water e-journal
Online Journal of the Australian Water Association
ISSN 2206-1991
Volume 3 No 2 2018
doi.org/10.21139/wej.2018.023

BENCHMARKING ENERGY USE FOR WASTEWATER TREATMENT PLANTS

A summary of the 2015-16 benchmarking study

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ABSTRACT

The results of the latest round of energy use benchmarking on wastewater treatment plants (WWTP) conducted for 2015-16 by the Water Services Association of Australia (WSAA) and Intelligent Water Network (IWN) are presented. In total, 245 WWTPs were covered, mostly in Australia, with two plants in Auckland (New Zealand) included. This represents a large increase (by 103) in the number of WWTPs, compared with the previous WSAA benchmarking round in 2013-14. Most of the WWTPs added in the latest round were extended aeration-type activated sludge plants and aerated lagoons. These types tended to be less energy efficient. Nevertheless, the results show significant improvements in energy efficiency for some plants. Within the subset of plants that participated in both the latest and previous rounds, slightly more than half showed some improvement in energy efficiency, and just over one third showed an improvement of more than 10%. The primary benchmark applied was specific energy use per unit of equivalent population per year (based on raw influent loads). A secondary benchmark of energy self-supply was applied for plants with on-site renewable energy, predominantly co-generation from biogas. Alternative benchmarks of specific energy use per unit of pollutant load removed were also investigated, namely Total Nitrogen (N), Chemical or Biochemical Oxygen Demand (COD or BOD).

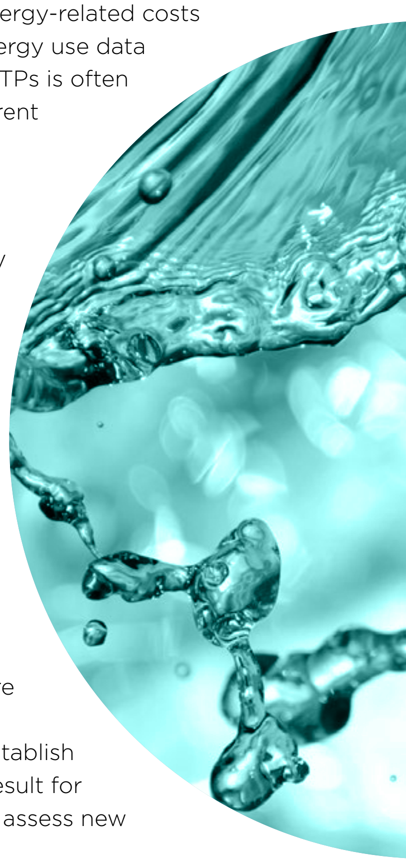
KEYWORDS

Wastewater treatment, energy, benchmarks, specific energy use, nitrogen removal, biochemical oxygen demand (BOD), chemical oxygen demand (COD), energy efficiency.

INTRODUCTION

Energy use accounts for a large portion of the operating cost and greenhouse gas (GHG) emissions profile of a typical wastewater treatment plant (WWTP). Understanding specific energy use of a WWTP plant, and benchmarking it against other similar plants, is an important step to reducing energy-related costs and GHG emissions. However, energy use data reported in the literature for WWTPs is often fragmented or expressed in different specific units.

In 2013-14, the Water Services Association of Australia (WSAA) conducted a first round of energy benchmarking for 142 WWTPs across Australia. A second-round benchmarking exercise was performed by WSAA and the Intelligent Water Network (IWN) for the 2015-16 data period, which included a total of 245 WWTPs (243 plants in Australia and two plants in Auckland, New Zealand). The purpose of the exercise was to benchmark specific energy consumption of WWTPs, compare these results to those from the previous benchmarking round, establish a baseline energy performance result for newly participating WWTPs, and assess new energy-related benchmarks.



This paper summarises the findings of the WSAA-IWN 2015-16 benchmarking round. It represents the consolidation of outputs from a large database of discrete and time-series data submitted by 31 water utilities that participated in the study (WSAA, 2017). Of these, 17 utilities had also participated in the previous (2013-14) benchmarking round. Nearly 50% of the WWTPs in the 2015-16 round reported here (121 out of 245 plants) were included in the first round as well.

METHODOLOGY

Overview

The approach to WWTP energy benchmarking selected for this study (WSAA, 2017) referenced an approach developed and applied in several European countries over the last two decades, including Switzerland, Germany, and Austria. In particular, this study's approach followed current best practice from published manuals, research reports and reviews from Germany (LfU, 1998; Baumann and Roth, 2008; Haberkern *et al.,* 2008; DWA, 2012; Baumann *et al.,* 2014; DWA, 2015). It is also in line with the recommendations of the Water Environment Research Foundation (USA) (Crawford, 2010), and application, for example, by SA Water in South Australia (Krampe, 2013; Steele *et al.,* 2013; Corena *et al.*, 2015; Malekizadeh, 2016).

The data collected from each WWTP covered a period between July 2015 and June 2016, with most utilities providing data covering this entire period. The data collected included:

- Details of plant type and processes used;
- Electrical energy (imported and exported);
- Raw influent flow and quality;
- Effluent flow and quality;
- Other imported waste not included in the raw influent, and whether or not this waste is anaerobically co-digested;
- On-site energy generated, including that from biogas or other sources, such as wind or solar;
- Details around influent and/or effluent pumping (flow, head and sub-metered energy use), where relevant and available; and
- Other energy sub-metering data, if available.

The methodology applied calculated WWTP energy use in terms of average annual electrical energy use (kWh) per equivalent person (EP), derived from influent wastewater loading and expressed in units of kWh per EP per year (kWh/[EP.y]) as the *primary benchmark.* The calculations of EP for each plant were based on influent raw wastewater load, taking into account both influent organics (COD or BOD) and nitrogen, where these data were available. The data submitted was filtered to exclude outliers, using a commonly applied statistical method (McGill *et al.,* 1978; Frigge *et al.,* 1989). The wastewater data (flow and concentration) as well as energy use were assumed to be log-normally distributed.

For the majority of plants included in this study (242 out of 245, by number), sufficient data was available to calculate adopted EP as an average from influent organic and nitrogen loads. For the remainder, the adopted average EP was calculated from raw influent organic load only (COD or BOD, whichever was available).

Due to common use elsewhere, average flow-based energy use (kWh per megalitre wastewater treated) was also calculated and reported.

For plants with on-site energy production, a *secondary benchmark* of percent electrical energy self-supply (%Ess) was applied.

Where possible, calculations of specific energy use were also performed for additional metrics, with a view to developing additional benchmarks in future, related to effluent quality and treatment performance, namely:

- Total Nitrogen (N) removed: kWh per kg N removed,
- COD removed: kWh per kg COD removed, and/or
- BOD removed: kWh per kg BOD removed.

Plant types

Five plant types (Types 1 to 5) were relevant to the WWTPs involved in this study and categorised according to treatment processes, with some sub-types defined. A high-level summary of the relevant five types is given in Table 1. Refer to ***Supplementary Information*** for more information.

Plant size classes

Five plant-class sizes (SC) were set according to various ranges of EP. These definitions were based on similar definitions applied in German WWTP energy benchmarking manuals (*inter alia* DWA, 2012; Baumann *et al.,* 2014), as shown in Table 2. Refer to ***Supplementary Information*** for more information.

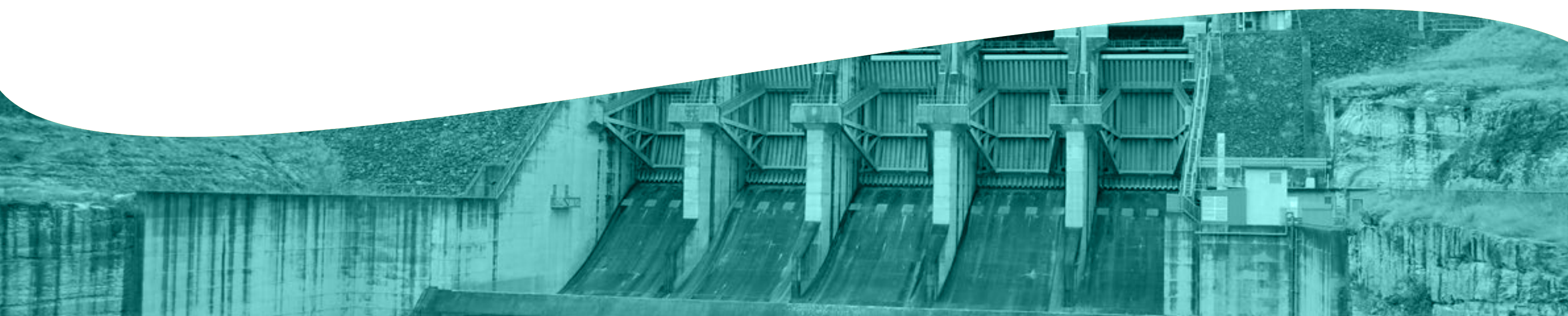


Table 1. Summary definition of Plant Types included in this study

Type	Features	Notes
Type 1	Activated sludge treatment with separate sludge stabilisation, including those with primary sedimentation, anaerobic digestion (or alternative[1]) and on-site co-generation (on-site energy produced from biogas).	In a limited number of cases, primary sedimentation and anaerobic digestion with on-site co-generation from biogas was present but activated sludge treatment lacking (i.e. no secondary treatment, notably plants with ocean outfalls). These plants were classified as Type 1 by default (subject to review in the future benchmarking rounds).
Type 2	Same as Type 1 but without on-site co-generation (no on-site energy produced from biogas).	-
Type 3	Extended aeration activated sludge, including aerobic digestion.	Sub-types recognised for Types 3, 4 & 5 according to plant configuration (refer to Supplementary Information). Refer to note[2] for MBRs
Type 4	Trickling filters and/or trickling filters combined with activated sludge	
Type 5	Lagoons (aerated or unaerated) and/or wetland systems	

[1]Alternative sludge stabilisation excludes Aerobic Digestion (refer to Type 3)

[2]Most membrane bioreactor (MBR) plants were Type 3 and designated a sub-type. Combinations of membrane bioreactors with other plant types (e.g. Types 1 or 2 with primary sedimentation) were benchmarked using energy supplements (refer to Supplementary Information).

Table 2. Definition of Size Classes

Size Class (SC)	EP Range
SC1	≤ 1,000 EP
SC2	1001 – 5,000 EP
SC3	5001 - 10,000 EP
SC4	10,001 - 100,000 EP
SC5	>100,000 EP

Energy benchmarks

Energy benchmarks were set as "Target" or "Guide" Values, based on German energy manuals (Haberkern *et al.,* 2008; DWA, 2012; and Baumann *et al.,* 2014). The Target and Guide Values are indicative of "best practice" and "typical" (or "average") performance respectively. The values applied vary according to plant Type and Size Class (refer to Figure 1), and typically decrease with increasing plant size, due to economies of scale.

For specific energy-intensive processes, an "energy supplement" was provided in the benchmarks. This represents the expected additional energy use from these processes, and is added to the Target or Guide Values for a given plant. For example, high pumping requirements (nominally >4 metres of head), specifically for influent wastewater or treated effluent, was present in many cases. For such cases, pressure (head) data was additionally requested to enable appropriate energy supplements for pumping to be applied. However, the relevant pressure information was only submitted for a small number of plants, which meant that the energy supplements for pumping could only be applied to those plants.

Refer to ***Supplementary Information*** and Figure 1 below for more information.

[1] Alternative sludge stabilisation excludes Aerobic Digestion (refer to Type 3)

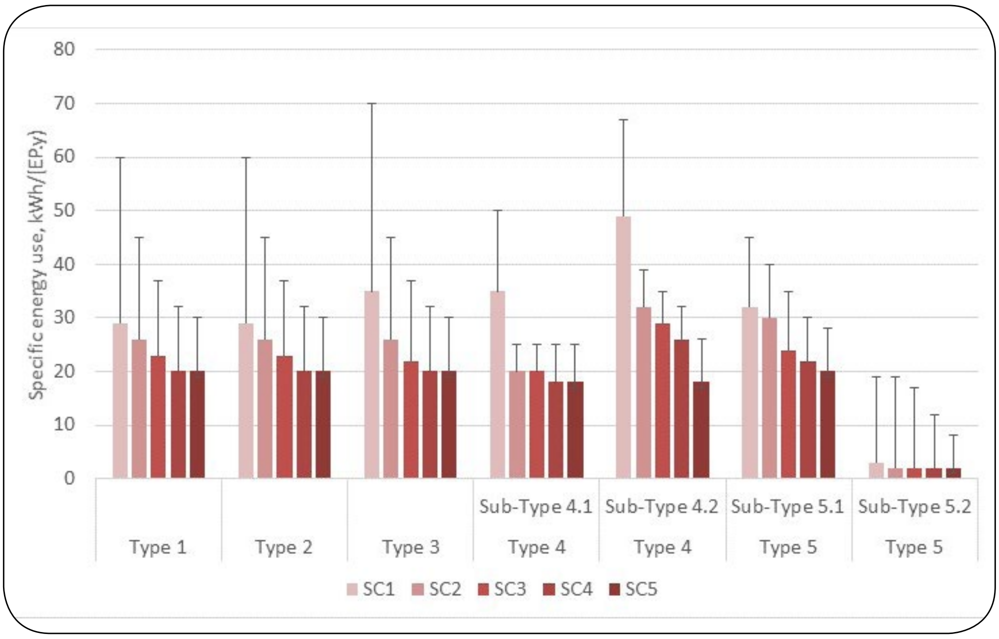


Figure 1. Benchmark Target Values (columns) and Guide Values (error bars) for WWTP specific energy use adopted (from German references) by plant Type and Size Class. Values shown exclude energy supplements that may be added for high-energy consuming processes and/or pumping, if applicable. Refer to Supplementary Information for details of sub-types and energy supplements.

RESULTS

Overall industry benchmarks

Table 3 , Table 4 and Table 5 provide high-level summaries of data collected from this study. ***Supplementary Information*** for this paper provides graphical summaries of the data for all plants, ranked in order of increasing energy use according to the primary benchmark of kWh/(EP.y), grouped by Plant Type and Size Class. The guide and target values applied were reviewed for this benchmarking round and revised in some cases, compared with the previous round. The average Target and Guide Values listed in Table 3, Table 4 and Table 5 include the energy supplements (where applicable) for the relevant WWTPs represented within each Type. Therefore, it is important to note that the Guide and Target Values tabulated (Table 3, Table 4 and Table 5) are weighted averages, based on the number and range of plants falling into each category (i.e. a combination of Type, Size Class and Supplements, where applicable).

Refer to ***Supplementary Information*** (Table 7) for a summary of the change in performance on primary benchmark for plants that participated in both this benchmarking round (2015-16) and the previous round (2013-14), broken down by Type and Size Class.

Table 3. Summary of WWTP total plant electrical specific energy use from this study (refer to Note[1])					
Type	WWTP Count	Average kWh/ ML#	Average kWh/ (EP.year)	Average kWh/(EP. year) Guide Value[1]	Average kWh/(EP.year) Target Value[1]
Type 1	22 [18]	613 [629]	41 [45]	40 [30]	26 [20]
Type 2	24 [16]	886 [973]	64 [66]	40 [38]	25 [24]
Type 3	133 [81]	1533 [924]	107 [68]	50 [44]	32 [26]
Type 4	13 [10]	612 [580]	76 [68]	32 [27]	24 [17]
Type 5	53 [17]	728 [668]	62 [57]	35 [34]	22 [17]
All	245 [142]	1166 [837]	86 [64]	44 [39]	28 [23]

#Flow-specific energy use (kWh/ML) is listed for comparative purposes (not used for benchmarking)

[1]**Note:** Benchmark Guide and Target Values vary according to Type and Size Class. Refer to text. Values without parentheses are for this WSAA benchmarking round (2015-16). Values in parentheses are from the previous benchmarking round (2013-14). All values for whole-of-plant electrical energy use (including pumping energy, if submitted as part of plant total).

Table 4. Summary of WWTP total plant electrical specific energy use for WWTPs that met the Target Values				
Type	WWTP Count	Average kWh/ML	Average kWh/ (EP.year)	Average kWh/(EP.year) Target Value[1]
Type 1	4 [2]	403 [364]	26 [14]	34 [19]
Type 2	1 [1]	431 [118]	26 [10]	29 [62]
Type 3	3 [7]	1367 [616]	65 [18]	74 [25]
Type 4	3 [2]	158 [160]	8.3 [11]	20 [15]
Type 5	11 [3]	229 [269]	16 [14]	25 [17]
All	22 [15]	415 [419]	24 [15]	33 [24]

[1]Refer to Note for Table 3.

Table 5. Summary of WWTP total plant electrical specific energy use for WWTPs that met the Guide Values				
Type	WWTP Count	Average kWh/ML	Average kWh/(EP.year)	Average kWh/(EP.year) Guide Value[1]
Type 1	10 [8]	506 [397]	33 [24]	46 [30]
Type 2	4 [3]	413 [309]	31 [22]	46 [60]
Type 3	15 [16]	702 [781]	47 [47]	59 [68]
Type 4	4 [5]	173 [227]	12 [20]	29 [25]
Type 5	22 [7]	280 [331]	20 [22]	33 [33]
All	55 [39]	438 [514]	30 [32]	43 [48]

[1]Refer to Note for Table 3.

PRIMARY BENCHMARK

Ranking all plants by specific energy use

Of the WWTPs in this study, the 'top 100' WWTPs were assessed by ranking in ascending order of primary benchmark result, i.e. average specific energy use (kWh/[EP.year]). All Plant Types (1 to 5) and all Size Classes (SC1 to SC5) were included in this ranking.

It was found that the 'top 100' plants had an average specific energy use of 50 kWh/(EP.y) or less. Furthermore, below approximately 15 kWh/(EP.y), only Type 4 (trickling filter types) and Type 5 (lagoon types) featured. The majority of the Type 1 plants (19 out of 22 in number) were placed in the 'top 100' list and had an average specific energy use ranging 15 to 49 kWh/(EP.y). There were three plants classified as Type 1 by default that lack secondary treatment and discharge via ocean outfalls. These three plants were ranked in first, second and fourth-lowest, with an average specific energy use ranging 15 to 25 kWh/(EP.y), and might be considered to be a type of their own in future benchmarking rounds.

Similarly, the 'middle 100' WWTPs assessed as part of this study had an average specific energy use in the range approximately 50 to 110 kWh/(EP.y). Although there are exceptions, the predominant plant types in the 'middle 100' list were Types 2 and 3, particularly the latter, which are more dependent on aeration for treatment and hence tend to use more energy.

Finally, the 'bottom 45' WWTPs assessed were predominantly plant Types 3 and 5, again because both include examples of plants with relatively high energy use i.e. extended aeration activated sludge processes (Type 3) or aerated lagoons (Sub-type 5.1). Some small membrane bioreactor plants (MBR, Sub-type 3.4) with relatively inefficient aeration systems, were amongst the highest specific energy consumers in this group.

General comments on specific energy use

Many local or plant-related factors underlie energy use on a given WWTP and constrain its performance against industry benchmarks. These might include plant size; type of process; operating energy efficiency of the installed equipment; pumping and mixing requirements; and water quality drivers (e.g. nutrient removal, disinfection and water recycling).

Nevertheless, looking broadly at the results from this study, compared with the primary benchmarks for each Type and Size Class (Figure 1 and ***Supplementary Information***), it is possible to make general comments about the energy efficiency performance of Australian WWTPs, as summarised in Table 6.

Table 6. General ranking of WWTP energy efficiency performance from this study, based on primary benchmark of specific energy use.

Ranking	Percentile[1]	Number of plants	Specific energy use (kWh/EP/year)	Implications
Top	≤10%	25	<25	Limited opportunities for further energy efficiency improvements or lowering energy use.
Above average	>10% to 40%	75	25-50	Some opportunities to improve efficiency or lower energy use.
Average	>40% to 50%	24	51-60	
Below average	>50% to 82%	75	61-110	Significant opportunities to improve efficiency or lower energy use.
Bottom	>82%	46	>110	Opportunities to substantially improve energy efficiency or reduce energy use, potentially involving revised plant design or operations.

[1]**Note:** Percentile range indicates approximate proportion of plants with benchmarked performance better than or equal to the stated specific energy use range

SECONDARY BENCHMARKS

Energy self-supply

For Type 1 plants, percent electrical energy self-supply (%Ess) performance was calculated and the results are summarised in Figure 2. The Guide Value is 60% Ess, with a Target Value of 100%.

Of the 22 Type 1 plants in review for this benchmark, none of the plants achieved the Target Value of 100% Ess on average. One plant achieved an average >90% Ess, which is an excellent result. A further six plants achieved better than the Guide Value (i.e. >60 % Ess) on average.

One plant reported 0% Ess. That plant was being upgraded during the review period. In future, it will include energy self-supply, but these facilities were not commissioned during the 2015-16 reporting period.

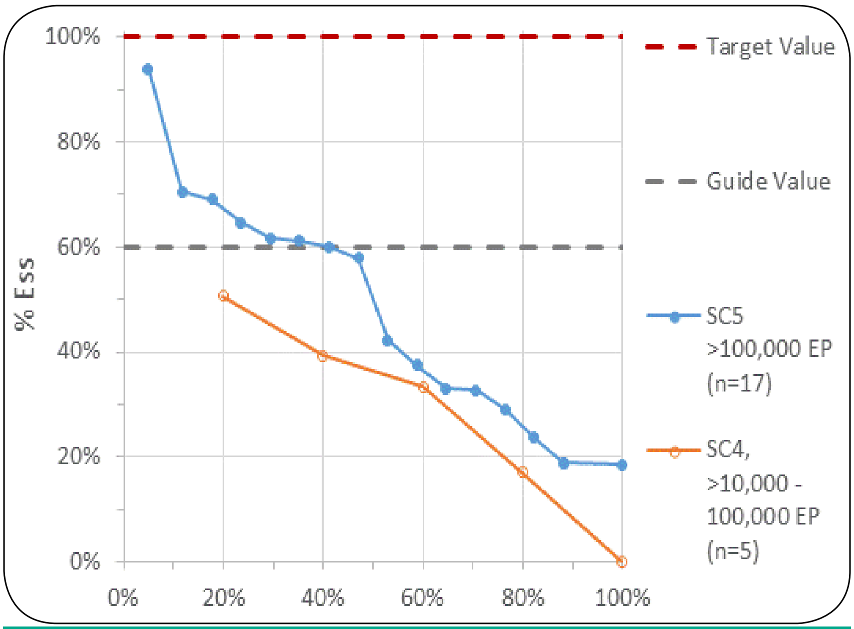


Figure 2. Probability distribution of Electricity Self-Supply, according to Size Class for Type 1 plants in this study (2015-16 data).

Alternative benchmarks

This study examined three new benchmarks that might be used as alternatives to, or in conjunction with, the primary benchmark. These are based on specific energy use relative to pollutant load removed, namely:

- Total N load removed: kWh/kgN removed;
- COD removed: kWh/kg COD removed; and/or
- BOD removed: kWh/kg BOD removed.

Where available, data was collected for the relevant influent and effluent parameters (flow and concentration) to enable the pollutant load removed to be calculated for each of the WWTPs in this study. Most plants reported either COD or BOD measurements for influent and/or effluent, but few plants reported both parameters. Where matching (or paired) measurements of influent and effluent COD or BOD were not reported, it was not possible to calculate pollutant load removed and hence the alternative benchmark. Similarly, not all plants reported influent and effluent Total N. Where possible, Total Kjeldahl Nitrogen (TKN) was taken as a close approximation of raw influent Total N. Similarly, where effluent Oxidised N (Nitrate plus Nitrite) and Ammonia was reported, the sum of these (Total Inorganic N) was taken as an approximation of effluent Total N, in the absence of other data.

Overall, out of the total number of 245 WWTPs in this review, the reported data enabled the following alternative benchmarks for specific energy use to be calculated:

- Per unit Total N load removed (kWh/kg N removed): for 242 WWTPs
- Per unit COD load removed (kWh/kg COD removed): for 70 WWTPs
- Per unit BOD load removed (kWh/kg BOD removed): for 171 WWTPs

The summary results are given in Table 7. Refer to ***Supplementary Information*** for more detail.

Results for alternative benchmarks

A more detailed analysis of the results for the alternative benchmarks (refer to ***Supplementary Information***) showed that the alternative benchmarks based on removal of organic load (expressed as kWh/kgCODrem or kWh/kgBODrem) were strongly correlated with the primary benchmark (kWh/[EP.y]). This can be intuitively understood to be because most WWTPs (particularly the types with activated sludge processes in Types 1, 2, 3) achieve nearly complete removal of COD and/or BOD (typically >93% removal on average – refer to Table 7).

However, the alternative benchmark based on nitrogen removal (expressed as kWh/kgNrem) was less strongly correlated with the primary benchmark (kWh/[EP.y]).

Table 7. Summary data for primary and alternative benchmarks

Type	WWTP Count	Average kWh/(EP.y)	Average kWh/ kg-COD removed	Average kWh/ kg-BOD removed	Average kWh/kg-N removed	Average% COD removal	Average %BOD removal	Average % N removal
Type 1	22	40.5	1.1	2.2	11.9	93%	98%	57%
Type 2	24	63.5	1.4	3.0	14.8	94%	93%	80%
Type 3	133	107.3	3.6	6.2	26.3	94%	98%	90%
Type 4	13	75.9	N/A	3.9	14.4	N/A	93%	56%
Type 5	53	61.8	1.8	3.2	15.6	81%	82%	76%
All	245	85.6	2.8	4.8	21.0	92%	93%	81%

N/A: Insufficient data available. All values are for whole-of-plant electrical energy use (including pumping energy, if submitted as part of plant total).

The underlying reason is that nitrogen removal is more variable for Australian WWTPs across the types represented in this review. That is evident even from the average percent N removal across all plants within a given type (refer to Table 7). As might be expected, extended aeration activated sludge plants (Type 3), which were strongly represented by numbers in this review, are typically designed for nutrient removal, giving an average of 90% N removal (Table 7). Although represented by a smaller number of plants, the Type 2 plants achieved an average of 80% N removal, whereas a similar number of Type 1 plants showed an average N removal of only 57%, or 71% excluding the three nominal Type 1 plants that lack secondary (activated sludge) processes and achieve little or no N removal (i.e. discharge to the ocean). Similarly, Type 4 and 5 plants are not typically designed for advanced nitrogen removal, although some N removal occurs through treatment processes associated with removal of organic material and/or suspended solids. Table 7 shows that these plant types achieved on average 56 to 76% N removal.

It is recommended for future benchmarking studies that an additional benchmark of specific energy use based on nitrogen removal (kWh/kgNrem) be included. Further inclusion of the alternative benchmarks based on COD or BOD removal (kWh/kgCODrem or kWh/kgBODrem) could be optional but are unlikely to add significant value to understanding or improving energy efficiency for WWTPs, compared with the existing primary benchmark (kWh/[EP.y]).

Table 8. Proposed (interim) Guide and Target values for alternative benchmarks based on pollutant removal specific energy use

Data	2015-16 data	2015-16 data	2015-16 data	Proposed	
Type	Average	Average	Average	Guide Value	Target Value
Units:	kWh/kg COD removed	kWh/kg BOD removed	kWh/kg N removed		
Type 1	(1.1)	(2.2)	11.9	10.0	5.0
Type 2	(1.4)	(3.0)	14.8	14.0	6.7
Type 3	3.6	6.2	26.3	18.0	10.0
Type 4	(6.3)	(3.9)	14.4	10.0	4.0
Type 5	(1.8)	(3.2)	15.6	8.0	3.0
ALL	2.8	4.8	21.0	-	-

Values in parentheses are tentative (based on limited data)

Table 9. Summary of benchmarking for WWTP influent/ effluent pumping from available data

Category	No. of plants2	Average pumping efficiency kWh/[ML.m] (range)	Average pumping efficiency (%) (range)	Average pumping contribution to plant specific energy use kWh/[EP.y]	Average pumping contribution to total plant specific energy use (%)
High Influent Pumping Head[1]	6	6.0 (4.6 to 9.3)	45% (59% to 29%)	11.2 (7.6 to 18.5)	15% (12% to 24%)
High Effluent Pumping Head[1]	8	18.0 (#2.7 to 20.7)	15% (#102% to 13%)	33.8 (11.1 to 47.4)	36% (13% to 54%)
Both High Influent and High Effluent Pumping Head1	3	6.1 (#2.7 to 9.3)	45% (#102% to 29%)	26.4 (14.6 to 35.3)	25% (22% to 26%)

#: Data outside theoretical range for 100% efficient pump (not possible).
[1]'High' Pumping nominally >4 m head.
[2]Number of plants with sufficient data reported to benchmark pumping efficiency

Proposed interim benchmark Guide and Target Values for alternative benchmarks

Based on available data from this review, Table 8 gives proposed interim benchmark Guide and Target Values for the alternative benchmarks based on removal of pollutants. Given the limitations of the underlying datasets, as far as possible, the Guide and Target Values have been based around the 50th and 10th percentiles calculated from available data.

The interim values in Table 8 may be revised in future benchmarking rounds, subject to matching datasets for the relevant influent and effluent quality parameters being available for a larger number of WWTPs. A further breakdown of guide and target values by size class within plant type may also be possible in future, subject to data availability and industry acceptance of the alternative benchmarks.

Pumping energy requirements

This study included data collection for plants that were nominated by water utilities as having high pumping requirements (defined as >4 metres head) for influent and/or effluent. In addition to flow, more detailed data (i.e. time-series data, or at least single average estimates) of system pumping head(s) were requested for the relevant pump(s), where available. The benchmarking methodology for pumping requires data (measured or estimated) for pumped flow and head (pressure) to be reported in order that the benchmark Target and Guide Values for a site receive the relevant energy supplements (refer to ***Methodology*** and ***Supplementary Information***).

Of the total number of plants reviewed (245 no. of all Types), the pumping data received can be summarised as follows:

- 57 plants (23%) reported high influent pumping requirements. Of these plants, sufficient data were provided to apply the relevant benchmark energy supplement (S3.1) at only six sites;
- 77 plants (31%) reported high effluent pumping requirements. Of these plants, sufficient data were provided to apply the relevant benchmark energy supplement (S3.2) at only eight sites; and
- 20 plants (8%) reported both high influent and high effluent pumping requirements. Of these plants, sufficient data were provided to apply both benchmark energy supplements (S3.1 and S3.2) at only three sites.

Despite the relatively small subsets of plants (see above) that reported sufficient data to benchmark pumping energy efficiency, the contribution from influent and/or effluent pumping to total plant average specific energy use was significant (i.e. 12 to 54% of total plant energy) – refer to Table 9.

The study findings suggest that the minority of plants have high influent and/or effluent pumping requirements directly linked to total plant energy records.

Furthermore, very few utilities have pump pressure data (measured or estimated) available for their WWTPs. The above results contrast with the results from the previous benchmarking round (WSAA, 2013-14) in which the majority of plants (117 out of 142 no. total or 82%) reported high pumping features (>4 m head). However, in the previous benchmarking round, no distinction was made between influent, effluent and internal plant high pumping requirements. In this round, influent and effluent pumping was separately identified for benchmarking purposes, using the energy supplements (see above). For this round, plant internal pumping was included in optional sub-metering data requested, but regarded as part of the treatment process for energy benchmarking purposes. Therefore, plant internal pumping was assumed to be incorporated in the base benchmark Target and Guide values nominated (Figure 1).

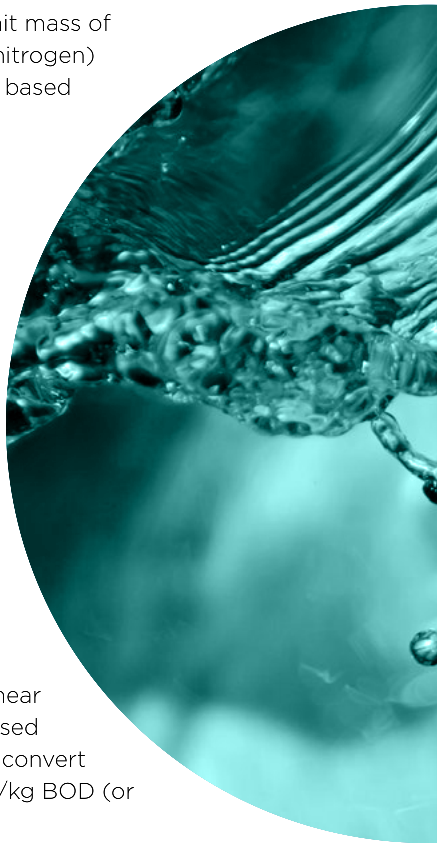
Taken as whole, the pumping data from this round suggests that utilities will need to focus more on collecting the relevant data records for plants that have high influent and/or effluent pumping requirements in order to improve the value of energy benchmarking and to enable more meaningful comparisons between plants.

DISCUSSION

The number of water utilities and WWTPs that participated in the latest (2015-16) WSAA energy benchmarking round was nearly double that of the previous round (2013-14). This reflects the growing emphasis placed on better understanding and improving energy efficiency in wastewater systems. The latest round had the largest increase in numbers for plants of the extended aeration activated sludge type (Type 3, various sub-types) and aerated lagoon plant type (Sub-type 5.1). These types of plant tend to be in the small to medium size classes (i.e. <100,000 EP and typically <1000 to 10,000 EP) and also less energy efficient, due to both diminished economies of scale and a greater reliance on aeration for treatment. Therefore, it is not surprising that the average results across all plants for this round showed an increase in specific energy use, relative to the previous round and the benchmarks applied. It reflects the challenge faced by many water utilities to improve energy efficiency, given the existing decentralised wastewater collection and treatment systems serving many suburban and regional metropolitan areas across Australia.

Based on specific energy use amongst the WWTPs across all types in the largest size class (SC5, >100,000 EP), this study showed results that were on average 12% lower in this benchmarking round (40 plants) than the previous round (35 plants). Similarly, Type 1 and Type 2 plants, which include primary treatment and anaerobic digestion and hence are less reliant on aeration for treatment, showed an improvement in energy efficiency on average. Irrespective of energy self-supply, the specific energy use, was 10% lower in this round for Type 1 (22 plants vs. 18 in the previous round), and 2% lower for Type 2 (24 plants vs. 16 in the previous round). These types of plant tend to be more feasible at the larger scale. This is reflected, for example, in this study where all the Type 1 plants (with anaerobic on-site cogeneration from biogas) were in the two largest size classes (SC4 and SC5) and the majority were in the largest class (i.e. >100,000 EP). It confirms that some of the best opportunities for improving energy efficiency lie in centralised WWTPs with plant configurations that include primary treatment and anaerobic processes. Typically, the trade-offs around energy efficiency are capital investment for centralised wastewater collection and treatment processes (e.g. aeration system, anaerobic digesters and their ancillary equipment), as well as effluent quality (e.g. nitrogen removal requirements).

This study investigated alternative benchmark metrics that express energy use per unit mass of pollutant (organic material or nitrogen) removed. It found that metrics based on removal of organics (kWh/kg removed as COD or BOD) offered little or no advantage over the primary benchmark adopted here of kWh/(EP.y), where EP is derived from raw wastewater loading. A metric such as kWh/kg BOD removed would have meaning to some practitioners. However, BOD (or COD) removal is nearly always virtually complete (>80% and typically around 90%) for most WWTPs, which results in the linear correlation with influent load population equivalents being relatively strong (R^2 >0.9). A linear relationship can therefore be used with reasonable confidence to convert between kWh/(EP.y) and kWh/kg BOD (or COD) removal.



Retaining the primary benchmark of kWh/(EP.y) in Australia/ New Zealand has the advantage of aligning with similar studies in some European countries that extend back over one to two decades.

However, N removal is more variable (ranging approximately 20 to 98% in this study, but typically >50%). It is dependent on WWTP type, configuration, loading and effluent TN target. When comparing plants with different N removal requirements, applying alternative metrics for specific energy use that include kWh/kgN removed might be more useful. Nevertheless, it is worth noting that most WWTPs in Australia are required to nitrify (oxidise ammonia), and hence at least partial denitrification is typically applied in activated sludge plants in order to recover oxidised N (oxygen equivalents) and hence reduce aeration costs. Therefore, it is not surprising that the results of this study showed a reasonable linear correlation (R^2 = 0.75) between the primary benchmark of kWh/(EP.y) and kWh/kgN removed.

Aeration is typically considered to be the single largest energy user on most WWTPs, which was confirmed in this study (sub-metering data is not discussed on this paper – refer to WSAA, 2017). Pumping energy is also a significant contributor to total plant energy use, as the limited data from this study for influent and/or effluent pumping has confirmed. More attention to collecting the necessary data (including pressure or head) to include pump efficiency in overall plant energy benchmarks is recommended. Alternatively, benchmarking influent or effluent pump energy efficiency could be segregated from that of the treatment process itself for a WWTP. This requires separate sub-metering of pump energy use, as well as flow and pressure (or head) data.

CONCLUSIONS

More than one hundred additional WWTPs were included in the latest (2015-16) energy efficiency benchmarking study, compared with the previous study (in 2013-14), bringing the latest round total number to 245. Around half the plants by number (121) that participated in the latest round, also participated in the previous round (all within Australia). Within that sub-set, slightly more than half showed some improvement in energy efficiency, and slightly over one-third showed an improvement of more than 10%. These are significant improvements and reflect the efforts of water utilities in Australia to improve energy efficiency. It also demonstrates the value of benchmarking as a monitoring tool for continuous improvement. At the other end of the range, more than 120 WWTPs were considered to be 'below average' in performance and not energy efficient. For these plants, there remains significant opportunity to improve energy efficiency and/or lower energy use.

A number of areas for future improvement can be identified from this study. These include data collection; data handling and sharing for benchmarking purposes, particularly in the context of 'big data'; data validation and security around shared information; and future legacy. For example, there is a need for continued cooperative efforts to agree on additional and/or future benchmarks, both in terms of metrics and Target and Guide Values, within the Australian/New Zealand wastewater treatment context. This study also highlighted the need particularly to better systematise the distinction between wastewater pumping vs. treatment, which presents challenges to the way in which energy and related parameters (e.g. flow, concentration, pressure) are measured or sub-metered, and reported for benchmarking purposes.

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SUPPLEMENTARY INFORMATION

Plant types and size classes

For this study, six plant-types were categorised according to treatment processes, together with some sub-types defined. Five plant-class sizes were set according to various ranges of equivalent person (EP). These definitions were based on similar definitions applied in German WWTP energy benchmarking manuals (inter alia DWA, 2012; Baumann et al., 2014). For specific energy-intensive processes, an "energy supplement" was provided. This represents the expected additional energy use from these processes. The details of these categories are provided in Table 1, Table 2 and Table 3 below.

Table 1. Definition of Plant Types

Type	Features	Notes
Type 1 **(PST + Act. Sludge + An. Dig. + Cogen.)**	Activated sludge treatment[1] with separate sludge stabilisation, including those with primary sedimentation, anaerobic digestion (or alternative) and on-site co-generation (on-site energy produced from biogas).	Alternative sludge stabilisation includes: • Incineration • Covered anaerobic lagoons • Chemical (e.g. Lime) treatment • etc.
Type 2 **(PST + Act. Sludge + An. Dig.)**	Activated sludge treatment with separate sludge stabilisation, including those with primary sedimentation, anaerobic digestion (or alternative[2]) but without on-site co-generation (no on-site energy produced from biogas).	Same as Type 1 but without co-generation. Biogas might be produced but is not used for energy generation. Biogas might or might not be captured and flared. Alternative sludge stabilisation includes: • Incineration • Covered or uncovered anaerobic lagoons • Chemical (e.g. Lime) treatment • etc.
Type 3 **(Extended Aeration Act. Sludge)**	Extended aeration activated sludge, including aerobic digestion	Sub-types recognised:
		Sub-type 3.1: Compartmentalised (all types, including those for biological nutrient removal configurations) and with clarifiers, but excluding Subtypes 3.2 to 3.5 defined below
		Sub-type 3.2: Oxidation ditch-type activated sludge (including ditches with external compartments such as anaerobic or selector reactors) and with clarifiers
		Sub-type 3.3: Intermittent activated sludge processes (e.g. SBR/IDEA/IDAL)
		Sub-type 3.4: Membrane bioreactors (MBR)
		Sub-type 3.5: Moving bed biofilm bioreactors (MBBR), where main aeration zone is MBBR (e.g. excludes tertiary MBBR)
Type 4 **(Trickling Filters)**	Trickling filters	Sub-types recognised:
		Sub-type 4.1: Trickling filters only
		Sub-type 4.2: Trickling filters in combination with activated sludge
Type 5 **(Lagoons)**	Lagoon and/or wetland systems	Sub-types recognised:
		Sub-type 5.1: Aerated lagoons
		Sub-type 5.2: Lagoon and/or wetland systems without aeration
Type 6 (RBC)	Rotating biological contactors	None reported in this study

1. In a limited number of cases, primary sedimentation and anaerobic digestion with on-site co-generation from biogas was present but activated sludge treatment lacking (i.e. no secondary treatment, notably plants with ocean outfalls). By default, these plants were classified as Type 1 (subject to review in the future benchmarking rounds).

2. Alternative sludge stabilisation excludes Aerobic Digestion (refer to Type 3)

Table 2. Definition of Energy Supplements		
Supplements		**Notes**
S1	Tertiary effluent treatment	Sub-types are recognised:
		S1.1: Filtration using Sand or Granular Media (including flocculation-filtration types)
		S1.2: Membrane filtration, including Ultrafiltration but excluding Reverse Osmosis
		S1.3: Membrane bioreactor (MBR)
		S1.4: Ultraviolet (UV) light, including UV disinfection systems
		S1.5: Ozone treatment systems
		S1.6: Cloth filtration, including cloth media disc systems
S2	Sludge drying	Thermal or solar drying systems, excluding conventional open-air drying beds, pans or lagoons
S3	High pumping requirements (>4 m head)	Sub-types are recognised:
		S3.1: High influent pumping
		S3.2: High effluent pumping

Table 3. Definition of Size Classes

Size Class (SC)	EP Range
SC1	≤ 1,000 EP
SC2	1001 – 5,000 EP
SC3	5001 - 10,000 EP
SC4	10,001 - 100,000 EP
SC5	>100,000 EP

Note: Connected Equivalent Persons (EP) has the same meaning as Person Equivalents (PE) often used in European literature

ENERGY BENCHMARKS

Energy benchmark values adopted for this study were defined as follows:

- **Guide Values:** The Guide Values are intended to reflect average (or typical) performance and were translated from the German references mentioned above, where necessary by extrapolation or scaling. It is anticipated that in future benchmarking projects (as possible extensions of this project), the Guide Values may be amended to reflect the results for Australian plants.
- **Target Values:** The Target Values are intended to reflect 'top' performance or current best practice (top 10%), and are derived from the German references mentioned above, where necessary by extrapolation or scaling.

This study applied two forms of energy benchmark:

1. The **primary benchmark** is specific energy use, expressed as kWh/(EP.year), based on whole-of-plant electrical energy use (average kWh/year) and EP is 'Equivalent Persons' calculated from raw influent wastewater load.
2. The **secondary benchmark** is extent of electrical energy self-supply, expressed as percent of average electrical energy use supplied from on-site generation from renewable energy sources (i.e. co-generation from biogas; wind, solar; or other renewable types). This benchmark is only applied to Type 1 plants, although other plant types might report energy self-supply (e.g. from solar or wind power).

The Guide and Target values adopted for the primary and secondary benchmarks respectively in each Plant Type and Size Class category are summarised in Table 4, Table 5 and Table 6 below. Note that Energy Supplement values (Table 6) are added to the base values for the primary benchmark (Table 4), calculated on a plant-by-plant basis, depending on whether the relevant processes (effluent treatment, sludge drying or high pumping requirement) are present or not.

Table 4. Adopted benchmarks for total WWTP electrical energy use (base values, excluding supplements) in kWh/(EP.year)

Type Note 1	Size Class	SC1		SC2		SC3		SC4		SC5	
	EP range	≤ 1,000 EP		1,001 – 5,000 EP		5,001 - 10,000 EP		10,001 - 100,000 EP		>100,000 EP	
	Sub-type	Guide Value	Target Value	Guide Value	Target Value	Guide Value	Target Value	Guide Value	Target Value	Guide Value	Target Value
Type 1	-	60	29	45	26	37	23	32	20	30	20
Type 2	-	60	29	45	26	37	23	32	20	30	20
Type 3	All sub-types	70	35	45	26	37	22	32	20	30	20
Type 4	Sub-type 4.1	50	35	25	20*	25	20*	25	18	25	18
	Sub-type 4.2	67*	49*	39*	32*	35*	29*	32	26	26	18
Type 5	Sub-type 5.1	45	32	40	30	35	24	30	22	28*	20*
	Sub-type 5.2	19	3	19	2	17*	2	12*	2	8*	2
Type 6	-	35	25	25	18	20*	15	-	-	-	-

* Asterisks denote extrapolation, scaling or inference from German benchmarks
Note 1: For Plant Types, refer to Table 1 for definitions
Note 2: Energy Supplements (refer to Table 6) are added to base Guide or Target Values tabled above for a given Size Class and Plant Type

Table 5. Adopted benchmarks for Electrical Energy Self-Supply (Ess), as percentage of total WWTP Electrical Energy use

Size Class	SC1	SC2	SC3		SC4		SC5	
EP range	≤ 1,000 EP	1,001 – 5,000 EP	5,001 - 10,000 EP		10,001 - 100,000 EP		>100,000 EP	
Type	% Ess		Guide Value	Target Value	Guide Value	Target Value	Guide Value	Target Value
Type 1 only	Not specified (for both SC1 and SC2)		37%	75%	60%	100%	60%	100%

Table 6. Adopted Electrical Energy Supplements. Refer to units stated within the table.

Supplement	Size Class	SC1		SC2		SC3		SC4		SC5	
	EP range	≤ 1,000 EP		1,001 – 5,000 EP		5,001 - 10,000 EP		10,001 - 100,000 EP		>100,000 EP	
	Sub-type	Add to Guide Value	Add to Target Value	Add to Guide Value	Add to Target Value	Add to Guide Value	Add to Target Value	Add to Guide Value	Add to Target Value	Add to Guide Value	Add to Target Value
		kWh/(EP.y)									
S1	S1.1	8.0*	4.0*	6.0*	3.0*	4.6	2.0	4.3	2.0	4.1	2.0
	S1.2	32*	21*	23*	15*	19.5*	13*	13.7	9.1	13.7	9.1
	S1.3	88*	83*	64*	60*	54	51	50	44	43	35
	S1.4	11*	5.4*	7.7*	3.8*	6.5*	3.3*	4.6*	2.3	4.6*	2.3
	S1.5	55*	36*	40*	26*	34*	22*	24	15	23	15
	S1.6	6.8*	3.7*	4.9*	2.7*	4.2*	2.3*	2.9	1.6	2.9	1.6
S2	-	5.9*	4.7*	4.2*	3.4*	3.6*	2.9*	2.5	2	2.5	2
Supplement	**kWh/(ML.m) – Note 2**										
S3	S3.1	5.45	3.89	5.45	3.89	5.45	3.89	5.45	3.89	5.45	3.89
	S3.2	4.55	3.64	4.55	3.64	4.55	3.64	4.55	3.64	4.55	3.64

* Asterisks denote extrapolation or inference from German benchmarks

Note 1: Supplement Types – refer to Table 2 for definitions

Note 2: Application of S3 Supplements(s) for high pumping require data for pump pressure (head, m) and unit flow (per EP, e.g. ML/(EP.y)) for conversion to kWh/(EP.y)

RESULTS

Number of plants

Figure 1 gives a summary breakdown of the number of plants by Type for this this benchmarking round (2015-16) and the previous round (2013-14). Similarly, Figure 2 gives a breakdown by Size Class (all Types).

Change in performance (this round vs. previous round)

Table 7 summarises the change in performance on primary benchmark for plants that participated in both this benchmarking round and the previous round, broken down by Type and Size Class.

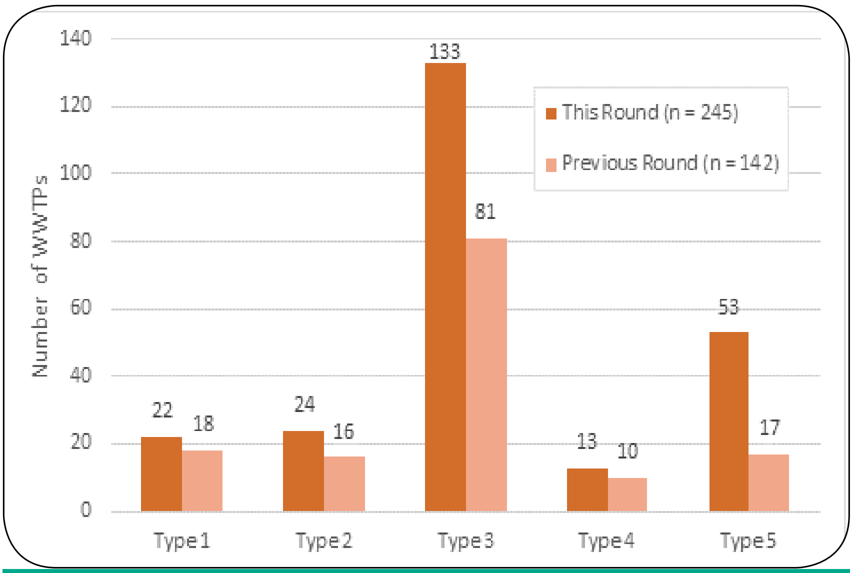

Figure 1. Summary WWTPs number surveyed, according to Type (Table 1) in this (2015-16) and previous (2013-14) benchmarking rounds. Plant count (n) labels displayed.

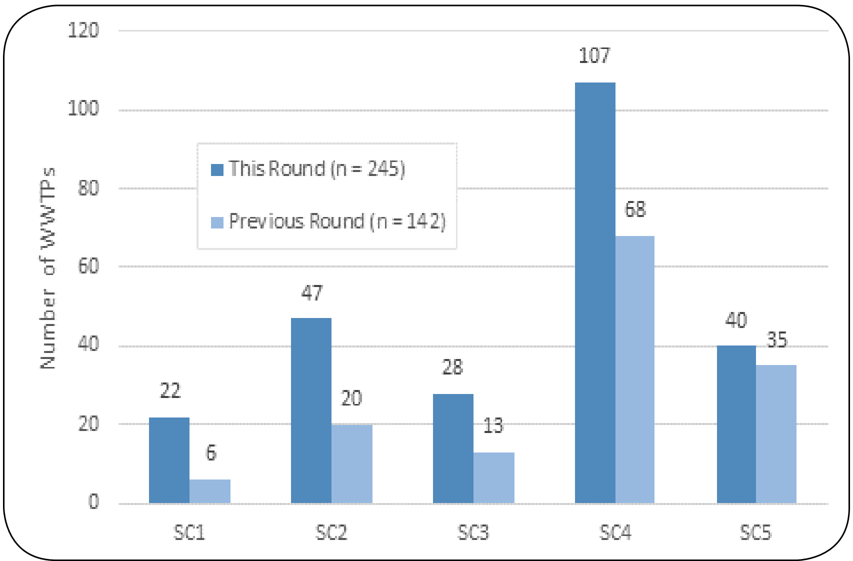

Figure 2. Summary WWTPs number surveyed, according to Size Class (Table 3) in this (2015-16) and previous (2013-14) benchmarking rounds. Plant count (n) labels displayed

Table 7. Summary of change in WWTP electrical specific energy use by Type and Size Class for plants tha participated in both this benchmarking round (2015-16) and the previous round (2013-14).

Type/ Size Class	WWTP Count	Average Flow (ML/d)		Average kWh/EP/year			Average Overall Percent Change. Note 1
		This round	Previous round	This round	Previous round	Previous-This round	(Previous-This)/ (Previous round)
Type 1	**17**	**141.8**	**147.2**	**39.5**	**45.1**	**5.6**	**12%**
SC4	3	11.6	11.0	38	29	-9	-32%
SC5	14	169.7	176.3	40	49	9	18%
Type 2	**13**	**36.6**	**36.5**	**67**	**65**	**-2**	**-3%**
SC3	1	1.2	1.3	99	71	-28	-40%
SC4	6	10.2	10.7	79.7	80.0	0.4	0.5%
SC5	6	69.0	68.1	48.8	48.7	-0.2	-0.3%
Type 3	**77**	**9.8**	**9.7**	**75**	**69**	**-6**	**-9%**
SC1	2	0.1	0.1	192	164	-28	-17%
SC2	8	0.8	0.8	106	99	-7	-7%
SC3	5	1.5	1.6	93	74	-19	-25%
SC4	51	7.3	7.5	70	63	-7	-11%
SC5	11	33.5	31.7	48	54	6	11%
Type 4	**5**	**4.4**	**4.4**	**-#**	**-#**	**-#**	**-#**
SC1	1	1.1	2.4	335#	59	-276	(-467%)#
SC4	4	5.3	4.9	46	45	-1	-2%
Type 5	**9**	**3.8**	**3.4**	**50.2**	**49.7**	**-0.5**	**-1%**
SC2	2	0.5	0.5	77	97	20	21%
SC3	2	1.5	1.7	59.5	55.5	-4	-7%
SC4	4	2.8	2.6	38.7	27.4	-11.3	-41%
SC5	1	18.9	15.7	25	33	8	25%
All	**121**	**30.6**	**31.2**	**69**	**63**	**-6**	**-9%**

Spurious result. Average for Type 4 excluded.

Note 1: Positive values imply better energy efficiency in this round (vs. previous). Negative values imply worse energy efficiency in this round (vs. previous).

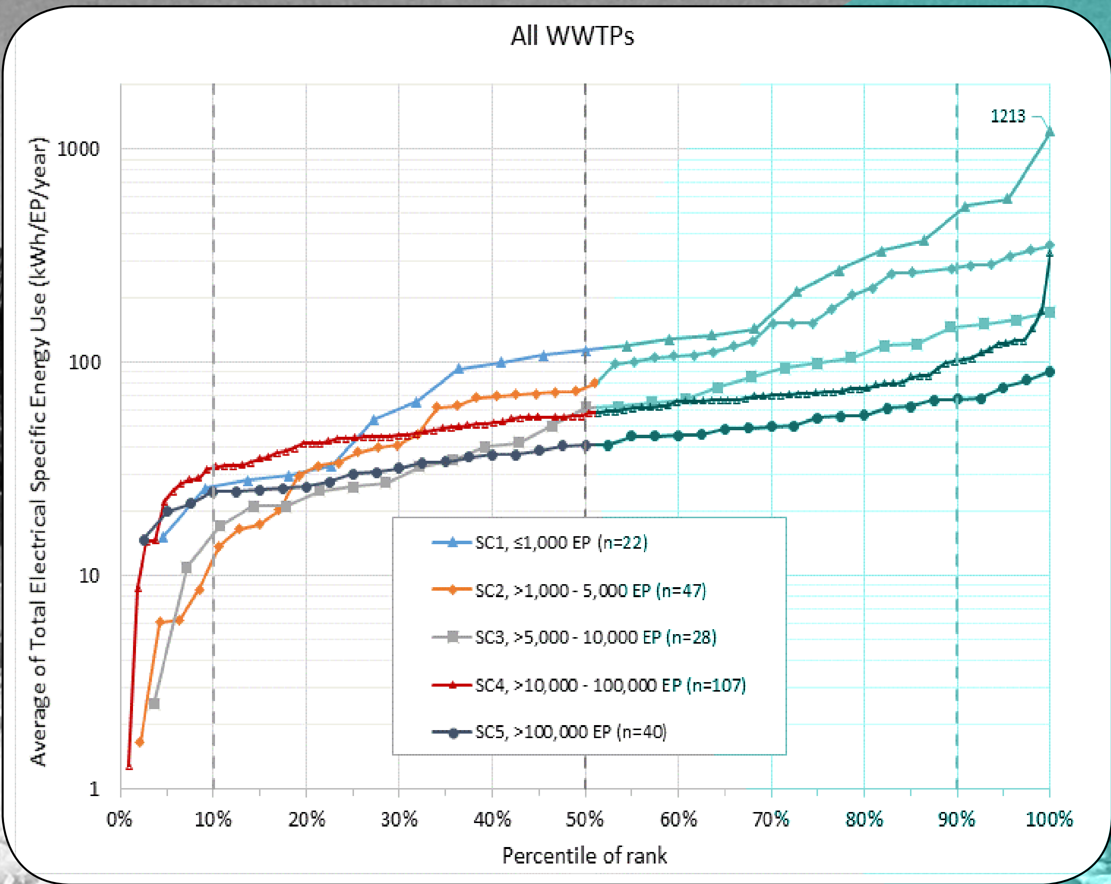

Figure 3. Probability distribution according to WWTP Size Class for all WWTPs in this benchmarking round (2015-16). Total WWTP count (n) = 244; includes all plant Types. (Note: Insufficient data for one plant to assess size class).

Primary benchmark – Probability distribution by Size Class

Figure 3 shows the probability plot of all plants (all Types) in this benchmarking round, broken up according to Size Class.

Figure 4 shows the probability plot of plants (all Types) in this benchmarking round that reported high pumping features (nominally >4m head) for influent and/or effluent, broken up according to Size Class.

Figure 5 shows the probability plot of plants (all Types) in this benchmarking round that did not report high pumping features for influent and/or effluent, broken up according to Size Class

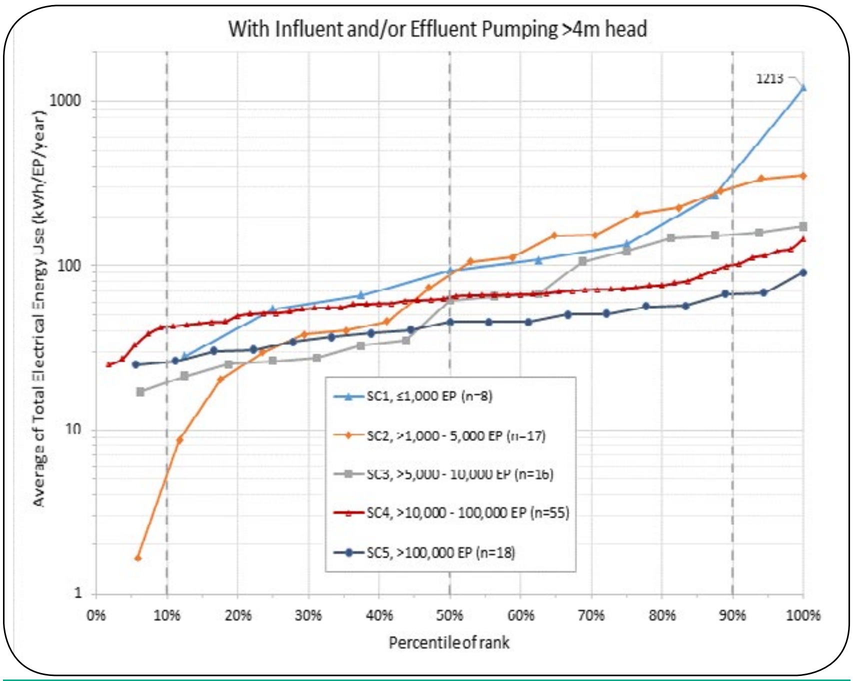

Figure 4. Probability distribution according to WWTP Size Class for plants with Influent and/or Effluent High Pumping (>4m head). Total plant count (n) = 114; includes all plant Types.

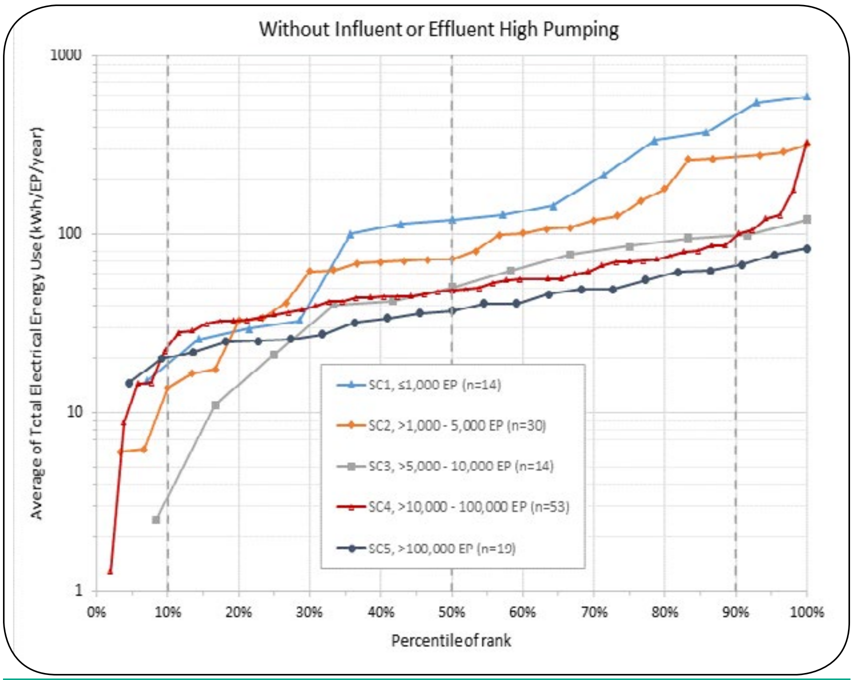

Figure 5. Probability distribution according to WWTP Size Class for plants without Influent or Effluent High Pumping features. Total plant count (n) = 130; includes all plant Types.

Primary benchmark – Probability distribution by Type and Size Class

The following figures shows probability plots for results from this benchmarking round according to Type, including a breakdown according to Size Class:

- Figure 6 for Type 1 plants
- Figure 7 for Type 2 plants
- Figure 8 for Type 3 plants, excluding MBRs (Sub-type 3.4)
- Figure 9 for Type 3 plants, Sub-type 3.4 (MBRs) only
- Figure 10 for Type 4 plants
- Figure 11 for Type 5, Sub-type 5.1 plants (Aerated Lagoons)
- Figure 12 for Type 5, Sub-type 5.2 plants (Unaerated Lagoons/ Wetlands).

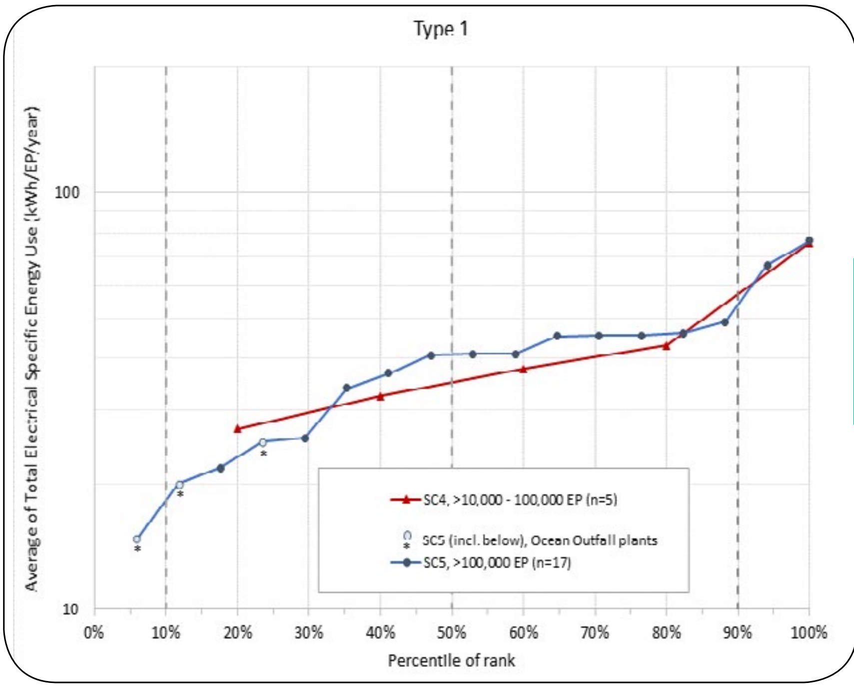

Figure 6. Probability plot of all Type 1 plants in 2015-16 benchmarking round, showing breakdown by Size Class

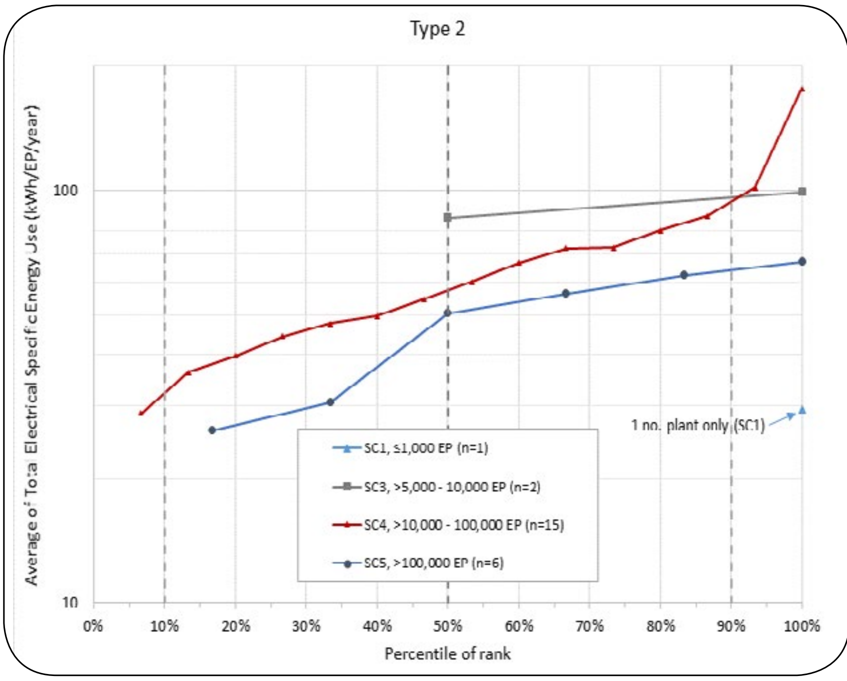

Figure 7. Probability plot of all Type 2 plants in 2015-16 benchmarking round, showing breakdown by Size Class

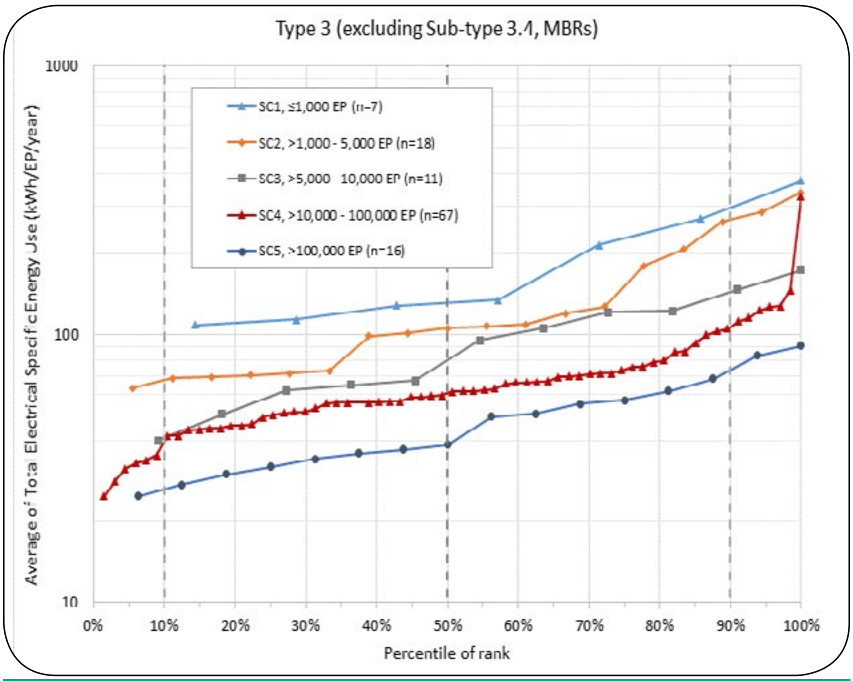

Figure 8. Probability plot of all Type 3 plants (excluding MBRs) in 2015-16 benchmarking round, showing breakdown by Size Class

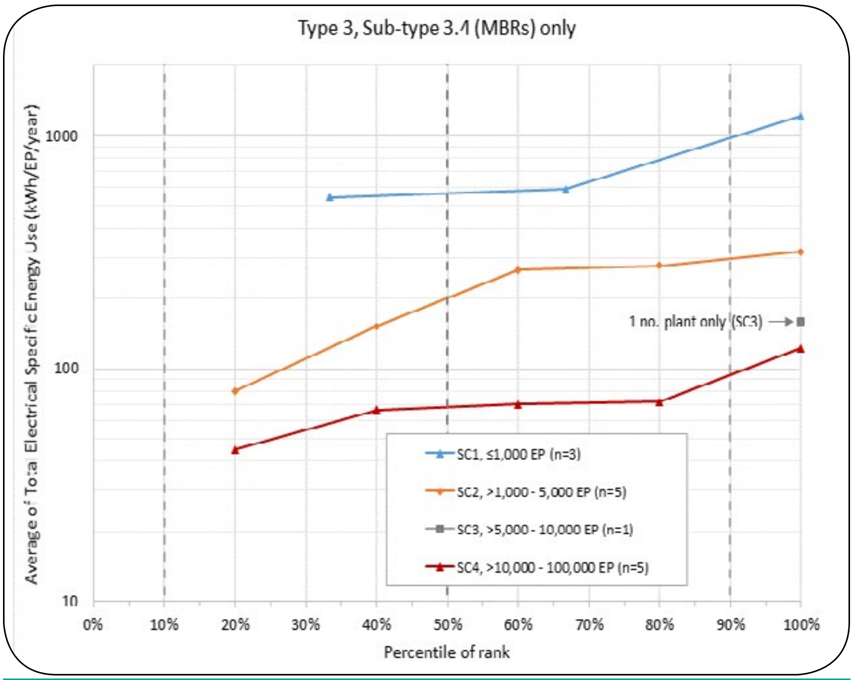

Figure 9. Probability plot of all Type 3 (Sub-type 3.4) MBR plants only in 2015-16 benchmarking round, showing breakdown by Size Class

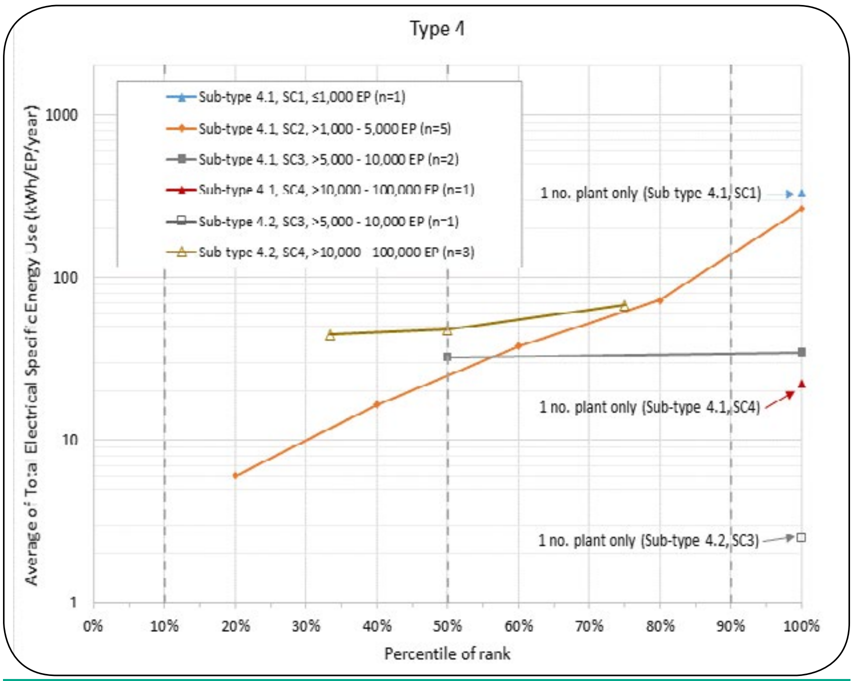

Figure 10. Probability plot of all Type 4 plants in 2015-16 benchmarking round, showing breakdown by Size Class

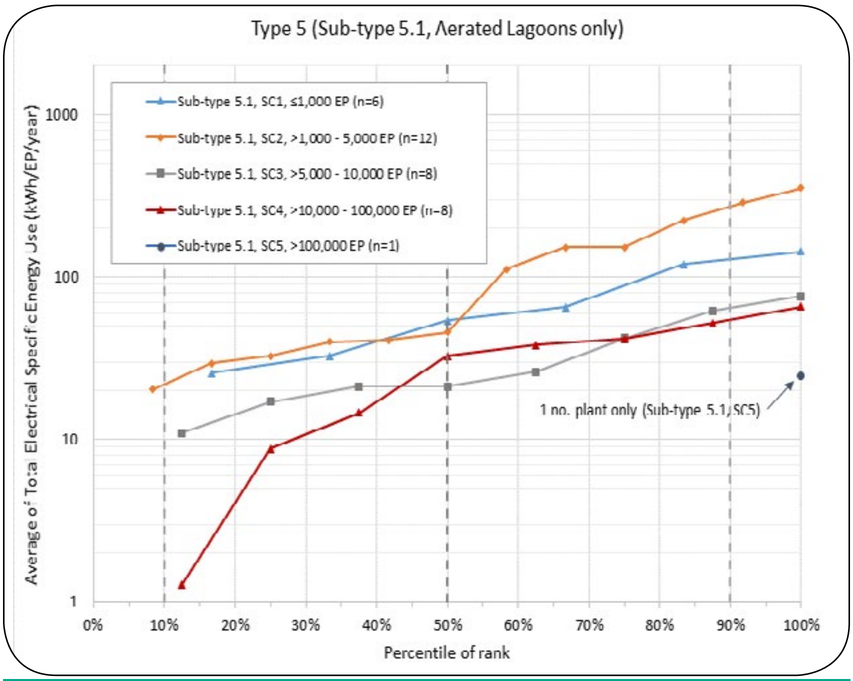

Figure 11. Probability plot of Type 5 (Sub-type 5.1) Aerated Lagoon plants in 2015-16 benchmarking round, showing breakdown by Size Class

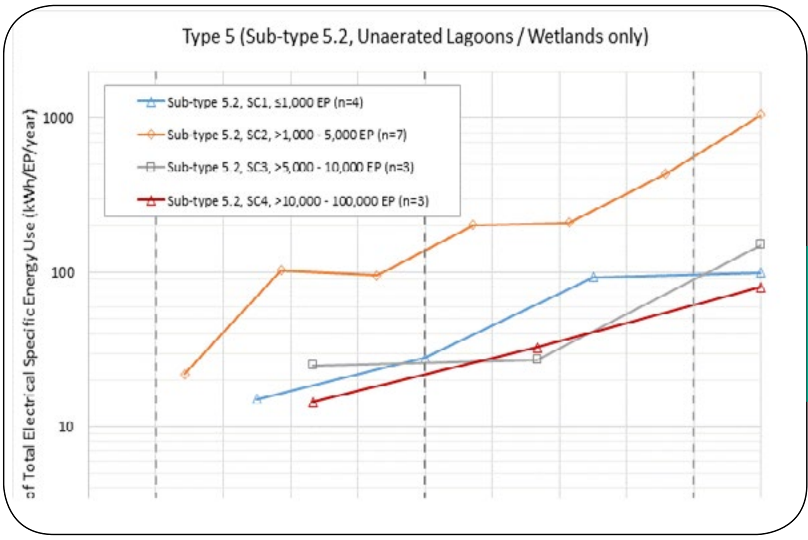

Figure 12. Probability plot of Type 5 (Sub-type 5.2) Unaerated Lagoon/ Wetland plants in 2015-16 benchmarking round, showing breakdown by Size Class

ALTERNATIVE BENCHMARKS

Removal of pollutants

The average percent removals across the plant Types (with breakdown by Size Class) are plotted for BOD and/or COD in Figure 13 and for BOD and/or Total Nitrogen removal in Figure 14.

Relationship to Primary benchmark

Figure 15 shows plots of the relationship between the Primary benchmark used in this study (kWh/[EP.y]) and specific energy use per unit removal of COD, BOD and Total N respectively.

Probability distribution by Type and Size Class for specific energy use per unit nitrogen removed

Figure 16 to Figure 21 show probability plots of kWh/kgN removed, according to Plant Type and Size Class. Breakdown by Sub-types is not given, except for Type 3, Sub-type 3.4 (MBRs), for which the number of plants and energy use profile was sufficient to merit separate representation.

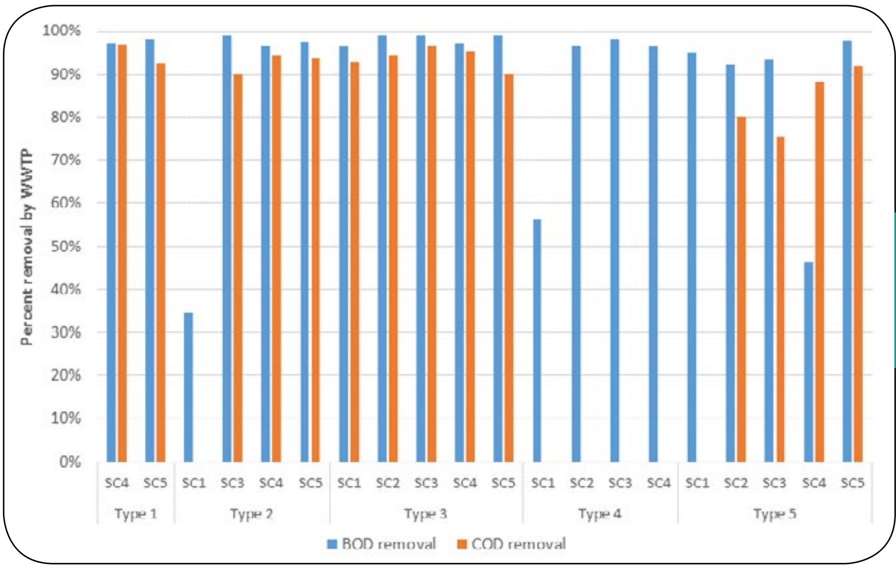

Figure 12. Probability plot of Type 5 (Sub-type 5.2) Unaerated Lagoon/ Wetland plants in 2015-16 benchmarking round, showing breakdown by Size Class

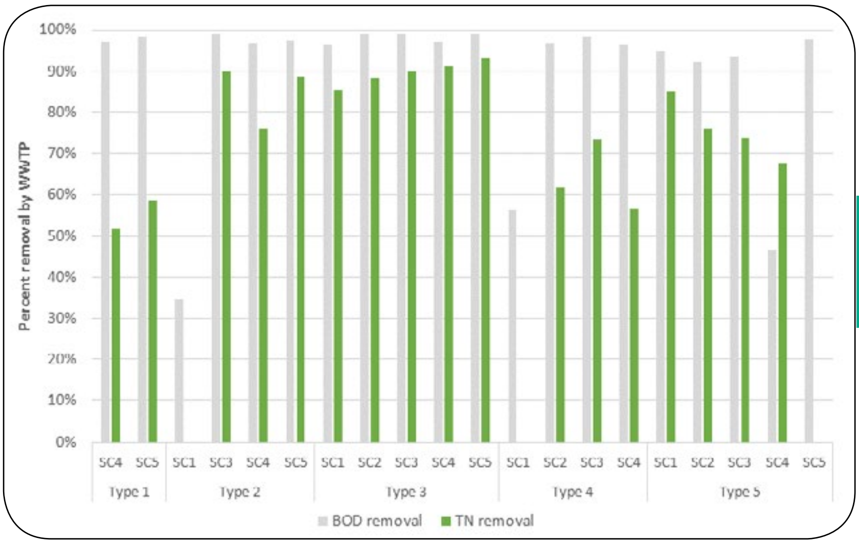

Figure 14. BOD and Total N (TN) removals across plant Types and Size Classes (2015-16 benchmarking round)

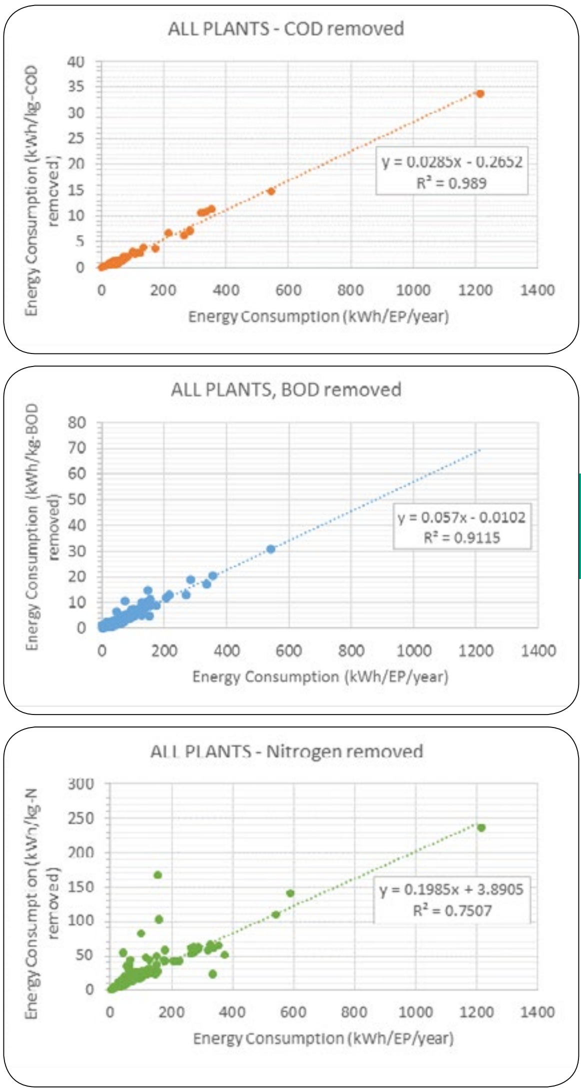

Figure 15. Linear regression plots of Alternative benchmarks vs. Primary benchmark (2015-16 round)

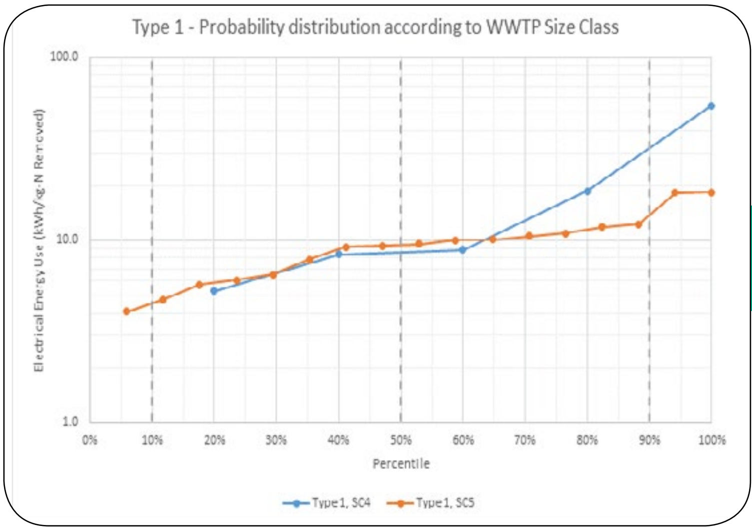

Figure 16. Probability plot of alternative benchmark kWh/kg N removed for Type 1 plants.

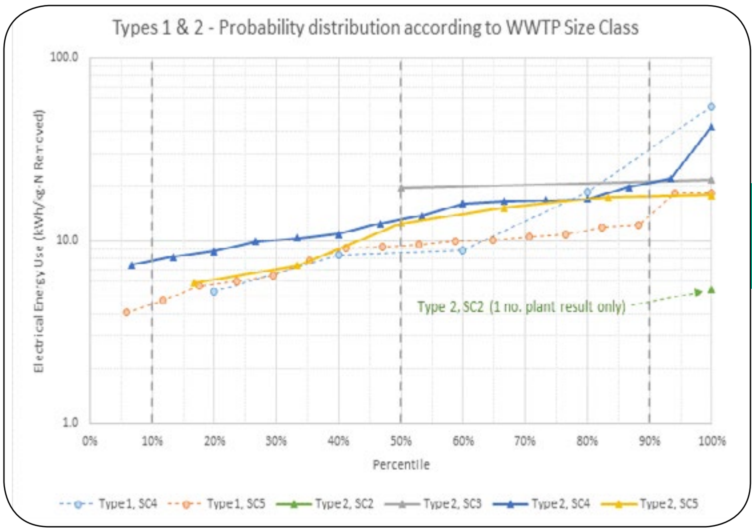

Figure 17. Probability plot of alternative benchmark kWh/kg N removed for Type 1 and Type 2 plants.

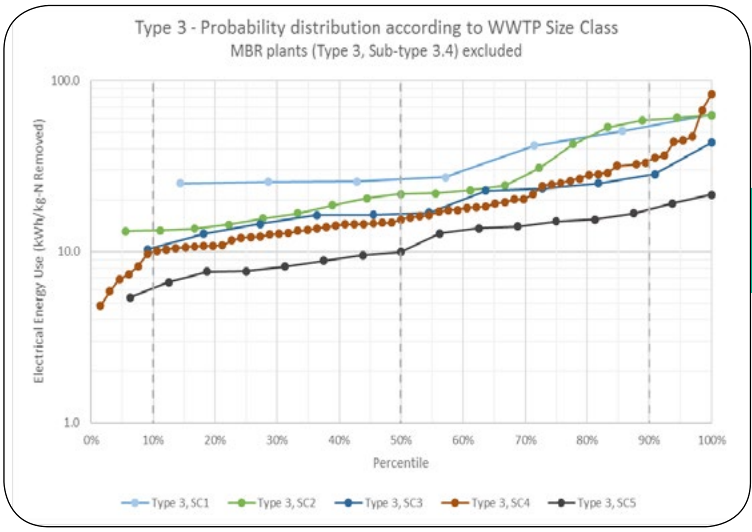

Figure 18. Probability plot of alternative benchmark kWh/kg N removed for Type 3 plants, excluding MBRs.

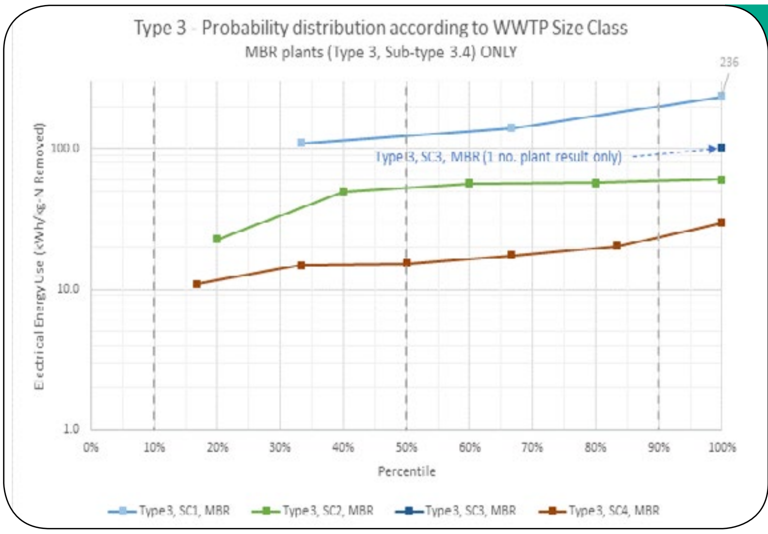

Figure 19. Probability plot of alternative benchmark kWh/kg N removed for Type 3 plants, MBRs only.

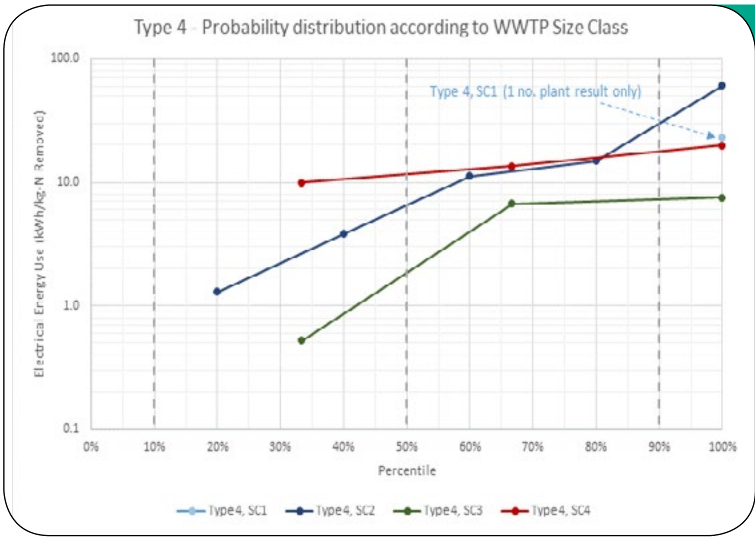

Figure 20. Probability plot of alternative benchmark kWh/kg N removed for Type 4 plants.

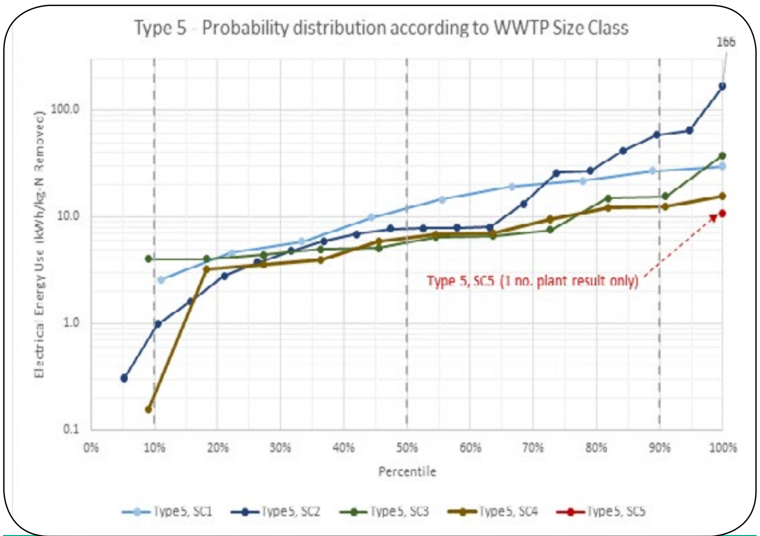

Figure 21. Probability plot of alternative benchmark kWh/kg N removed for Type 5 plants.

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