Analysis of carbon emission hot spot and pumping energy efficiency in water supply system

Jr-Lin Lin and Shyh-Fang Kang

ABSTRACT

Evaluation of carbon emission hot spots for water treatment plants (WTPs) is crucial to reduce carbon emissions. This study aims to analyze carbon emission data generated at Bansin WTP following the PAS 2050 guidelines. The boundary of inventory and assessment includes water intake, purification, and distribution stages. In addition, pumping efficiency, power consumption per pump lift and specific energy consumption were used to estimate the potential of energy reduction in pumping for Bansin and Baoshan WTPs. The results have revealed that the carbon footprint of Bansin WTP is 0.39 kg CO_2e/m^3 in 2011. There is 95% of carbon emissions generated by pumping from the intake and distribution stages, and the use of pumping is responsible for 65% of total carbon emissions in the clarification stage. The power consumption per pump lift can be calculated to evaluate the difference between rated power and operational power. This relationship can provide information indicating to operators when to replace or maintain poorly-functioning pumps. The data on pump lift, flow rate and power can also be calculated to determine the relationship between pumping efficiency (%) and specific energy consumption (kW/Q), and then used to identify the optimum condition of pump combinations for a given production of water supply.

Key words | carbon footprint, energy efficiency, pump, water treatment plants (WTPs)

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INTRODUCTION

As greenhouse gas emissions that contribute to global warming increase, it is becoming more important to consider carbon reduction in engineering projects. To further understand the opportunities for carbon reduction in water treatment plants (WTPs), a widespread indicator, known as the 'carbon footprint', is used to identify the main sources of carbon emissions in WTPs (Environment Agency 2008; Scottish Water 2011). Within each carbon footprint analysis, there is often a 'hot spot' correlated to the highest CO_2 emission rate within the footprint. Thus, evaluation of carbon emission hot spots for WTPs is crucial to identify specific sources of excess emission.

The carbon emission hot spot of a WTP changes with different water clarification processes, the water delivery manner and the boundary of the carbon footprint assessment. For instance, the carbon emission hot spot of a desalination WTP is the use of pumping energy in operating the reverse osmosis (RO) module (Biswas 2009). The carbon emission hot spot of an advanced WTP is the energy consumption from ozone module operation (Friedrich *et al.* 2009) or chemical consumption (Vince *et al.* 2008). A previous study has reported that the volume of water treated is the main factor responsible for the energy intensity in WTPs using rapid gravity filter systems (Molinos-Senante & Sala-Garrido 2017). Furthermore, the electricity consumption would decrease with network expansion, because the reclaimed water system becomes less energy efficient per unit volume with increasing flow rate, while the potable water system energy efficiency remains fairly constant (Barker *et al.* 2016). Therefore, the energy consumption varies with the facilities and operational modes of WTPs. The observation of energy being a key datum in the water

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sector is in accordance with previous studies (Raluy *et al.* 2006; Godskesen *et al.* 2010), but the carbon footprints can be very different for different water treatment processes (Liu *et al.* 2015). Therefore, in order to reduce carbon emissions in water supply systems, carbon emission hot spots from different WTPs have to be investigated and evaluated through carbon footprint assessment, and it has to be concerned in enhancing the energy efficiency in operating the WTP.

In 2010, the Environmental Protection Administration (EPA) made an announcement about calculating the carbon footprints of Taiwan with a study entitled 'Taiwan Carbon Footprint Calculation Guidance for Products and Services' (i.e. Taiwan's Product Category Rules (PCR)). Taiwan's PCR are founded on CNS 14040 and CNS 14044, which established the life cycle assessment (LCA) methods and the reference PAS 2050 (EPA 2010). From that time on, the Taiwan water sector began to pay more attention to carbon reduction in water supply systems, using the LCA methods (NSC 2006; Hu *et al.* 2012), especially for WTPs. The carbon emission hot spot for water supply distribution in most of Taiwan's conventional WTPs is generally from the distribution stage, which could cause a significant greenhouse effect. However, those studies did not focus on the evaluation of energy-use efficiency in operating pumping systems for WTPs.

As mentioned above, the carbon emission hot spot of most conventional WTPs is energy consumption from pumping in a water supply system. Thus, improving pumping energy efficiency is crucial to reduce carbon emissions for water distribution. Pumping efficiency and energy consumption are significantly affected by water supply flow rate. It is difficult to properly adjust the combination of pumps, leading to the highest efficiency, while satisfying the requirement of potable water distribution. As of now, limited studies have investigated the combined model of pump operation with the highest energy efficiency at different flow rates. Therefore, the aim of this study is first to evaluate the carbon footprint of tap water production from one large conventional WTP (Bansin) in Taiwan following the PAS 2050 guidelines established by the British Standards Institution (BSI 2011). To further evaluate the potential of energy reduction in different pumping systems, pumping efficiency, power consumption per pump lift and specific energy consumption were innovatively used as indicators to estimate the energy-use efficiency in pumping for two conventional WTPs (Bansin and Baoshan WTP).

RESEARCH METHODOLOGY

Bansin is a conventional WTP in northern Taiwan with raw water intake from the Dahan River and Yuanshanyan Watershed. Its water supply capacity is about 680,000 m^3/d, and three phases of treatment processes have been set up to clarify water and echo the water supply demands. The Phase I and Phase II treatment processes include pre-chlorination, coagulation-sedimentation, gravity sand filtration and post-chlorination processes, while there is an alternative sludge blanket sedimentation unit instead of the horizontal-flow sedimentation unit in the Phase III treatment process. In addition, there are 21 water supply pumps operating and feeding to five water distribution systems for Bansin WTP. Occasionally Bansin WTP may purchase water from Taipei Water Department to meet municipal demands. This study follows the guidelines of PAS 2050 to evaluate the carbon footprint of Bansin WTP. The boundary used in carbon footprint assessment in this study includes the water intake, clarification, and distribution stages. All activity data in 2011 within the process map (Figure 1) for energy and chemical consumption in each water treatment process and waste disposal in each stage was collected. For this study, life cycle assessment software (DoITPro) was employed to calculate the carbon emissions in each stage based on a previous study (Chiu *et al.* 2000). According to Chu *et al.* 2011, DoItPro was originally developed in 2000 under the support of the Ministry of Economic Affairs (MOEA) and Industrial Technology Research Institute (ITRI) in Taiwan to estimate the carbon footprint of the region in LCA. Its database contains Taiwan's electricity, oil, fuel, metals, chemicals, plastics and solid waste, compared to foreign database data software. In order to understand the overview of the raw material carbon sequestration database, some information is compiled here using the data from MOEA. The inventory data for Bansin WTP, such as electricity, chemicals, oil, materials, solid waste, in three stages (i.e. intake, clarification, distribution) were calculated by the DoITPro computation procedure to evaluate their contributions to carbon emissions. All emission factors

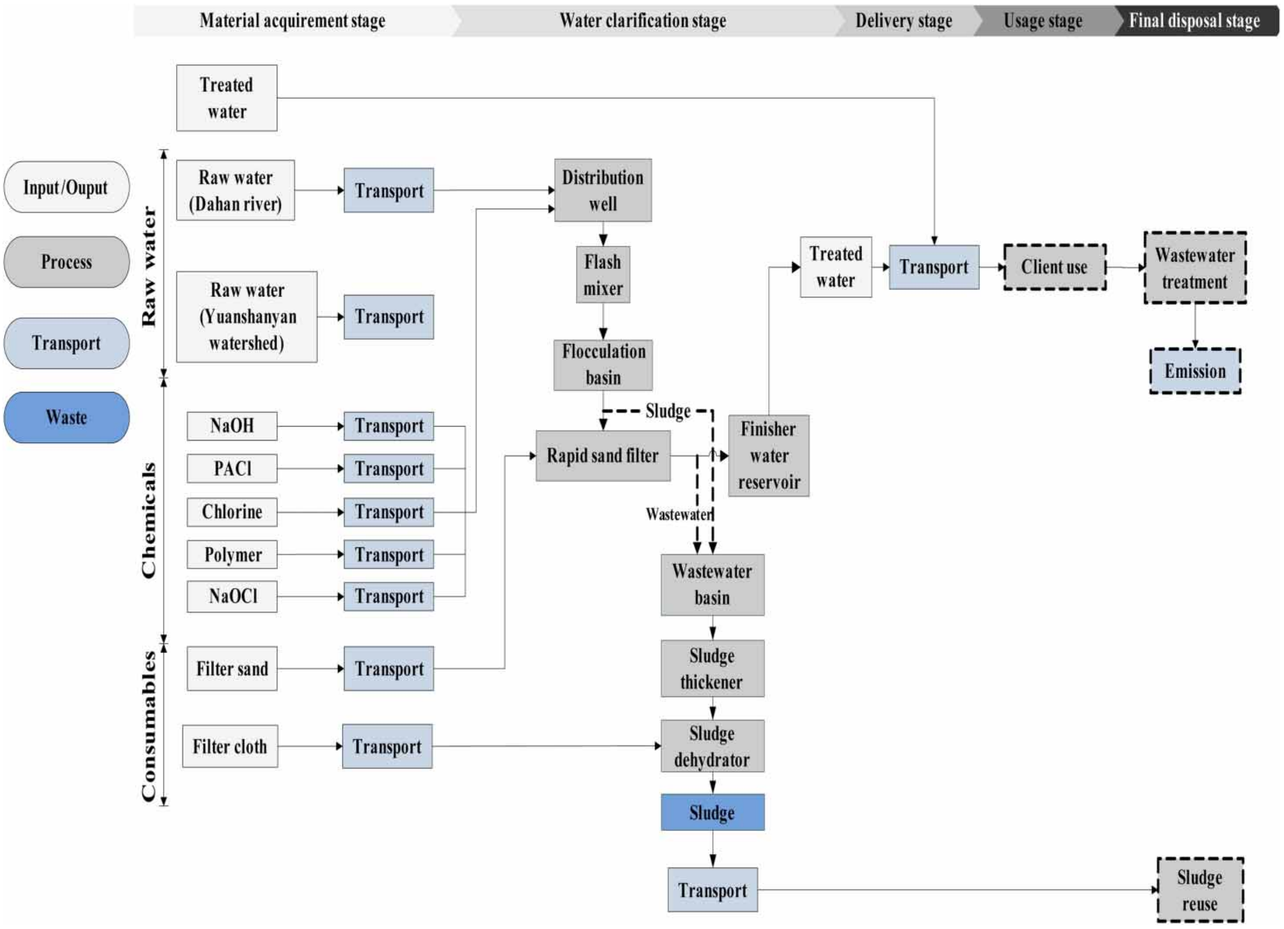

Figure 1 | Process map of Bansin WTP.

in DoITPro were referenced from a local database to increase the accuracy of the carbon emission simulation results.

Because the majority of carbon emissions are definitely generated from pumping operations for WTPs, pumping efficiency, power consumption per pump lift and specific energy consumption were used as indicators to determine the energy-use efficiency in pumping operations for this study. Three indicators are calculated by the following equations:

$$\text{Pumping efficiency } (\%) = \text{shaft horsepower (HP)/water horsepower (HP)}$$

$$\text{Power consumption per pump lift} = \text{horsepower (KW)/pump lift (m)}$$

$$\text{Specific energy consumption} = \text{consumed energy (KW)/flow rate } (\text{m}^3/\text{d})$$

In this study, Bansin and Baoshan WTPs were selected to evaluate their energy-use efficiency in pumping separately because the evaluation of energy consumption is undertaken in different ways. Baoshan is a conventional WTP with a capacity of 340,000 m^3/d, and it includes pre-chlorination, coagulation-sedimentation, gravity sand filtration and post-chlorination processes, which is similar to Bansin WTP. To evaluate the energy consumption in pumping for the two WTPs, the data on energy-use efficiency were collected from the operation records of the major pumps. There are eight pumps operating in parallel at the Bansin WTP for feeding to the Banchiao water distribution system. Four similar pumps are rated at 500 horsepower and the rest are rated at 900 horsepower. Moreover, the Baoshan WTP has three pumps in parallel in the Chutung water supply system. For this study, two pumps are rated at 60 hp and one pump is rated at 40 hp.

Pumps were generally operated in parallel to increase the quantity of water supply. The performance curve of water supply systems at each lift station is depicted by summing up each pump flowrate. According to a previous study (Ajayi & Mofikoya 2012), the actual measurement of pump lift and flow are close to the performance curve of each water supply system obtained by overlaying each respective pump curve.

Three indicators have been applied to the assessment of pump energy efficiency: power consumption per pump lift, pumping efficiency and specific energy consumption. These indicators were used to determine the optimum pump combination with the highest energy efficiency. Power consumption per pump lift describes the relationship between the pump lift and power. In addition, pump efficiency is defined as the ratio of the power imparted on the fluid by the pump in relation to the power supplied to drive the pump. Moreover, the term specific energy consumption refers to power per unit volume of water. These three indicators are used to estimate the potential of energy reduction in pumping for Bansin and Baoshan WTPs.

RESULTS AND DISCUSSION

Carbon emission hot spot analysis in WTP

The carbon footprint of Bansin WTP per volume of water sold is 0.36 kg CO_2 e/m^3, as shown in Table 1. Moreover, carbon emissions in the distribution stage account for 86% of total carbon emissions, and most emissions are generated from pumping energy in the water supply system. Carbon emissions in the intake and clarification stages account for 9% and 5% of total carbon emissions, respectively. The ratio of carbon emissions generated from each specific input in the clarification process is shown in Figure 2. Energy consumption is the main source of carbon emissions during clarification, followed by chemical consumption. The carbon emission hot spot is liberated from pumping energy used in the clarification stage, accounting for 65% of total carbon emissions. In contrast, the chemical used in the clarification stage is responsible for about 33% of total carbon emissions. For Bansin WTP, it is necessary to operate intake and distribution systems with pumping devices in each station, leading to huge energy consumption. Therefore, there are about 95% carbon emission generated from intake and distribution stage in operating WTP.

Table 1 | Carbon emissions of different stages in Bansin WTP

Carbon footprint	Stage	Carbon emission (kg CO_2 e/m^3)	Ratio
0.36 kg CO_2e /m^3	Intake stage	3.21E-02	9%
	Clarification stage	1.96E-02	5%
	Distribution stage	3.07E-01	86%

Pumping energy efficiency assessment in WTP

The energy-use efficiency in pumping operation for two WTPs (Bansin and Baoshan) was evaluated with different indicators. The pump energy efficiency of eight pumps in the Banchiao water supply system of Bansin WTP was evaluated to understand power consumption per pump lift. The data from pump operation, including hourly pump lift, daily total flow rate and daily average power, were calculated for the assessment of pumping energy efficiency. A segmented time analysis was used because the number of operational pumps and operation times in the Banchiao water supply system are different every day. Thus, it is difficult to assess daily flow rate for each pump. We used power consumption per pump lift to assess pumping energy efficiency. The data

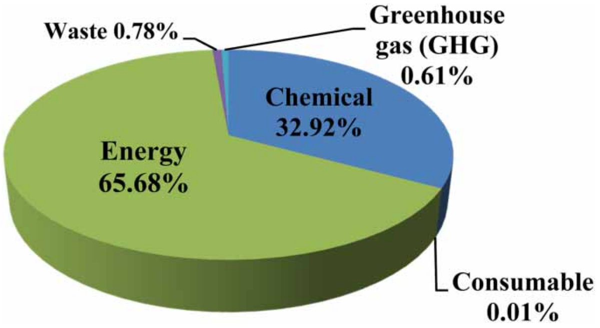

Figure 2 | The ratio of carbon emissions in the clarification stage in Bansin WTP.

of power consumption per pump lift for four pumps are shown in Figure 3. When pump lift is undertaken at 20 meters, power consumption of each of the four pumps is 536, 533, 730 and 526 kW, respectively. The operation of pump #3 results in significantly more power consumption under the same pump lift compared to other pumps. In addition, the power consumption per pump lift for pump #3 shows an abnormal distribution. It is clearly evident that pump #3 needs maintenance and adjustment of operation.

Generally, pumping efficiency and specific energy consumption are used as indicators to investigate energy-use efficiency in a combined pumping system. We applied these two tools in the analysis of the operation of three parallel pumps in the Chutung water supply system for Baoshan WTP. The pumping efficiency and specific energy consumption in Chutung water supply system are illustrated in Figure 4. It is shown that energy efficiency calculated by rated and actual performance curves are different (Figure 4(a) and 4(b)). The combination of the #1 60 HP pump and the #2 60 HP pump can operate at higher energy efficiency at high flow rate than the combination of the 40 HP pump and the #1 60 HP pump. In addition, specific energy consumption of different pump combinations has been plotted, as illustrated in Figure 4(c). Reducing the number of operational pumps will decrease specific energy consumption. Theoretically, a single pump rated at lower flow rate is more effective in energy use and pumping efficiency than combined pumps for withdrawing water to a given distance at a specific altitude. In addition, the specific

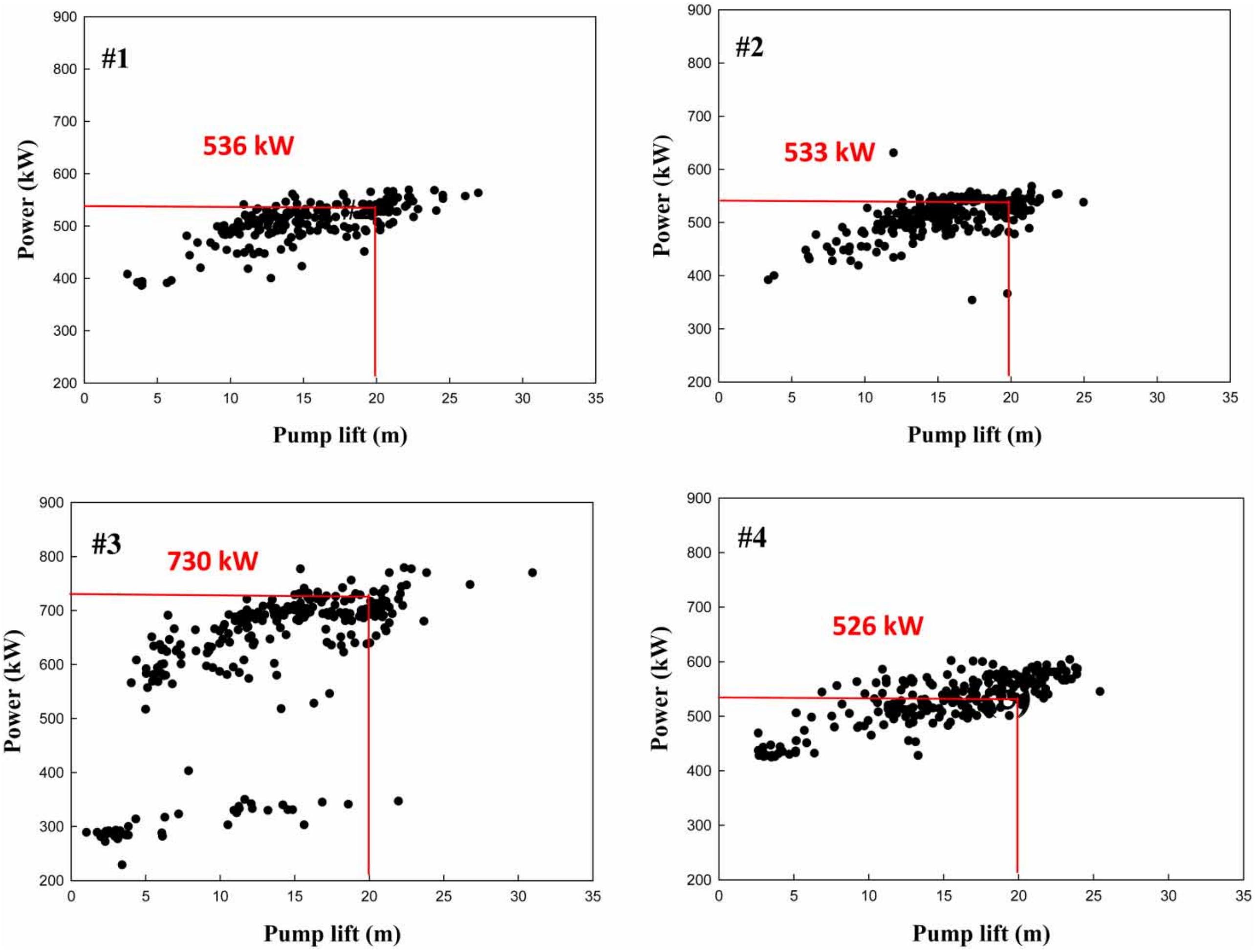

Figure 3 | Power consumption per pump lift of 900 HP pumps in Banchiao water supply system in Bansin WTP.

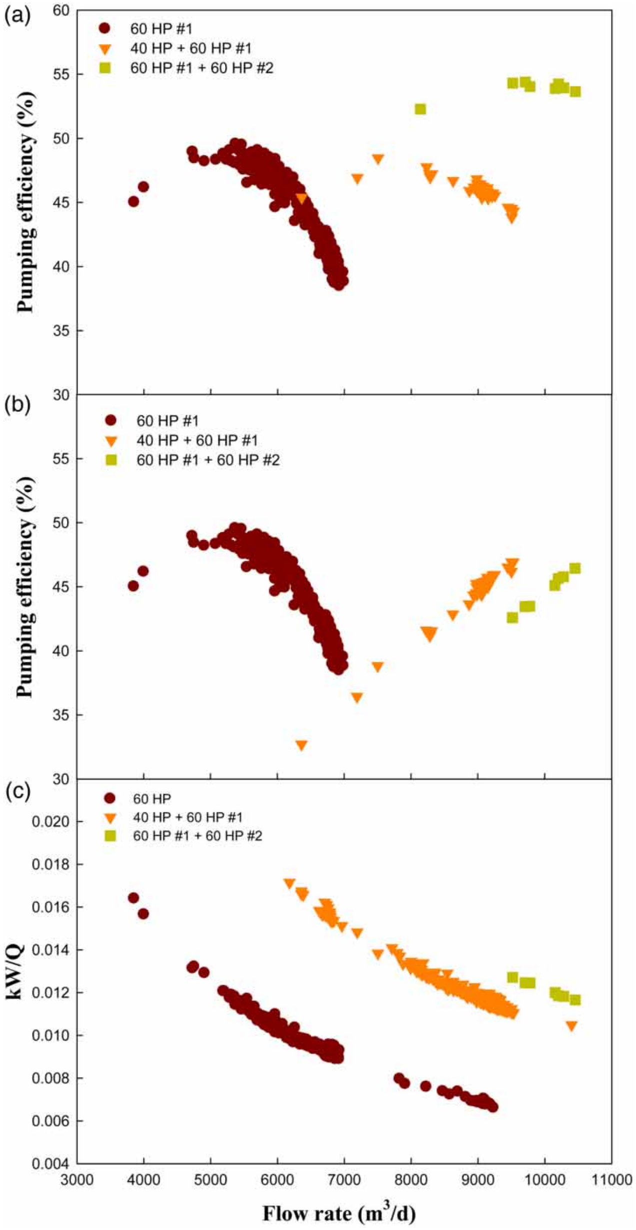

Figure 4 | Pumping efficiency of different pump combinations under specific flows in Baoshan WTP: (a) pump efficiency (calculated by rated performance curve); (b) pump efficiency (calculated by actual performance curve); (c) specific energy consumption.

energy consumption decreases as high flow rate increases, even though the pumping efficiency approaches optimum in the actual performance curve. Pumping efficiency and specific energy consumption are definitely effective indicators to determine adequate pump combinations under a specific flow rate. In practice, the optimal pump combination could be employed at the highest actual pumping efficiency with lower specific energy consumption to save energy consumption for water supply at a specific flow rate.

CONCLUSIONS

This study has determined the carbon footprint of tap water production and distribution along with energy efficiency during water treatment. The results have shown that energy consumption accounts for more than 97% of total carbon emissions from the Bansin WTP, equipped with a conventional water treatment process; of this, 95% is attributed specifically to pumping. Pumping efficiency and specific energy consumption are effective indicators to determine the optimal pump combination at a given flow rate. In addition, power consumption per pump lift can be used to analyze the power consumption tendency for the operation of each individual pump.

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