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Comparative analysis of energy intensity and carbon emissions in wastewater treatment in USA, Germany, China and South Africa

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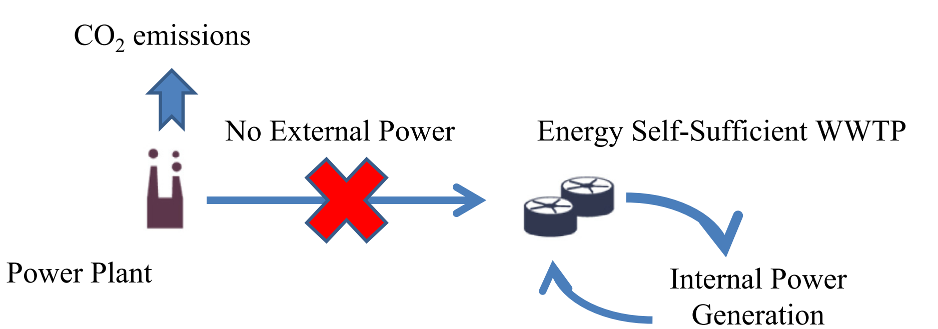
HIGHLIGHTS

- Energy self-sufficiency is feasible for wastewater treatment.
- There is a large gap between current practice and energy self-sufficiency.
- Emission factors, treatment objective, technologies and capacity make differences.
- It provides a global perspective on the state of WWTPs.
- It serves to improve the understanding, designing and operating of WWTPs.

GRAPHICAL ABSTRACT



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ABSTRACT

Currently almost all wastewater treatment plants (WWTPs) require a large amount of energy input to process the influent, mostly as electricity, and the associated carbon emissions are in aggregate significant. In order to achieve carbon neutrality, it is important to understand direct and indirect carbon emissions generated by WWTPs. Here, we focused on electricity use in WWTPs as it is a major source of carbon emissions. Specifically, we compared the electricity intensity and associated carbon emissions of WWTPs in four countries: the USA, Germany, China, and South Africa. We found that 100% energy self-sufficient WWTPs are feasible by a combination of increased energy efficiency and energy harvesting from the wastewater. Carbon emissions of WWTPs depend strongly on the electricity fuel mix, wastewater treatment technologies, treatment capacity, and influent and effluent water quality. A few WWTPs operating in developed countries (USA and Germany) have already achieved almost 100% (or higher) electricity self-sufficiency through energy efficiency and harvesting biogas and electricity. In comparison with Germany, WWTPs in the USA are more heterogeneous and the range of unit carbon emission intensity is much wider. In some areas where the organic content in wastewater is lower and less biogas is produced, it is still possible to achieve energy self-sufficiency by using thermal energy from wastewater. Industrial wastewater in China in general consumes more electricity and the carbon intensity of electricity is also higher, resulting in much higher unit carbon emissions as compared with other countries. In megacities such as Shanghai, larger capacity of centralized WWTPs can decrease the unit carbon emissions significantly. These findings provide a global perspective on the state of WWTPs and are helpful to improve the understanding, designing and operating of WWTPs from the perspective of achieving carbon neutrality.

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1. Introduction

Over the past few decades there has been an increase in the harvesting of energy from wastewater [1–5]. Rather than a waste to dispose of, wastewater is now being considered more as a resource for energy, nutrients and purified water [6–15]. Some WWTPs have even changed their whole perspective on "waste" to "input" from which energy, nutrients (N and P), and treated water can be produced with a substantial social value, shifting the operation from a cost to a profit center [4,16–25]. In addition, WWTP designers and operators can make substantial contributions to the reduction of greenhouse gases (GHGs) through energy capture and process modifications [26,27].

The reduction of GHG emissions [28] through, for example, increased energy use efficiency [29] is important in the effort to curb global climate change. Seeking carbon neutrality in WWTPs is a valuable contribution to this goal. Energy use has shown to be a major source of carbon emissions of WWTPs [30]. First, WWTPs account for a significant portion of municipal energy consumption [31]. Even in regions where energy is very expensive and there have been significant technological advances, WWTPs can be a major local energy consumer. For example, WWTPs are estimated to account for about 20% of the total energy consumption of municipalities in Germany [31]. Most of this energy input is in the form of electricity, to power pumps, valves, compressors and other equipment [30]. In addition, depending on the source of electricity, associated carbon emissions can be very substantial [32–34]. Thus, a simultaneous reduction of energy consumption and increase in energy harvesting from wastewater would be important elements on the road toward carbon neutrality.

There is great potential for the WWTPs to reduce the energy consumption and GHG emission by technology innovation [35]. Anaerobic digestion of sewage sludge is a key process to harvesting energy from wastewater [36,37]. A recent full-scale WWTP project demonstrated that WWTPs can achieve energy self-sufficiency by anaerobic digestion of sludge which generates biogas that is converted into electricity [38]. The utilization of biogas from anaerobic digestion of sludge in WWTPs in China is expected to contribute to about 24% of the total carbon reduction [39]. Case studies demonstrated that the energy demand of WWTPs can be reduced by 76% in Tunisia and 44% in Germany after completing the upgrade of WWTPs [31]. This was achieved by converting the process from aerobic to anaerobic sludge stabilization, which recovered energy from the sludge. The Strass WWTP in Austria can produce an energy surplus of 8% [40]. It is also important to recover the thermal energy in wastewater using heat exchangers and heat pumps, which can result in energy self-sufficient wastewater treatment and transform the WWTPs into net energy generators [41]. In addition, there is potential for microbial fuel cells (MFC) to directly convert the organic materials in the wastewater into electricity [14,42], although MFC still needs significant advances to it make competitive with other technologies like anaerobic biological conversion [6,43].

In spite of the above-mentioned progress, there are still important gaps in carbon emissions of wastewater treatment. Generally, there is a lack of understanding of the status quo of WWTPs at the international level in terms of their electricity consumption and carbon emissions. Particularly, it is unclear how electricity consumption and carbon emissions by WWTPs differ across countries.

In this study, we focus on electricity consumption and associated carbon emissions of WWTPs in several developing and developed countries. We seek to provide a global perspective of WWTPs with respect to differences in technology, energy use, and carbon intensity. The results will help us understand the gap between the objective of carbon neutrality and the reality in different regions of the world. The electricity intensity (electricity consumed in the treatment of wastewater, kW h/m^3) was calculated for WWTPs in different countries/states, different wastewater treatment technologies, different treatment capacity, and different water quality objectives. The corresponding carbon emissions for the WWTPs were then calculated based on the electricity intensity. We also highlight a WWTP as an example of efforts to achieve energy self-sufficiency via energy efficiency and generation. It shows that although electricity intensity is important in terms of emissions, low electricity intensity doesn't necessarily mean low carbon emissions. A better understanding of the energy consumption and GHG emissions of WWTPs should contribute to the technology innovation, energy use efficiency improvement, and mitigation of climate change.

2. Materials and methods

2.1. Wastewater treatment capacity and energy consumption

We calculated the electricity intensity and GHG emissions of WWTPs from two different perspectives. First, we conducted onsite investigations and surveys in fourteen WWTPs in China during July to August, 2014. We investigated the influent and effluent water quality, wastewater treated capacity and actual flowrate treated, treatment technologies, and electricity consumption of the WWTPs. Then we collected data about electricity consumption of typical WWTPs in the USA, Germany, and South Africa from literature. We used these data to calculate the electricity consumption intensity and GHG emissions of some typical WWTPs in the four countries.

To determine whether the estimates of average electricity consumption per m^3 of treated wastewater were reasonable, we also calculated it from a "top-down" perspective. We collected data on the total annual discharged wastewater volume of each of the four countries from the AQUASTAT database [44] developed by the Food and Agriculture Organization of the United Nations. This database focuses on annual volumes of water and wastewater at national levels [44]. Then we collected data about the annual national electricity consumption for WWTPs in each of these four countries from the International Energy Statistics (EIA) database [45]. Dividing the national electricity consumption by total discharged wastewater volume, we then calculated the energy intensity and GHG emissions.

2.2. Electricity intensity calculation

Unit electricity intensity was calculated by dividing the total electricity consumption (kW h) with treatment capacity (m^3). This intensity (kW h/m^3) was multiplied by emission factors (kg CO_2e/kW h) to calculate the GHG emissions (kg CO_2e/m^3) of these WWTPs. It should be noted that only emissions from electricity generation were counted in this study. In addition, in consideration of the different pollutants in the influent and effluent of the WWTPs, we also calculated the energy consumption per unit pollutant (such as kW h/kg COD and kW h/kg NH_3—N) by dividing the electricity consumption of WWTPs (kW h) by removed pollutants (kg COD or kg NH_3—N).

2.3. Estimation of carbon emission factors for electricity

We estimated the life-cycle GHG emissions [46] associated with electricity generation in different countries. Carbon emissions of WWTPs were then calculated based on multiplying electricity intensity with emission factors (kg CO_2e/kW h) for different

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Table 1
GHG emission factors for electricity compiled from different sources (kg CO_2e/kW h).

	Ref [1]	Ref [1]	Ref [1]	Ref [2]	Ref [3]		Average
China	1.15	1.17	1.49	1.01	1.04		1.17
	Ref [1]	Ref [1]	Ref [1]	Ref [3]	Ref [4]		Average
USA	0.76	0.77	0.84	0.66	0.59		0.72
	Ref [1]	Ref [1]	Ref [1]	Ref [3]			Average
Germany	0.65	0.66	0.72	0.71			0.68
	Ref [3]	Ref [5]	Ref [5]	Ref [5]	Ref [5]	Ref [6]	Average
South Africa	1.18	0.91	0.93	0.99	0.94-1.04	0.96	0.99

Note: References (Ref): 1 - [49]; 2 - [50]; 3 - [51]; 4 - [47]; 5 - [52]; 6 - [53].

countries (provided in Table 1) or states in the United States of America (USA) (provided in Table S1). Our estimates of each country's carbon emission factors were mainly derived from life-cycle models and literature (Table 1), and the factors account for both direct and indirect greenhouse gas emissions generated by 1 kW h electricity delivered to wastewater plants in different countries. Direct emissions result from burning of fossil fuels at power plants and indirect emissions result from production and transportation of the fuels.

3. Results

3.1. Comparative GHG emission factors for electricity

Table 1 summarizes the emission factors for electricity delivered to WWTPs in four different countries from different references. As there are variations among the references, we report their average value. The variations are due in large part to differences in assumptions, data year, and system boundaries. Some studies, for example, only included direct emissions (EPA 2014) from power plants while others also included indirect emissions (CLCD 2014), although indirect emissions are generally small compared with the direct. China has the highest emission factors, followed by South Africa, both of which were well above the USA and German averages. In fact, even the range of emissions for USA and Germany were below the lower bound of the ranges for China and South Africa, reflecting to a large extent the current fuel choices of each country. In the US, fuel mix differs greatly in different states, resulting in a wide variation in electric GHG intensity from 0.12 kg CO_2e/kW h in Idaho to 1.15 kg CO_2e/kW h in Washington, DC (see Table S1 for other states). We used these state-specific emission factors, derived from the eGRID database [47], to calculate the corresponding GHG emissions WWTPs in different states. For other countries, we used national average emission factors as they are in general less heterogeneous than the U.S. For example, China relies heavily on coal for electricity generation [48].

3.2. Typical GHG emissions associated with wastewater treatment in USA

We considered 15 WWTPs in the USA for which comparative data was available [16]. They are located in Wisconsin, California, New York, Pennsylvania, Kansas, Georgia, Iowa, Colorado and Delaware. Their capacity ranges from 1.5×10^4 m^3/d to 1.0×10^6 m^3/d. In general, they represent the typical treatment process in the USA, except the Sheboygan, WI plant which is a special example. Detailed information about these WWTPs can be found in the Supporting Information (Table S2). The resulting carbon emission intensities of these plants are presented in Table 2. Excluding the Sheboygan plant, the Owls Head WWTP operated by the New York City Department of Environmental Protection has the lowest electricity intensity (0.287 kW h/m^3) and a capacity of 45×10^4 m^3/d. The Douglas L. Smith Middle Basin WWTP in Kansas, possesses the highest electricity intensity (1.12 kW h/m^3). The average electricity input for the 15 plants is 0.55 kW h/m^3. The technologies and processes used in the NYCDEP Owls Head WWTP and the Douglas L. Smith Middle Basin WWTP are shown in Figs. S1 and S2. It is clear that both WWTPs adopt primary settling + biological treatment + secondary settling + disinfection for wastewater treatment and anaerobic digestion for sludge disposal. However, chlorine is used for disinfection in the NYCDEP Owls Head WWTP, while JCW Douglas L. Smith Middle Basin WWTP uses UV (Ultraviolet) for the disinfection of the effluent. UV disinfection requires electricity consumption, while chlorine disinfection needs chemicals which have embodied energy. Table 2 shows that the treatment goals (effluent discharge permit limitations, such as nitrogen, phosphorus, BOD or TSS removal) in different WWTPs varied, which also contributed to the differences in energy consumption and GHG emissions.

The Sheboygan Regional Wastewater Treatment Facility (WWTF) in Wisconsin is one of the few WWTPs in the world that can currently achieve nearly 100% energy self-sufficiency [54]. It serves 68,000 people, with an average capacity of 37,854 m^3/d (10 million gallons per day) and a peak design capacity of 221,824 m^3/d (58.6 million gallons per day). Based on an interview with the plant's superintendent, the average annual electrical energy self-sufficiency is 80%. The treatment technology of the Sheboygan facility is shown in Fig. S3.

The treated effluent from the Sheboygan WWTP is discharged into Lake Michigan, while the excess sludge is treated by an anaerobic digestion which produces biogas. The heated primary anaerobic digesters convert the sludge to methane gas (65%), carbon dioxide gas (30%), and hydrogen sulfide gas (5%). Then the methane gas is used as a fuel to produce 2300 MW of electricity annually, to heat the digesters as well as to fuel an internal combustion engine that provides power to the influent lift pump. The digested sludge is dewatered and can be used as fertilizer. The high value (0.43 kW h/m^3) presented in Table 3 reflects the electricity needed (i.e. without harvesting energy via the biogas) for the entire plant. The low value reflects their best operating condition when they are 100% self-sufficient. The reported typical self-sufficiency of electricity (80%) was considered the average value. This plant would thus be within the typical USA range, but achieves 80–100% self-sufficiency, with no carbon emissions from their electricity input due to their energy harvesting processes.

The most common wastewater treatment technologies in USA include (1) basic aerobic secondary treatment; (2) nitrification; (3) biological nitrogen removal; (4) enhanced nitrogen removal and (5) membrane bioreactors [16]. The typical target effluent values for these technologies differ (Table 3). We calculated the GHG emissions using the typical USA electricity intensity. The reported best practice for each treatment technology is generally 30–50% more energy efficient than the typical practice, indicating a large potential for improvement as WWTP upgrades permeate the industry.

3.3. GHG emission in wastewater treatment in Germany

Based on two studies, the typical electricity intensity of WWTPs in Germany is 0.40–0.43 kW h/m^3 [31,55] without considering their use of biogas for part of their energy requirements (Table 4). Considering the GHG emission factors for German electricity, this translates to GHG emissions of 0.26–0.31 kg CO_2e/m^3. However, German WWTPs cover an average of ~25% of their energy demand by using biogas produced in their facilities [31]. Therefore, we also calculated the GHG emissions considering a 25% energy reduction in electricity consumption (Table 4). The GHG emissions in Table 4 were calculated by multiplying electricity intensity with emission

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Table 2
Typical electricity intensity and GHG emission of WWTPs in USA.[a]

WWTPs	Electricity intensity (kW h/m^3)	Emission factor (kg CO_2e/kW h)	GHG emissions intensity (kg CO_2e/m^3)[b]	Effluent discharge permit limitations	Average treatment capacity (m^3/d)
Sheboygan WWTP, WI	0.0 (low) 0.086 (median) 0.43 (high)	0.81 0.81 0.81	0.00 0.70 0.35	BOD: 30 mg/L TSS: 30 mg/L Phosphorus: 1 mg/L NH_3—N: 23 mg/L	37,854
Los Angeles County JWPCP, CA	0.375	0.31	0.12	BOD: 30 mg/L TSS: 30 mg/L Removal of BOD & TSS: ⩾85%	1,059,915
Thousand Oaks Hill Canyon WWTF, CA	0.555	0.31	0.17	BOD: 30 mg/L TSS: 30 mg/L	32,176
Gloversville-Johnstown joint WWTF, NY	0.703	0.36	0.25	BOD_5: 30 mg/L TSS: 30 mg/L (NY SPDES permit)	113,562
PWD Northeast WCPC, PA (forecast)	0.268	0.63	0.17	BOD: 30 mg/L TSS: 30 mg/L Removal of BOD & TSS: ⩾85% (NPDES permit)	620,808
JCW Douglas Smith middle basin WWTP, KS	1.119	0.86	0.96	BOD: 30 mg/L TSS: 30 mg/L Removal of BOD & TSS: ⩾85% (NPDES permit)	43,532
Ithaca wastewater treatment plant, NY	0.472	0.36	0.17	BOD: 30 mg/L Phosphorus: 1 mg/L TSS: 30 mg/L Removal of BOD &TSS: ⩾85%	24,605
South Columbus water resource facility, GA	0.422	0.68	0.29	BOD: 30 mg/L TSS: 30 mg/L	264,978
Encina Water WPCF, CA	0.516	0.31	0.16	BOD: 30 mg/L TSS: 30 mg/L Removal of BOD & TSS: ⩾85% (NPDES permit)	83,279
Des Moines WRF, IA	0.495	0.85	0.42	BOD: 25 mg/L TSS: 25 mg/L	238,480
Denver Metro WWRP	0.604	0.95	0.57	BOD: 10 mg/L Removal of BOD: ⩾90%	–
Madison nine sprints WWTF, WI	0.524	0.81	0.42	(WPDES permit)[c]	158,987
Kent county regional WWTF, DE	0.658	0.8	0.53	BOD: 30 mg/L TSS: 30 mg/L Removal of BOD & TSS: ⩾85% (NPDES permit)	45,424
NYCDEP Owls Head WWTP, NY	0.287	0.36	0.10	BOD: 25 mg/L TSS: 30 mg/L NH_3—N: 26 mg/L	454,249
Derry TWP. Clearwater roads WWTP, PA	0.887	0.63	0.56	BOD: 25 mg/L TSS: 30 mg/L NH_3—N: 26 mg/L	14,763

Note:
[a] Data source: Electricity intensity data from [16]; emission factor data from [47].
[b] Only emissions from electricity generation are being counted.
[c] Wisconsin Pollutant Discharge Elimination System (WPDES).

factors (kg CO_2e/kW h), which is 0.65 (low), 0.68 (average), and 0.72 (high), from Table 1. Overall, German WWTPs are slightly more energy efficient than USA WWTPs, and even more when biogas is considered. The slightly lower average GHG emission factors for German electricity indicate that most of their WWTPs are closer to carbon neutrality than USA WWTPs.

The Steinhof WWTP (61,643 m^3/d) provides a good example of the state of wastewater treatment in Germany. The overall total electricity demand of the WWTP amounted to 12.9 M kW h/yr in 2010 [56]. The typical influent and effluent concentrations of the Steinhof WWTP are listed in Table S3. Its process flow diagram is shown in Fig. S4. We calculated the energy consumption of each process and its corresponding GHG emissions (Table 5). Similar to Table 4, the GHG emissions in Table 5 were calculated by multiplying electricity intensity (cited or calculated from *Remy 2012*) with emission factors (kg CO_2e/kW h), which is 0.65 (low), 0.68

Table 3
Typical electricity intensity and GHG emission of different wastewater treatment processes in USA.

Treatment process	Typical target effluent values	Typical practice (kW h/m^3)	Best practice (kW h/m^3)	Difference (%)	GHG emissions[a] (kg CO_2e/m^3)		
					Low	Median	High
Basic aerobic secondary treatment[b]	BOD < 10 mg/L TSS < 15 mg/L	0.37	0.26	30	0.22	0.27	0.31
Nitrification[b]	NH_3 < 2 mg/L TSS < 15 mg/L BOD < 10 mg/L	0.51	0.33	35	0.30	0.37	0.43
Biological nitrogen removal[b]	NH_3 < 2 mg/L TN < 10 mg/L TP < 2 mg/L	0.49	0.30	39	0.29	0.35	0.41
Enhanced nitrogen removal[b]	TN < 5 mg/L TP < 1 mg/L	0.52	0.32	38	0.31	0.37	0.43
Membrane bioreactor (MBR)[c]	BOD < 1 mg/L SS < 1 mg/L NH_3 < 0.21 mg/L TP < 0.28 mg/L[b]	1.50	0.74	51	0.88	1.08	1.26

Note:
[a] Only emissions from electricity generation are being counted.
[b] Water Environment Research Foundation (WERF), 2014. http://www.wef.org/EnergySolutionsHandout/.
[c] US EPA, 2008: http://water.epa.gov/scitech/wastetech/upload/2008_01_23_mtb_etfs_membrane-bioreactors.pdf.

Table 4
Electricity intensity and GHG emission of WWTPs in Germany.

	Electricity intensity (kW h/m^3)	GHG emission (kg CO_2e/m^3)[a]		
		Low	Average	High
Average of 5668 WWTPs	0.43[b]	0.28	0.29	0.31
Considering 25% energy reduction from biogas	0.32	0.21	0.22	0.23
Average of 10,200 WWTPs	0.40[c]	0.26	0.27	0.29
Considering 25% energy reduction from biogas	0.30	0.20	0.20	0.22

Note:
[a] Only emissions from electricity generation are being counted.
[b] Data source: [55].
[c] Data source: Husmann (2009).

(average), and 0.72 (high), respectively. Electricity consumption is dominated by aeration. Pumping, sludge dewatering and biogas purification consume more energy than the other processes, but still much less than aeration. Therefore, a highly efficient aeration system is a key to realizing carbon neutrality.

The electricity requirements for unit processes 1–7 sum up to 0.316 kW h/m^3, but a "top-down" approach considering the total electricity input results in a consumption of 0.573 kW h/m^3. The difference was ascribed to other processes not accounted in the operation [56]. Table 5 indicates that the Steinhof WWTP has an average electricity intensity of 0.373–0.413 kg CO_2e/m^3, and it can offset 0.558–0.618 kg CO_2e/m^3 (~150%) via the Combined-Heat-Power (CHP) plant, which means all of the carbon can be neutralized and the WWTP can produce more electricity than it consumes. In addition, the CHP plant produces additional heat that can be sold.

3.4. GHG emission in wastewater treatment in China

Energy intensity and GHG emission per m^3 of treated wastewater for five WWTPs interviewed are shown in Table 6, including Bailonggang WWTP, which is the largest WWTPs in Asia, and one of the largest WWTPs in the world. Bailonggang is located in Shanghai and has a capacity of 2,000,000 m^3/d. Initially this WWTP used chemically enhanced primary treatment (CEPT) as its technology [58], but it has been upgraded to a secondary treatment plant [59]. The major technology used in this WWTP is the multi-mode A^2/O (anaerobic/anoxic/oxic) process, which is characterized by its flexibility to switch and optimize flowrates of mixed liquid and returned sludge (Fig. S5 and Table S4). The technologies used for other WWTPs are as follows: A^2/O for Jiaxing and Kunshan, rapid filtration for Shangtang Village, and humus media biofilter (HF) for Xiacao Village.

Table 5
Electricity intensity and GHG emission of Steinhof WWTP in Germany.

Energy consumption and generation	Treatment unit	Electricity intensity[a] (kW h/m^3)	GHG (kg CO_2e/m^3)[b]		
			Average	Low	High
Electricity consumption	(1) Pumping	0.005	0.003	0.003	0.004
	(2) Aeration	0.296	0.202	0.193	0.213
	(3) Thickening of excess sludge	0.001	0.001	0.001	0.001
	(4) Mixing digesters and sludge pumping	0.002	0.002	0.002	0.002
	(5) Sludge aeration	0.00017	0.000	0.000	0.000
	(6) Sludge dewatering	0.0037	0.003	0.002	0.003
	(7) Biogas purification	0.007	0.005	0.005	0.005
	Sub-total	0.316	0.215	0.205	0.227
	Total	0.573	0.390	0.373	0.413
Energy generation	Combined-Heat-Power plant[c]	0.858	0.583	0.558	0.618

Note:
[a] Data source [57].
[b] Only emissions from electricity generation are being counted.
[c] The Combined-Heat-Power plant (CHP) harvests 19.3 M kW h electricity (0.858 kW h/m^3) and 10.4 M kW h heat per year.

Table 6
Electricity intensity and GHG emission of municipal WWTPs in China.

WWTP	Capacity (m^3/d)	Electricity intensity (kW h/m^3)	GHG emission (kg CO_2e/m^3)[a]		
			Average	Low	High
Bailonggang	2,000,000	0.13	0.15	0.13	0.19
Jiaxing Lianhe	600,000	0.45	0.53	0.45	0.67
Kunshan	22,500	0.40	0.47	0.40	0.60
Shangtang Village	150	0.50	0.59	0.51	0.75
Xiacao Village	45	0.15	0.18	0.15	0.22

[a] Note: Only emissions from electricity generation are being counted.

To show the influence of water quality of the influent and effluent on GHG emissions, we also investigated some industrial WWTPs in China. Most of the industries in China have their own WWTPs for pretreatment before they can discharge their wastewater into the municipal WWTPs. We investigated two typical industries: a printed circuit board (PCB) industry and a textile industry (Table 7). The PCB WWTP has a capacity of 300 m^3/d and uses activated sludge + MBR (membrane bioreactor), while the textile WWTP has a capacity of 2000 m^3/d using A/O (anoxic/aerobic) treatment. Their electricity intensity and GHG emissions are shown in Table 7. It should be noted that electricity used for sludge disposal is not included because most of the industrial sludge is handled and disposed of as a hazardous waste in appropriate landfills or incineration.

3.5. South Africa

The most widely used technologies in Africa are lagoon/stabilization ponds and trickling filters [60], although activated sludge and oxidation ditch/extended aeration plants are occasionally adopted. Table 8 presents the GHG emission of these four technologies using the GHG emission factors for electricity in South Africa. The GHG emissions in Table 8 were calculated by multiplying electricity intensity with emission factors (kg CO_2e/kW h): 0.91 (low), 0.99 (average), and 1.18 (high), from Table 1.

Table 7
Electricity intensity and GHG emission of typical industrial WWTPs in China.

WWTP	Capacity (m^3/d)	Electricity intensity (kW h/m^3)	GHG emission[a] (kg CO_2e/m^3)		
			Average	Low	High
Printed circuit board (PCB)	300	0.6	0.7	0.61	0.90
Textile	2000	0.5	0.59	0.51	0.75

[a] Note: Only emissions from electricity generation are being counted.

Table 8
Electricity intensity and GHG emission of typical technologies in South Africa.

Treatment technology	Electricity intensity (kW h/m^3)[a]	GHG emissions (kg CO_2e/m^3)[b]		
		Average	Low	High
Lagoon	0.079–0.28	0.08	0.07	0.33
Trickling filter	0.19–0.41	0.18	0.17	0.48
Activated sludge	0.33–0.61	0.33	0.30	0.72
Oxidation ditch/extended aeration plants	0.48–1.03	0.47	0.43	1.22

[a] Note: Data source: https://www.dwaf.gov.za/dir_ws/dwqr/subscr/ViewComDoc.asp?Docid=417.
[b] Only emissions from electricity generation are being counted. Emission factors were provided in Table 1.

4. Discussion

According to the AQUASTAT database, the discharged wastewater volume in the USA was 44.69×10^9 m^3 in 2008 [44], and the total USA electricity generation for 2008 was 3865 billion kW h [45]. The electricity consumption by wastewater treatment is estimated to account for 0.6% of the annual electricity consumption in the USA [16]. Therefore, the unit electricity consumption for wastewater treatment was around 0.52 kW h/m^3 in 2008, which is very close to the average value (0.57 kW h/m^3) of the 15 WWTPs. This indicated that the average electricity consumption intensity of the 15 WWTPs is reasonable and those WWTPs represent the typical wastewater treatment level and their electricity consumption intensity in the USA.

The average electricity consumption intensity in Germany can be calculated using the same top-down method. The electricity consumption of the 10,200 WWTP in Germany is 4.4 TW h/year, which accounts for 0.7% of the total electricity consumption in Germany [31]. This indicates that the average electricity consumption of WWTPs in Germany is 0.40 kW h/m^3, which is very close to the result calculated by Tang [55] considering a subset of the WWTPs (0.43 kW h/m^3).

Similarly, we calculated the unit electricity consumption intensity for WWTPs in China. The electricity consumption in WWTPs accounts for only 0.25% of the total electricity consumption in China (http://www.weibo.com/p/1001603746042834213039). According to the data available from AQUASTAT and EIA, the wastewater treated in 2009 was 44.69×10^9 m^3 and the electricity consumption in China was 3270×10^9 kW h in the same year. Therefore, in 2009 the unit electricity consumption intensity of WWTPs was 0.31 kW h/m^3 in China, which is in general agreement with the results in Table 6. Another study indicated that the average energy consumption of 1856 WWTPs in China in 2009 was 0.254 kW h/m^3 [61], which is also within the results for the larger WWTPs in Table 6.

Table 2 shows that although the carbon emissions from electricity for the Sheboygan WWTP can be as high as 0.36 kg CO_2e/m^3, they can be reduced to zero by maximizing the production of biogas and using heat transfer. Although the energy self-sufficiency can be as high as 94% (Table S2), the average value is only 10% [16], which means energy recovery and carbon neutralization are still far for most WWTPs. Based on the 15 WWTPs studied in the USA, the average electricity intensity is 0.57 kW h/m^3, and the corresponding GHG emission is 0.41 kg CO_2e/m^3 (data not shown in Table 3), but it can range from 0 to 0.96 kg CO_2e/m^3 (median). This broad range is likely due to differences in treatment capacities and technologies. As reflected in Table 3, the basic secondary technology has the lowest emission intensity of 0.27 kg CO_2e/m^3 (median), and MBR has the highest of 1.08 kg CO_2e/m^3, indicating that a large part of the difference resides with treatment technology. For the other three typical technologies for wastewater treatment (nitrification, biological nitrogen removal and enhanced nitrogen removal), the GHG emission intensity is very similar, ranging from 0.35 to 0.37 kg CO_2e/m^3 (Table 3).

Anaerobic digestion is the major source of biogas and electricity harvesting from wastewater [17,62–64]. It has been estimated that anaerobic digestion could reduce the need for 628–4940 million kW h annually in the USA [65]. Research from the Electric Power Research Institute (EPRI) shows that anaerobic digestion with biogas utilization can produce about 350 kW h of electricity for each million gallons of wastewater treated at the plant (about 0.1 kW h/m^3) [65]. Therefore, anaerobic digestion is strongly recommended for sewage sludge in WWTPs to reduce overall energy use and close the gap for carbon neutrality.

Table 6 shows that there is a very large range of electricity intensities for WWTPs in China, reflecting in part the efficiencies of scale (e.g., Bailonggang), and in part the lower level of treatment (Xiacao and Shangtang Village WWTPs) due to differences in technologies considered. From Table 6 we can also see that WWTPs with larger capacity can result in lower electricity intensity and GHG emissions. For example, the Bailonggang WWTP in Shanghai has the lowest electricity intensity (0.13 kW h/m^3) and consequently the lowest unit GHG emissions (0.13–0.19 CO_2e/m^3). However, capacity is not the only factor for reducing energy use and GHG emissions. Appropriate technology is also important to reduce electricity intensity. For example, the Xiacao Village WWTP has a small capacity of 45 m^3/d, but its electricity intensity is also very low (0.15 kW h/m^3). The major reason is the adoption of humus media biofilter (HF), a relatively new technology, which is appropriate for decentralized treatment of rural domestic wastewater. The structure and performance of HF is shown in Fig. S6. In comparison, another small WWTP (Shangtang Village, 150 m^3/d) has a similar rural domestic wastewater influent, but its electricity intensity is much higher. Thus, technological innovation can result in significant energy savings for WWTPs.

Influent concentration and thus the required level of treatment to meet water quality objectives is also a factor. For example, two WWTPs in Table 6 (Jiaxing Lianhe WWTP and Kunshan WWTP) have high energy consumption intensity (0.45 and 0.40 kW h/m^3, respectively). One important factor is that the influent contains higher concentration of pollutants. These two WWTPs receive some industrial wastewater (50% for Jiaxing Lianhe WWTP and 15% for Kunshan WWTP), which usually means higher concentration of pollutants. For example, the COD in the influent of Jiaxing Lianhe WWTP is 406 mg/L, which is much higher than that of the other WWTPs (142 mg/L in Xiacao Village WWTP and 250 mg/L in Shangtang Village WWTP). Most of the industrial wastewater is from textile dyeing processes. Some pollutants in the textile dye wastewater are difficult to degrade and require considerably more energy during the pretreatment process. This can also be seen in Table 7 for the industrial WWTPs. Industrial wastewater typically contains much higher pollutant concentrations. For example, the printed circuit board (PCB) industrial wastewater contains high levels of metals (e.g., 20 mg/L Cu and 15 mg/L Ni), which require more energy to treat. Similarly, the textile industrial wastewater has a COD concentration of 2000 mg/L, which is almost 10 times higher than that of municipal wastewater.

Table 8 indicated that on average the lagoon systems have the lowest electricity intensity. This technology is energy-saving in comparison with other treatment technologies because it doesn't need intensive aeration. However, it should be noted that this technology requires a much larger land footprint. This explains the common use of lagoon systems in African countries where there is sufficient land near towns and villages. In developed countries, especially in the coastal areas, industrial zones, and large cities where land is very limited, this technology is generally not an option. Another technology which is also used in African countries is the trickling filter. It is also energy-saving and its GHG emissions are relatively low (0.17–0.48 kg CO_2e/m^3). But due to its low handling capacity, this technology has not been widely used in African countries. Activated sludge and Oxidation Ditch/Extended Aeration Plants are popular not only in developed countries, but also in many developing countries such as some African countries and China. This is due to the fact that they have a better removal efficiency of pollutants from wastewater, but this results in higher GHG emissions (0.30–0.72 kg CO_2e/m^3 for activated sludge and 0.43–1.22 kg CO_2e/m^3 for Oxidation Ditch/Extended Aeration Plants) during the wastewater treatment processes.

Although useful for certain comparisons, electricity intensity (kW h/m^3) is not the ideal indicator to characterize the energy consumption in WWTPs, because it doesn't consider the water quality of the influent and the effluent. In fact, the electricity consumption for the treatment of the same volume of wastewater (e.g., 1 m^3) might vary widely due to the different amount of pollutants removed. Therefore, there is a need to explore more comprehensive indicators to characterize the electricity consumption of WWTPs, and thus GHG emissions and carbon neutrality. One possible indicator is the energy consumption per unit pollutant (such as kW h/kg COD) [61]. However, a difficulty with this indicator is that no single pollutant can represent the overall water quality, and different pollutants in the same wastewater might have various concentrations, removal processes and removal efficiencies. For example, in Table 7, the electricity intensity (0.6 kW h/m^3) corresponds to 4 kW h/kg COD or 2.73 kW h/kg NH_3—N.

Although anaerobic digestion of sludge serves to generate biogas and electricity, it may be difficult to achieve carbon neutrality by anaerobic digestion in some developing countries due to low levels of organic pollutants in the wastewater. As we mentioned above, the COD in the influent of municipal WWTPs in China is often much lower than that in the USA and Germany, which makes it difficult to harvest sufficient energy from the anaerobic digestion of sludge [8]. Hao et al. [35] found that typical municipal WWTPs in China can only produce about 50% energy from biogas and reduce half of the GHG emission. However, it is feasible to recover more than 50% of the energy via water source heat pump (WSHP) and achieve carbon neutrality by the combination of anaerobic digestion and WSHP [35].

Due in large part to a lack of data, it is difficult to accurately quantify the impact on national mitigation targets when all WWTPs are improved to be energy self-sufficient in different countries. However, the contribution of WWTPs in national total carbon emissions provides a rough estimate, more of an upper bound, of such impact where all WWTPs became energy self-sufficient (Tables S5–S7). In general, wastewater treatment accounts for 0.29–0.68% of the national total carbon emission (Table S7). Although WWTPs are not the major sources of carbon emissions, they are still an important contributor. This is especially true for developing countries such as China and South Africa considering economic growth is expected to result in increasing need for wastewater treatment. Besides, to combat climate change entails an all-hands-on-deck solution [66]. Therefore, the realization of energy self-sufficiency can make valuable contribution to national mitigation targets.

According to the experience in some European countries, energy optimization in WWTPs is typically financially attractive, and the potential savings are larger than the required investments [67]. Energy optimization often results in economic benefits due to the increased electricity production from biogas, CH_4/H_2 in anaerobic digesters and value-added products (e.g., phosphorus fertilizer) [67,68]. The practice of energy saving in WWTPs in Switzerland indicated that real savings amounted to 8 million EUR/a, which equals 120 million EUR over an investment lifespan of 15 years. Extrapolation of findings from 344 WWTPs in North Rhine Westphalia (NRW) in Germany leads to an overall saving potential of 3–4 billion EUR over 15 years [67]. Therefore, self-sufficient energy WWTPs are financially feasible [67].

However, it should be noted that economic feasibility may restrict the energy self-sufficiency in some WWTPs. Some technologies such as Combined Heat and Power systems (CHPs) may be expensive. The installation of CHPs requires relatively high investment (approximate $7500/kW for fuel cell, $2000/kW for internal combustion engine, and $4500/kW for microturbine). However, it has been reported that the CHPs are still cost-effective for the large WWTPs (flow rate above 5 million gallons per day) [69,70].

In this study, we focused only on carbon emissions from electricity consumption by the WWTPs. There are other sources of carbon emissions that future studies may take into consideration.

They include carbon emissions embodied in chemical inputs and direct carbon emissions from the WWTPs. Typical processes of carbon emission in the WWTPs include the following [71]: (1) the respiration of microorganisms in the biological reactor (typically activated sludge unit); and (2) combustion of biogas. In addition, the sludge transport, disposal (such as landfill and incineration) and reuse process also emit carbon and other GHGs like fugitive CH_4. Nevertheless, our study with detailed survey data are valuable for future studies attempting to provide a full picture of carbon footprint associated with WWTPs.

5. Conclusions

In this study, we compared the carbon emission intensity (kg CO_2e/m^3) for WWTPs in typical developing and developed countries. The results indicate that net-zero electricity for WWTPs is feasible. Some operating WWTPs in developed countries such as the USA and Germany have already achieved 100% (or higher) electricity self-sufficiency through energy efficiency and harvesting biogas and electricity. However, the majority of WWTPs in those countries still have a significant gap to close. In comparison with Germany, WWTPs in the USA are more heterogeneous and the range of unit GHG emission intensities is much wider. Industrial wastewater in China in general consumes more electricity and the carbon intensity of electricity is also higher, resulting in much higher unit carbon emissions as compared with other countries. In megacities such as Shanghai, larger capacity of centralized WWTPs can reduce electricity consumption and decrease the unit carbon emissions significantly. A better understanding and a more accurate calculation of the energy consumption and GHG emissions of WWTPs will contribute to the mitigation of climate change.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2016.07.061.

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