ENERWATER

Standard method and online tool for assessing and improving the energy efficiency of waste water treatment plants

H2020-EE-2014-3-MarketUptake

Deliverable 2.1 Study of published energy data

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

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1 Scope of the document

Representative energy data from several countries was gathered by the consortium to create a reference database. Best practises and best-case scenarios for benchmarking were identified. The information was retrieved from several sources such as journals, reports, direct communication with the stakeholders, mandatory EU registers etc. The consortium was able to gather energy data from 588 wastewater treatment plants (WWTPs).

1.1 Introduction

Due to fluctuating energy costs and in order to reduce the release of GHG, it becomes more and more important to have a better understanding of the energy consumption in WWTPs. The energy consumption of WWTPs is about 4200 GWh/year only in Germany. This energy is used for about 10000 WWTPs [6]. The treatment of 3,000 million m³/year of urban wastewater accounts for about 1% of national energy consumption (278,000 GWh/year). Similar trends are seen in other European countries. Considering the consumption of transport, water treatment and water reuse, it can be concluded that the water sector is a major consumer of energy. Some studies suggest that domestic and industrial water cycles respond to 2-3% of total energy consumption and considering water management and agricultural demand, could reach 4 -5% [11]. Similar total energy consumption is also reported for Italy: the total electricity consumption in municipal wastewater treatment plants (WWTPs) corresponds to about 1% of the total electricity consumption per year of a country. In Italy, the electricity consumption in WWTPs is about 3.250 GWh/year which corresponds to about 0.5 billions Euros per year [10].
The energy consumption of WWTPs is not distributed equally. In Spain the average specific energy consumption for wastewater treatment plants in Spain is around 50 kWh per population equivalent and year (kWh/PE*y) but in large treatment plants, where optimised design, dimensioning and process control is implemented, specific energy consumption is reduced to 20-30 kWh/PE*y.

To reduce energy costs and to protect the environment it is required to improve these plants. If WWTPs have state-of-the-art automation and instrumentation, the improvements have to be done in how the process is operated. In any case, monitoring is essential to ensure proper evaluation of the actions put into practice. In a context of benchmarking to improve the operation efficiency, the reported data of WWTP energy consumption become extremely valuable.

In order to reduce energy consumption, the first step is to gather energy data of WWTPs to get a better understanding of typical high-energy consumers and the energy consuming processes. This will help to discover the most power consuming parts in a plant. Task 2.1 focuses particularly on publically available data from reliable sources.

2 Study of published energy data

Collecting energy data of WWTPs from different world regions is the first step in the ENERWATER project, to provide a database for evaluating the further progress. In addition to the energy data gathering, at this initial phase, the consortium also targets 1) to identify which are the most broadly used KPIs to communicate energy performance in WWTP, 2) to detect best practices and cases scenarios and 3) to identify which are the most energy consuming sections in a WWTP and which parameters affect the energy consumption.
To do so, a thorough search has been carried out to identify available sources and databases offering energy data of WWTPs. In particular, the design dimensions (flow rate, population equivalent) and the actual operating conditions (measured flow rate and population equivalent in the WWTP area) were collected as predictors of the WWTP energy consumption. Disaggregated published energy data, i.e. energy consumption of each of the processes and sections of a WWTP are considerably scarcer than overall energy consumption data. In section 2.2 the aggregated energy data are presented and discussed, while section 2.3 focuses on the disaggregated data and the previous discussion is enriched with process specific information.

2.1.1 Sources of information

This review uses sources from several countries in different world regions, while focusing on the countries of the participating project partners, i.e. Italy, Spain, England and Germany. The sources of information include reports about energy checks and analysis from local water associations and companies. Additionally, information from other research projects was collected providing aggregated and disaggregated data from several plants and information concerning their approaches. Further information was collected from wastewater associations and several journals that provide anonymous plant data.

A total of 588 plant data sets were collected. The group of data can be broken down into the following sources

- 7 plant data out of a technical book [13]
- 196 plant data out of research articles [1; 2; 12; 18; 19; 22; 23; 26; 28]
- 237 plant data out of technical reports [14; 17; 21; 25]
- 65 plant data of German regional agencies by private communication
- 82 plant data of Spanish regional agencies by private communication

2.1.2 Data sample

As the information collected related to some WWTPs was deemed incomplete (e.g. no plant characteristics or treatment technology of the sample were sometimes reported from the source), data from 211 WWTPs were excluded. The final sample on which the analysis was conducted is 369 WWTPs, representing the treatment of about 15,742,816 PE and a total energy consumption of 1,736,735 kWh/day.

Dataset was classified according to five different WWTP class sizes: PE < 2,000; 2,000 < PE < 10,000; 10,000 < PE < 50,000; 50,000 < PE < 100,000; PE > 100,000. The distribution of the samples within the different class size, treatment technology and plant location is reported in Figure 1, Figure 2 and Figure 3. The majority of the WWTPs were located in Europe (principally in Spain, Germany and France) and North America, while a smaller number of plants in China and Japan were found. The sample is characterised by a large number (118) of small plants (less then 2K PE). Although those plants are 32% of the total sample, they represent only 0.5% of the total population served and account for about 2.2% of the total energy consumption. On the other side, the 49 WWTPs (13% of the total), which are parts of the bigger class size (larger than 100K PE), represent 77% of the population served and 70% of the total energy consumption. Regarding the treatment technologies, the most common was Aerated Pond (32%), Biological Nutrient Removal (BNR) (23%) Extended Aeration plants (17%) and Convectional Activated Sludge (CAS) (8.6%).

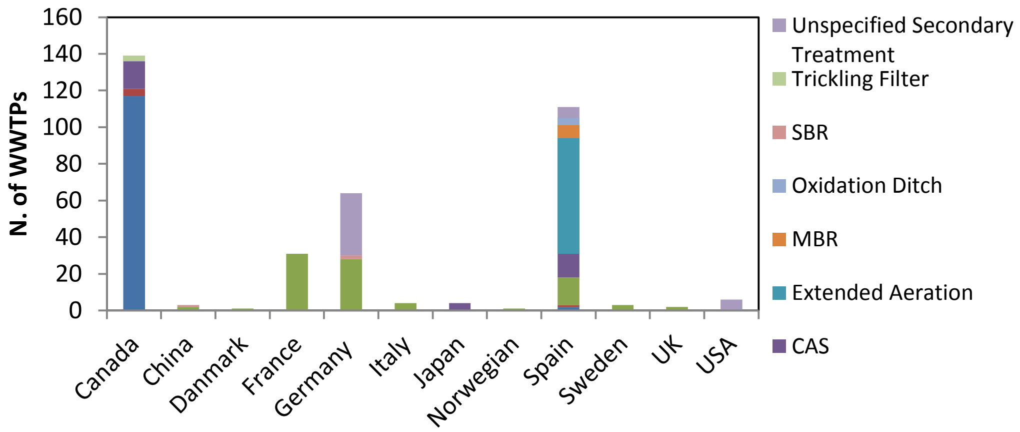


Figure 1 - Treatment technology for different country

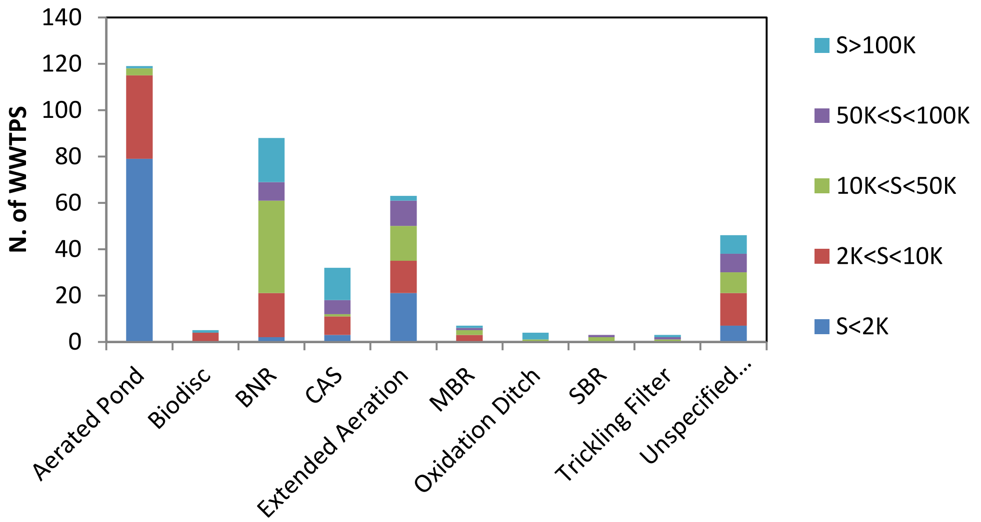


Figure 2 - Treatment technology for different class size

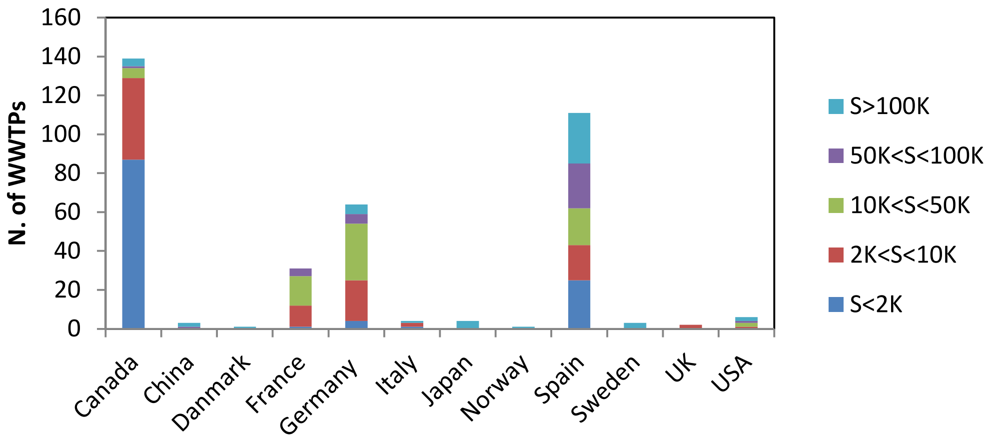


Figure 3 - Number of plant for different country and class size

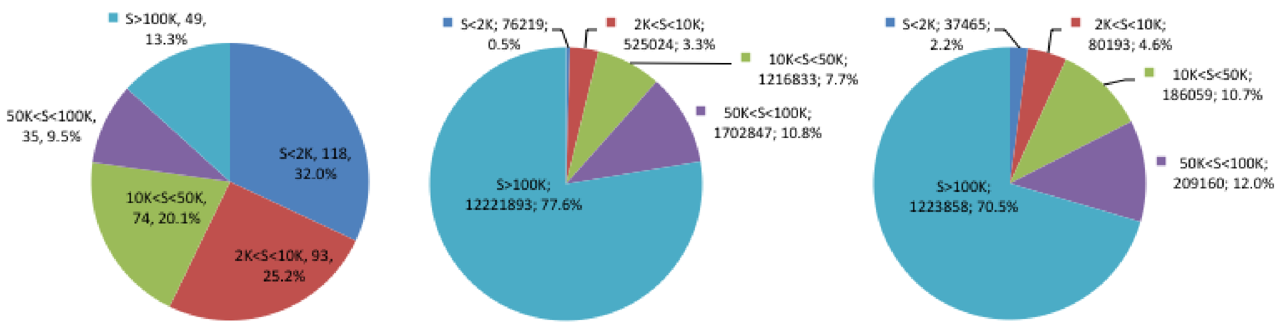


Figure 4 - Size (a), total connected people PE (b) and total energy consumption of the analysed WWTPs

2.1.3 Reported energy data and used methodology

The consulted sources provide very heterogeneous data: from highly detailed to a generic overview of the energy consumption. Data were reported for different processes, like data of the physical or biological processes. The energy consumption of major pieces of equipment, such as blowers, mixers, pumps, aeration systems and filters was found. Additionally, more general data of the buildings with their consumption by lighting and heating are reported.

Three specific energy consumption performance indicators were defined referred to volume of treated wastewater, population equivalent (PE) and kg of COD removed. It should be noted that the definitions and values of PE can differ between countries. In this study 60 gBOD/PE*d was considered (following Directive 91/271/EEC). When BOD values were not available, the calculation was done based on COD, considering 120 gCOD/PE*d. In the case of North American plants, the conversion was done considering 80 gBOD/PE*d or 160 gCOD/PE*d [33].

The indices were defined as follow:

KPI $_2$ = $\frac{electric\ energy\ consumption}{volume\ of\ treated\ wastewater}\ [kWh/m^3]$

KPI $_1$ = $\frac{electric\ energy\ consumption}{population\ equivalent\ (PE)}\ [kWh/PE*y]$

KPI $_3$ = $\frac{electric\ energy\ consumption}{COD\ load\ removed\ daily}\ [kWh/kgCODrem]$

Given the high variability of the values found in the sample, the arithmetic average is an indicator particularly influenced by extreme values. It was therefore considered more useful to take as reference a robust indicator such as the median. To represent graphically the data variability, collected energy data are presented by the use of box plot. The box plot is a standard technique for presenting a summary of the distribution of a dataset. The typical construction of the box plot, which can be seen in Figure 5, partitions a data distribution into quartiles, that is, four subsets with equal size. A box is used to indicate the positions of the upper and lower quartiles; the interior of this box indicates the interquartile range, which is the area between the upper and lower quartiles and consists of 50% of the distribution. Finally, the box is intersected by a crossbar drawn at the median of the dataset.

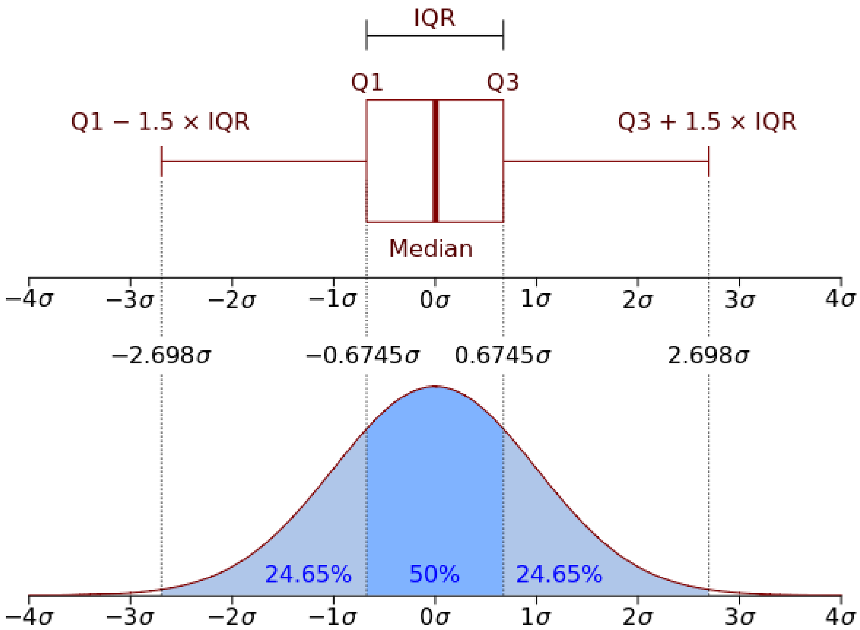


Figure 5 – Box plot. Example on normal distribution

2.2 Analysis of the aggregated energy data

2.2.1 Total energy consumption of WWTPs

First, the total electric energy consumption of the sample was evaluated. As can be seen in Figure 6A, a very good correlation between total energy consumption and influent flow rate. Increasing the capacity of the system, its power consumption increases according to the power law shown in the figure (note the log-log scale in the figure). In terms of specific energy consumption per volume of wastewater treated, it can be observed that this index tends to be smaller for larger plants. A specific energy consumption of 0.13 kWh/m^3 can be observed for larger plants, while for smaller plants values up to 5.5 kWh/m^3 can be found.

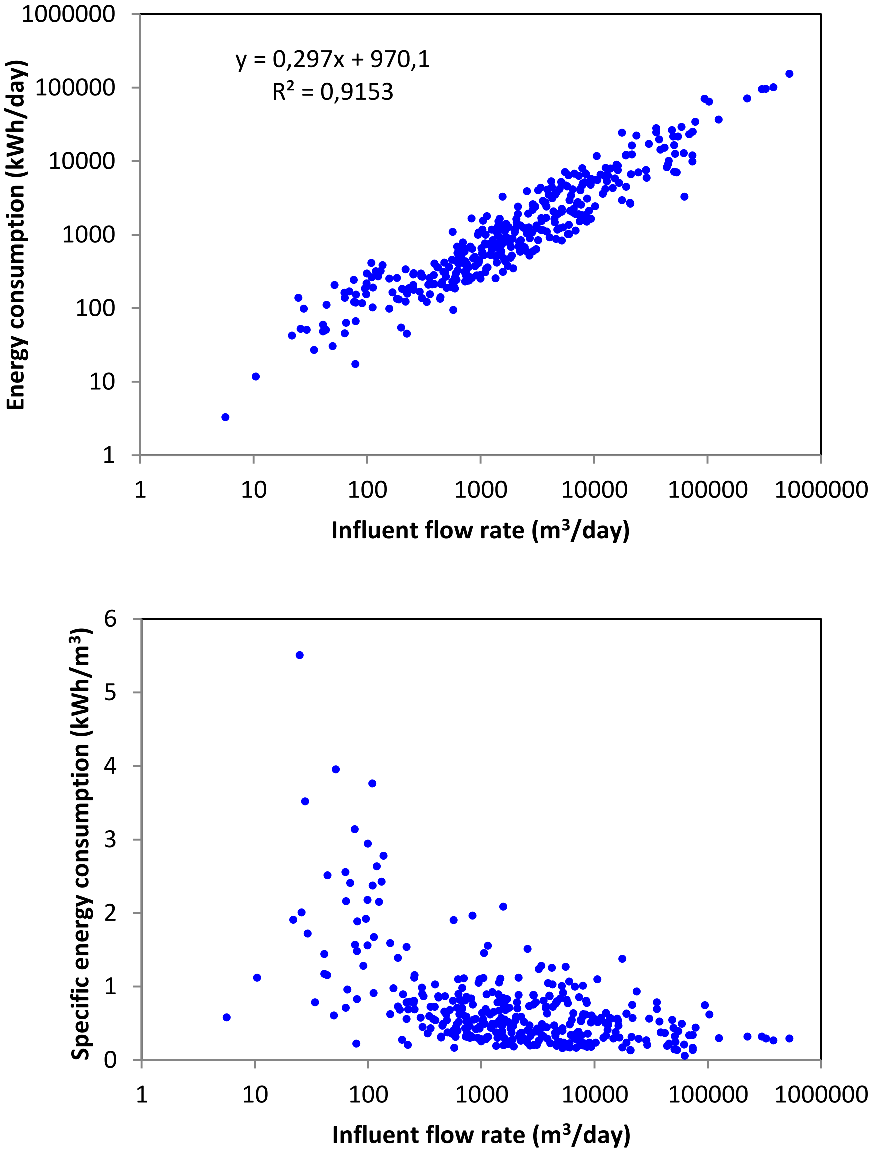
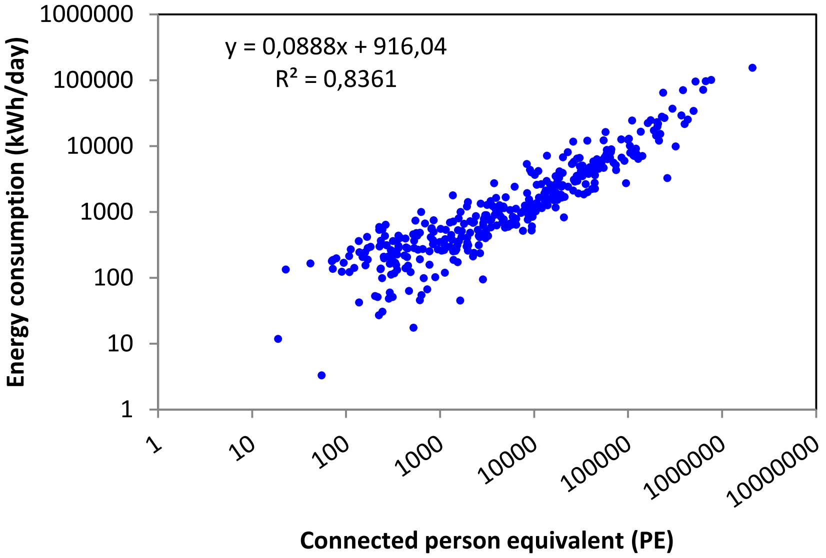


Figure 6 - Energy consumption vs influent flow

A correlation between energy consumption and served population equivalent is also seen. As previously, data can be described by the use of a power law (Figure 7). Energy consumption per volume of treated wastewater varies with the dimension of the plant, being lower for larger plants. Energy consumption per PE varies considerably within the samples analysed. Values up to 2000 kWh/PE*y were found for smaller plants, while larger plants are characterized by energy consumption between 20 and 60 kWh/PE*y.



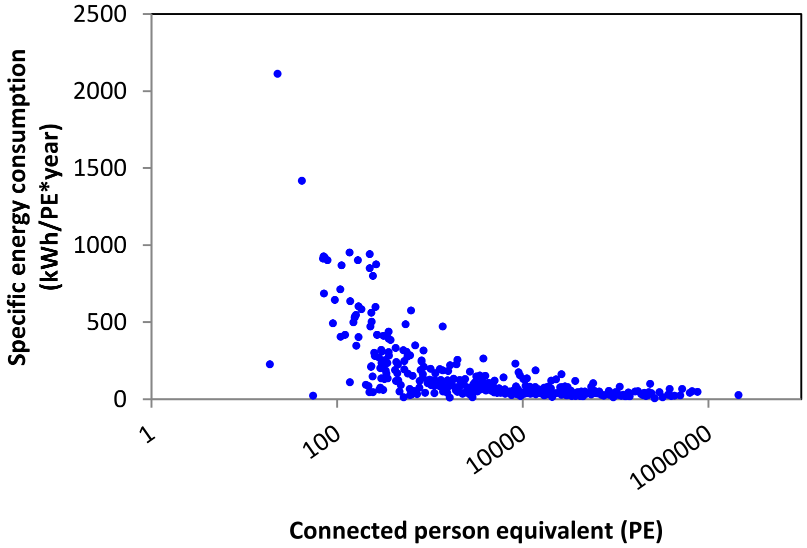
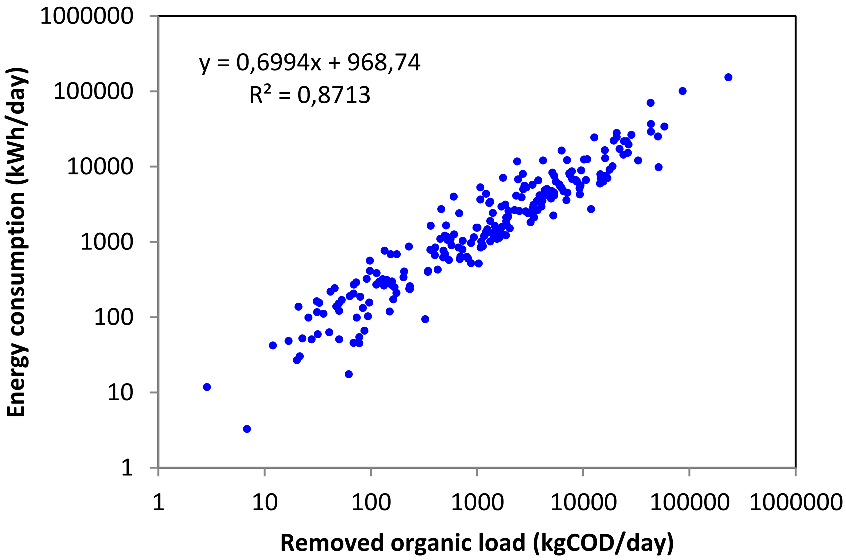


Figure 7 - Energy consumption vs connected person equivalent

In Figure 8 it is reported the correlation between energy consumption and the organic load removed. Also in this case a very good correlation it can be found according to the power law indicated in the graph. In terms of specific energy consumption per kg of COD removed, it can be observed that this index is normally higher for smaller plant and presents a very large variability for medium to large plants.



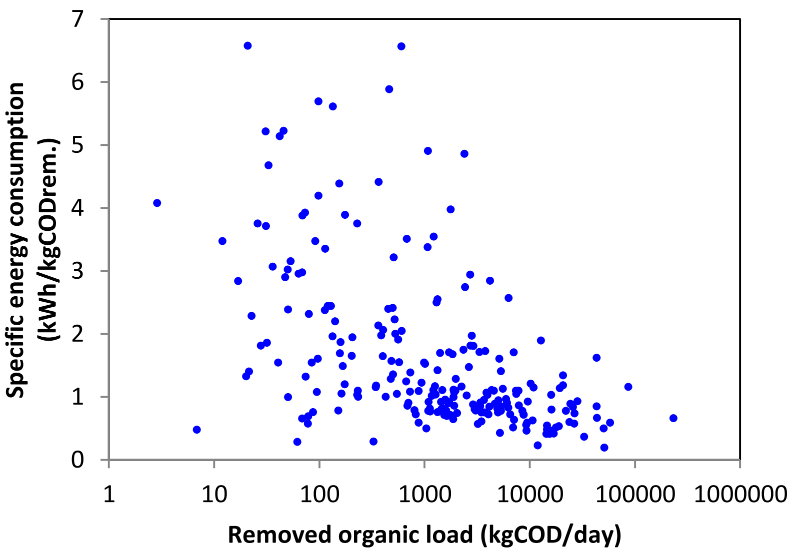


Figure 8 - Energy consumption vs removed organic load

2.2.2 Energy consumption with respect to scale

For each of the previously defined indexes, Figure 9 shows the box plots of the sub-samples obtained by the division into classes of population equivalent. In each graph the energy consumption decreases when increasing the population equivalent. This can be due to:

- Exploiting economies of scale, by using large and generally more efficient equipment, in particular larger pumps and compressors.
- Ensuring that the process operates at more stable conditions, which is reflected on a more regular operation of electromechanical equipment and avoiding energy-intensive transitional periods;
- Providing the automation for the treatment process (for example, regulation of the oxygen levels by controlling the operation of the aeration pumps).
- More and especially better trained staff operating large plants, which is seldom the case for small WWTPs.

Energy consumption in smaller WWTPs varies considerably. This is confirmed by the high variability of the group of small plants, where energy consumption is strongly influenced by external factors. This difference is more clearly observed in the indices relative to the load input (expressed as population equivalent PE, Figure 9 B), rather than in reference to the flow treated (Figure 9 A) which do not necessarily represent the extent of the treatment needed.

Therefore, the bigger plant class size was the most efficient one, with specific energy consumption between 0.28-0.61 kWh/m^3, 27.4-47.9 kWh/PE*y and 0.55-1.10 kWh/kgCODrem. Specific energy consumption increases as plant size decreases, being higher for plants which size is less than 2K PE. For the latter size class the specific energy consumption was 0.42-0.86 kWh/m^3, 106-472 kWh/PE*y and 1.35-3.39 kWh/kgCODrem.

As a conclusion, a clear trend of increasing energy consumption with decreasing plant size was identified: however the large intra-group variability for each class size suggests that other factors are responsible for the difference of energy consumption in WWTPs.

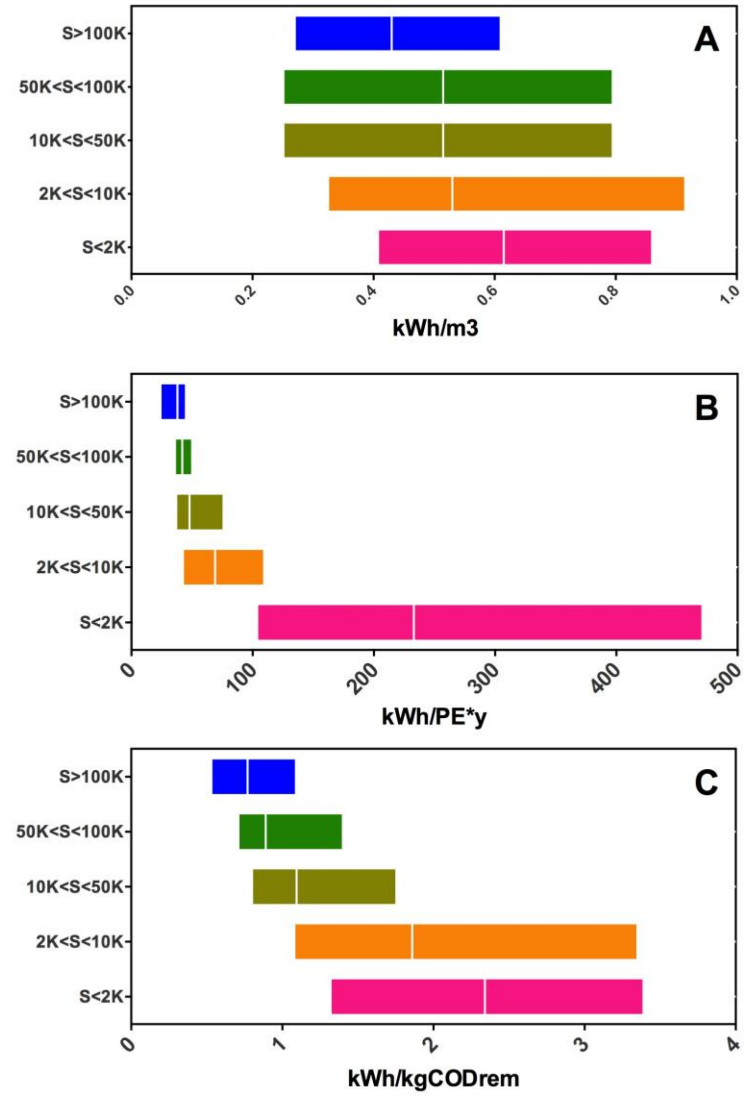


Figure 9 - Specific energy consumption according to different KPIs and sorted per PE class size

2.2.3 Energy consumption with respect to country

Energy consumption among different countries is reported in Figure 10, which shows how the energy consumption varies between various countries. In order to analyse the effect of other factors, the energy consumption for plants between 10K and 50K PE is presented in Figure 11. The different energy consumption for other plant class size can be found in the Appendix A and Appendix B of this document.

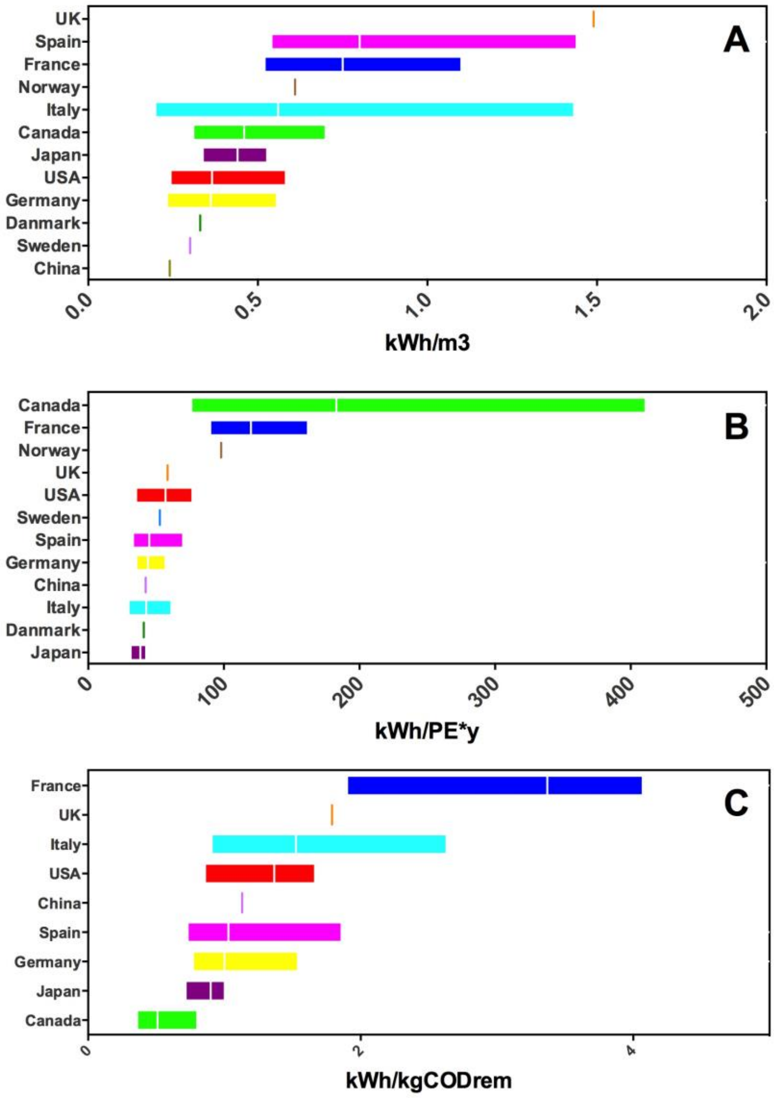


Figure 10 - Specific energy consumption respect to country

Energy consumption in wastewater treatment plants is closely correlated with the type of treatment technology used. Therefore, it is reasonable to expect large differences between different countries, where for economic and/or environmental reasons a particular type of treatment prevails.

With the exception of France WWTPs, which turned out to have a particularly high-energy consumption, similar values were found for different countries. Considering the median value, German WWTPs showed to be the most efficient European country of the sample analysed, with an energy consumption of 38.8 kWh/PE*y and 0.87 kWh/kgCODrem, followed by Spain with a consumption of 53.7 and 1.11 kWh/kgCODrem. Canadian WWTPs result particularly efficient and showed the best performance of the sample with a consumption of 31.87 kWh/PE*y and 0.82 kWh/kgCODrem. It should be noted, however, that Canadian plants belonging to this size class do not require nutrient removal and consequently it is reasonable expecting a lower energy consumption if compared with European WWTPs where nutrient removal process is involved. The differences in specific energy consumption per volume of treated wastewater (kWh/m3) are less clear. In effect, this indicator does not represent necessarily the plant performance since, e.g., in the case of mixed sewer system this index is affected by dilution of the wastewater. Therefore, large variations in this indicator are caused by regional factors (climate, urban planning, sewer network design).

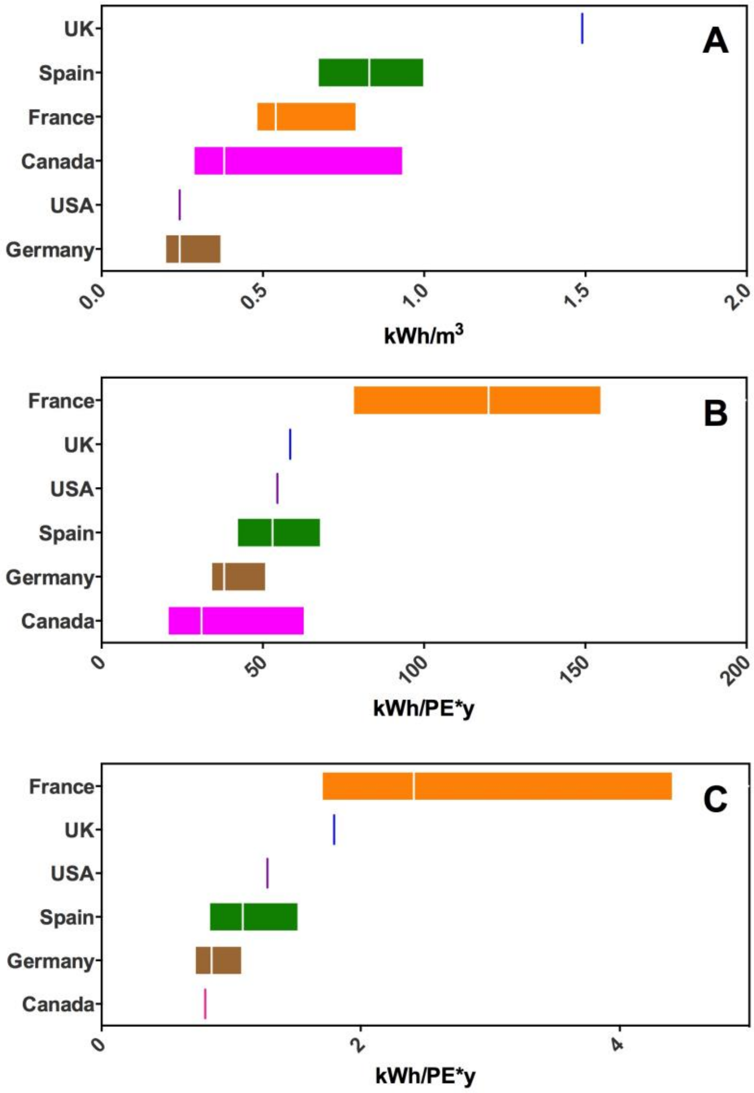


Figure 11 - Specific energy consumption with respect to country for WWTPs between 10K and 50K PE

2.2.4 Energy consumption of WWTPs per treatment technology

As previously shown, the type of treatment has a large impact on the energy consumption of WWTPs. In Figure 12 a general overview of the energy consumption is reported for the sample analysed and different technology. Energy consumption among different technologies for plants between 50K and 100K PE is presented in Figure 13. The different energy consumption for the rest of plant class sizes can be found in the Appendix A and Appendix B of this document.

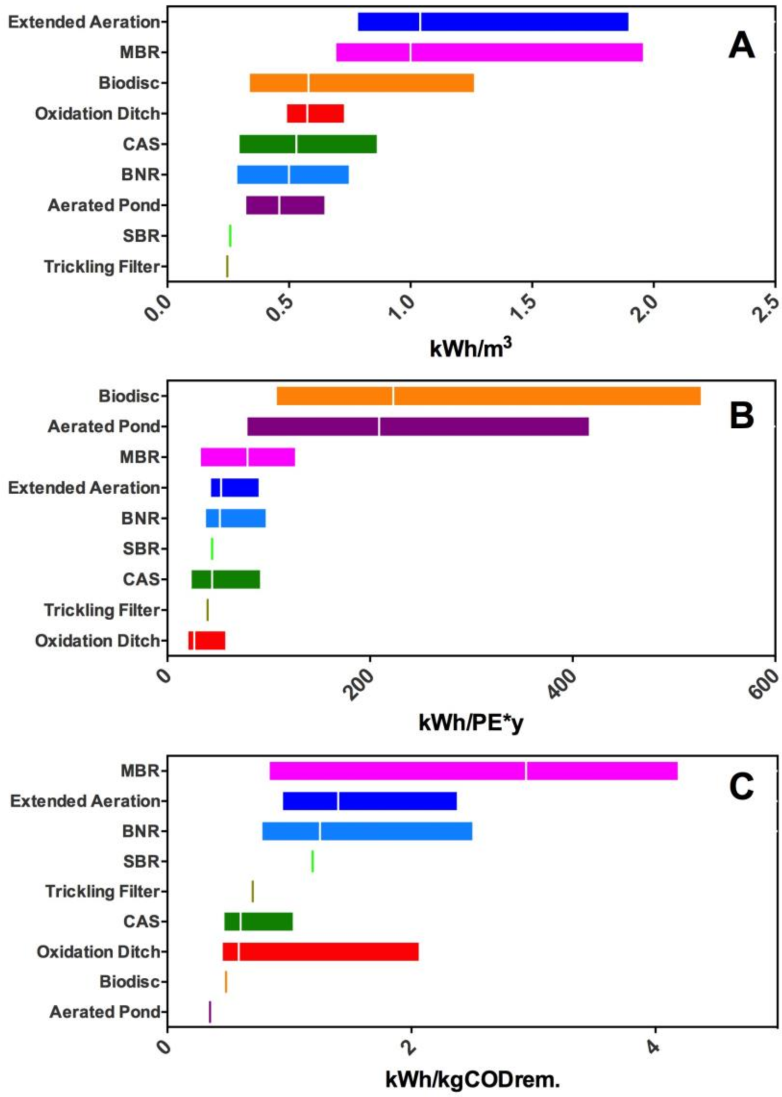


Figure 12 - Specific energy consumption respect to treatment technology

As in the previously analyses, the volumetric energy index differs from the other indices. On the other side indices relative to the load input expressed as population equivalent (Figure 13 B) or COD load removed (Figure 13 C) are more consistent.

According to the box plot graph, plants that carry out BNR processes showed the highest energy consumption, followed by Membrane Bioreactor (MBR), Extended Aeration and CAS process. Considering median value BNR process showed an energy consumption of 80.8 kWh/PE*y or 1.71 kWh/kgCODrem. MBR systems result in an energy consumption equal to 50.7 kWh/PE*y or 0.96 kWh/kgCODrem. Extended Aeration systems showed an energy consumption of 40.46 kWh/PE*y or 0.85 kWh/kgCODrem. The least energy consuming process was CAS system with a specific energy consumption of 27.28 kWh/PE*y. It is also possible to observe how the variability for BNR is particularly large. This could be due to the fact that BNR category in the sample analysed includes different configuration such as Ludzack-Ettinger, Modified Ludzack-Ettinger (MLE), Bardenpho, A/O or A2/O, hence WWTPs with different function. Moreover, different plant location and thus different influent characteristics could also be responsible for this variability. From the sample analysed, it seems that the higher complexity of the treatment process corresponds to higher energy consumption. In fact, Extended Aeration or CAS system are characterized by lower energy consumption if compared to MBR system.

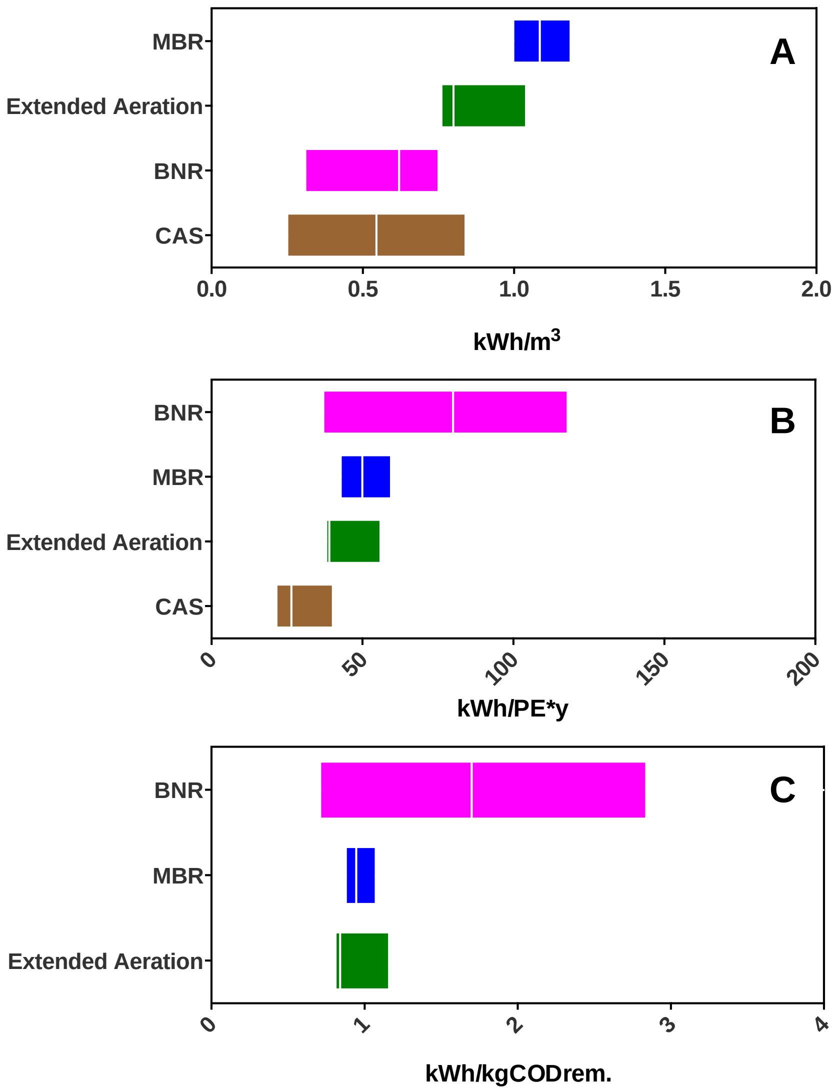


Figure 13 - Specific energy consumption respect to technology for WWTPs between 50K and 100K PE

2.3 Analysis of the disaggregated data

Disaggregated data are available mainly from USA, Canada and Italy. 58 case studies were collected and grouped as following:

- 6 Italian WWTPs from research papers
- 4 American WWTPs from technical book, (27 different process and size class)
- 4 Canadian WWTPs from technical book (4 different process divided in 6 different size class)
- 1 Austrian WWTP from technical book

The following table shows the collected case study for the disaggregated data review.

Table 1 – List of case study used for the analysis of disaggregated data

WWTP	Main process	Reference	Country	Case study
Rudiano	CAS	[3; 5; 10; 18; 31; 32]	ITALY	1
Folgaria	CAS	[3; 5; 9; 10; 31; 32]	ITALY	1
Taio	CAS	[3; 5; 10; 31; 32]	ITALY	1
Pietramurata	CAS	[3; 5; 10; 31; 32]	ITALY	1
Drena	CAS	[3; 5; 10; 31; 32]	ITALY	1
Viareggio	MBR	[8]	ITALY	1

EPA	Primary scheme I	[27]	USA	3
EPA	Primary scheme II	[27]	USA	3
EPA	CAS scheme II	[27]	USA	3
EPA	CAS scheme III	[27]	USA	3
EPA	Trickling	[27]	USA	3
INRS	CAS	[14]	CANADA	6
INRS	Bio-filtration	[14]	CANADA	6
INRS	No – Nitrification	[14]	CANADA	6
INRS	Nitrification	[14]	CANADA	6
Towanda	CAS	[20]	USA	1
ELY	CAS	[20]	USA	1
ELY	CAS	[20]	USA	1
ELY	CAS	[20]	USA	1
ELY	CAS	[20]	USA	1
Strass	CAS	[4]	AUSTRIA	1
EPRI	(MBR – SBR- CAS – Trickl.)	[7]	USA	7

The disaggregated data review contains the most important parameters of WWTPs. With this data, it is possible to identify the most energy consuming stages and sections in the WWTPs and to prepare best practices as well as best cases scenarios for benchmarking.

In WWTPs, different energy consumers are common. Starting with the general facilities with heating and lighting through to screeners, blowers, pumps, etc. in the individual treatment stages. Figure 14, shows an overview of the several process stages which are common on most WWTPs. Usually, blowers and pumps are the main energy consuming parts, due to the fact that this hardware is running 24 hours and produces a high electrical load. Therefore, the biological treatment (biological process) and especially the aerated tanks are expected to be the highest energy consumers [23].

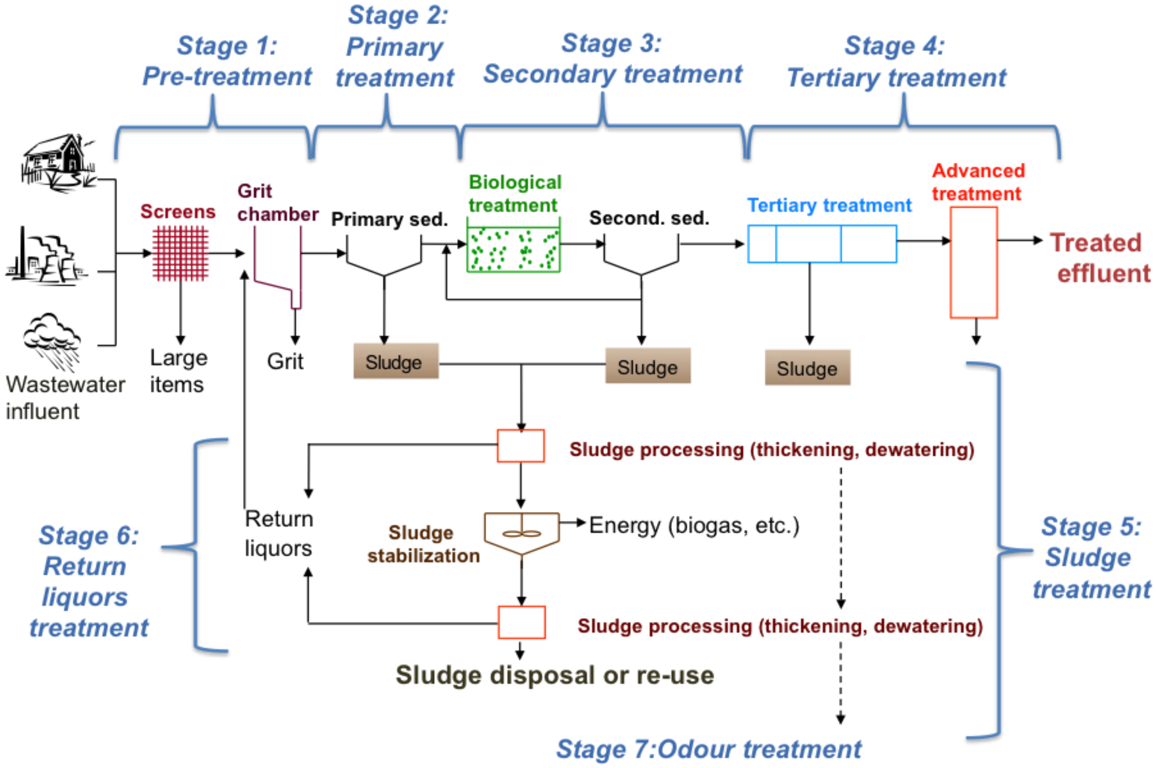


Figure 14: Overview of the several WWTP treatment stages

2.3.1 Main process classification

The different process treatments were classified to individual stages reported in Figure 15. The classification for the stage 3 (Figure 16) was done in conventional activated sludge system (CAS), membrane bioreactor (MBR), sequencing batch reactor (SBR) and trickling filters. For the stage 5 the classification was done in anaerobic and aerobic stabilization.

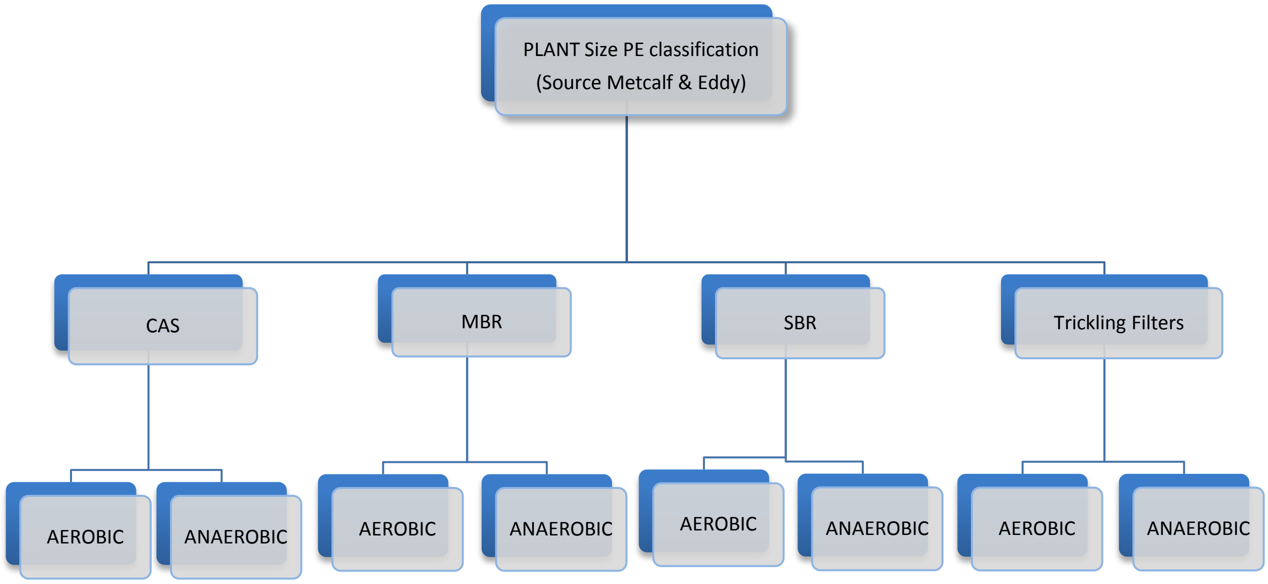


Figure 15: Process treatment classification

2.3.2 Specific energy consumption per different stages treatment

Specific energy consumption, kWh/m^3, among different size classification, is reported in Figure 16. As can be seen, specific energy consumption for the Stage 3 is higher in all different size class.

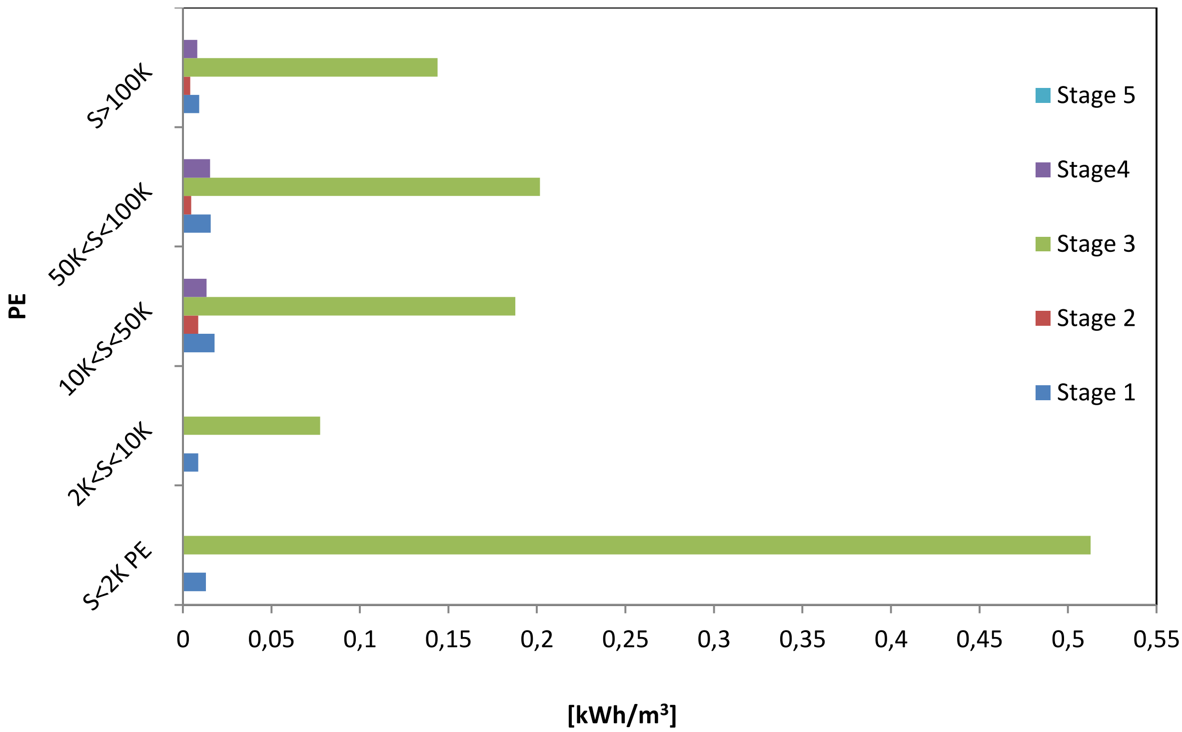


Figure 16 – Specific energy consumption per different stages treatment

The table 2 shows the specific energy consumption for each stage and size classification. In the data reported in Table 2, it has to be considered that only two size classes (10K-50K and >100K) have a sufficient number for statistical consideration. In general, the specific energy consumption decreases with increasing of size classification. The stage 3 is the largest energy consumer in the WWTPs.

Table 2 - Specific energy consumption per different size classification

	< 2K PE	2K & 10K PE	10K & 50K PE	50K & 100K PE	> 100K PE
			kWh/m^3 - (%)		
Stage 1	0.013 (2%)	0.009 (8%)	0.018 (7%)	0.016 (6%)	0.009 (5%)
Stage 2	-	-	0.0086 (3%)	0.005 (2%)	0.004 (2%)
Stage 3	0.51 (64%)	0.77 (71%)	0.17 (68%)	0.2 (72%)	0.15 (74%)
Stage 4	-	-	0.027 (11%)	0.023 (8%)	0.026 (13%)
Stage 5	0.27 (34%)	0.023 (21%)	0.028 (11%)	0.034 (12%)	0.012 (6%)

2.3.2.1 Specific energy focus on each stages treatment

Through the evaluation of the disaggregated data, the specific energy consumption for the stage 1, stage 2 and stage 4 is comparable. Likewise, the energy consumption of stages 3 and 5 are comparable for small plants.

The table below shows the single consumers considered on each stages treatment and the availability of the disaggregated data.

Table 3 - Availability of the disaggregated data

STAGES	CONSUMERS	< 2K PE	2K - 10K PE	10K -50K PE	50K -100K PE	> 100K PE
NUMBERS OF CASE STUDY		1	2	16	5	33
STAGE 1	Influent pumping	NO	YES	YES	YES	YES
	Micro-screening	NO	NO	YES	NO	YES
	Screen	YES	YES	YES	YES	YES
	Comminutors	NO	NO	YES	NO	YES
	Degritting	NO	YES	YES	YES	YES
STAGE 2	Primary settling	NO	NO	YES	YES	YES
STAGE 3	Trickling filters	NO	NO	YES	YES	YES
	Mixer anoxic	NO	YES	YES	YES	YES
	ML recirculation	NO	YES	NO	NO	NO
	Blowers oxidation	YES	YES	YES	YES	YES
	Final settling	NO	YES	YES	YES	YES
	Sludge recirculation	YES	NO	YES	YES	YES
	Bio-filtration	NO	NO	YES	YES	YES
	MBR	NO	NO	YES	YES	YES
	SBR	NO	NO	YES	YES	YES
STAGE 4	Chemicals	NO	NO	YES	YES	YES
	Chlorine disinfection	NO	NO	YES	YES	YES
	Tertiary filtration	NO	NO	YES	YES	YES
	UV	NO	NO	YES	YES	YES
STAGE 5	Sludge from I° settler	NO	NO	YES	NO	YES
	Excess sludge	NO	YES	YES	NO	YES
	Gravity Thickening	YES	NO	YES	YES	YES
	Flotation Thickening	NO	YES	YES	NO	YES
	Centrifuge thickening	NO	NO	YES	YES	YES
	Mix. Aerobic Stabilization	NO	YES	NO	NO	NO
	Blowers Aerobic Stabilization	YES	NO	YES	YES	YES
	Anaerobic digestion	NO	NO	NO	YES	YES

	Motor for gas recirculation	NO	NO	YES	NO	YES
	Heating sludge	NO	NO	YES	NO	YES
	Vacuum filtration	NO	NO	YES	NO	YES
	Incineration	NO	YES	YES	NO	YES
	Centrifuge dewatering	NO	NO	YES	YES	YES
	Belt filter press	NO	NO	NO	YES	YES
	Screw press	NO	NO	YES	YES	YES

2.3.2.2 Focus stage 1 - 2 - 4

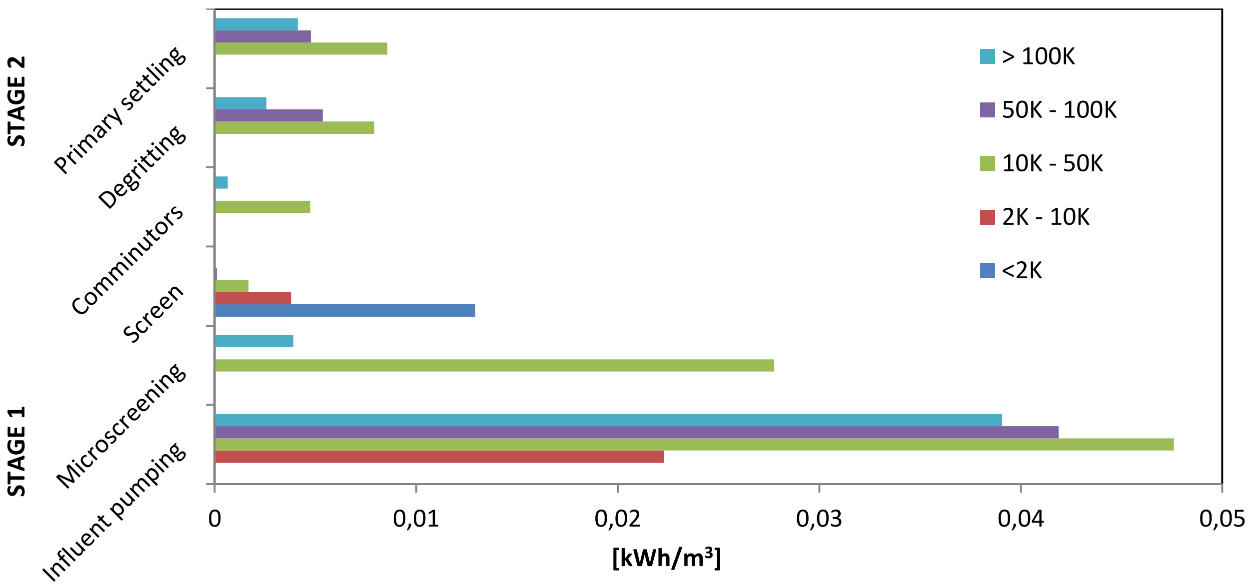


Figure 17 – Specific energy consumption in Stage 1 and Stage 2 per different size classification

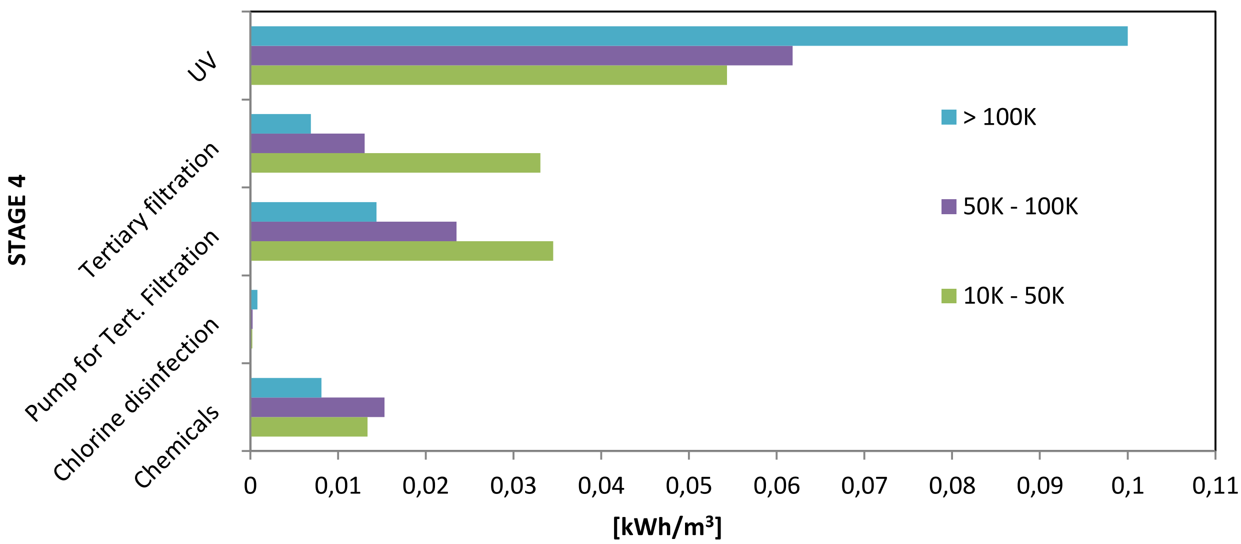


Figure 18 – Specific energy consumption in Stage 4 per different size classification

The Influent pumping is the highest energy consumer in Stage 1 and 2 (Figure 17) regardless of the plant size. For stage 4, data are not available for the smallest size classes, as small WWTPs seldom carry out tertiary treatment. As expected, the UV treatment is the processes that consume more energy per cubic meter treated in the stage 4.

2.3.2.3 Focus stage 3

Due to its significance, this section especially focuses on the different technologies that can be used in stage 3. The following figure shows the specific energy consumption for CAS, MBR, SBR and Trickling process in function of the different size classification. MBR, SBR and oxidation reactors are the most energy consuming processes due to the large demand of aeration. It can be observed that the energy consumed by mixing in anoxic reactors greatly increases with the plant size becoming comparable to other aerated processes. In effect, mixing energy scales superlinearly with the size of the tank making it an energy consuming option for large plants.

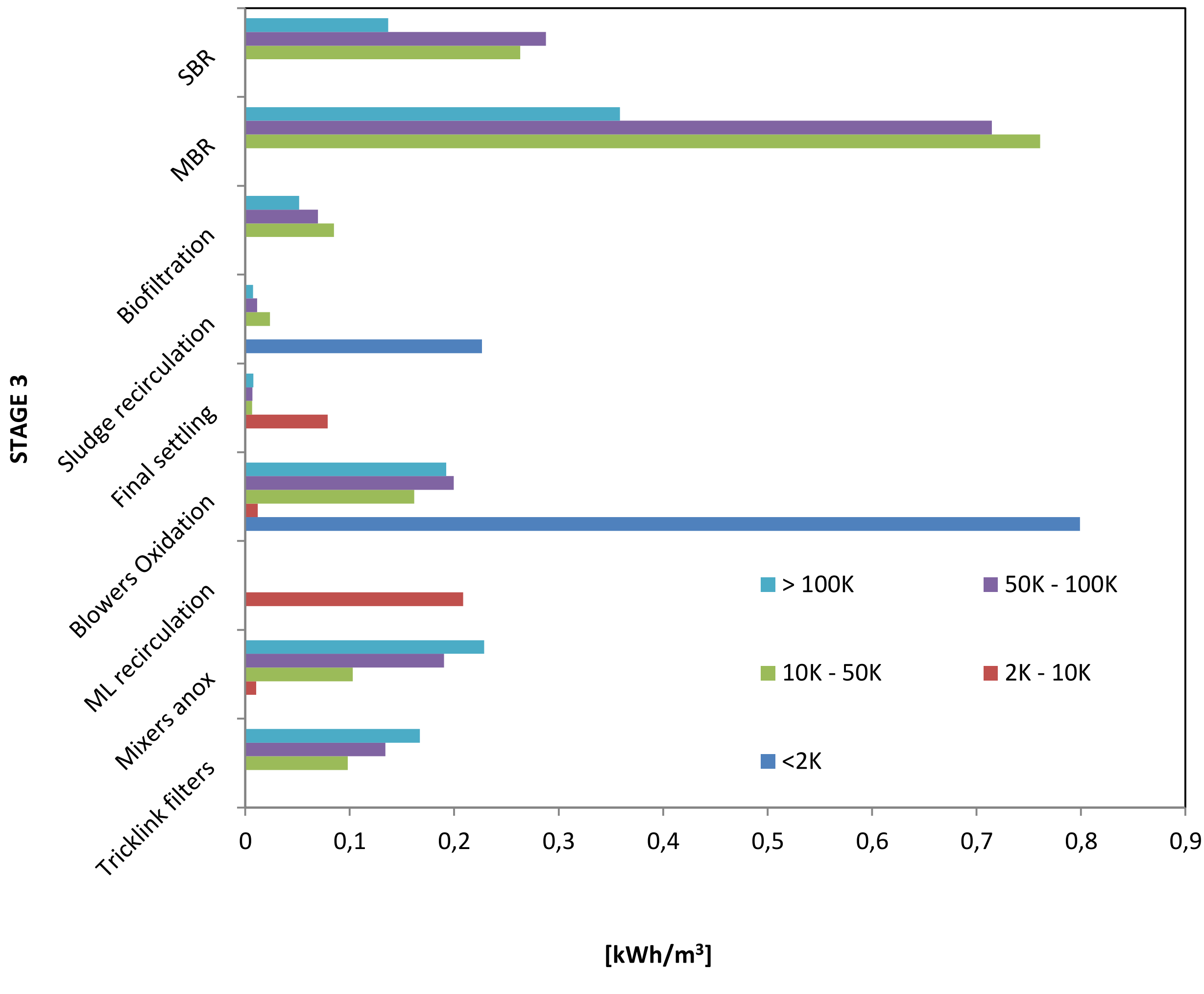


Figure 19 – Specific energy consumption in Stage 3 per different size classification

2.3.2.4 Focus on stage 5

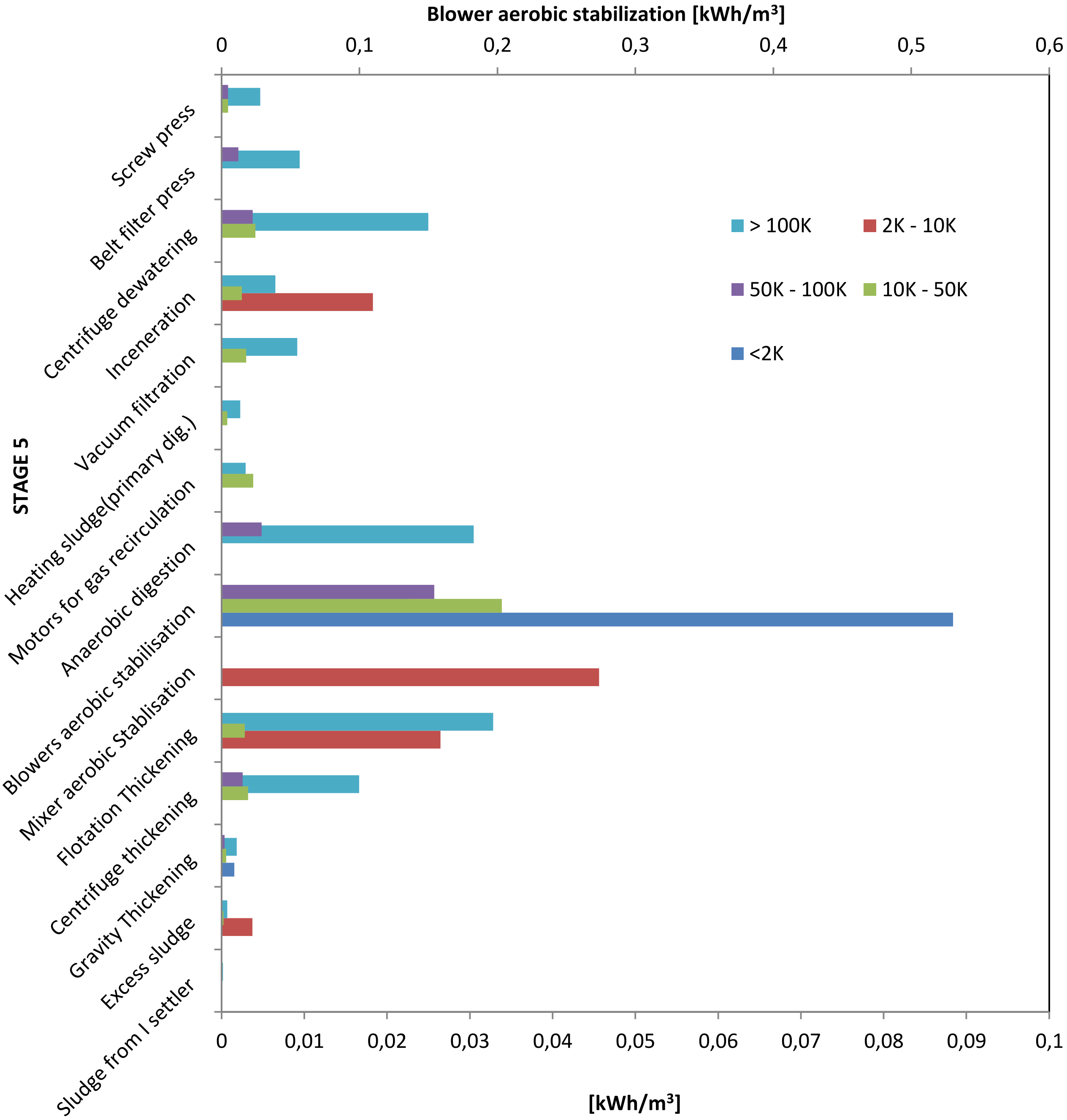


Figure 20 – Specific energy consumption in Stage 5 per different size classification

The following Figure 20 shows the specific energy consumption on the sludge treatment distinguishing between the aerobic and anaerobic stabilization. The blowers for the aerobic stabilization are the most energy consumers in the stage 5. In the chart the KPI values of aerobic stabilization are reported on a second x-axis in order to help the comparison with the other processes.

The KPI values for the aerobic stabilization are, 0.53 kWh/m^3 for PE<2K, no data available for PE between 2K and 10K, 0.21 for PE between 10K and 50K, 0.15 kWh/m^3 for PE between 50K and 100K and 0.02 kWh/m^3 for PE>100K. Generally the stage 5, a part the aerobic stabilization, does not present processes that consume high energy.

2.4 Best practices and best case scenarios for benchmarking

During the last few years, many papers have been published on energy minimisation or 'optimisation' of WWTPs [17; 24]. Energy minimisation, however, must never negatively affect treatment efficiency as water quality protection is more important for sustainable development than the possible reduction in energy demand [17]. This must be seen against the background that the energy costs are only in the range of about 5–10% of the total yearly costs (construction and operation) of municipal WWTPs [17]. Accordingly, at existing WWTPs, at first the wastewater treatment process has to be optimised towards best performance in terms of quality of the effluent and the waste sludge, and then the treatment plant operators can go for savings of energy, chemicals, etc.

The target of 'energy self-sufficient sewage plants' has also been reported [16; 29]. In Austria, two municipal WWTPs (the Strass WWTP and the Wolfgangsee-Ischl WWTP) operated with nutrient removal are now energy self-sufficient. This is the result of an optimisation process that has lasted at both plants for about two decades.

Both of these treatment plants are activated sludge plants with nutrient removal with phosphorus effluent concentrations well below 1 mg P/L and about 80% nitrogen removal, for which no external carbon source is needed. Both plants are equipped with primary sedimentation. In the oxidation ditch type aeration tanks of both plants fine-bubble diffusers are installed. They are both operated with a combination of pre-denitrification and intermittent nitrification-denitrification by means of an optimised aeration control system. Both plants are equipped with mesophilic anaerobic sludge digesters. The energy from the biogas is used in combined heat-power (CHP) units.

2.4.1 Energy self-sufficiency at Strass WWTP

The Strass WWTP is designed as a two-stage activated sludge plant, a so-called A–B-plant, with a very high- loaded first stage with solids retention time (SRT) below 0.5 days. COD removal in this high-loaded stage is around 50%. The SRT in the second, low-loaded stage (aeration tank volume of 10,740 m^3) is about 12 to 14 days and the temperature varies between 9 and 18WC. The aeration is controlled not only by DO probes but also by means of an online ammonia analyser. If the ammonia concentration exceeds a certain value in the effluent from the aeration tanks, the second aeration tank in line, which is normally intermittently aerated, is then aerated permanently. If this is not enough for full nitrification (NH4-N below ca. 4 mg/L), the aeration in the 'pre-denitrification tanks' is switched on in addition and the internal recycle is deactivated.

Due to the two-stage biological process, a lot of biomass with a lot of nitrogen is transferred to the digesters, and therefore the nitrogen load as ammonia in the reject water from sludge dewatering is very high. Nitrogen from the reject water is removed by deammonification (anammox) to a high extent. The digester gas is utilised in the conventional CHP units with an electrical efficiency of now close to 40%.

Since 2008, pre-conditioned organic substrate (food left-overs) is directly fed into the digester together with excess sludge of the treatment plant in order to increase the electricity production from the biogas. On the average 21.4 kWh/(PE*y) of electric energy were produced from the gas from sludge digestion. Peak energy demand has still to be taken from the grid; surplus electrical energy from the plant, however, is fed into the grid. So, 3.2 kWh/(PE*y) could be fed into the grid, and 1.7 kWh/(PE*y) were provided from the grid. In total, 19.9 kWh/(PE*y) of electricity were consumed at the WWTP of which 9.1 kWh/(PE*y) used for aerating and stirring the aeration tank, the 'rest' (10.8 kWh/(PE*y)) used for all the other treatment steps and devices including the influent pumps which consumed 1.9 kWh/(PE*y).

Over the whole period of three years, 6.3% more electricity was produced through the anaerobic digestion of the excess sludge from both stages from the biogas by means of CHP units than was needed in the plant.
In September 2004 energy self-sufficiency was reached. However, it also can be seen that in some months more electrical energy was needed than provided by CHP. In 2009 (and 2010), the electricity production was sometimes up to 200% of the demand of the plant for electrical energy.

2.4.2 Energy self-sufficiency at Wolfgangsee-Ischl WWTP

The Wolfgangsee-Ischl WWTP is a single-stage activated sludge system with primary sedimentation and anaerobic sludge digestion. The aeration tanks (5,100 m^3) are equipped with fine-bubble aeration and stirring devices. The treatment plant was put into operation in the mid-1980s and afterwards only upgraded by changing and optimising mechanical devises.

In 2009, the mean influent load was about 40,000 PE. Due to summer tourism, in the months of July to September, the influent load equals around 50,000 PE, whereas during the rest of the year the influent load is in the range of 33,000 to 40,000 PE. Originally, the plant was designed for 100,000 PE, but only for carbon removal – and for phosphorus removal, because the recipient flows later into a lake. However, because it was clear during plant design that at least in the beginning of the operation of the plant, the influent load would be much lower than 100,000 PE, the aeration tanks were designed in a way that makes nitrification and denitrification practicable. Hence, the aeration tanks are operated with a combination of pre-denitrification and intermittent nitrification-denitrification.

The N:COD ratio of the influent is in the range of 0.09 and 0.10 g N/g COD on average. COD removal by primary sedimentation was found to be about 37%. In the aeration tank, the SRT is about 8 days in summer and about 12 days in winter. The extent of nitrogen removal of the plant is around 76% on the yearly average, and about 80% on the average of all days with more than 12 W C in the effluent. This plant is equipped with two large digesters operated in series with a solids retention time of almost 80 days in total. The digester gas is mainly used in conventional CHPs. A second CHP unit was installed about 2 years ago. The reject water from sludge dewatering is not treated separately, but only equalised by means of a storage tank. The digested sludge is dewatered by means of a chamber filter press and used in agriculture.

After a more efficient CHP unit was installed with an electric efficiency of about 34% and all biogas utilised for electricity production and after the energy demand of the plant was further reduced by optimisation energy self-sufficiency condition were reached.

2.5 Conclusion

The analysis of the energy consumption of 369 WWTPs located in different world regions was carried out, with a sample accounting for 15.5 million of served PE. Most of the plants were activated sludge system, and as a consequence, the study focuses on this type of plants. Additionally, 58 case studies of the disaggregated specific energy consumption were also gathered. The main conclusions of the analysis are:

1. Considering median value and contemplating all facilities regardless of their potential and treatment technology, the specific energy consumption amounted to 0.70 kWh/m^3, 80.2 kWh/PE*y, 1.61 kWh/kgCODrem.
2. In general, stage 3 is the largest energy consuming section (regardless of the KPI value and size) due to the large energy demand of the aerated processes. MBR was seen as the most energy consumer process, followed by SBR and aerobic oxidation.
3. For the rest of the stages, the energy consumption is comparable. Influent pumping is the most relevant in stages 1 & 2. In stage 4, the UV treatment presents the higher KPI value for each classification size.
4. Finally, aerobic stabilization is the only process in stage 5 that presents relevant contribution to the energy consumption.
5. In terms of specific energy consumption, the most useful indexes were found to be kWh/PE*y and kWh/kgCODrem as they represent the actual task carried out by a WWTP (i.e. to produce a clean effluent). The frequently used index kWh/m^3 can be misleading, in particular for comparisons of different regions, as systems with significant input of white waters would appear more efficient.
6. As a general trend, the specific energy consumption tends to decrease when the dimensions of the plant, the flow rate or the served PE increase. This is caused by the possibility to exploit economies of scale in larger systems, leading to larger but efficient equipment, better performing automation and regulation, and, often, more and better train staff operating the plant.

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Appendix A

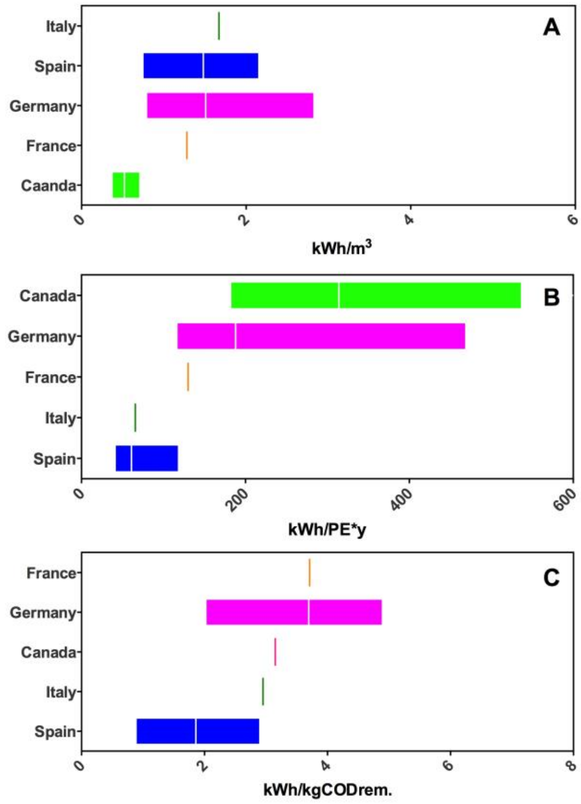

Figure 21 - Specific energy consumption respect to country for WWTPs smaller that 2K PE

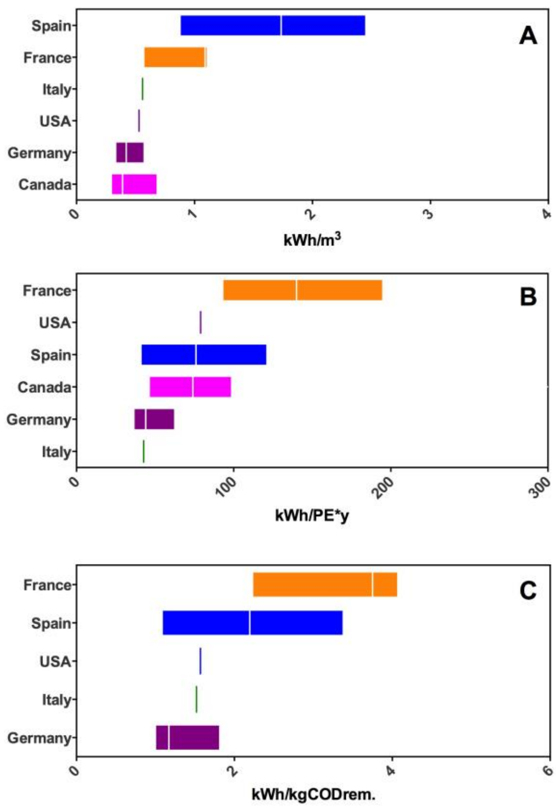

Figure 22 - Specific energy consumption respect to country for WWTPs between 2K and 10K PE

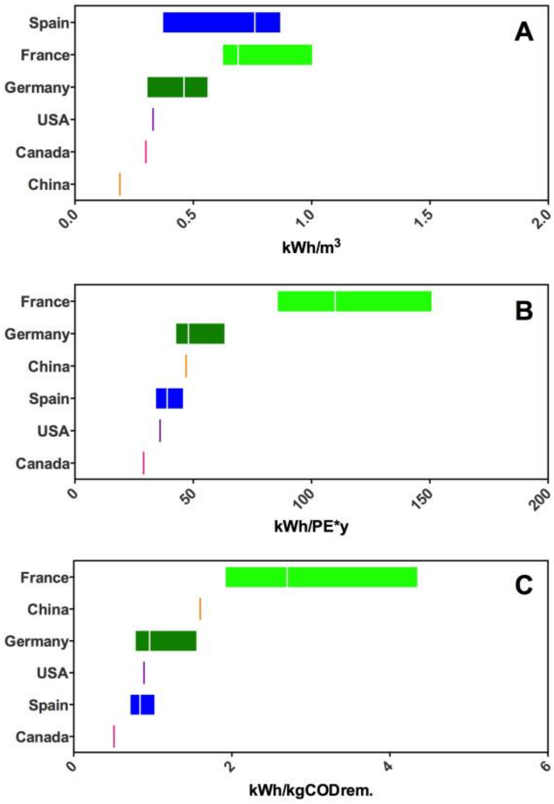

Figure 23 - Specific energy consumption respect to country for WWTPs between 50K and 100K PE

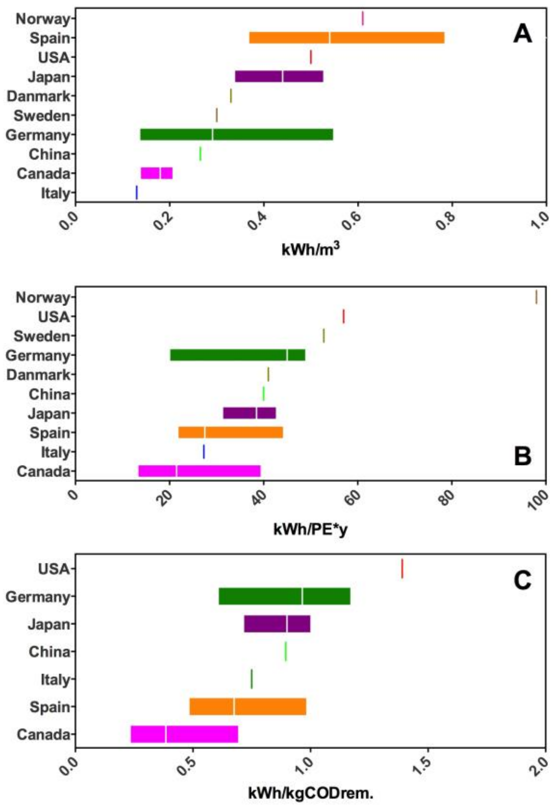

Figure 24 - Specific energy consumption respect to country for WWTPs larger than 100K PE

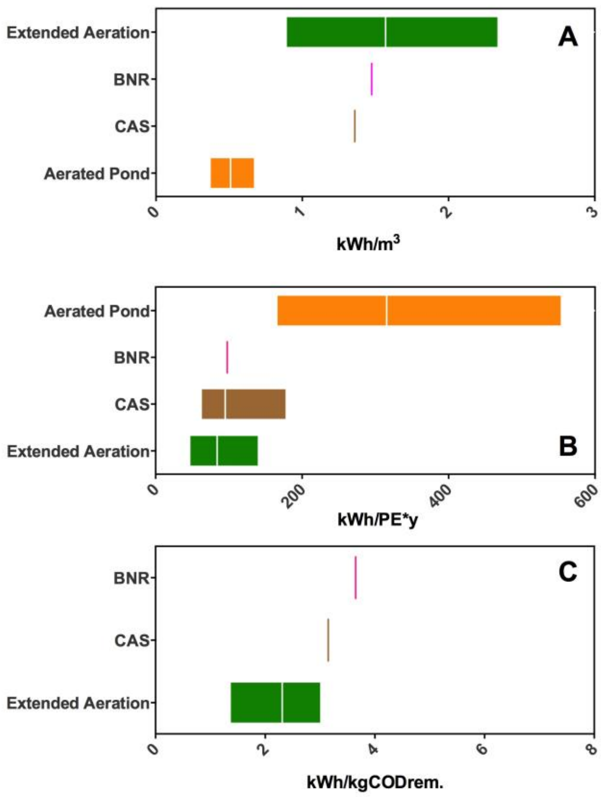

Figure 25 - Specific energy consumption respect to treatment technology for WWTPs smaller that 2K PE

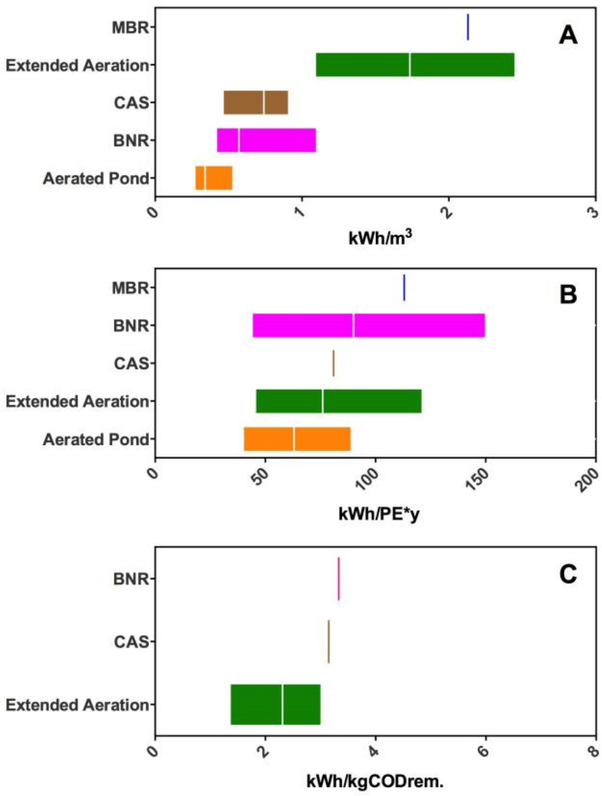

Figure 26 - Specific energy consumption respect to treatment technology for WWTPs between 2K and 10K PE

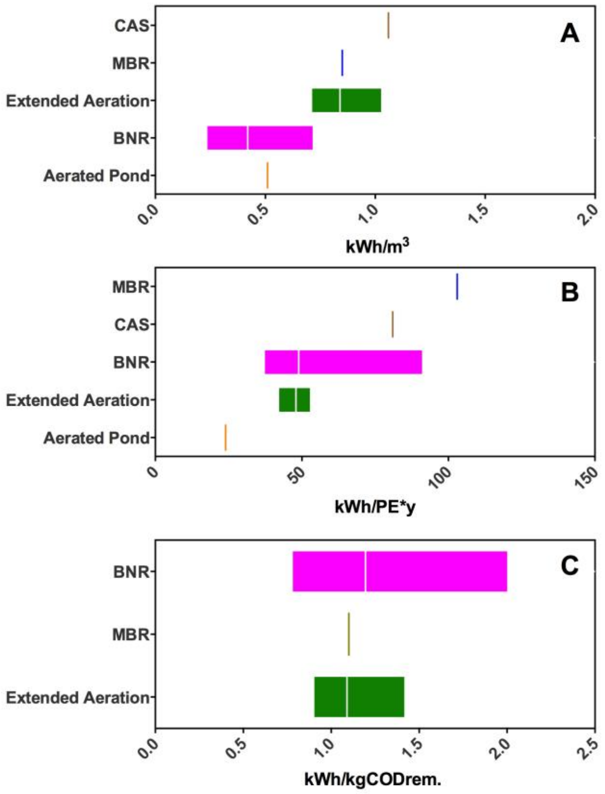

Figure 27 - Specific energy consumption respect to treatment technology for WWTPs between 10K and 50K PE

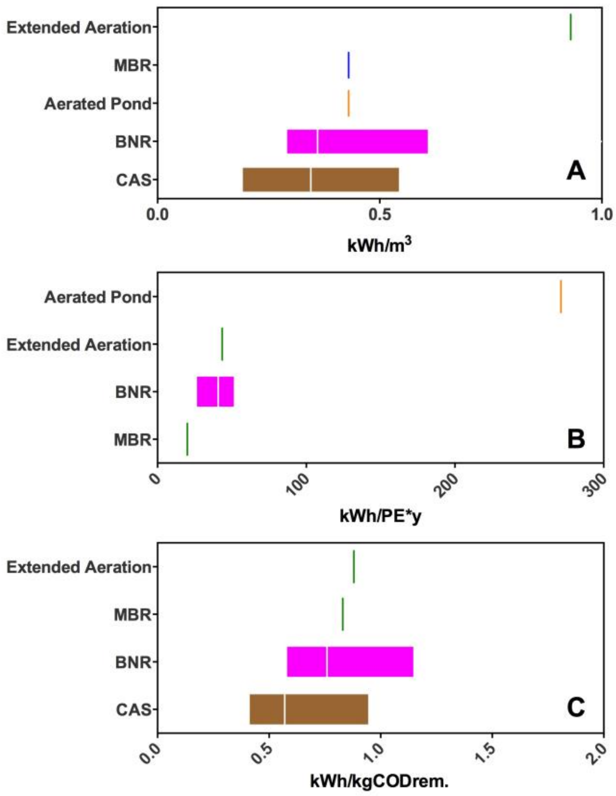

Figure 28 - Specific energy consumption respect to treatment technology for WWTPs larger than 100K PE

Appendix B

Table 4 – Total energy consumption respect to class size

kWh/m^3	S<2K	2K<S<10K	10K<S<50K	50K<S<100K	S>100K
Minimum	0.18	0.16	0.16	0.13	0.05
First quartile	0.42	0.33	0.26	0.35	0.28
Median	0.61	0.53	0.51	0.57	0.43
Third quartile	0.86	0.91	0.78	0.80	0.61
Maximum	5.50	3.76	2.08	1.51	1.37
kWh/PE*y	**S<2K**	**2K<S<10K**	**10K<S<50K**	**50K<S<100K**	**S>100K**
Minimum	9.9	11.8	18.3	20.8	5.0
First quartile	104.6	43.0	37.1	36.6	24.8
Median	233.2	69.5	48.0	42.3	37.6
Third quartile	462.3	109.3	73.7	49.3	45.0
Maximum	2110.7	575.3	262.0	162.0	98.0
kWh/kgCODrem	**S<2K**	**2K<S<10K**	**10K<S<50K**	**50K<S<100K**	**S>100K**
Minimum	0.48	0.28	0.57	0.46	0.19
First quartile	1.32	1.08	0.80	0.73	0.53
Median	2.34	1.86	1.09	0.89	0.77
Third quartile	3.23	3.28	1.73	1.28	1.06
Maximum	6.57	5.69	6.56	4.86	1.89

Table 5 – Total energy consumption respect to treatment technology

kWh/m^3	Aerated Pond	Biodisc	BNR	CAS	Extended Aeration	MBR	Oxidation Ditch	SBR	Tricking filter
Minimum	0.16	0.30	0.13	0.13	0.22	0.43	0.47	0.19	0.21
First quartile	0.32	0.37	0.29	0.30	0.79	0.70	0.52	0.19	0.22
Median	0.46	0.58	0.50	0.53	1.04	1.00	0.58	0.19	0.23
Third quartile	0.64	0.98	0.75	0.85	1.89	1.50	0.65	0.29	0.27
Maximum	0.97	1.55	2.08	2.40	5.50	3.76	0.77	0.39	0.30
kWh/PE*y	**Aerated Pond**	**Biodisc**	**BNR**	**CAS**	**Extended Aeration**	**MBR**	**Oxidation Ditch**	**SBR**	**Tricking filter**
Minimum	11.84	21.63	10.36	11.07	12.08	19.62	17.89	40.00	29.18
First quartile	78.12	192.02	37.15	23.31	41.70	37.18	23.25	42.50	37.03
Median	209.31	222.53	51.80	43.76	53.10	79.42	26.60	45.00	44.87
Third quartile	416.39	471.11	96.50	88.97	88.30	123.74	38.20	46.10	45.10
Maximum	2110.65	584.00	262.00	575.28	213.65	188.38	68.28	47.21	45.32
kWh/kgCODrem	**Aerated Pond**	**Biodisc**	**BNR**	**CAS**	**Extended Aeration**	**MBR**	**Oxidation Ditch**	**SBR**	**Tricking filter**
Minimum	0.28	0.48	0.23	0.19	0.28	0.75	0.41	0.91	0.51
First quartile	0.32	0.48	0.77	0.46	0.94	0.87	0.51	0.99	0.65
Median	0.35	0.48	1.25	0.60	1.40	2.94	0.58	1.07	0.79
Third quartile	0.39	0.48	2.47	1.03	2.38	3.70	1.10	1.33	0.80
Maximum	0.42	0.48	6.56	3.15	6.57	5.61	2.55	1.60	0.80

Table 6 – Total energy consumption respect to country

kWh/m³	Canada	China	France	Germany	Italy	Japan	Spain	Sweden	UK	USA
Minimum	0.13	0.19	0.22	0.05	0.13	0.32	0.13	0.29	0.19	0.19
First quartile	0.32	0.21	0.53	0.23	0.33	0.37	0.55	0.30	0.21	0.21
Median	0.46	0.24	0.75	0.36	0.56	0.44	0.80	0.31	0.24	0.24
Third quartile	0.70	0.26	1.09	0.55	0.96	0.50	1.41	0.31	0.26	0.26
Maximum	2.40	0.29	1.28	3.14	1.67	0.54	5.50	0.32	0.29	0.29
kWh/PE*y	**Canada**	**China**	**France**	**Germany**	**Italy**	**Japan**	**Spain**	**Sweden**	**UK**	**USA**
Minimum	11.07	26.40	46.00	5.00	27.30	28.62	9.91	40.80	26.40	26.40
First quartile	80.36	36.80	91.50	36.50	34.95	35.37	33.05	46.30	36.80	36.80
Median	183.23	47.21	120.00	44.00	42.70	38.52	44.55	51.80	47.21	47.21
Third quartile	412.19	50.42	158.50	57.00	52.35	40.45	69.27	58.85	50.42	50.42
Maximum	2110.65	53.63	262.00	545.00	65.70	43.53	213.65	65.90	53.63	53.63
kWh/kgCODrem	**Canada**	**China**	**France**	**Germany**	**Italy**	**Japan**	**Spain**	**Sweden**	**UK**	**USA**
Minimum	0.19	0.65	1.10	0.49	0.75	0.66	0.23	n. a.	0.65	0.65
First quartile	0.49	0.90	1.95	0.78	1.22	0.83	0.74	n. a.	0.90	0.90
Median	0.51	1.14	3.37	1.00	1.53	0.90	1.03	n. a.	1.14	1.14
Third quartile	1.39	1.37	4.02	1.47	1.99	0.95	1.86	n. a.	1.37	1.37
Maximum	3.15	1.60	6.56	5.22	2.95	1.03	6.57	n. a.	1.60	1.60