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Integrated Life-cycle Data Envelopment Analysis for Techno-environmental Performance Evaluation on Sludge-to-energy Systems

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Abstract

Sludge-to-energy (STE) systems have been widely recognized as a favourable approach to treat sewage sludge and recover energy from the energy-rich biomass waste simultaneously. An inclusive efficiency benchmarking tool for STE systems is lacking. This study developed a life-cycle data envelopment analysis (LC-DEA) framework, by integrating life-cycle assessment and data envelopment analysis, for evaluating STE systems. The LC-DEA approach highlights the strong linkage between sludge treatment and energy systems and included all the essential performance metrics in benchmarking the efficiency of the STE systems. Using LC-DEA, this study compared the relative operation efficiency of nine Hong Kong STE systems and seven systems in other urban cities based on the volatile solid reduction, energy recovery, energy consumption, chemical consumption, sludge residues generation and direct environmental emissions. The results showed that 44% and 69% of the sixteen STE systems were efficient in terms of overall and pure technical efficiency, respectively. The LC-DEA results also informed the appropriate strategies for improving efficiency, such as increasing energy recovery, reducing energy consumption and scaling up/down the systems, for the less efficient systems. The LC-DEA framework is widely applicable for guiding decision-making on enhancing STE systems worldwide.

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1 Introduction

With rapid population growth and economic development, urban cities are coping with imminent waste and energy problems. Considering the high population densities and limited land resources in urban areas, the modern waste hierarchy, in addition to dealing with public hygiene problems, emphasizes energy recovery from waste as a simultaneous solution to both the waste and energy problems (Ohnishi, Fujii, Ohata, Rokuta, & Fujita, 2018; Sun, Fujii, Tasaki, Dong, & Ohnishi, 2018). Sewage sludge, as an energy-rich biomass waste, is often treated as a source for renewable energy through waste-to-energy technologies, such as anaerobic digestion (AD) and incineration (Houillon & Jolliet, 2005; Milbrandt, Seiple, Heimiller, Skaggs, & Coleman, 2018). The energy-recovering treatment technologies are adopted in combinations with different techniques, such as thickening, dewatering, aerobic digestion and drying, for treating sludge in wastewater treatment plants (WWTPs) before disposal or final uses. The treated sludge can be disposed of at landfills or used for land application and cement production (Murray, Horvath, & Nelson, 2008). Numerous factors, such as the conditions of inlet sludge, types of treatment technologies, chemical dosages and configurations of processes, affect the performance efficiency of sludge treatment and sludge-to-energy (STE) systems. Although energy recovery from sludge are mainly achieved through AD and incineration, the selection and configurations of the other treatment processes influence the energy and materials inputs, as well as emissions and energy outputs of the STE systems. Therefore, it is crucial to evaluate the interrelated sludge treatment processes from a system perspective, meaning that no single process should be excluded from benchmarking the STE systems.

In the field of sewage sludge management, numerous life-cycle assessment (LCA) studies have been conducted to evaluate the environmental performance of different sludge treatment approaches. The LCA study conducted by Di Maria, Micale, & Contini (2016) compared sludge co-digestion and composting with food waste, and revealed the increased energy recovery achieved by co-digestion. The environmental impacts of different conventional sludge treatment scenarios, including stabilization processes, transportation and disposal, were evaluated using LCA (Remy, Lesjean, & Waschnewski, 2013; Suh & Rousseaux, 2002). The study conducted by Sadhukhan (2014) focused on the environmental performance of AD-based sludge treatment technologies assessed through LCA and Monte Carlo simulation. Besides the environmental aspects, some studies also evaluated the economic performance of the sludge treatment scenarios. Studies have been conducted using LCA and economic analysis to evaluate sewage sludge management options in Japan (Hong, Hong, Otaki, & Jolliet, 2009), Hong Kong (Lam, Lee, & Hsu, 2016), China (Xu, Chen, & Hong, 2014) and Sweden (Lundin, Olofsson, Pettersson, & Zetterlund, 2004).

However, besides environmental and economic performance, the treatment levels achieved by treatment processes, which could be measured as volatile solid (VS) reduction, energy balance and final waste disposal are also essential factors for benchmarking the sustainability and efficiency of sludge management scenarios. To fulfil such goal, this study proposes a multi-criteria decision analysis using an integrated LCA and data envelopment analysis (DEA) approach to evaluate the operation efficiency of sludge management scenarios. The characteristics of DEA enable an objective determination of weightings between the evaluated inputs and outputs, thus giving DEA supremacy in accommodating the different factors involved in performance evaluation, such as energy consumption, environmental emissions and waste generation, without the need of subjective weights (Charnes, Cooper, & Rhodes, 1978; Kuosmanen & Kortelainen, 2005). DEA is one of the commonly adopted tools for analysing WWTPs (Torregrossa, Marvuglia, & Leopold, 2018), water-energy-food nexus (Dai et al., 2018) and energy systems (Martín-Gamboa, Iribarren, García-Gusano, & Dufour, 2017). The incorporation of DEA with LCA has been proposed in literatures for estimating the relative efficiency of the decision-making units (DMUs), which are the units of assessment that represent homogeneous entities with the same function, based on the benchmarks defined through DEA (Iribarren, Vázquez-Rowe, Moreira, & Feijoo, 2010; Iribarren, Vázquez-Rowe, Rugani, & Benetto, 2014; Lorenzo-Toja et al., 2015).

DEA has been demonstrated as an appropriate benchmarking tool for wastewater management in previous research studies. Longo et al. (2016) reviewed numerous benchmarking systems and found a recent growing interest in adopting DEA in the wastewater treatment sector. Longo, Hospido, Lema, & Mauricio-Iglesias (2018) adopted DEA for assessing the energy efficiency of WWTPs. Molinos-Senante, Hernández-Sancho, Mocholí-Arce, & Sala-Garrido (2014) adopted the DEA methodology to evaluate the efficiency of the WWTPs in terms of their economic and environmental performance. With known operation costs and levels of pollutant removal, the potential of greenhouse gas (GHG) reduction was quantified for each plant as the improvement targets. In the DEA study conducted by Castellet & Molinos-Senante (2016), pollutant removals and operation costs were considered as the outputs and inputs of the WWTPs, respectively. The total potential economic savings and the distribution of cost savings in different aspects were identified for the inefficient WWTPs. Dong, Zhang, & Zeng (2017) conducted a DEA to investigate the eco-efficiency of WWTPs based on economic costs, energy consumption, contaminant removals, and global warming effects. Some studies combined LCA with DEA for evaluating the efficiency of WWTPs. Lorenzo-Toja et al. (2015) conducted an eco-efficiency analysis by integrating the LCA and DEA techniques to benchmark the environmental efficiency of the WWTPs in Spain. Considering energy usage, waste sludge production and environmental impacts of chemicals as inputs, and organics removal and methane production as outputs, Torregrossa et al. (2018) combined LCA, DEA, time series analysis and statistical methods to automatically detect the daily eco-efficiency of WWTPs.

There is also growing interest in the integrated LCA and DEA approach in evaluating energy systems in terms of sustainability (Martín-Gamboa et al., 2017). As a decision-supporting tool, the integrated LCA and DEA on energy systems has been used to guide the energy policy in various aspects, such as improving efficiency, energy security and reducing greenhouse gas emissions. Ewertowska, Galán-Martín, Guillén-Gosálbez, Gavaldá, & Jiménez (2016) used a combined LCA and DEA approach to evaluate the environmental performance of different electricity fuel mixes, including both fossil fuels and renewable energy sources, for twenty-seven European countries. Galán-Martín, Guillén-Gosálbez, Stamford, & Azapagic (2016) conducted LCA to assess the environmental impacts and DEA to evaluate the overall sustainability, considering the economic, environmental and social performance, of different electricity generation technologies in the UK. Such approach has been applied to assess the sustainability of different biodiesel production (Ren, Manzardo, Mazzi, Fedele, & Scipioni, 2013) and biohydrogen production alternatives (Martín-Gamboa, Iribarren, Susmozas, & Dufour, 2016). Combined LCA and DEA have also been demonstrated in benchmarking the efficiency of wind farm for electricity generation (Iribarren et al., 2014; Martín-Gamboa & Iribarren, 2016).

The above reviewed performance evaluation studies on sewage sludge treatment, wastewater management and energy systems have demonstrated the appropriateness of the evaluation tools, such as LCA and DEA, for such sectors and highlighted the demand for comprehensive benchmarking approaches to guide decision-making. However, previous studies on sewage sludge management only focus on the environmental and economic performance of the scenarios. A lack of inclusive benchmarking approach that fully covers the influencing factors on the efficiency of STE systems, such as treatment level, energy balance, environmental emissions, material consumption and waste generation, is observed. Therefore, this research study developed a life-cycle data envelopment analysis (LC-DEA) framework for benchmarking STE systems through the integration of LCA and DEA. This study contributes to illustrate the strong interrelationship between modern sludge treatment systems and energy systems, thus provides insights on decision-making for sludge management from an energy system perspective. This is the first LC-DEA study conducted on sewage sludge management that views the sludge treatment scenarios as waste treatment systems and energy systems simultaneously. This study aims to benchmark the techno-environmental efficiency of different STE systems through DEA. The environmental performance was evaluated by LCA. Areas and targets for improvement were identified for inefficient systems so that recommendations could be made to assist decision-makers or operators to enhance the efficiency of such systems.

2 Materials and methodology

2.1 Sludge treatment processes

Sewage sludge is the by-product of wastewater treatment processes. Containing health-threatening contents including pathogens and other organic substances, sewage sludge requires proper treatment before final disposal or reuse. Generally, primary sludge and surplus activated sludge collected from primary and secondary wastewater treatment processes will undergo a series of sludge treatment processes, such as thickening, digestion, dewatering and incineration (Figure 1). Electricity, fuel and chemicals are required for such processes. Energy recovery could be achieved through AD and some of the incineration technologies. The treated sludge will be dispose of at landfills or reuse for different purposes, such as land application and cement production (Murray et al., 2008). This study focuses on the operation of sludge treatment processes, which is from the inlet of sludge to the generation of wastes, such as dewatered sludge cake and incineration ash (Figure 1).

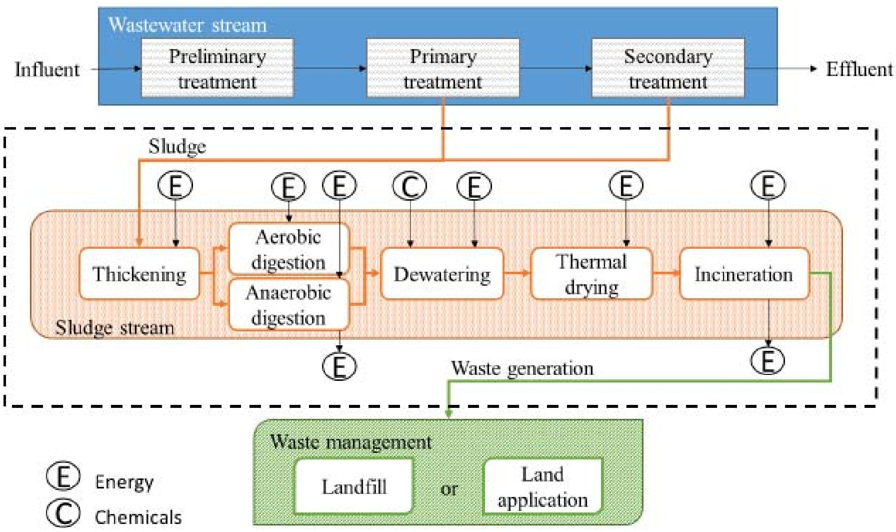

Figure 1 Schematic diagram of wastewater and sludge treatment processes

2.2 Sludge treatment processes and data in this study

Enhancing waste-to-energy systems in urban cities is of high significance due to the characteristics of high population density and lack of land resources in such areas. Waste generation and energy consumption of densely populated areas are immense. STE approach is a favourable solution for cities running out of landfill space, such as Hong Kong, to tackle waste and energy problems simultaneously with limited land resource. Therefore, this study focuses on the STE scenarios in Hong Kong by including nine sewage treatment works (STWs) that contribute nearly 100% of sludge generation in Hong Kong. To reveal the relative performance of Hong Kong STE systems among those in other cities and countries, this study compared the nine STE scenarios in Hong Kong with seven non-Hong Kong scenarios, which are sludge treatment systems in urban cities in different countries. All the scenarios were defined as DMUs in DEA, thus there are sixteen DMUs in this study.

2.2.1 Hong Kong sludge treatment and data

In Hong Kong, the wastewater and sludge treatment services provided by the STWs are managed by the Drainage Services Department (HK DSD) of the government. There are in total 69 STWs providing preliminary, primary, secondary, and tertiary sewage treatment in Hong Kong (HK DSD, 2015a), with four of the major secondary STWs applying AD to treat sludge with energy recovery (HK DSD, 2015b). Sludge thickening and dewatering are employed by the STWs to reduce the water content, and thus the volume, of sludge before disposal. A new sludge treatment facility has recently begun operating in Hong Kong to deliver waste-to-energy through sludge incineration. The facility treats 2,000 tonnes of sewage sludge per day and is capable of reducing 90% of the sludge volume (HK EPD, 2016).

Data of the DMUs in Hong Kong were collected from the HK DSD and the Hong Kong Environmental Protection Department (HK EPD). Nine of the local STWs that contributed nearly 100% of sludge generation in Hong Kong, namely the Shatin (DMU01), Tai Po (DMU02), Shek Wu Hui (DMU03), Yuen Long (DMU04), Stonecutters Island (SCI) (DMU05), Siu Ho Wan (DMU06), Stanley (DMU07), Sham Tseng (DMU08) and Sai Kung (DMU09) STWs, were included in this DEA. Information on raw sludge, sludge thickening, AD, dewatering and the operation of the STWs was collected from the HK DSD. The data on incineration and landfills, was obtained from the HK EPD. For the unavailable data, information from the relevant published literature and databases was used.

2.2.2 Overseas sludge treatment and data

To evaluate the relative performance of the Hong Kong DMUs compared to sludge treatment scenarios overseas, seven DMUs of non-local sludge treatment systems were included in this

DEA. Data on sewage treatment plants located in China, Korea, Italy, Japan, and Denmark was acquired from literatures.

The study conducted by Murray et al. (2008) evaluated four biological secondary wastewater treatment plants in Chengdu, the capital of Sichuan Province, China. The four plants produced 84 dry tons of sludge per day. Two sludge handling scenarios in Chengdu were extracted from the study for inclusion in the DEA in this study. The two extracted scenarios involved AD (DMU10) or aerobic digestion (DMU11), followed by sludge dewatering and land application. For land application, the treated sludge was used for replacing the phosphorus and nitrogen fertilizers.

Piao, Kim, Kim, Kim, & Kim (2016) studied the performance of the wastewater and sludge treatment practices of the WWTPs in Korea. The data on sludge treatment from two WWTPs was extracted for DEA evaluation: WWTP-N (DMU12), which administered a conventional activated sludge process, and WWTP-S (DMU13), which employed an anaerobic/anoxic/oxic (A2O) process. In both cases, sewage sludge was treated by thickening, AD, and dewatering before landfill disposal.

The performance of wastewater and sludge treatment processes was investigated in the study conducted by Tomei et al. (2016). The sludge treatment data of a secondary WWTP with a treatment capacity of 70,000 person-equivalents was extracted for DEA evaluation in this study. Sewage sludge generated from wastewater treatment was treated by thickening, AD and dewatering before land application (DMU14).

The data of a sewage sludge treatment plant in Japan was extracted from the research conducted by Soda, Iwai, Sei, Shimod, & Ike (2010). The treatment processes included thickening, AD, dewatering, incineration, and landfill disposal (DMU15).

The performance of the Avedøre wastewater treatment plant, which is located in Copenhagen, Denmark, was evaluated by Yoshida, Christensen, Guildal, & Scheutz (2015). The plant was a secondary WWTP that treats 25.3 million m^3 of wastewater per year. The sewage sludge, which mainly came from the primary and secondary wastewater treatment processes, was treated by AD, dewatering, drying, and incineration, before being disposed in a landfill (DMU16).

The sixteen DMUs evaluated in this DEA study are summarized in Table 1. The DMUs consist of different combinations of sludge treatment technologies, including thickening (T), anaerobic digestion (AD), aerobic digestion (AeD), dewatering (Dw), drying (Dry) and incineration (I), as well as final destinations of end-products, such as landfill (Lf) and land application (LA).

Table 1 Summary of sludge treatment DMUs

DMUs	Treatment processes								Remarks
	T	AD	AeD	Dw	Dry	I	Lf	LA	
01	●	●		●		●	●		Shatin
02	●	●		●		●	●		Tai Po
03	●	●		●		●	●		Shek Wu Hui
04	●	●		●		●	●		Yuen Long
05				●		●	●		Stonecutters
06				●		●	●		Siu Ho Wan
07	●			●		●	●		Stanley
08				●		●	●		Sham Tseng
09			●						Sai Kung
10		●		●				●	Chengdu S3
11			●	●				●	Chengdu S4
12	●	●		●			●		Korea N-WWTP
13	●	●		●			●		Korea S-WWTP
14	●	●		●				●	Italy
15	●	●		●		●	●		Osaka
16		●		●	●	●	●		Copenhagen

2.3 LC-DEA framework for STE systems

This study emphasizes the strong linkage between sludge treatment systems and energy systems. Figure 2 shows the system boundaries of the STE systems when viewed from waste treatment and energy system perspectives. The system boundary of waste treatment systems generally includes the input of waste (e.g. sludge), chemical consumption and energy consumption, as well as environmental impacts and waste generation. The function provided by sludge treatment systems is the reduction of organic matters. Energy recovery from sludge could be another function or the by-product of sludge treatment. The system boundary of energy systems typically includes the inputs of fuels and auxiliary energy, outputs of environmental impacts and wastes, and the generation of electricity and/or heat. Similarity between waste treatment and energy system perspectives is observed due to the overlapping inputs, outputs and function of the STE systems. While the sludge management philosophy is shifting from merely tackling hygienic problems to extracting energy from waste, STE systems are serving as waste treatment and energy systems simultaneously. Thus, the boundary of STE systems includes both perspectives to comprehensively cover the environmental and technical efficiency of the systems. Although the DMUs include different sludge treatment processes, all the DMUs serve the same functions, which are to reduce pollutants from sludge before disposal and recover energy from sludge. The DMUs also have the same types yet varying quantities of inputs, including chemical and energy consumption, as well as undesirable outputs, including environmental impacts and waste generation. Therefore, all these factors are included in the LC-DEA for comprehensive efficiency evaluation.

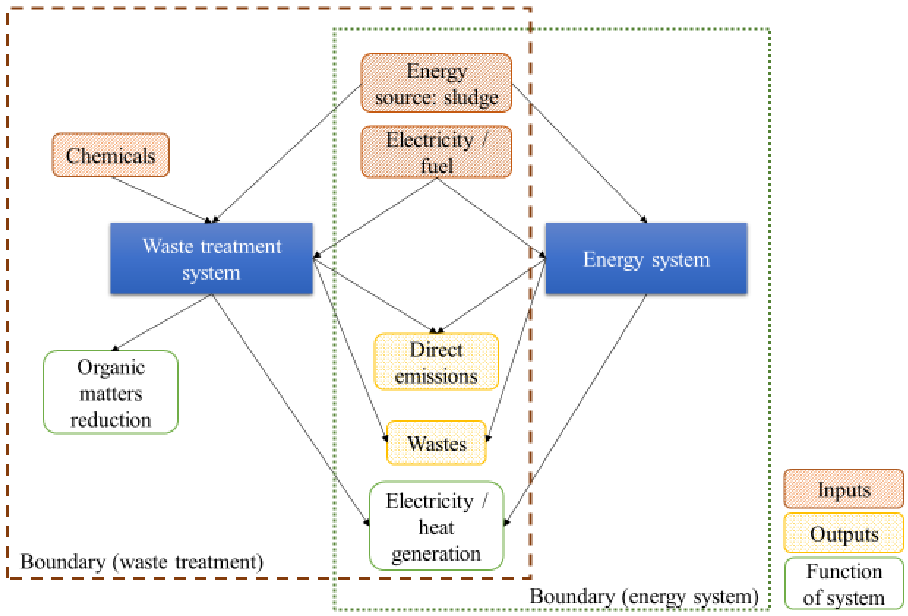

Figure 2 System boundaries of STE systems in perspectives of waste treatment system and energy system

The scope of this LC-DEA for STE systems includes components of technical and environmental efficiency evaluation. Common indicators for technical efficiency of energy systems include electricity generation and direct energy consumption (Martín-Gamboa et al., 2017), while indicators for WWTPs include contaminants removal (Castellet & Molinos-Senante, 2016; Hernández-Sancho & Sala-Garrido, 2009). Thus, this LC-DEA includes VS reduction and energy recovery as the outputs. To consider the environmental performance, this study includes chemical consumption, energy consumption, waste generation and environmental impacts from the treatment processes. The inclusion of such factors is consistent with previous DEA and LCA studies on WWTPs (Corominas et al., 2013; Lorenzo-Toja et al., 2015; Torregrossa et al., 2018). As the characteristics and amounts of chemicals used in sludge treatment are highly variable, this study uses environmental impacts for a unified indicator for measuring and comparing chemical consumption of the DMUs (Lorenzo-Toja et al., 2015;

Torregrossa et al., 2018). Waste generation in this LC-DEA measures the volume of sludge residues to be disposed of at landfills; treated sludge reused for other purposes, such as land application, is excluded from waste generation.

The relative efficiency of each DMU with reference to the most efficient DMUs was obtained as the results of this study and the areas that required improvements were identified for the inefficient plants. This study demonstrated the application of the LC-DEA framework through benchmarking the efficiency of STE systems in Hong Kong against the overseas practices.

2.4 Methodology of life-cycle data envelopment analysis (LC-DEA)

2.4.1 Performance evaluation by DEA

DEA is a mathematical programming model for evaluation of a set of peer entities, which are referred to as DMUs, through empirically obtaining the production frontier or best-practice frontier from the observed data (Cooper, Seiford, & Zhu, 2004; Zhu, 2014). In this study, the DMUs were defined as the sixteen sludge management scenarios described in Section 2.2. Serving as a benchmarking tool, DEA identifies the best-practice DMUs and evaluates the relative efficiency with respect to the conversion of multiple inputs into multiple outputs. Such performance evaluation and benchmarking using DEA enable operations to become more productive and efficient by revealing the strengths and weaknesses of processes, as well as identifying opportunities for improvements to meet operation targets in more efficient ways (Zhu, 2014).

2.4.2 DEA model

Envelopment DEA models have been developed to identify the efficient (best-practice) frontier that envelop all the observed DMUs. Assume that there are a set of n DMUs that consume m types of inputs to produce s types of outputs. DMU_j consumes x_{ij} of input i to produce y_{rj} of output r. It is assumed that $x_{ij} \geq 0$ and $y_{rj} \geq 0$, and each DMU has at least one positive input and one positive output. DEA models demonstrate two underlying properties, namely convexity and inefficiency (Zhu, 2014). The property of convexity defines the level of inputs and outputs that could be utilized and produced by DMU_j as $\sum_{j=1}^{n} \lambda_j x_{ij}$ (i = 1, 2, …, m) and $\sum_{j=1}^{n} \lambda_j y_{rj}$ (r = 1, 2, …, s), respectively. The λ_j (j = 1, 2, …, n) are non-negative scalars where $\sum_{j=1}^{n} \lambda_j = 1$. The property of inefficiency states that the same level of outputs could be produced by using more inputs, and the same level of inputs could be producing less outputs. Therefore, for DMU_j with inputs x_i and outputs y_r:

$$\begin{cases} \sum_{j=1}^{n} \lambda_j x_{ij} \leq x_i & i = 1, 2, \ldots, m \\ \sum_{j=1}^{n} \lambda_j y_{rj} \geq y_r & r = 1, 2, \ldots, s \\ \sum_{j=1}^{n} \lambda_j = 1 & \end{cases}$$

(Equation 1)

The efficiency frontier to be identified by the DEA models could demonstrate different types of return-to-scale (RTS), such as constant return-to-scale (CRS) and variable return-to-scale (VRS). DMUs are identified to be operating under CRS when an increase in inputs leads to the same proportional increase in outputs, and vice versa; while operations under VRS do not demonstrate a proportionate change in outputs when inputs are altered (Castellet & Molinos-Senante, 2016). CRS and VRS measures different technical efficiencies of a DMU. CRS measures the overall technical efficiency (OTE), which is a single score representing the combined pure technical efficiency (PTE) and scale efficiency (SE) (Marti, Novakovic, & Baggia, 2009). The PTE purely reflects the productivity of the utilization of inputs (Kumar & Gulati, 2008), while the SE shows the level of efficiency achieved at a particular production scale (Andrea Guerrini, Romano, & Campedelli, 2013). For DEA models adopting the assumption of VRS, the efficient frontier only reflects the measurement of PTE without the SE (Kumar & Gulati, 2008), while the SE can be obtained by the ratio of OTE to PTE (SE = OTE / PTE). By running the DEA model with CRS and VRS assumptions, this study investigates the OTE, PTE, and SE of the DMUs. The nature of RTS, such as increasing and decreasing returns to scale, could further be investigated. According to Avkiran (2001), the nature of returns to scale could be revealed by running the DEA model under the assumption of non-increasing returns to scale (NIRS). For the DMUs with inefficient SE, if the PTE score equals the efficiency score under NIRS, then the DMU is exhibiting decreasing returns to scale (DRS); if the PTE score is not equal to the score under NIRS, the DMU is exhibiting increasing returns to scale (IRS) (Avkiran, 2001).

DEA models could also be categorized into two types of orientations, namely input-oriented and output-oriented models. Input-oriented models target to reduce the utilization of inputs to produce the same level of outputs, while output-oriented models target to increase output levels using the same amount of inputs. Literatures indicate that the governing principle of most wastewater treatment facilities is input minimization (A. Guerrini, Romano, Leardini, & Martini, 2015; Sala-Garrido, Hernández-Sancho, & Molinos-Senante, 2012), meaning that the WWTPs aim to reduce environmental impact and resource consumption, without compromising the quality of sewage and sludge treatment services provided. Thus, input-oriented approach was used in this study.

2.4.2.1 Input-oriented VRS DEA model

Suppose DMU_o is the entity within the set of DMUs being evaluated by the input-oriented model. The objective of minimizing the utilization of inputs while maintaining the same level of outputs could be represented by the following equation (Banker, Charnes, & Cooper, 1984; Zhu, 2014):

$$\theta^* = min\theta$$

subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{io} \quad i = 1, 2, \dots, m;$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{ro} \quad r = 1, 2, \dots, s;$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_j \geq 0 \quad j = 1, 2, \dots, n.$$

(Equation 2)

θ^* represents the efficiency score of the DMU_o, with a value between 0 and 1. If θ^* equals 1, the input levels could not be further decreased proportionally, meaning that DMU_o is efficient (on the efficient frontier).

When solving the model ((Equation *2*), input and output slacks may appear due to the possibility of yielding multiple optimal solutions. The input slack (s_i^-) and output slack (s_r^+) could be represented as:

$$\begin{cases} s_i^- = \theta^* x_{io} - \sum_{j=1}^{n} \lambda_j x_{ij} \quad i = 1, 2, \dots, m \\ s_r^+ = \sum_{j=1}^{n} \lambda_j y_{rj} - y_{ro} \quad r = 1, 2, \dots, s \end{cases}$$

(Equation 3)

The following programming model could be used to obtain any non-zero slack:

$$max \sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+$$

subject to

$$\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = \theta^* x_{io} \quad i = 1, 2, \dots, m;$$

$$\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{ro} \quad r = 1, 2, \dots, s;$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_j \geq 0 \quad j = 1, 2, \dots, n.$$

(Equation 4)

DMUs with DEA score (θ^*) equal 1 and zero slacks are identified to be efficient; DMUs with DEA score equal 1 and non-zero slack(s) are classified as weakly efficient (Zhu, 2014). The VRS DEA model measure the PTE of the DMUs.

2.4.2.2 CRS and NIRS DEA models

The OTE of DMUs were evaluated using the CRS DEA model. The CRS model is the same as the VRS model described in Section 2.4.2.1 except the absence of the constraint $\sum_{j=1}^{n} \lambda_j = 1$. The nature of returns to scale, namely increasing and decreasing RTS, of the DMUs was revealed using the NIRS DEA model, by changing the constraint $\sum_{j=1}^{n} \lambda_j = 1$ in VRS model to $\sum_{j=1}^{n} \lambda_j \leq 1$.

After running the VRS, CRS and NIRS DEA models, the OTE, PTE and SE efficiency score, as well as the nature of RTS of the DMUs could be obtained. The targets for improvement could also be revealed through benchmarking and based on the slack values.

2.4.3 Performance metrics of DMUs in LC-DEA

In relation to production functions in economic theories, on which the concept of DEA is based, the performance metrics of DMUs have been commonly referred to as inputs and outputs (Zhu, 2014). For improving the efficiency of production operations, operators would aim to minimize the inputs and maximize the outputs. In DEA applications on benchmarking, the DEA inputs and outputs generally refer to metrics that operators would like to minimize and maximize, respectively. Based on the reasons described in Section 2.3, the inputs of this LC-DEA include i) chemical consumption (measured in environmental impacts), ii) energy consumption, iii) sludge residues generation, and iv) environmental impacts from treatment processes, while the outputs include i) VS reduction and ii) energy recovery.

2.4.3.1 LC-DEA inputs

Chemical consumption

Chemicals are commonly applied to enhance the effectiveness of thickening and dewatering of sludge. Common chemicals used in sludge conditioning include ferric chloride and polymers. According to the information provided by the HK DSD, ferric chloride ($FeCl_3$) and polyelectrolyte, which is a type of polymer, have been used to enhance dewatering. Information on the types of chemicals used and the corresponding dosages was collected from the HK DSD for the Hong Kong DMUs. Information on chemical consumption of other DMUs was estimated based on the corresponding literatures (Section 2.2.2) and the Handbook Estimating Sludge Management Costs (US EPA, 1985).

Chemical consumption of DMUs was measured as the life-cycle environmental impacts associated with chemical usage. The environmental impacts were estimated by LCA, which is a widely recognized methodology for evaluating the potential environmental impacts of the life-cycles of products (Iribarren et al., 2015; Xu et al., 2014). The LCA was conducted according to the guidelines and framework specified in the ISO 14040 and 14044 standards

(ISO 14040, 2006; ISO 14044, 2006). Life-cycle impact assessment was conducted with the aid of SimaPro 8.3 software, which is a commonly used LCA tool, and ReCipe Endpoint method was adopted in this study (Huijbregts et al., 2016). The total impacts were obtained through summation of the characterized impacts after normalization and represented by a unitless LCA score.

Energy consumption

Energy is required for the thickening, AD, aerobic digestion, dewatering, incineration and landfill disposal of sludge. For the Hong Kong DMUs, information on the electricity consumption of the sludge treatment processes is not available according to the HK DSD. Therefore, based on the operation information, such as daily sludge flow rate and amount of daily handled solids, the electricity requirements of the thickeners, digestors, and dewatering machines were estimated according to the Handbook Estimating Sludge Management Costs published by the Environmental Protection Agency in the US (US EPA, 1985). The information on electricity consumption of the sludge incinerator was collected from the HK EPD. Fuel consumption for sludge drying was estimated based on the Handbook Estimating Sludge Management Costs (US EPA, 1985). The energy requirements, including the electricity and diesel consumption of landfill operation was obtained from published literature (Abduli, Naghib, Yonesi, & Akbari, 2011; Hong, Li, & Zhaojie, 2010; Koroneos & Nanaki, 2012; Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Chau, 2017; Wei, Wang, Tahara, Kobayashi, & Sagisaka, 2009).

Information on energy consumption of other DMUs was obtained from the corresponding literatures (Section 2.2.2).

Sludge residues generation

Raw sewage sludge contains more than 90% of water content, which contributes significantly to its total volume. Sludge thickening and dewatering can substantially reduce the water content by more than 20%, thus reducing the sludge volume (HK DSD, 2009). Sludge incineration can eliminate the moisture content and combustible portion of sludge, thus achieving up to 90% volume reduction (HK EPD, 2018).

The volume of sludge residues generated after dewatering for the DMUs was calculated based on the inlet sludge volume and solid concentration (US EPA, 1985). For example, in the Shatin STW, the inlet sludge consisted of primary sludge (PS) and surplus activated sludge (SAS), thus the inlet volume was calculated as the summation of PS flow (m^3/d) and SAS flow (m^3/d) (data provided by HK DSD). The volume of the dewatered sludge (outlet) was calculated using the equation (US EPA, 1985):

$$\text{TDSS} = \frac{(SV)(SS)(SSG)(1000)}{100}$$

(Equation 5)

where

TDSS = daily dry solids handled (kg/d)

SV = daily sludge volume (m3/d)

SS = sludge solids concentration (%)

SSG = sludge specific gravity (unitless)

These calculation parameters were obtained through the following methods:

i. TDSS of the dewatering process is equal to the dry solids in the digested sludge, which was calculated based on the digested sludge volume (data from HK DSD), SS of digested sludge (data from HK DSD), and SSG of digested sludge (US EPA, 1985).

ii. SS of the dewatered sludge was provided by HK DSD.

iii. SSG of dewatered sludge was calculated based on the *Handbook Estimating Sludge Management Costs* (US EPA, 1985).

The volume of sludge ash after incineration was estimated to be 10% of the inlet volume (HK EPD, 2018). Sludge residues generation in this study only includes the treated sludge waste to be disposed of in landfills. Sludge residues, such as sludge ash, recycled for substituting other products were excluded.

Environmental impacts from treatment processes

The environmental impacts are undesirable outputs of the STE systems, thus were included as an LC-DEA input. The environmental impacts of the DMUs were estimated using LCA. The impacts of AD and incineration were estimated based on the literatures (Gould, Tsang, & Bandi, 2008; Murray et al., 2008; Xu et al., 2014). The impacts associated with energy consumption and recovery were excluded to avoid double counting as they were included as separate LC-DEA input and output. As this study investigates the efficiency of the operation stage of sludge treatment, the impacts of the construction of facilities, such as land occupation, were excluded. The environmental impacts of other sludge treatment processes were majorly originated from energy and chemical consumption. As these aspects have already been included separately in other LC-DEA inputs, they were not covered in the LCA.

2.4.3.2 LC-DEA outputs

VS reduction

The VS contents represent the organic solids of sewage sludge. The reduction of volatile solids before disposal is essential to avoid the odor problem. Stabilization of sludge can be achieved through AD, in which the anaerobic bacteria consume the organics in sludge for cell growth and methane production. Sludge stabilization can also be achieved through aerobic digestion without the production of methane.

The VS reduction achieved by the sludge treatment process was calculated as the difference between the VS contents of the inlet and outlet sludge.

The VS content was calculated using the equation (US EPA, 1985):

$$\mathrm{DVS} = \frac{(SV)(SS)(VS)(SSG)(1000)}{(100)(100)}$$

(Equation 6)

where

DVS = daily volatile solids handled (kg/d)

SV = daily sludge volume (m3/d)

SS = sludge solids concentration (%)

VS = volatile solids concentration (% of SS)

SSG = sludge specific gravity (unitless)

The SV, SS and VS of the inlet and outlet sludge were obtained from the HK DSD to calculate the DVS before and after treatment. SSG was calculated according to the *Handbook Estimating Sludge Management Costs* (US EPA, 1985).

The volatile solids could be ignited at the temperature of 550-600°C, thus could be eliminated in sludge incineration, which reaches temperatures above 850°C. All the VS content in sludge was assumed to be destroyed after incineration.

Volatile solids reduction is included as an LC-DEA output to reflect the function achieved by the STE systems.

Energy recovery

Energy recovery could be achieved in the AD of sludge through the production of biogas, which is a by-product of the process and contains 65% of methane (HK DSD, 2017). Methane (CH_4)

is a clean source of energy and the gas collected from AD could be used for electricity and heat generation. The data of biogas yield from the AD process was collected from the HK DSD. The electricity and heat recovered from CH_4 through combined heat and power (CHP) and dual fuel engine (DFE) systems were included as a favorable output of the treatment process (Fung & Yeung, 2012). Energy recovery through sludge combustion could also be achieved in some sludge incinerators, such as the fluidized-bed incineration in Hong Kong. The electricity generation from the sludge incinerator in Hong Kong was estimated based on the information provided by the HK EPD. Although biogas could also be yielded from landfill gas, the organic contents in sludge was destructed in incineration prior to landfill disposal in the local scenarios, thus no energy recovery was available from landfill disposal of sludge ash. Information on energy recovery of other DMUs was obtained from the corresponding literatures (Section 2.2.2).

3 Results and discussions

3.1 LC-DEA performance metrics

The performance metrics of DMUs, including VS reduction, energy recovered, chemical consumption, energy consumption, sludge residue generation and environmental impacts from treatment processes, were computed based on the methods described in Section 2.4.3 and used as LC-DEA outputs and inputs for evaluating efficiencies of the STE systems.

Table 2 Performance metrics as LC-DEA inputs and outputs

	Outputs		Inputs			
DMU	VS reduction (kg/yr)	Energy recovered (kWh/yr)	Chemical consumption (kPt/yr)	Energy consumption (kWh/yr)	Sludge residue generation (m3/yr)	Env. Impact (kPt/yr)
01	17,613,025.85	28,406,192.51	115.95	9,293,176.87	5,203.75	269.91
02	4,718,144.90	9,288,558.19	86.58	2,420,133.81	1,102.42	55.03
03	3,847,964.04	7,724,122.37	62.46	3,759,079.85	1,165.74	46.98
04	2,306,558.17	3,171,535.73	47.42	770,418.34	421.64	25.47
05	95,735,850.00	61,396,269.34	284.74	76,491,078.68	52,827.23	2,474.38
06	2,018,777.58	1,069,310.46	15.74	1,314,126.27	890.08	43.05
07	631,517.39	334,503.49	7.27	420,300.67	426.49	13.49

08	811,440.08	429,805.33	0.39	598,850.12	396.26	17.35
09	2,062,085.19	-	-	818,521.14	278.42	8.01
10	9,011,830.64	28,483,140.00	64.59	3,123,275.80	92,837.43	58.14
11	9,011,830.64	-	87.39	22,481,999.80	92,837.43	58.14
12	4,721,640.00	2,948,248.81	43.01	4,655,356.81	33,215.00	28.44
13	8,636,995.00	5,880,860.29	61.56	6,089,652.09	41,610.00	44.10
14	1,186,578.50	1,768,906.78	2.07	1,130,883.61	6,168.50	3.64
15	8,205,200.00	10,439,173.10	57.62	57,020,875.70	9,881.95	124.49
16	8,067,116.85	31,738,207.77	28.11	10,201,111.92	2,287.68	97.89

Being the DMU with the highest sludge treatment loading (annual inlet sludge flow rate of 6.4 million m^3) among the Hong Kong DMUs, DMU05 (SCI STW in Hong Kong) presented the highest environmental impact associated with chemical consumption, energy consumption and environmental impact from treatment processes. At the same time, DMU05 achieved the highest VS reduction and energy recovery from sludge. The high sludge flow rate of SCI STW is attributed to the large wastewater treatment capacity of 2.45 million m^3 per day, after the extension under the Harbour Area Treatment Scheme (HATS) Stage 2A in Hong Kong (HK DSD, n.d.). The Shatin STW (DMU01), with a wastewater treatment capacity of 340,000 m^3 per day is another large contributor to sludge production in Hong Kong, generating approximately 2.5 million m^3 of sludge annually. DMU01 showed the second highest values in all the performance metrics among the Hong Kong DMUs.

3.2 Performance in energy consumption and recovery

Four Hong Kong DMUs (DMU01, DMU02, DMU03 and DMU04) and six non-local DMUs (DMU10, DMU12, DMU13, DMU14, DMU15, and DMU16) achieved energy recovery from AD; eight Hong Kong DMUs (DMU01 to DMU08) recovered energy through sludge incineration. Electricity and fuel were consumed for sludge treatment processes in all the DMUs. The energy consumption and recovery per 1 m^3 of inlet sludge are shown in

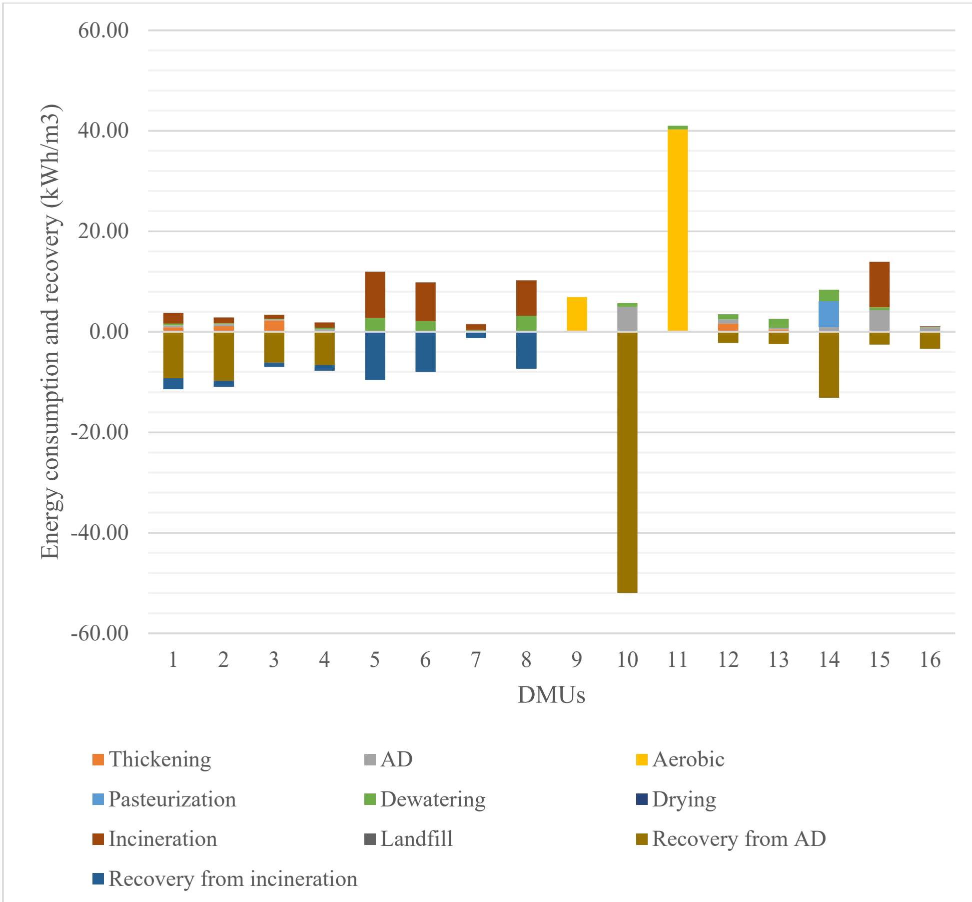

Figure 3. For the DMUs that adopted aerobic digestion for sludge treatment (DMU09 and DMU11), the energy consumption for aeration was intensive. While aeration is an energy-demanding process in DMU09 and DMU11, there was no waste-to-energy treatment technologies adopted in these two DMUs, making them the DMUs with the third highest and highest net energy consumption, respectively. The analysed sewage sludge treatment plants in Japan (DMU15) presented the second-highest energy consumption per m^3 of inlet sludge. Incineration and AD were the most energy-demanding processes in DMU15. Thermal energy was consumed for sludge drying and combustion, while electrical energy was used by components of the incinerator, such as pumps and blowers; energy recovery was not available from the process (Soda et al., 2010). Although energy recovery was achieved in AD, it was outweighed by the energy consumption of the process. The relatively high energy consumption

for AD was attributed to the supplementary energy used for heating the thermophilic digestion tanks (Soda et al., 2010).

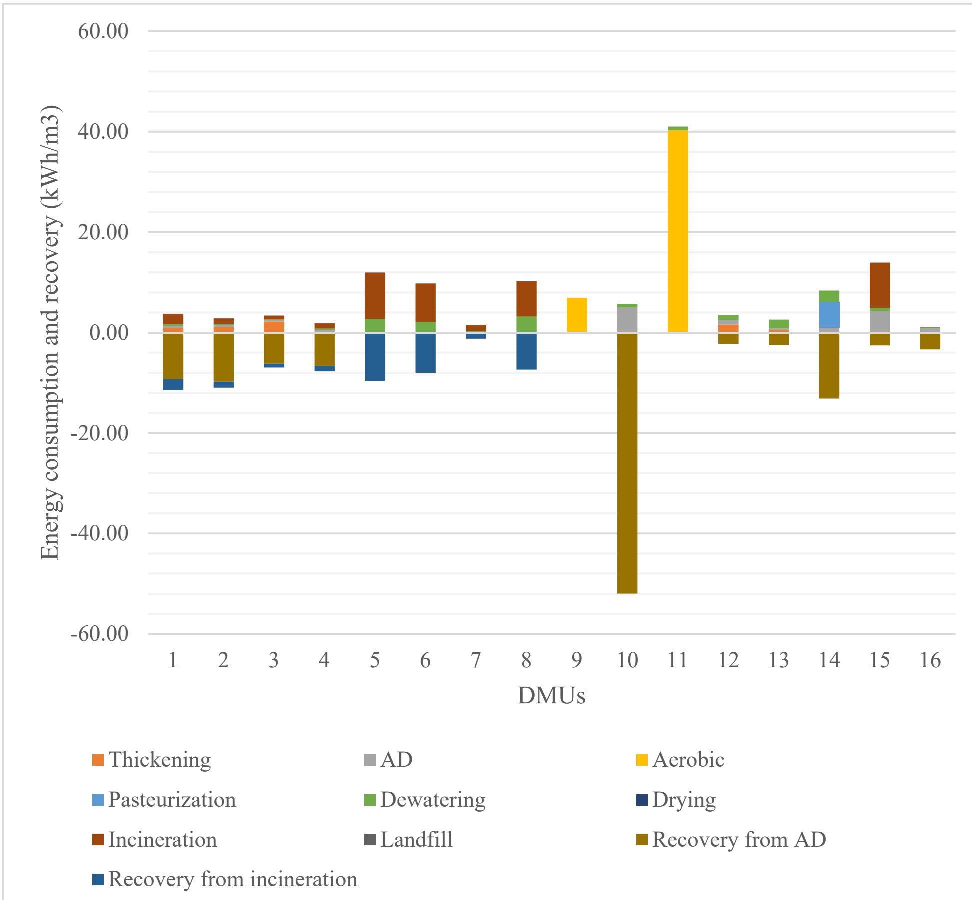

Figure 3 Energy consumption and recovery of DMUs (kWh/m^3)

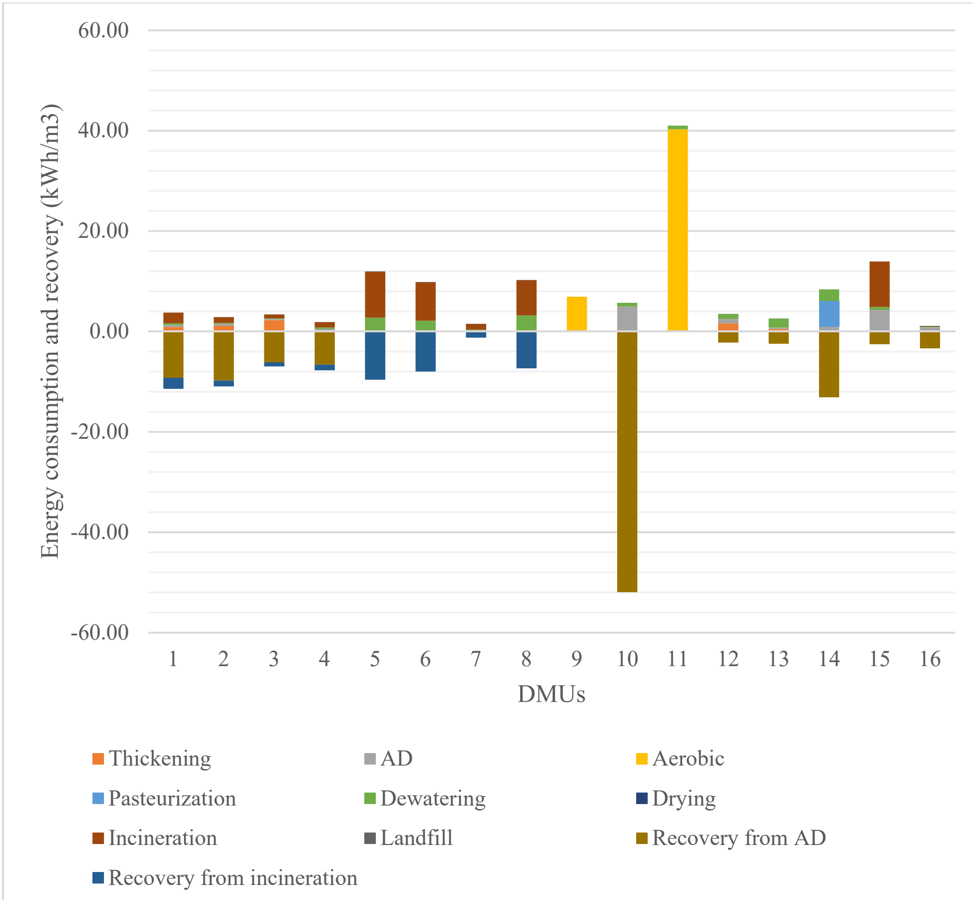

Figure *3* shows the energy balance of the DMUs per m^3 of inlet sludge because the energy consumption for several processes, such as thickening and dewatering, is related to the volume of inlet sludge (US EPA, 1985). To further reveal the energy recovery efficiency, which is related to the organic contents of sludge, the energy recovery per kilogram of volatile solids in sludge is presented in Figure 4. For the major secondary STWs in Hong Kong, including Shatin (DMU01), Tai Po (DMU02), Shek Wu Hui (DMU03) and Yuen Long (DMU04), the energy recovered from AD ranged from 1.18 to 1.77 kWh/kg-VS, while the range for the non-local DMUs was 0.48 to 3.93 kWh/kg-VS. The energy recovery achieved by the centralized sludge incineration in DMU01 to DMU08 was 0.67 kWh/kg-VS. The information on chemical coagulants used for enhancing dewatering was obtained from the HK DSD, while that for non-local DMUs, such as DMU12, DMU13, DMU16, was obtained directly from the published literature. For other DMUs, the chemical requirements were estimated based on the mass of sludge dry solids (US EPA, 1985).

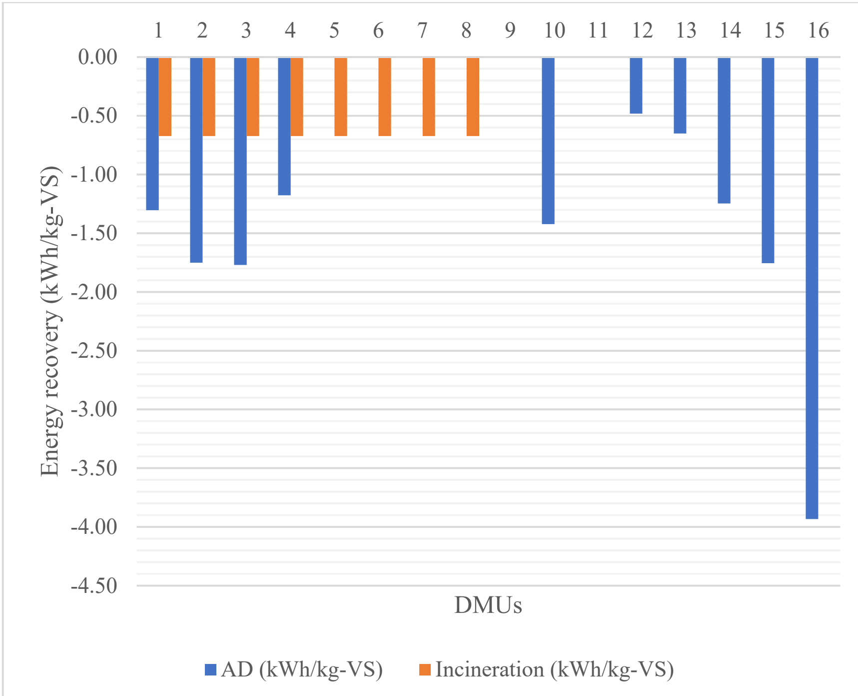

Figure 4 Energy recovery per kilogram of sludge VS

3.3 LC-DEA results

As the energy consumption, energy recovery, chemical consumption, waste generation and environmental performance of the DMUs depend on numerous factors—such as the inlet sludge conditions, treatment targets and treatment technologies—they could not be directly related to the flow rate or solid loading, which are the common functional units defined in conventional wastewater and sludge LCA studies. Therefore, based on the above inventory data, this study evaluated the efficiency of the DMUs in relation to the levels of treatment and energy recovery using the LC-DEA approach.

Based on the inputs and outputs in Table 2, LC-DEA results, including OTE, PTE and SE scores and natures of RTS, were obtained for the sixteen DMUs (Table 3). The OTE scores indicate the relative overall efficiency of the DMUs. DMUs with the maximum score 1.00 are the most efficient ones, while DMUs with scores below 1.00 are less efficient. The results show that, among the sixteen DMUs, the Shatin (DMU01), Tai Po (DMU02), Yuen Long (DMU04), and Sai Kung (DMU09) STWs, as well as the Chengdu S3 (DMU10), Italy (DMU14) and Denmark (DMU16) WWTPs achieved the highest efficiency. The DMUs with lower scores are less efficient. The most inefficient DMU is the Japan WWTP (DMU15); the most inefficient Hong Kong DMU are Stanley (DMU07), SCI (DMU05) and Siu Ho Wan (DMU06) STWs.

Table 3 Efficiency scores and nature of returns to scale of DMUs

DMU	OTE	PTE	SE	RTS
01	1.00	1.00	1.00	Constant
02	1.00	1.00	1.00	Constant
03	0.76	0.77	0.98	Decreasing
04	1.00	1.00	1.00	Constant
05	0.60	1.00	0.60	Decreasing
06	0.62	0.66	0.95	Increasing
07	0.57	1.00	0.57	Increasing
08	0.98	1.00	0.98	Increasing
09	1.00	1.00	1.00	Constant
10	1.00	1.00	1.00	Constant
11	0.48	0.92	0.52	Decreasing
12	0.61	0.80	0.76	Decreasing
13	0.76	1.00	0.76	Decreasing
14	1.00	1.00	1.00	Constant
15	0.42	0.74	0.56	Decreasing
16	1.00	1.00	1.00	Constant

The OTE scores represent the overall efficiency in relation to both the technical performance of the treatment processes and the scales of the DMUs. To further investigate the effect of the economies of scales, the OTE scores were decomposed into PTE and SE, which indicate the contributions of the technical aspects and the scale of treatment facilities to the overall efficiency, respectively. For example, the Shek Wu Hui STW (DMU03) showed a PTE score of 0.77 and an SE score of 0.98, meaning that both technical performance and the scale of operation had notable effects on the overall performance of the DMU. DMUs 05, 07, 08 and 13 are inefficient DMUs, each with a PTE score of 1.00, implying that the inefficiency was solely caused by the unfavorable sizes of treatment facilities. The DMUs with unfavorable operation sizes, as reflected by SE scores lower than 1.00, could be either oversized or undersized. The nature of RTS provides guidance for scaling-up or scaling-down the facilities: an increasing RTS suggests the expansion of facilities, while a decreasing RTS suggests reducing the size of facilities.

For the DMUs with inefficient PTE scores, the technical aspects of the treatment processes are required to improve. Through the benchmarking the DMUs according to different aspects of performance, the DEA results provide information on the required improvements for the DMUs to achieve efficiency. Table 4 shows the required improvements, including the reduction of inputs and expansion of outputs, for the DMUs to be efficient. For example, the sludge treatment process of the WWTP in Osaka, Japan, would have to reduce the chemical consumption, energy consumption, sludge residue generation and direct environmental impact by 42.78%, 83.04%, 25.93% and 25.93%, respectively; and increase the energy recovery by 172.24% to become efficient.

Table 4 Required improvements for DMUs to achieve efficiency

		Outputs		Inputs			
DMU	STWs	VS reduction (kg/yr)	Energy recovered (kWh/yr)	Chemical consumption (kPt/yr)	Energy consumption (kWh/yr)	Sludge residue generation (m3/yr)	Env. Impact (kPt/yr)
1	Shatin	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2	Tai Po	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
3	Shek Wu Hui	0.00%	0.00%	-65.15%	-22.55%	-22.55%	-22.55%
4	Yuen Long	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
5	Stonecutters	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
6	Siu Ho Wan	0.00%	0.00%	-34.39%	-34.39%	-34.39%	-61.79%
7	Stanley	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
8	Sham Tseng	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
9	Sai Kung	0.00%	N.A.	N.A.	0.00%	0.00%	0.00%
10	Chengdu S3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
11	Chengdu S4	0.00%	N.A.	-26.96%	-72.32%	-56.82%	-7.93%
12	Korea N-WWTP	0.00%	0.00%	-36.77%	-31.76%	-41.17%	-20.17%
13	Korea S-WWTP	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
14	Italy	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
15	Osaka	0.00%	+172.24%	-42.78%	-83.04%	-25.93%	-25.93%
16	Copenhagen	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

3.3.1 Factors for inefficiency and recommendations for improvements

DMU15, which represents the STE system of WWTP in Japan, had the lowest OTE score and the second least favourable performance in PTE. DMU15 required improvement in energy recovery by 172.24%. The reason for the low energy recovery of DMU15 was its incapability of energy recovery from incineration in the STE system. While fuel and electricity were demanded for the energy-intensive incineration process, energy or heat recovery were not available in DMU15. The daily energy consumption of DMU15 was 156 MWh, while only 29 MWh could be recovered from sludge AD. Incineration was the most energy-demanding process in this STE system, contributing to 65% of the total energy consumption, while the energy consumption of AD contributed to 31% of the total consumption. The raw sludge solids contained 80% of organic matter content and AD could digest 55% of it, meaning that the digested sludge still contain a notable amount of organic matters. Upgrade of incinerators to enable energy recovery from sludge combustion were suggested for DMU15 to improve the overall energy recovery of the STE system. The energy content of organic matters in sludge could either be recovered in forms of heat and electrical energy or transferred to the environmental as an energy loss of the system. Incineration with energy recovery could achieve the former, thus improving the overall efficiency of the DMU. DMU15 required a reduction of chemical consumption for 42.78%. Chemicals were used as coagulants for enhancing the dewaterability of sludge. Previous studies have investigated the improvement of sludge dewaterability by other means, including thermal pre-treatment (Neyens & Baeyens, 2003) and lowering the pH (Chen, Yang, & Gu, 2001; Neyens & Baeyens, 2003; Elisabeth Neyens, Baeyens, Dewil, & De heyder, 2004). Yet the feasibility and suitability of applying such techniques in DMU15 are out of the scope of this study, thus need to be further investigated in future laboratory-based research studies. Energy consumption of DMU15 needed to be reduced by 83.04% to achieve efficiency. Incineration was the most energy-consuming process in this

DMU, contributing to 64.80% of its total energy consumption. Adoption of thickening or drying to reduce the water content of sludge is favourable to the combustion process, thus is a possible means to decrease the energy requirement for sludge incineration (Mininni, Di Bartolo Zuccarello, Lotito, Spinosa, & Di Pinto, 1997). Selection of different incineration technologies also affect the requirement of auxiliary fuels (Murakami et al., 2009). Reduction of sludge residue generation by 25.93% was recommended. As the amount of sludge residue generated was closely related to the amount of raw sludge, based on the flow rate and solid content, reduction of sludge production from the wastewater stream in WWTPs could be a possible solution for reducing the final sludge residues. Mild temperature and low organics loading tended to produce lower amount of sludge from wastewater treatment stream (Lorenzo-Toja et al., 2015). Sludge yield could also be reduced by controlling the solid retention time and dissolved oxygen level in wastewater treatment (Semblante et al., 2014). Reducing the environmental impacts originated from sludge treatment processes by 25.93% was recommended. As relatively high environmental impacts of DMU15 could be attributed to the high sludge loading for incineration. Although AD was adopted in DMU15 to eliminate a portion of VS before sludge incineration (10 tons of dry solids were eliminated through AD), 144 ton/day of sludge from another WWTP was mixed with the dewatered sludge for incineration (Soda et al., 2010). The addition of sludge increased the dry solids from 16.5 ton/day after AD to 22.3 ton/day for incineration. The addition loading of sludge for incineration could be a reason for the unfavourable environmental performance. DMU15 scored 0.56 in SE with a decreasing RTS. Therefore, scaling down the STE system is recommended to improve the efficiency of DMU15.

When focusing on the pure technical efficiency of the DMUs, DMU06 (Siu Ho Wan STW in Hong Kong) was the STE system with the lowest PTE score among the sixteen DMUs. LC-DEA results revealed that, for DMU06 to achieve maximum efficiency, reduction of chemical consumption, energy consumption and sludge residue generation by 34.39%, and reduction of environmental impact from treatment processes by 61.79% were required. DMU06 presented the fourth highest energy consumption among the sixteen DMUs (Figure *3*), with incineration contributing to 77.73% of its total consumption. The relatively high environmental impact of DMU06 could be attributed to the exclusion of AD and high environmental impacts of incineration. The STE system of DMU06 included processes of dewatering, incineration and landfill disposal. While AD was absent for eliminating part of the solids (VS), a higher solid loading would be entering incineration. The direct environmental impact induced by incineration of 1 dry ton of sludge was more than 6 times higher than AD of same weight of sludge (Xu et al., 2014). Although incineration eliminates all the VS in the STE systems with or without AD, higher reliance on incineration for VS elimination causes higher direct environmental impacts. Thus, application of AD for sludge treatment in DMU06 is suggested as a possible means to reduce the direct environmental impacts. DMU06 scored 0.95 for SE and presented an increasing RTS. Such results reveal that the scale of DMU06 was slightly under the optimal level, thus an increase in the size of STE system could increase the SE and, therefore, the OTE of DMU06.

3.4 Contributions and Limitations of LC-DEA

The waste-to-energy management approach has been widely recognized and adopted for treating sludge and other organic waste. Although environmental and economic performance of sludge management scenarios have been evaluated in numerous published studies, the strong linkage between sludge treatment and energy systems, as well as the operation efficiency benchmarking approach for STE systems, have not yet been covered in previous literatures. By the inclusion of essential factors that affect the efficiency of both sludge treatment and energy systems, and the integration of LCA and DEA, this LC-DEA study filled the research gap by providing a multiple criterion benchmarking tool that could objectively evaluate the performance of STE systems.

The LC-DEA evaluation tool developed in this study is widely applicable to guide decision-making for improving the techno-environmental efficiency of STE systems so that sustainability could be achieved. The LC-DEA framework can provide comprehensive information to decision-makers for benchmarking the sludge management systems with energy recovery in different WWTPs, which in turn can be used to prioritize appropriate remedial actions to improve the performances of relatively inefficient systems. For example, high priority for upgrade of STE system could be recommended to the authority in Japan for improving DMU15 as it was the DMU with the lowest efficiency. Targets for improvements in different aspects were identified for improving the PTE and scaling down the STE system was recommended for improving the SE of DMU15, as described in Section 3.3.1. This study has demonstrated LC-DEA as a suitable evaluation tool to guide decision makers, government officers and practitioners in improving the efficiency of STE systems. Such tool could also be a comprehensive approach to reveal the performance of the STE systems to the general public such that public education on waste-to-energy systems and their associated benefits could be achieved.

The limitation of this LC-DEA for STE systems is that the inadequacy in the system configurations of the treatment facilities and the technical approaches to achieve the improvement targets are excluded from the study scope. This LC-DEA study focuses on benchmarking the operation performance of the existing STE systems from a management perspective, so that the information on relative efficiency of the systems, as well as improvement targets of different aspects could be provided to decision makers. However, the alterations on system configurations of sludge treatment facilities, such as temperature and solid retention time for sludge AD, for efficiency improvement are out of the scope of this LC-

DEA. Based on the recommendations for improvement obtained from the LC-DEA findings, further laboratory-based studies could be conducted to investigate the technical method for achieving the improvement targets.

4 Conclusions

The LC-DEA approach developed in this study, through integration of LCA and DEA, for benchmarking STE systems is a comprehensive and widely applicable tool for guiding decisions on improving waste-to-energy systems. The development of this innovative tool contributed to fill the research gap by highlighting the strong linkage between waste and energy systems, as well as evaluating the operation efficiency with considerations of all the essential performance metrics of the STE systems. This LC-DEA approach provides an objective basis for comparing STE systems with different sludge handling technologies yet having the same set of inputs and outputs.

The LC-DEA approach was demonstrated in this study on benchmarking sixteen STE systems as a suitable tool to guide decision-making on improving the techno-environmental efficiency of the systems. The DEA findings could firstly assist in identifying the relatively inefficient DMUs that prioritized for improvements. The least efficient STE system was DMU15, which only scored 0.42 for the OTE score, implying that the authority could consider improving the performance of the STE system. For decision-makers and authorities in Hong Kong, Stanley (DMU07), SCI (DMU05) and Siu Ho Wan (DMU06) STWs should be prioritized for improvements, as these were the least efficient DMUs (with the lowest OTE scores) among the Hong Kong DMUs. The findings could secondly ensure the efficient use of resources in making the appropriate improvements, as the PTE and SE scores inform decision-makers on the sources of inefficiency (technical performance of treatment processes or size of treatment facilities). DMU15 required significant improvement on energy recovery (by 172.24%) and upgrading the sludge incinerators to models that could achieve energy recovery was recommended. Scaling up DMU07 and scaling down DMU05 could improve the efficiency of the DMUs. With such information, the agency could further investigate whether changing the scales of the facilities is feasible in future town planning policies. For DMU06, besides increasing the operation scale, the technical performance also required enhancement.

The developed LC-DEA framework will be widely applicable to different STE systems worldwide. While this study evaluated the performance of the STE systems from a management perspective, only the aspects that required improvement and the improvement targets are provided in the findings. The technical approaches to achieve the targets, which are closely related to the engineering design of the treatment facilities, were not investigated in this study. More comprehensive results could be obtained if the actual operation data of more DMUs could be collected and included in the LC-DEA analysis.

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