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Evaluation of the potential for operating carbon neutral WWTPs in China

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ABSTRACT

Carbon neutrality is starting to become a hot topic for wastewater treatment plants (WWTPs) all over the world, and carbon neutral operations have emerged in some WWTPs. Although China is still struggling to control its water pollution, carbon neutrality will definitely become a top priority for WWTPs in the near future. In this review, the potential for operating carbon neutral WWTPs in China is technically evaluated. Based on the A^2/O process of a typical municipal WWTP, an evaluation model is first configured, which couples the COD/nutrient removals (mass balance) with the energy consumption/recovery (energy balance). This model is then applied to evaluate the potential of the organic (COD) energy with regards to carbon neutrality. The model's calculations reveal that anaerobic digestion of excess sludge can only provide some 50% of the total amount of energy consumption. Water source heat pumps (WSHP) can effectively convert the thermal energy contained in wastewater to heat WWTPs and neighbourhood buildings, which can supply a net electrical equivalency of 0.26 kWh when 1 m^3 of the effluent is cooled down by 1 °C. Photovoltaic (PV) technology can generate a limited amount of electricity, barely 10% of the total energy consumption. Moreover, the complexity of installing solar panels on top of tanks makes PV technology almost not worth the effort. Overall, therefore, organic and thermal energy sources can effectively supply enough electrical equivalency for China to approach to its target with regards to carbon neutral operations.

1. Introduction

Global warming and climate change have increasingly prompted efforts to reduce carbon footprints (Victor et al., 2014). For this reason most countries have begun to cooperate in reducing greenhouse gas (GHG) emissions which are the chief cause of global warming (National Research Council, 2010). Although wastewater treatment plants (WWTPs) can purify wastewater, they usually consume a large amount of electricity, up to 0.3–0.8 kWh/m^3 (Hernandez et al., 2011; Garrido et al., 2013), which in turn produces a great quantity of CO_2 emissions due to the use of fossil fuels in power plants. It has been estimated that 3% of the total electrical consumption annually flows to WWTPs in the U.S.A. (USEPA, 2006), whereas this figure in China is, on average, 0.3%, due to the total high electrical consumption in China's booming economy and hence about 114 million metric tons of CO_2 equivalency is released annually (Administration of China (2011); National Energy State Council, 2012; Yang, 2012).

In fact, wastewater is a carrier of energy and resources in its own right, even though it is traditionally regarded as a waste (McCarty et al., 2011; van Loosdrecht and Brdjanovic, 2014). The organic energy contained in wastewater is about 9–10 times higher than that used to treat it (Shizas and Bagley, 2004), and moreover the potential energy of wastewater containing 500 mg/L COD might produce 1.93 kWh/m^3 (McCarty et al., 2011) which could cover the energy requirements of conventional wastewater treatment (0.3–0.8 kWh/m^3) (Hernandez et al., 2011; Garrido et al., 2013). For this reason, many studies and practical trials have been conducted to ascertain the possibility of energy self-sufficiency by recovering energy from wastewater to feed its treatment and afterwards achieving net zero GHG emissions over the life time of a WWTP – also known as the concept of “carbon neutrality” (Mo and Zhang, 2012). Regarding the carbon neutrality of WWTPs, remarkable progress has been made; some countries and/or organizations have proposed guidelines/roadmaps towards carbon neutral WWTPs, such as the Energy Star program in America and the Energy Manual in some European countries (Jonasson, 2007; Energy Star, 2014). Table 1 summarizes the typical case studies, concerning energy

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self-sufficiency and even carbon neutrality around the world.

As shown in Table 1, carbon neutrality has partly or fully emerged in some case studies of WWTPs. Among them, the Strass plant in Austria indicates its leading position on carbon neutrality, as it attained its carbon neutral goal at an early stage in 2005, simply by use of anaerobic digestion of excess sludge for heat and electricity production (CHP: combined heat and power) (Wett et al., 2007). Nowadays, the Strass plant has actually become a "power" plant with co-digestion of kitchen waste, and has set its carbon neutral efficiency at 160% (Reardon, 2014). Furthermore, the "power" plant is just one of the proposed goals in the Netherlands (van Loosdrecht et al., 1997) and the Dokhaven plant could actually have reached its carbon neutral operation in 2013 if all the produced heat had been used for exchanging electricity outside; according to the roadmap of STOWA, future WWTPs have been described as 'NEWs' (Nutrients + Energy + Water factories) (Roeleveld et al., 2011).

In practice, there are narrow and generalized definitions on carbon neutrality. In other words, carbon neutrality is not only limited to recovering organic energy from excess sludge; it should also be related to co-substrate digestion, water source heat pumps (WSHP), solar energy, wind power, biomass incineration (narrow definition) and should even include resource (effluent, sludge, nutrient) utilization, chemicals' dosing, etc. (generalized definition) (Force, 2009; Lazarova et al., 2012). Thus, carbon neutrality in this study should be referred to by a specific (narrow) definition: energy neutrality.

These successful applications are lighting the way for WWTPs to move towards carbon neutrality throughout the world. China has also noticed this developing trend in wastewater treatment even though carbon neutrality is still an unpracticed concept in China. However, the today of western nations will become the tomorrow of China in technologies. Therefore, China urgently needs to know its potential for transforming WWTPs in order to move towards carbon neutrality. Nowadays, there are about 3500 municipal WWTPs in China, which have reached a daily treatment capacity of 1.5×10^8 m^3/d (MOHURD, 2014).

Compared to the wastewater characteristics in European countries (Fig. 1), COD in China's municipal wastewater is quite low, typically between 200 and 400 mg/L, which reveals a low potential for organic energy. This also corresponds to an average low specific electrical consumption (also quite low at 0.29 KWh/m^3) in wastewater treatment, as shown in Fig. 1 (Hernandez et al., 2011; Yang, 2012). Inherently organic insufficiency might not meet the needs of operating carbon neutral WWTPs in China. For this reason, other energy sources have to be taken into consideration in working towards China's goal of carbon neutrality.

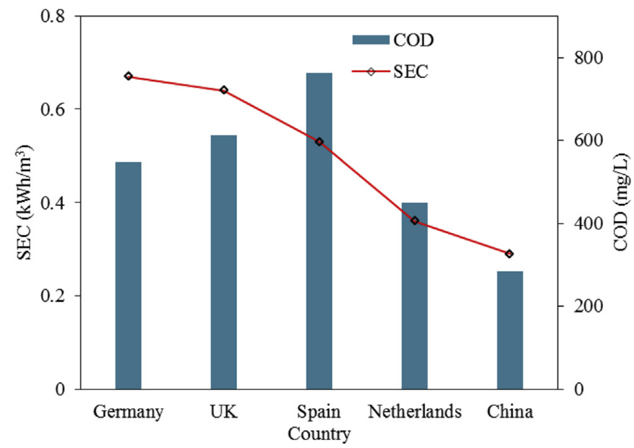

Fig. 1. Influent COD concentration vs. specific electrical consumption (SEC) in different countries.

This review was initiated to evaluate the potential of operating carbon neutral WWTPs in China. It focuses first on evaluating the potential for carbon neutrality simply based on anaerobic digestion of excess sludge (organic energy). Next, such energy sources as thermal energy contained in wastewater and solar energy are then evaluated for offsetting the predicted energy deficit. All of these evaluations are based on rigorous modelling and scientific calculations.

2. Potential energy sources in WWTPs

Based on a bomb calorimetry method, inherent energy reserves in wastewater and/or WWTPs are strongly dependent on its organic (COD) concentration as it contains significant metabolic heat, up to 12–15 MJ/kg COD (Halim, 2012). The organic energy could be extracted through AD of excess sludge for CH_4 production, currently the easiest and most efficient pathway for organic energy conversion.

Table 1
Summary of the practical cases in energy self-sufficiency and/or carbon neutrality throughout the world.

WWTP	Capacity (m^3/d)	Influent quality	Process	Energy source	Carbon neutral efficiency[a] (%)	Reference
As Samra (Jordan)	267,000	COD = 1449 mg/L; TN = 130 mg N/L	Anoxic–oxic activated sludge	Hydraulic turbine for energy production; Sludge digestion	95	Lazarova et al., 2012
Aquaviva (Cannes, France)	88,000 (m^3/h)	Municipal wastewater	UF + MBR	Solar (PV) panels (4000 m^2)	100	Josephs, 2012
Dokhaven (the Netherlands)	121,000	COD = 350 mg/L; TN = 35 mg/L; TP = 4.8 mg P/L	A/B + Sharon/Anammox	AD of sludge	44 (Electricity, 2013) 71 (Heat; 45% discharged, 2013)	Lotti et al., 2015; Duin and van Erp Taalman Kip, personal communication, May 31, 2015
Howard Curren (USA)	363,400	BOD_5 = 159 mg/L; TN = 27 mg/L; TP = 5.1 mg P/L	Aerobic–Aerobic–Anoxic activated sludge	Effluent reuse; Anaerobic digestion; Nutrient recycling	110	Mo and Zhang, 2012
Sheboygan (USA)	70,000	BOD_5 = 222 mg/L; TP = 4.9 mg P/L	A/O	Co-digestion with organic waste; Equipment upgrading	90–115	SRWTF, 2012
Steinhof (Germany)	60,650	COD = 966 mg/L; TN = 67 mg N/L; TP = 11 mg P/L	A^2/O	AD of sludge; Effluent reuse; Phosphorus recovery.	79~	Remy, 2012
Strass (Austria)	27,500	COD = 605 mg/L; TN = 44 mg N/L; TP = 7.5 mg P/L	A/B + Anammox	AD of sludge (~2005); Co-digestioin with organic waste (2006~)	108 (2005); 160 (2013)	Wett et al., 2007; Reardon, 2014

[a] Carbon neutral efficiency (%) = (Total recovered energy/Total consumed energy) × 100%.