved oxygen to ensure aerobic conditions for the growth of autotrophic bacteria (nitrificants) which perform oxidation of ammonium and nitrite
   Oxygen uptake: 4,3 kgO_2/ kgN [DWA-A 131, 2016]

$$OU_{d,N} = Q \cdot 4{,}3 \cdot \left(S_{NO3,D} - S_{NO3,inB} + S_{NO3,eff}\right) \ / 1000 \quad \left[\frac{kgO_2}{d}\right]$$

3. Denitrification: $NO_3{}^- + 2H^+ + 10[H] \rightarrow N_2 + 6H_2O$ $\qquad [H]\ equals\ organic\ matter$

   Demand of undissolved bound oxygen, which is already available due to the end-products of nitrification (NO_3^-); reduction of oxidized nitrogen compounds to pure nitrogen through growth of heterotrophic bacteria under anoxic conditions
   Oxygen output: 2,86 kgO_2/kg$S_{NO3,D}$ [DWA-A 131, 2016]

$$OU_{d,D} = Q \cdot 2{,}86 \cdot S_{NO3,D} \ / 1000 \quad \left[\frac{kgO_2}{d}\right]$$

The oxygen uptakes and output were calculated based on the guideline of DWA-A 131 (2016). As comparison, former versions or otherwise used approaches were taken into account.

Especially for determining the oxygen demand for carbon removal, a detailed COD fractioning is essential which will be addressed later. Furthermore, information on biomass and sludge age (see below) is necessary for carbon removal as well as for nitri- and denitrification, while for the latter also data on the nitrogen cycle is essential. In Table 10 an overview of the influencing parameters for the respective calculations are given. Highlighted in blue are the parameters which are indispensable for a proper calculation of the oxygen demand, in light blue the ones which are nice to have but could be substituted. The other listed parameters can be derived from the highlighted ones and from scientifically proven assumptions.

Table 10 – Influencing and indispensable parameters for determining the oxygen demand

Influencing parameters		units	Oxygen uptake during carbon removal	Oxygen uptake during Nitrification	Oxygen output during Denitrification
Flow rate		$[m^3/d]$	✓	✓	✓
$C_{COD,inB}$ (if not available: $C_{COD,inf}$)	$C_{COD,degrad,inB}$	[mg/l]	✓	-	-
$S_{COD,inert,inB} = S_{COD,inert,eff} = C_{COD,eff}$		[mg/l]	✓	-	-
$X_{COD,inert,inB} = X_{COD,inert,eff}$		[mg/l]	✓	✓	✓
($C_{COD,dosed}$)		[mg/l]	(✓)	-	-
$X_{COD,inB}$		[mg/l]	✓	-	-
$X_{SS,inB}$ (if not available: $X_{SS,inf}$) (if neither available, Sieker's fractionation approach could be used, which bypasses this parameter)		[mg/l]	✓	-	-
$X_{COD,BM}$		[mg/l]	✓	✓	✓
$X_{COD,inert,BM}$		[mg/l]	✓	✓	✓
$C_{N,inB}$ (if not available: $C_{N,inf}$)	$S_{NO3,D}$	[mg/l]	-	✓	✓
$S_{orgN,eff}$		[mg/l]	-	✓	✓
$S_{NH4\text{-}N,eff}$		[mg/l]	-	✓	✓
$S_{NO3\text{-}N,eff}$		[mg/l]	-	✓	✓
$X_{orgN,BM}$		[mg/l]	-	✓	✓
$X_{orgN,inert}$		[mg/l]	-	✓	✓
$S_{NO3,inB}$ (if not available, assumption $S_{NO3,inB} = 0$)		[mg/l]	-	✓	-
Volume of aerated tank V_{aer}	Sludge age t_{SS}	$[m^3]$	✓	✓	✓
Volume of anoxic tank V_{anox}		$[m^3]$	✓	✓	✓
$MLSS_{AT}$		[g/l]	✓	✓	✓
$B_{BOD5,inB}$ (if not available: $B_{BOD5,inf}$ or daily excess sludge production)		[kg/d]	✓	✓	✓
Temperature in aeration tank		[°C]	✓	✓	✓
Share of municipal/ industrial wastewater	Influence on factors estimating COD-fractions	[-]	✓	-	-
Use of primary clarification		[-]	✓	-	-
Retention time in primary clarifiers or volume of primary clarifiers		[h] / $[m^3]$	✓	-	-

The easily degradable COD is not considered in the calculations, since this value is just involved when designing/ dimensioning a WWTP and in this case depends on the kind of process used for denitrification such as pre-denitrification, simultaneous or intermittent denitrification.

A.2 – COD fractionation

The whole COD fractionation depends on the COD concentration at the inflow of the biological reactor ($C_{COD,inB}$) or, in other words, the COD concentration after primary clarification. About 65 % of the contributing plants use primary clarification of which more than half stated their measured COD concentrations after primary clarification. For the rest, a reduced concentration of the inflow to the plant was taken as a substitute according to DWA-A 131 (2016).

Based on $C_{COD,inB}$, the subdivision in dissolved ($S_{COD,inB}$) and particular ($X_{COD,inB}$) COD was done. For this, two approaches presented below were taken into consideration in order to compare and check plausibility. The second approach according to DWA-A 131 is rated as the normative/ relevant one.

1. **Approach described by** (Sieker, 2018):
   This approach, displayed in Figure 31, is a very general one and can be applied as a quick and simplified overview of the dissolved and particular components before biological treatment. Various wastewater characteristics are not considered and information on formed biomass or anorganic total solids, which are required for the calculations on oxygen demand, are not given here.

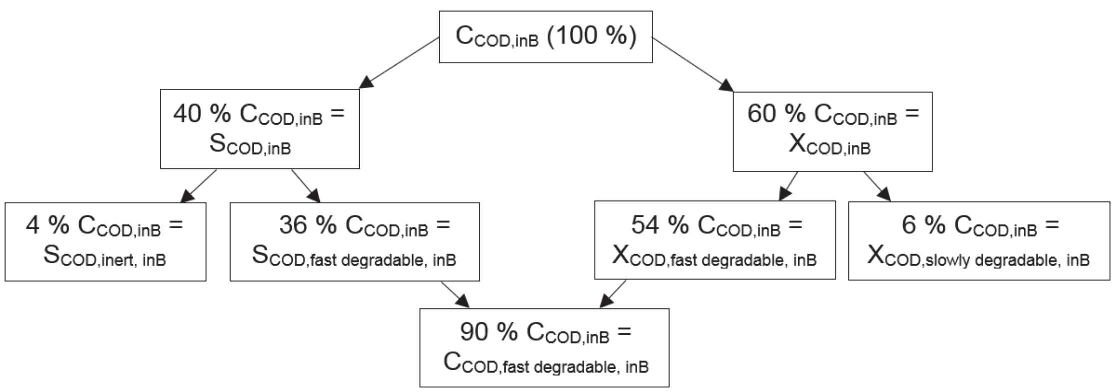
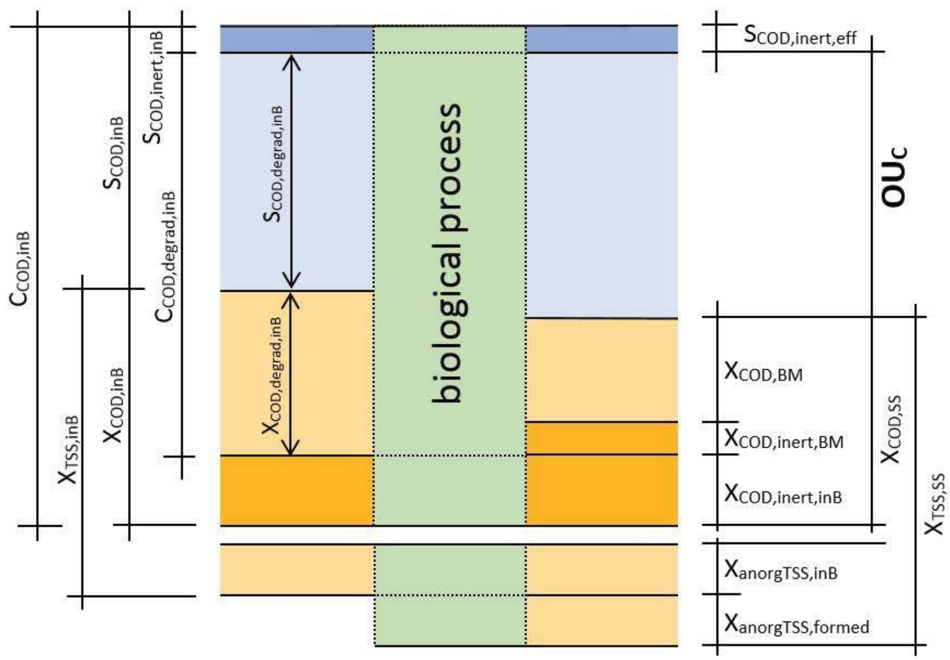


Figure 31 – Fractionation of the chemical oxygen demand according to Sieker [2018]

2. **Approach according to DWA-A 131:**

This approach, illustrated in Figure 32, allows a much more differentiated fractionation. All components can be determined based on evolved formulas including recommended factors to integrate wastewater characteristics.



$$C_{COD,inB} = S_{COD,inB} + X_{COD,inB} \quad [mg/l]$$

Figure 32 – Fractionation of the chemical oxygen demand adopted from [DWA-A 131, 2016]

In the approach according to DWA-A 131 the type of wastewater (municipal/ industrial) as well as the use and retention time in primary clarification is considered given that information was available in the database.

Comparing both approaches it was found out that there are consistently high deviations. The particular concentrations (X) obtained by Sieker's approach are higher than the ones calculated by DWA guideline. In consequence, when regarding dissolved concentrations (S) a vice versa observation was made. However, in the end, lower and higher deviations of the fractions counterbalance and the degradable COD ($C_{COD,degrad,inB}$) is at similar range having a median deviation of around 10 %.

Data wise, when explicitly looking at $X_{COD,inB}$, Sieker's approach provides more usable data than the DWA approach, where the value is linked to the concentration of suspended solids. Many German plants did not state their C_{SS} which is resulting in a not veritable oxygen demand. Thus, it was chosen to determine $X_{COD,inB}$ based on Sieker's approach. $X_{COD,inB}$ influences solely the $C_{COD,degrad,inB}$ and here, as it was explained in the former segment, the deviation between both approaches are just around 10 %. In this way the explained substitution is tolerable.

A.3 – Calculation of the sludge age

For calculating the sludge age, the following 3 approaches have been considered:

1. Sludge age based on BOD_5 load:	$t_{SS} = \frac{(V_{aer} + V_{anox}) \cdot MLSS_{AT}}{L_{BOD5,inB}} \quad [d]$
2. Sludge age based on calculated daily sludge production: 3. Sludge age based on daily sludge production given by WWTP:	$t_{SS} = \frac{(V_{aer} + V_{anox}) \cdot MLSS_{AT}}{SP_d} \quad [d]$

While deviations between first and second approach are reasonably low, there were some high deviation peaks to the third approach based on the sludge production stated by the WWTP. In these outlier cases, calculated sludge production was 3 to 5 times higher than the sludge production stated by the WWTP. Source of error might be mistakenly entered or construed data inputs.

Even though the second approach takes the sludge production caused from carbon and phosphorous removal into account and thus could be considered as a more advanced approach, the first calculation based on BOD5 is taken as basis for further analysis. This decision was done due to the fact that it provides the largest amount of sludge ages and that deviations to the second approach are low.

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