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Conversion of landfilled waste-to-electricity (WTE) for energy efficiency improvement in Shenzhen (China): A strategy to contribute to resource recovery of unused methane for generating renewable energy on-site

Xue Liang [a,1], Tonni Agustiono Kurniawan [b,**,1], Hui Hwang Goh [a,*], Dongdong Zhang [a], Wei Dai [a], Hui Liu [a], Kai Chen Goh [c], Mohd Hafiz Dzarfan Othman [d]

[a] School of Electrical Engineering, Guangxi University, Guangxi, China
[b] College of Environment and Ecology, Xiamen University, Xiamen, 361102, Fujian province, China
[c] Department of Technology Management, Faculty of Construction Management and Business, University Tun Hussein Onn, Parit Raja, Johor, Malaysia
[d] Advanced Membrane Technology Research Centre (AMTEC), School of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310, Skudai, Johor Baru, Malaysia

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ABSTRACT

Recent growth of population and rapid urbanization have increased the generation of municipal solid waste (MSW) in Shenzhen (China). As a result, the city strives to implement circular economy (CE) by converting its landfilled waste into electricity. As a primary component in landfill gas (LFG), methane (CH_4) emissions need to be mitigated to deal with climate change. This exploratory study investigates the utilization of LFG based on CH_4 formation at a waste-to-energy (WTE) plant in Shenzhen (China) by converting landfilled waste into electricity. This work also explores the scheme of incorporating a combined cooling, heating, and power (CCHP) system into the WTE power station by utilizing the waste heat of a LFG power generation process. To maximize LFG utilization efficiency and optimize the return on investment (ROI) in the city's WTE, an economic viability of energy generation that incorporates a CCHP system into the plant is presented. The WTE's capacity for power generation and total energy provided by waste heat utilization are estimated. The benefits to local community and the project's long-term impacts on the environment are elaborated. It was found from modeling study that about 2.22E+11 kg of landfilled MSW during a 15-year period yielded 1.34E+10 kg of CH_4, while 90% of CH_4 production still occurred about 20 years after landfilling. During the 20-year of timespan, when harnessing the waste heat from power generation, the landfilled MSW in 2021 could generate 9.68E+8 kWh of electricity and 1.75E+13 kJ of heating, or 1.17E+13 kJ of cooling. The outputs can meet the energy demands of Shenzhen's urban buildings and its population for electricity, cooling, and heating. This implies that incorporating technological values to the landfilled waste for electricity generation not only promotes a CE, but also facilitates resource recovery from unused waste, thereby contributing to the UN Sustainable Development Goals (SDGs) by 2030.

1. Introduction

Recent population growth and consumption style have resulted in a significant increase in the production and diversity of municipal solid waste (MSW) (Hosseini et al., 2018). As a result, MSW management has become increasingly complex and expensive over the past decades (Tehrani et al., 2020). With a growing population and an increasing demand for water, food, and energy, it is expected that MSW generation will continuously increase over the next decade (Khan et al., 2022). As one of the global issues, MSW needs to be managed comprehensively in an integrated way from upstream to downstream to provide economic benefits for people (Fig. S1) (Kurniawan et al., 2011). China, the world's most populous country, generates over 235 million metric tons (Mt) of MSW annually (Kurniawan et al., 2021a) equivalent to 120 kg per capita, while Shenzhen contributes 3% (7.124 million tons) to the

* Corresponding author.
** Co-corresponding author.
E-mail addresses: tonni@xmu.edu.cn (T.A. Kurniawan), hhgoh@gxu.edu.cn (H.H. Goh).
[1] The first and the second author equally contribute to this work and mutually share the first authorship

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List of abbreviations

4IR	4th Industrial Revolution
BEP	breakeven point
CCHP	combined cooling, heating, and power
CE	circular economy
COP	coefficient of performance
EIA	environmental impact assessment
GW	gigawatt
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
LFG	landfill gas
kWh	kiloWatt hour
MSW	municipal solid waste
Mt	metric tonne
Mtoe	million tons of oil equivalent
ROI	return on investment
SWM	solid waste management
TEQ	toxic equivalency (TEQ)
Tg	teragram
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WTE	waste to energy

country's total waste output (Gu et al., 2017). Shenzhen, as the study's model city for China, is currently confronted with a significant amount of MSW. Such a huge production of trash critically threatens the sustainability of China's economy, society, and environment (Ahmadi et al., 2021), as the current waste management system neither can identify specific properties, types, and amounts of MSW collected in sorting facilities, nor provide accessible or accurate information for applying the most suitable treatment technology. As a result, this does not address the socio-economic and environmental aspects of waste management.

Due to its cost-effectiveness, about 80% of MSW in China is disposed of in landfills (Table S1) (Kurniawan et al., 2021b). When landfills are overburdened, the excessive waste is often disposed in uncontrolled ways in open dumps, increasing the transmission of disease, pollution, and toxic emissions into the air (Osra et al., 2021). After landfilling, the MSW undergoes physico-chemical decomposition, generating landfill leachate (Fu et al., 2021b). Unless properly treated, the leachate can freely infiltrate the underlying groundwater, posing health risks to people, who live close to the landfills. Apart from leachate, LFG is an unavoidable by-product of landfilled MSW. After landfilling, MSW rich in organic matter decomposes and produces LFG that contains CH_4 and CO_2 under the 1997 Kyoto Protocol (Fig. S2) (Liang et al., 2022). In the absence of O_2, biodegradation of organic matter generates CH_4, which has a global warming potential of 21 times that of CO_2 (Mozaffari et al., 2021). This biogas can be captured and used as a source of energy. As an anthropogenic source, LFG contributes 14% (1.6 billion Mt of CO_{2eq}) to global emissions (Fig. S3) (Scheehle and Kruger, 2006). This will have increased by 62.5% to 2.6 billion Mt CO_{2eq} by 2050, unless the LFG in landfills is converted to sustainable electricity (Larson et al., 2021). Rather than allowing CH_4 to escape into the atmosphere, LFG is collected, while converting CH_4 to CO_2 through combustion. Untreated LFG emits bad odour and has detrimental effects on the environment and public health. Hence, this needs to be tackled by promoting a CE in waste management (Zhu et al., 2020a).

As over half of the country's population has moved to cities as migrants, China's energy demand has increased substantially (Coskuner et al., 2020). Harnessing LFG as a renewable energy reduces reliance on fossil fuels, which minimize treatment costs and CO_2 emissions into the atmosphere. For this purpose, WTE technologies such as pyrolysis have been deployed to obtain energy from solid waste. Although the technology enables product recovery from unused waste stream (Zhu et al., 2021), avoiding its generation is ideal to deal with the waste with respect to economic and environmental implications. WTE is considered as a promising strategy to reduce waste volume by 90%, while recovering energy and minimizing health concerns (Cheng and Hu, 2010). This is preferable to other options such as wind and solar due to their intermittent characters affected by weather (Yu et al., 2021). Cities in China has taken steps by building WTE plants to capture and utilize LFG as a part of national plan in decreasing GHG emissions. For this reason, since 2013, China has constructed 166 WTE facilities, converting about 10% of total MSW generated to energy (11 million Mt annually) (Fu et al., 2021c). As one of the major cities in China, Shenzhen has developed a 'Waste-Free City' as a pilot plan to deal with its MSW. As Shenzhen's electrical supply is insufficient to meet its energy demand, it is necessary to adopt renewable energy such as WTE to expand access to electricity, while reducing CO_2 emission (Table S2). LFG can facilitate resource recovery and mitigate CO_2 emission into the atmosphere (Shea and Ramgolam, 2019).

A previous work on the conversion of landfilled waste to LFG carried out by Manasaki et al. (2021) addressed its techno-economic evaluation. In spite of its novelty, their work did not directly address the CE aspects of MSW conversion to electricity as a mean of mitigating CO_2 emission from MSW landfilling to the atmosphere (Kurniawan et al., 2021d). To bridge this research gap, this exploratory work investigates the utilization of LFG derived from CH_4 formation at a WTE plant to meet the city's energy demand. This study explores the incorporation of a CCHP system into a WTE power station by utilizing the waste heat of a LFG power generation. To maximize LFG utilization efficiency and optimize the return on investment (ROI) in the city's WTE, this study presents an economic viability of energy generation that incorporates a CCHP into the plant. The WTE's capacity for power generation and total energy generated by waste heat utilization are estimated. The project's benefits to community and its long-term environment impacts are also elaborated.

2. Conceptual framework of co-generation system based on LFG

In recent years, China has improved the sustainability of waste management practices through the applications of co-generation system based on LFG. After the CCHP system generates electricity using ICE, it uses waste heat for cooling and heating, which results in a high utilization rate and energy supply efficiency (Wang et al., 2015). Due to its efficiency, the system can maximize energy output and ROI, while minimizing energy costs and improving the efficiency of LFG consumption (Fig. 1).

Fig. 1 displays that LFG is generated after the MSW is transported to local landfills, which is subsequently converted into electricity by a WTE plant and supplied to residents. The electricity generation produces waste heat, recovered and reused by adopting a CCHP system. The introduction of the CCHP utilizes waste heat to produce cold, hot, hot water and other energy needed by residents. The production, transportation, utilization and reproduction of MSW form a cycle in the framework of CE. This promotes the reuse/recycling of MSW, which eventually minimizes the impacts of MSW on the environment and saves virgin resources and the recovery of secondary resources (Ghisellini et al., 2018).

Practically, electricity is generated using ICE, turbines, microturbines, and gradual oxidizer (GO). Due to its high efficiency in power generation, ICE is a primary equipment utilized in LFG power generation (Manasaki and Gikas, 2014). LFG enters the combustion chamber of ICE and generates heat to power generator. The electricity is

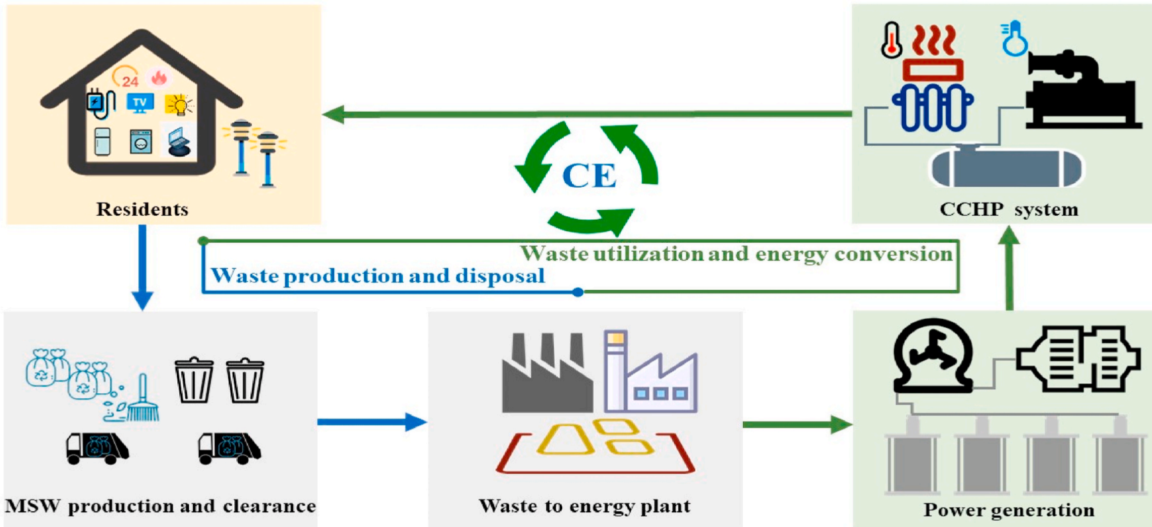

Fig. 1. CCHP system based on WTE.

then transmitted to the building's power via transmission lines. Heat source such as high temperature flue gas and low grade heat sources such as low temperature flue gas and cooling water have an effective recovery (Mondejar et al., 2018). The heat energy generated by fuel combustion is used for power generation. The medium temperature heat energy is formed after high temperature utilization is used for heating, and the low temperature heat energy is used for heating to contribute to an efficient use of energy formed by fuel combustion (Nuñez-Cacho et al., 2018).

Waste heat recovery encompasses flue gas from waste heat and cylinder liner with waste heat, while waste heat equipment covers waste heat boilers, flue gas with hot water absorption chillers, steam absorption chillers, absorption heat pumps, and heat exchangers (Fig. S4). The waste heat from ICE's flue gas generation remains hot. On one hand, high temperature flue gas can be used directly to power flue gas, hot water with absorption chiller uses LiBr as an absorbent and water as a refrigerant to give buildings cold and heat. On the other hand, it can be used as a heat source to power a waste heat boiler and recover the internal energy in the flue gas to generate high temperature and high-pressure steam.

The cooling system of the ICE operates continually to maintain the operating temperature, creating residual heat from water. The waste heat generated by a cylinder liner can be used directly to power the flue gas, hot water absorption, and cold water equipment, which serves as a source of cold and heat for buildings. The waste heat can be used to heat low temperature water vis-à-vis liquid-liquid heat transfer, providing domestic hot water for buildings (Weber and Stadlbauer, 2017).

The recycling of waste heat increases the efficiency of LFG consumption (Lin et al., 2017). In terms of energy supply, the efficiency of LFG's total use is enhanced, while the energy supply modes of LFG are broadened. With respect to energy consumption, the CCHP system meets the loadings of heat, cooling, and electricity, demanded by the building. With respect to energy cycle, the MSW is fully utilized in the conversion of MSW into electricity. It is anticipated that this would assist Shenzhen to meet its energy demand, while assisting policy-makers to attain a sustainable growth in the long-term.

By introducing CE principles to sustain the production and consumption within the waste hierarchy (Fig. S5), it is expected that this work would improve the energy utilization of LFG and energy supply in the form of electricity to local residents (Hong et al., 2015). The CE in this study has been complementing and connecting cleaner production concepts to make materials and energy circulate for longer in each system, thus contributing to saving virgin materials. The application of this scheme will close the energy gap in Shenzhen between market supply and demand by maximizing the energy production capacity of waste, making the waste resources recirculated, and promoting the implementation of CE in waste management.

3. Methodology

LFG production consists of five stages: initial aerobic phase, anaerobic acid phase, methanogenic phase, stabilized methanogenic phase, and humic phase (Mukherjee et al., 2015). The first two stages are short-lived, and the volume of nitrogen and hydrogen attains its peaks during the phases. During the third stage, the accumulated acid from the second stage is converted by methanogenic bacteria into CH_4 and CO_2, and the rate of CH_4 production increases (Wijekoon et al., 2022). Until a stable methanogenic stage is reached, CH_4 production reaches a stable point, accounting for 45–60% of LFG (Kurniawan et al., 2022a). When most of the biodegradable organic matter in MSW is converted to CH_4 and CO_2, the remaining biodegradable organic matter is converted to gas, but the rate of gas release is significantly reduced. The LFG formation occurred in a stable phase that produced CH_4 and CO_2 until the organic waste completely decomposed (Benato et al., 2017). As the CH_4 facilitated the production of fuel for LFG, estimating its production enabled the capacity and utilization value of LFG to be determined. It is assumed that all MSW produced by residents is transported to landfill and that the landfill generates LFG immediately after receiving the MSW, while the LFG is consumed by local residents in the city (Chen et al., 2020).

3.1. Methane production from MSW

Kinetic models are applied to calculate the rate and volume of CH_4 produced (Kurniawan et al., 2022b), while statistical models are used to determine the overall quantity of CH_4 generated from a particular amount of MSW. As it did not specify the distribution of CH_4 emissions during the cycle of LFG formation, the statistical model could not be utilized directly for calculating CH_4 production. Therefore, dynamic models were used to investigate the relationship between the time variation in LFG production and the utilization value of CH_4. As a result, a dynamic model was applied to investigate the characteristics of the LFG formation from the Shenzhen landfill (Fair and Moore, 1932).

Dynamic models such as Scholl-Canyon, Palos-Verdes, and Sheldon-Arleta were tested to estimate gas generation (Bowerman et al., 1977). However, the Scholl-Canyon model did not take account the stage between the start and the peak of gas production. There was no basis to assume that the peak of gas production occurred when the gas produced by the Palos-Verdes and Sheldon-Arleta models reached a half of total gas production. As a result, the models had limitations to estimate CH_4 generation.

For this reason, LFG production is divided into two stages: a growing phase from waste placement to the peak of gas production and a declining phase, following the peak of gas production (Li and Chen, 2017). The formation of LFG was a complex biochemical process that involved microbes for the development of micro-organisms, substrate breakdown, and metabolite formation. Therefore, the CH_4 generation was examined using microbial growth dynamics.

The Monod equation was used to understand the dynamics of microbial development (Pot et al., 2022). The same equation also described the transition between low and high substrate concentrations, implying that microbial growth occurred via the first-order reaction (Akujieze and Idehai, 2014), while linking the rate of microbial growth with the concentration of substrate (Equation (1)):

$$\mu = \frac{1}{X}\cdot\frac{dX}{dt} = \mu_{max}\frac{S}{K+S} \tag{1}$$

where: μ is the microbial ratio growth rate, X is the concentration of active bacteria, t is time, μ_{max} is the maximum ratio of growth rate of micro-organisms, K is the constant of the half-full, S is the concentration of single limiting substrate.

From the start of LFG production to its peak of gas production, the rate of gas production gradually increases (Equation (2)):

$$q_1 = \frac{dG}{dt} = k_1 t + a_1 \tag{2}$$

where: q_1 is the rate of LFG production in the first stage, G is the amount of CH_4 produced within time t, k_1 is the gas production constant in the first stage, a_1 is the gas production factor in the first stage, while t_m is the time of maximum CH_4 production rate. The CH_4 production rate decreases after t_m and CH_4 production process enters the second stage, the total gas production continues to grow.

Although the rate of gas production slowed down in the 2nd stage, the overall gas production continued to grow (Equation (3)):

$$q_2 = \frac{dL}{dt} = -k_2 L \tag{3}$$

where: q_2 is the rate of CH_4 production in the 2nd stage, L is the potential CH_4 generated after time t, k_2 is the gas production constant in the 2nd stage. The integral of Equations (2) and (3) yielded Equations (4) and (5):

$$G = \frac{k_1 t^2}{2} + a_1 t + b_1 \tag{4}$$

$$L = b_2 exp[-k_2(t - t_m)] \tag{5}$$

Under the initial conditions, both the CH_4 production and its production rate are equal to 0, while $a_1 = 0$, $b_1 = 0$ can be obtained by substituting Equations (4) and (5). As the CH_4 production per unit mass of waste in the landfill was L_0, it was assumed that the maximum CH_4 production rate, q_m was reached at aL_0, t_m was the time to reach maximum CH_4 production rate. Then k_1 and b_2 can be expressed as:

$$k_1 = \frac{2aL_0}{t_m^2} \tag{6}$$

$$b_2 = (1-a)L_0 \tag{7}$$

The CH_4 production can be calculated as:

$$G = \frac{aL_0}{t_m^2}t^2 (0 \le \mathrm{t} < t_m) \tag{8}$$

$$\begin{cases} L = (1-a)L_0 exp[-k_2(t-t_m)] \\ G = L_0 - (1-a)L_0 exp[-k_2(t-t_m)] \end{cases} (\mathrm{t} \ge t_m) \tag{9}$$

Therefore, the CH_4 production of landfill for subsequent years can be expressed as:

$$G_t = \sum_{i=1}^{n} G_i = \sum_{i=1}^{n} \frac{aL_{0i}}{t_{mi}^2} t_i^2 (0 \le \mathrm{t} < t_{mi}) \tag{10}$$

$$G_t = \sum_{i=1}^{n} G_i = \sum_{i=1}^{n} \{L_{0i} - (1-a)L_{0i} exp[-k_{2i}(t_i - t_{mi})]\} (\mathrm{t} \ge t_{mi}) \tag{11}$$

Assuming the time, gas production rates and the time to reach maximum CH_4 production rate of the waste remain constant throughout the year, Equations (10) and (11) can be expressed as follows:

$$G_t = \sum_{i=1}^{n} G_i = \sum_{i=1}^{n} \frac{aL_{0i}}{t_m^2} t_i^2 (0 \le \mathrm{t} < t_m) \tag{12}$$

$$G_t = \sum_{i=1}^{n} G_i = \sum_{i=1}^{n} \{L_{0i} - (1-a)L_{0i} exp[-k_2(t_i - t_m)]\} (\mathrm{t} \ge t_m) \tag{13}$$

Both L_0 and k_2. L_0 can be calculated according to the IPCC model (Change, 2006):

$$L_0 = DDOC_m \cdot F \cdot \frac{16}{12} \tag{14}$$

where: $DDOC_m$ is the amount of decomposable degradable organic carbon, F is the fraction of CH_4 in LFG (volume fraction), $\frac{16}{12}$ is the ratio of molecular weight. $DDOC_m$ is expressed as:

$$DDOC_m = W \cdot DOC \cdot DOC_f \cdot MCF \tag{15}$$

where: W is the mass of waste deposited, DOC is the fraction of degradable organic carbon in the year of deposition, DOC_f is the fraction of DOC that decomposes, MCF is the CH_4 correction factor.

Based on the daily output of waste per capita and the number of population in the base year, the W is estimated as follows :

$$W = R_s(1+r_1)^t \times S_0(1+r_2)^t \times 365 \tag{16}$$

where: R_s is the daily output of domestic waste per capita in base year, r_1 is the average of annual growth rate of daily production of household waste/capita, S_0 is the population of base year, and r_2 is the average of annual increase in population size. It is worth noting that five years of the data were used to obtain an average of the growth rate.

DOC is a key parameter that affects CH_4 emission from waste treatment. Its value is related to the composition of the waste:

$$DOC = \sum_j (DOC_j \cdot W_j) \tag{17}$$

where: DOC_j is the fraction of degradable organic carbon in waste type, j is the waste category, W_j is the fraction of waste type. This article investigated the amount of CH_4 production in the model of MSW production, influenced by its composition and the effects of other factors on the MSW output.

3.2. Methane utilization

The CH_4 in this process can be used to generate power. The ICE was utilized for generating energy from LFG (Manasaki et al., 2021). Hence, this article examined the capability of the power supply and the usage of waste heat based on ICE.

When flue gas enters the combustion chamber of the ICE, the temperature and pressure of the gas rapidly increase. The amount of useable heat after the burning of fuel can be expressed as:

$$Q = G_t \times H_u \times \rho_P \times \rho_F \times \rho_H \quad (18a)$$

where: H_u is the low calorific value of gas, ρ_F is the combustion efficiency of fuel in a combustor, ρ_H is the thermal efficiency of ICE, and ρ_P is the CH_4 utilization rate.

The compressed gas can be used to power the generator. The ICE's capacity to generate power (Q_t) can be calculated as (Kurniawan et al., 2022c):

$$Q_t = Q \times \rho_G \quad (18b)$$

where: ρ_G is the electricity generation efficiency of the ICE.

ICE recovers waste heat from flue gas, cylinder piston water, and lubricating oil cooling water, while the primary sources of waste heat are flue gas and cylinder piston water. The useable value of the flue gas in waste heat (Q_{gh}) can be expressed as:

$$Q_{gh} = G_t \times H_u \times \rho_P \times \rho_F \times \rho_{gh} \quad (19)$$

where: ρ_{gh} is the heat coefficient of flue gas in waste heat. The value of cylinder piston water in waste heat (Q_{wh}) is calculated as:

$$Q_{wh} = G_t \times H_u \times \rho_P \times \rho_F \times \rho_{wh} \quad (20)$$

where: ρ_{wh} is the heat coefficient of cylinder piston water in the waste heat. As the waste heat from the ICE can be used for heating or cooling, the available heat energy (Q_h) can be expressed as:

$$Q_h = (Q_{gh} + Q_{wh}) \times \rho_R \times COP \quad (21)$$

where: ρ_R is the recyclable heat efficiency, *COP* is the heating performance/refrigeration coefficient. Following this, a CCHP system was developed to exploit the waste resource via LFG formation.

4. Result and discussions

In 2008, the United Nations Framework Convention on Climate Change (UNFCCC) adopted a tool to calculate CH_4 emission from landfills (Ma et al., 2017a). Based on the UNFCCC's guideline, kitchen waste is easily degradable with a high rate of CH_4 production, while other waste such as wood and paper has different rates. The annual temperature of Shenzhen is 22.4 °C and its annual precipitation is 1933.3 mm (Gu et al., 2015). Based on its environmental characteristics, the values of k and DOC_j of different waste were selected according to the UNFCCC. Table S3 presents the parameter values.

Based on the Law of gas production, it was found that for the easily decomposed organic matter with a rapid fermentation speed, the average of G value is 0.4 L_0. China's MSW in landfills have high water content (40–60%) and organic waste (50–70%) (Lou et al., 2015). Therefore, the value of a was 0.4. The Law assumes that the maximum gas production rate is reached when the produced gas reaches 40% of the total recoverable gas production and that the change of gas production rate starts changing from the first stage to the second stage by assuming that the t_m is 4.5. To forecast MSW output, CH_4 production and energy generation from the landfilled MSW in Shenzhen, the *Matlab* software was adopted for modeling study and data acquisition.

4.1. MSW production and consumption

As people's lifestyle changes, the type of waste generated becomes complex. According to the Shenzhen's Statistical Yearbook (2020), the MSW disposal in local landfills increased by 40% from 5.41 million Mt in 2014 to 7.6 million Mt in 2019. The city's rapid population growth led to a concomitant increase in MSW production and its diversity (Tehrani et al., 2020). The annual output of the MSW for the next 15 years was estimated based on the historical trends of the total population and the volume of MSW disposal in 2021. As illustrated in Fig. 2, the annual MSW output showed obvious upward trends. In 2021, it was about 8.73E+9 kg in 2021 and increase to 2.29E+10 kg in 2035.

It is anticipated that all MSW collected would be disposed of in landfills, where it generates LFG after being landfilled. As depicted in Fig. 2, the CH_4 production capacity of MSW in 2021 was about 5.29E+8 kg and in 2031 it increased to 10^9 kg. By 2035, it will reach to 1.39E+9 kg, an increase of 163% after 15 years of MSW landfilling. This suggests that MSW had a high CH_4-producing potential after landfilling. The CH_4-producing phase last for decades (Wijekoon et al., 2022).

The MSW is categorized based on its impacts on CH_4 production (Fig. 3). Food waste is the main component of MSW in China with an average ratio of 60.2% from 1989 to 2014 (Gu et al., 2017). In Shenzhen, food waste accounts for the MSW with a higher rate of gas production (Chen et al., 2016). The potential for CH_4 production from food waste in 2021 was approximately 2.93E+8 kg and increased to 7.71E+8 kg in 2035. As the second largest contributor to CH_4 generation in local landfills, paper waste contributed 1.95E+8 kg of CH_4 in 2021 and will reach 5.14E+8 kg in 2035. The presence of wood waste can complement food waste and promote gas production (Brown and Li, 2013). Further analysis of the garbage components shows that the standard deviation of food waste was 1.52E+8 kg, while those of paper and wood waste were

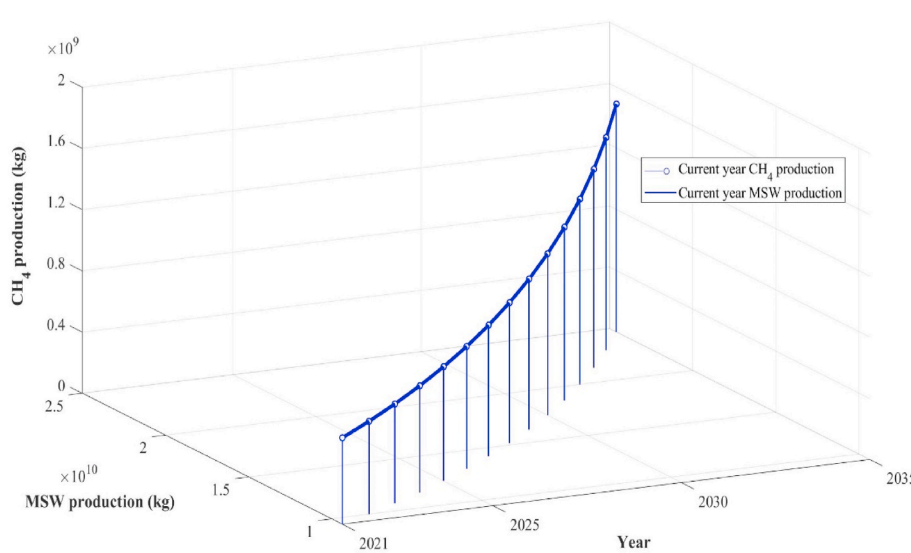

Fig. 2. Projected annual MSW generation and CH_4 production.

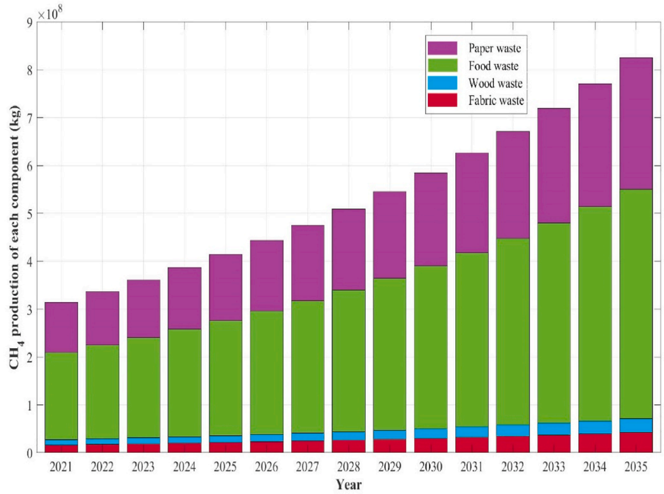

Fig. 3. Methanogenic potential of various types of MSW.

1.01E+8 and 7.77E+6 kg, respectively.

4.2. Annual methane production

Although MSW contributes to CH_4 generation (Ma et al., 2017b), its utilization in this modeling was determined based on the year 2021's CH_4 output. It is necessary to determine the amount of CH_4 produced by MSW landfilling in subsequent years. CH_4 production is anticipated to continue over 40 years after MSW landfilling with its peak in 4.5 years.

As displayed in Fig. 4, after MSW landfilling, the annual CH_4 production grew rapidly, slowed down and then remained flat. This was attributed to the continuous increase of CH_4 production in the landfilled MSW through the initial methanogenic phase that stabilized its decomposition until it was gradually decomposed and the CH_4 production capacity decreased. The trend of the CH_4-producing capacity tended to be flat and then decreased after 20 years of MSW landfilling. This reveals the change of CH_4 production and energy output during the period (Kurniawan et al., 2006).

MSW landfilling in 2021 resulted in a total CH_4 production of 9.4E+7 kg by 2024 and increased to 4.6E+8 kg of CH_4 by 2036, respectively. The total amount of CH_4 produced in 2036 accounted for 0.87 of the CH_4 fraction. To undertake in-depth analysis, this article focused on the CH_4 generation within 20 years after MSW landfilling with MSW input in 2021 as the basis.

Each subsequent year, the local landfill accepts more MSW than the preceding year. As a result, the CH_4 potential in the first year after landfilling increases proportionately. According to Fig. 4, the amount of CH_4 generated in the 1st year increased, following MSW landfilling. MSW landfilling in 2035 is expected to produce about 2.47E+8 kg of CH_4 in 2038 and will reach to 1.26E+9 kg of CH_4 in 2055.

The annual amount of CH_4 produced can be obtained by calculating CH_4 production potential. The annual CH_4 production from the MSW landfilling, depicted in Fig. 5 for 2021, shows that when the rate of CH_4 production is not maximum, the annual CH_4 production increases rapidly. Once the rate of CH_4 is maximum, the annual rate of CH_4 continues to decline until it levels to zero. In the first few years after MSW landfilling, a higher carbon content in MSW led to a higher CH_4 emission until the gas production attained its peak. As the biodegradable organic carbon in MSW is consumed by bacteria, the resulting CH_4 emissions also decreases gradually (Kurniawan et al., 2021c).

MSW landfilling in different years results in varying CH_4 production. Fig. 6 depicts that the total CH_4 production showed an increasing trend. In 2025, the MSW input between 2021 and 2024 will produce CH_4, while an MSW input in 2025 will produce CH_4. Thus, the total CH_4 production in 2025 will result from the MSW landfilling from 2021 to 2024 plus the CH_4 production from MSW landfilling in 2025.

4.3. Energy production using CCHP system

Waste heat recovery technology is regarded as one of the most effective means to improve energy efficiency, while reducing energy consumption and GHG emission (Su et al., 2020). Assuming that the waste heat is heated by waste heat boiler after recovery, the heating and cooling capacity generated after waste heat utilization can be estimated. The MSW landfilling in 2021 can be used to estimate the generation of various types of energy.

The CCHP system enabled energy supply from various sources can be integrated (Fig. 7a) (Xu et al., 2021). In the 4th year, about 1.78e+12 kJ of cooling capacity or 2.68E+12 kJ of heating capacity might be obtained through waste heat utilization. In the 5th year, the amount of waste heat reached its peak with 1.98E+12 kJ of cooling or 2.96E+12 kJ of heating and then started diminishing. It is important to note that in the 18th year, about 1.58E+11 kJ of cooling or 1.05E+11 kJ of heating is still produced.

By using ICE to convert LFG to electricity (Fig. 7b), about 1.48E+8 kWh is generated in the 4th year after MSW landfilling and 1.64E+8 kWh in the 5th year, respectively. The capacity of the power plant reached its peak and gradually decreased. The varying trends of LFG power generation, waste heat cooling generation and waste heat generation were consistent, similar to that of CH_4 generation rate. The output of LFG power generation and the generation of waste heat cooling and waste heat show a rapid growth to the highest rate and then gradually decreases until zero.

Fig. 8 illustrates the generation of electricity based on CH_4 production in subsequent years. The differences in waste heat utilization

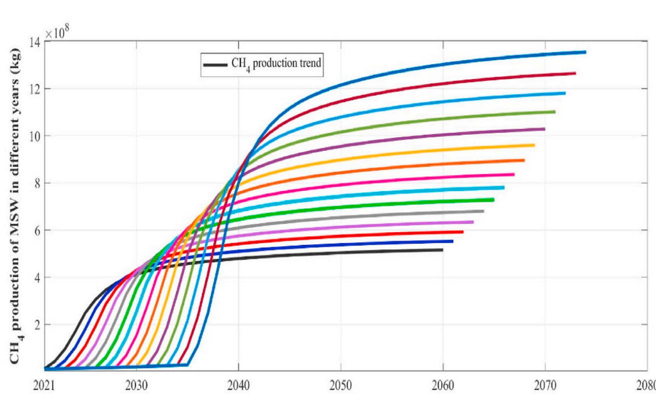

Fig. 4. Trends of annual CH_4 production from MSW landfilling (2021–2025).

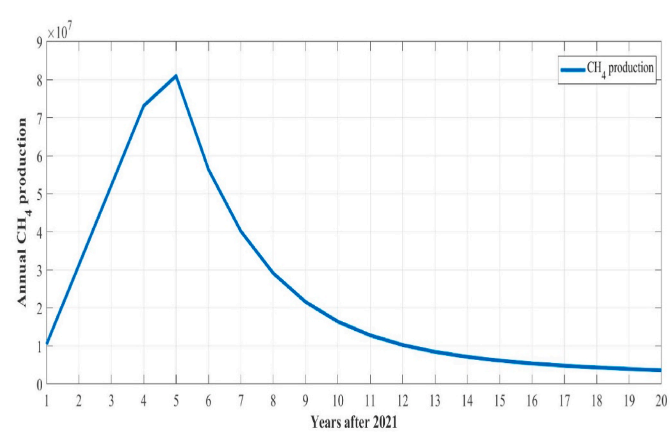

Fig. 5. Projected annual CH_4 production of MSW input after 2021.

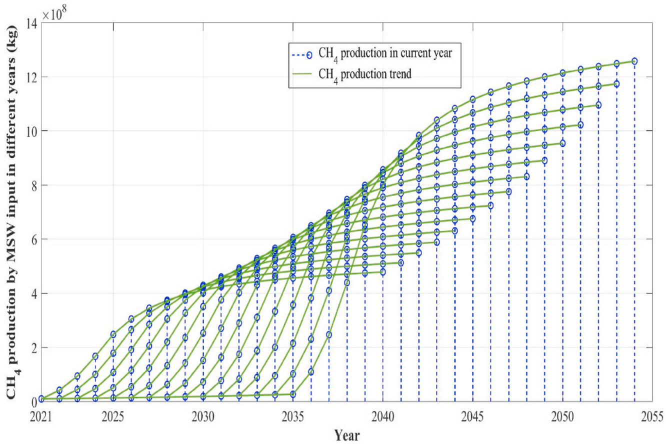

Fig. 6. Cumulative CH_4 production of MSW landfilling in different years.

equipment and the coefficient of performance (COP) values resulted in the varying amount of energy required to produce cooling and heating for buildings (Kaynakli and Kilic, 2007). By 2025, MSW landfilling in 2021 could produce about 5.02E+8 kWh of electricity and 9.08E+12 kJ of heating or 6.05E+12 kJ of cooling via waste heat recovery and utilization.

The MSW landfilling between 2021 and 2024 produced about 1.19E+9 kWh of electricity and 2.15E+13 kJ of heating or 1.43E+13 kJ of cooling via waste heat recovery and utilization. As compared to the sole LFG power generation, both energy consumption and output efficiency can be improved with waste heat recovery and utilization through the CCHP system (Godefroy et al., 2019). Both waste heat cooling and waste heat heating represented energy efficiency improvement that can provide additional energy on top of electricity to leverage the economic value of the landfilled MSW.

4.4. Potential revenue for users

China has actively promoted the construction of 'zero-waste cities' nationwide and committed to MSW reduction to improve their environment (Ministry of Ecology and Environment of the People's Republic of China, 2020). Through its zero-waste goal, the country has transformed traditional waste management into a CE to achieve a sustainable waste management. Hence, the waste is regarded as a 'transformational resource' that needs to be returned to manufacturing (Zaman, 2016). As a 'zero-waste city' construction pilot, Shenzhen is committed to promote CE in waste management.

Shenzhen's per capita power consumption in 2019 was 1.08 kWh (Table S2) (Shenzhen Statistical Yearbook, 2020). The electricity generated by MSW between 2021 and 2035 is sufficient to cover the energy demand of 13.11 million of inhabitants. Because the city's annual temperature exceeds 25 °C, most of urban buildings do not require heating. Assuming that a building in Shenzhen has 32,000 m^3 of floor area with 42 m of height, the building's electricity loading ranges from 100 to 1000 kW and its cooling capacity varies from 500 to 3000 kW. If the building is used with its maximum capacity, the annual power demand is 8.76E+6 kWh, while the annual cooling demand is 9.46E+10 kJ.

Within 15 years, the MSW landfilled in 2021 provides sufficient energy and cooling capacity to cover the building's electrical and cooling requirements. In terms of energy consumption, the cumulative

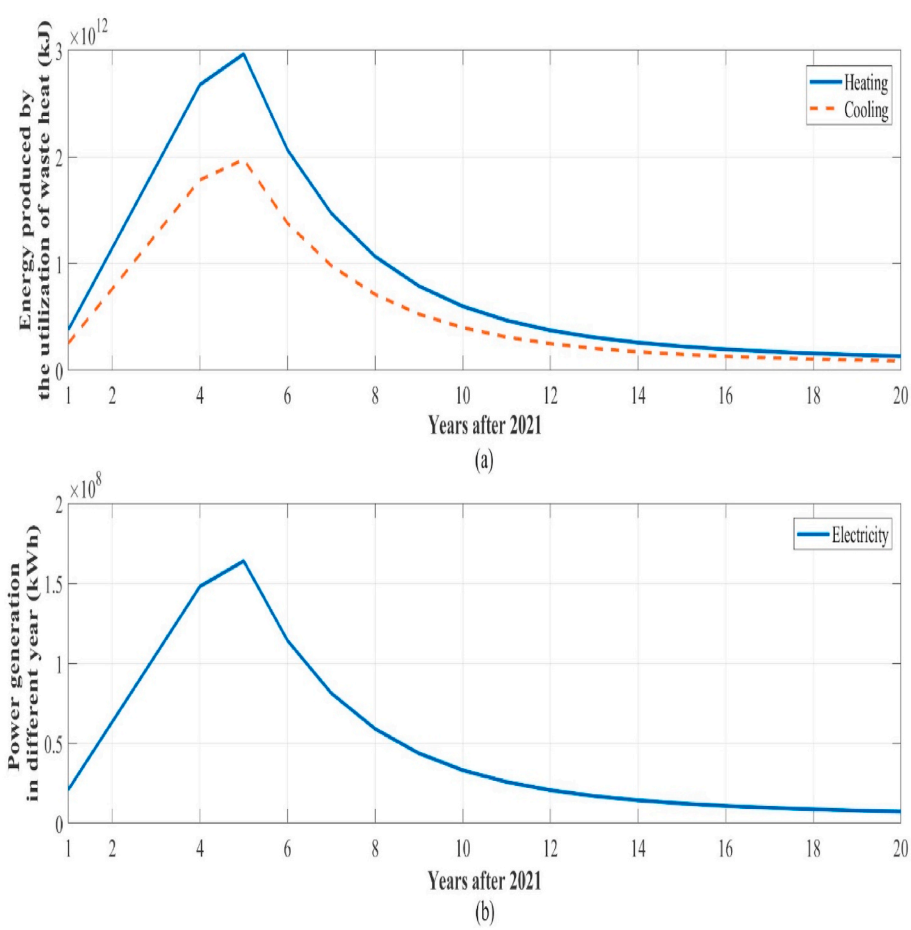

Fig. 7. Energy production of MSW input in 2021.

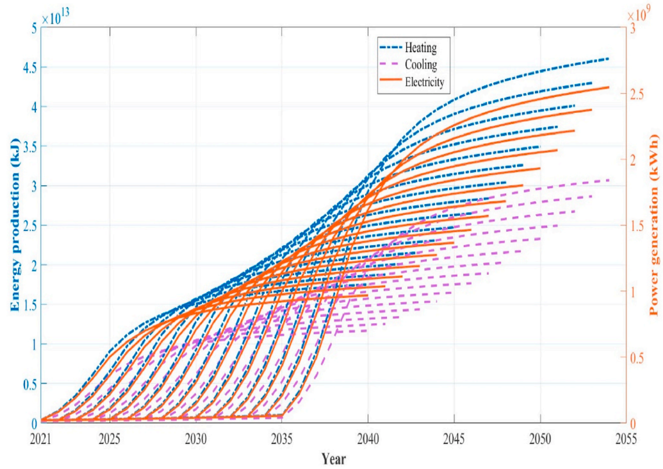

Fig. 8. Output of CCHP system.

electricity generation and cooling production of MSW intake from 2021 to 2035 is equivalent to 1655 years of electricity demand and 1849 years of cooling capacity at maximum occupancy. As a result, the energy generation can meet the diverse energy requirements of buildings in Shenzhen (Bian et al., 2018).

Practically, about 200 ton per day capacity is the minimum amount for a WTE to be commercially viable and the fluctuation of MSW input needs to be maintained within 20% (Handayani and Filatova, 2021). An average of low heating value higher than 5 MJ/kg is essential to complete combustion without requiring auxiliary fuel. The MSW generation in Shenzhen have fulfilled the prerequisites. Consequently, it is technically feasible to harness electricity from the unused waste through WTE facilities (Fu et al., 2022a, 2022b).

Opportunities to use digitalization also exist with the city's buildings. Shenzhen can be benefited from developing smart, data-driven solutions that lead to higher energy efficiency, less CO_2 emissions and better living environments (Xu et al., 2021). Data from its buildings can be analysed to discover patterns, where renovations in property sector are necessary. Heating, cooling and ventilation systems used in the sector require a lot of energy. Accordingly, smart control systems that increase energy efficiency can generate enormous savings and mitigate climate change. The fans controlling building cooling and the fans inside individual servers determine how to get them to interoperate.

Digitalization enables the city to utilize the heat for district heating by establishing circular flows, as this solution reduces energy demand and manages heat distribution efficiently. This provides new opportunities to integrate buildings and systems to distribute energy supply effectively. Eventually, this contributes to the development of smart solutions in the built environment so that energy, water, and transportation in the city can be benefited. This enables cities to reduce their energy demand (Fu et al., 2019).

4.5. Environmental implications of WTE on the environment

Currently one-seventh of the world's population lacks of access to electricity, while the global supply of fossil-based oil has dwindled recently (Ajayi et al., 2022). As electricity has become the lifeblood in the era of Industrial Revolution 4.0 (4IR), the quest to find out smart solutions to power the world in renewable and sustainable ways has intensified in recent years. Resource recovery from waste stream is a means of waste management strategy that could lead the world to a low carbon future (Kaza et al., 2018). The upcycling drives the movement to adding value to waste that have the potential to be recirculated in the system in the recycled or recovered forms of energy (Shi et al., 2017). In any case, the CE concepts organize and locate cleaner production action. This mitigation pathway and their intended outcomes are portrayed as inherently positive for the environment. Therefore, the conversion of waste to energy has emerged as a niche area in the waste sector (Zhu et al., 2020b). The demand for LFG has increased due to the need to shift to clean energy and increase electricity production.

In recent years, China has actively harnessed energy from unused waste and WTE operators obtained a steady revenue via the sale of electricity to local community. Considering China's population, LFG has massive potential to generate around 99,595.6 Mm^3/year (Reshadi et al., 2020), representing a big-scale of business. By implementing WTE, the cost of waste treatment can be offset by revenues from energy customers, who pay for the heat provided by the waste treatment plants. The shift from landfill disposal to WTE plants represents a transformation in waste treatment (Maiurova et al., 2022).

Electricity from the unused MSW could be the energy of the future for the world's inhabitants, who have no access to it (Li et al., 2014). Although installing a huge number of WTE in landfills is a logistical problem due to the cost involved, commercially the WTE facilities could be applied to save operational costs by recovering energy during WTE process and feeding it back into the system. Although energy creation from landfills via LFG is important, maximizing LFG production can cause toxic leachate with respect to high NH_4^+ levels (Kurniawan et al., 2022d).

The electricity obtained from LFG and the heat generated by waste heat recycling can be re-used. The source of energy production optimizes the advantage of LFG (Fu et al., 2017). Not only it reduces waste heat emissions, but also minimizes electricity consumption, which contributes to sustainable development in the long-term. Sound policies such as renewable energy tariffs encourage private investment in capital-intensive energy recovery systems. This enhances landfill's capacity to accept organic waste, while minimizing odour and reducing GHG emission from landfills (Kurniawan et al., 2013).

One of the environmental impacts of waste disposal in landfills is climate change. The CH_4 released from the decomposition of organic waste in landfills contribute to the total CO_2 emissions from waste landfilling, which ranges from 4 to 5% of total global CO_2 emissions (Reshadi et al., 2020). Unlike all waste disposal option that eventually decomposes organic waste into CO_2 and/or CH_4, composting avoids the formation of CH_4 since the organic fraction aerobically biodegrades (Gillingham et al., 2021). Hence, no CH_4 is generated. At current prices for internationally traded emission reductions of USD 4.50/ton under the Clean Development Mechanism in the 1997 Kyoto Protocol, composting obtains a subsidy of about US$12 per ton (Xu et al., 2021). This is about 2.5 times higher than the equivalent amount that would likely accrue from the LFG recovery (Bogale and Viganò, 2014).

In developed countries with rich experience in waste management, WTE has been recognized as one of the most effective methods for MSW treatment, as it reduces waste volume and eliminates CH_4 emissions (Kalyani and Pandey, 2014). The implementation of CE through WTE conversion can facilitate cities to contribute their share to the UN's SDGs such as #7 (Affordable and Clean Energy), #11 (Sustainable Cities and Communities), #12 (Responsible Consumption and Production), and #13 (Climate Action) (Liang et al., 2022) (Fig. S6). To mitigate climate change, WTE technology can recover the waste heat from incineration and produces electricity and heat (Fig. S5). By substituting fossil fuel combustion and avoiding CH_4 formation, it reduces GHG emissions and mitigates climate change. Using abundant MSW as fuel makes WTE plants attractive and a reliable source of renewable energy (Premakumara et al., 2014). It is estimated that energy from biomass can meet 20% of the global demand (Fu et al., 2021a).

In spite of its technological strengths, there are risks associated with the potential future. One is attributed to the risks associated with implementing the pathway such as combustion, while involving unintended negative consequences (Li et al., 2016). The combustion gases contain impurities such as HCl and chloride salts that result in a high corrosion rate of boiler tubes. Chlorine and sulfur are the elements in the corrosion. The high moisture content of waste and its tendency to generate HCl and SO_2 after oxidation erodes WTE facilities (Vilve et al., 2010).

Current domestic WTE technologies such as pyrolysis and gasification are not competitive (Liang et al., 2022), as they are based on low environmental standards. Dioxin and heavy metal emission of the WTE plant is less than the EU standard, while the emission of SO_2 and HCl is within the EU Standard (Table S4). The average of dioxin emissions was about 0.2 ng TEQ Nm^{-3} and met China's standards in 2007 (Lo et al., 2010). In 2014, China's standards were changed to set a maximum emission of 0.1 ng TEQ Nm^{-3} according to international standards (Yi et al., 2009). Due to the relatively loose national standard for NO_x emission and public awareness of its harmful risks, the plants that reserve room for NO_x control equipment do not implement a stringent control due to additional costs (Susorova et al., 2013). Therefore, technical improvements are essential to meet stringent emission standards by acquiring advanced technologies that align with the recent development of WTE technologies (Kurniawan et al., 2022e).

With respect to treatment cost, the largest expenses in operating WTE plants is the breakthrough even point (BEP) of the initial capital investment of USD 600 to 750 per annual Mt of capacity, which results in capital charges of USD 60–75 per ton of the MSW processed (Chang et al., 2016). The capital cost for the WTE in China is expected to be lower, but the prevailing low gate fees and electricity generation per Mt of waste still cause the profitability of the plants under feasibility study. Hence, future studies need to consider WTE's own energy demand for electricity, heat, cold and hot water, and explore the potential of digitalization in WTE's energy demand to deal with an increasing operational cost (Zhu et al., 2022).

5. Conclusions

In this study, LFG has emerged as a viable option for Shenzhen to diversify its energy mix. The paradigm of resource recovery has been implemented from the generation of waste, its energy conversion, to energy supply to local urban residents. This process converts the unused resources from landfilled MSW to a sustainable and renewable energy. The utilization of a CCHP system in a WTE diversifies energy supplies and improves the efficiency of energy utilization in the city.

Although it is not a silver bullet for the city to deal with its MSW over-generation recently, this exploratory study has demonstrated that the conversion of landfilled waste to electricity to reduce GHG emissions in Shenzhen (China) represents a seminal strategy to promote resource recovery and CE in waste management. It was evident from the modeling study that about 2.22E+11 kg of landfilled MSW during a 15-year period yielded 1.34E+10 kg of CH_4, while 90% of CH_4 production still occurred 20 years after its landfilling. During the 5-year of time-span (2021–2025), when the waste heat from power generation is harnessed, the landfilled MSW still generates 1.19E+9 kWh of electricity and 2.15E+13 kJ of heating, or 1.43E+13 kJ of cooling (Fig. S7). The outputs can meet the energy demands of Shenzhen's buildings and population for electricity, cooling, and heating. For a city with increasing population and waste production, this scheme has promoted waste recycling and improved the energy utilization of the landfilled MSW (Menikpura et al., 2016). This reduces the city's landfilled waste, while diversifying its energy supply. Overall, this implies that incorporating technological values to the landfilled waste for electricity generation not only has promoted a CE (Fig. S8), but also facilitated resources recovery from the unused waste in local landfills.

CRediT authorship contribution statement

Xue Liang: Investigation, Writing – original draft, data collection. **Tonni Agustiono Kurniawan:** Writing – original draft, Writing – review & editing. **Hui Hwang Goh:** Formal analysis, Supervision, Funding acquisition. **Dongdong Zhang:** Resources, Project administration. **Wei Dai:** Resources, Project administration. **Hui Liu:** Resources, Project administration. **Kai Chen Goh:** Conceptualization, validation. **Mohd Hafiz Dzarfan Othman:** Conceptualization, validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.133078.

Conversion of landfilled waste-to-electricity for energy efficiency improvement in Shenzhen (China): A strategy to contribute to resource recovery of unused methane for generating on-site renewable energy.

References

Ahmadi, S., Ezeliora, C.D., Sharki, S.H., Osagie, C., Ghosh, S., Igwegbe, C.A., Khan, N.A., 2021. Assessment of health impacts attributed to PM10 exposure during 2015–2017 in Zabol City, Iran. Int. J. Environ. Sci. Technol. 1–14. https://doi.org/10.1007/s13762-021-03587-6.

Ajayi, O.O., Mokryani, G., Edun, B.M., 2022. Sustainable energy for national climate change, food security and employment opportunities: implications for Nigeria. Fuel Comm 10, 100045. https://doi.org/10.1016/j.jfueco.2021.100045.

Akujieze, C.N., Idehai, I.M., 2014. Standardization of the electricity and economic potentials of landfill gas (LFG) in Lagos, Nigeria. Int. J. Sci. Eng. 7, 1–9. https://doi.org/10.12777/ijse.7.1.1-9.

Benato, A., Macor, A., Rossetti, A., 2017. Biogas engine emissions: standards and on-site measurements. Energy Proc. 126, 398–405. https://doi.org/10.1016/j.egypro.2017.08.278.

Bian, R., Xin, D., Chai, X., 2018. A Simulation model for estimating methane oxidation and emission from landfill cover soils. Waste Manage. (Tucson, Ariz.) 77, 426–434. https://doi.org/10.1016/j.wasman.2018.04.029.

Bogale, W., Viganò, F., 2014. A preliminary comparative performance evaluation of highly efficient waste-to-energy plants. Energy Proc. 45, 1315–1324. https://doi.org/10.1016/j.egypro.2014.01.137.

Bowerman, F.R., Rohatgi, N.K., Chen, K.Y., Lockwood, R.A., 1977. A Case Study of the Los Angeles County Palos Verdes Landfill Gas Development Project. Ecological Research Series. EPA-600/3-047.

Brown, D., Li, Y., 2013. Solid state anaerobic co-digestion of yard waste and food waste for biogas production. Bio Technol. 127, 275–280. https://doi.org/10.1016/j.biortech.2012.09.081.

Change, I.P.O., 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan.

Chang, Y., Huang, Z., Ries, R.J., Masanet, E., 2016. The embodied air pollutant emissions and water footprints of buildings in China: a quantification using disaggregated input–output life cycle inventory model. J. Clean. Prod. 113, 274–284. https://doi.org/10.1016/j.jclepro.2015.11.014.

Chen, D.M.C., Bodirsky, B.L., Krueger, T., Mishra, A., Popp, A., 2020. The world's growing municipal solid waste: trends and impacts. Environ. Res. Lttrs 15, 074021. https://doi.org/10.1088/1748-9326/ab8659.

Chen, G., Liu, G., Yan, B., Shan, R., Wang, J., Li, T., Xu, W., 2016. Experimental study of co-digestion of food waste and tall fescue for bio-gas production. Renew. Energy 88, 273–279. https://doi.org/10.1016/j.renene.2015.11.035.

Cheng, H., Hu, Y., 2010. Municipal solid waste (MSW) as a renewable source of energy: current and future practices in China. Bio Technol. 101, 3816–3824. https://doi.org/10.1016/j.biortech.2010.01.040.

Coskuner, G., Jassim, M.S., Nazeer, N., Damindra, G.H., 2020. Quantification of landfill gas generation and renewable energy potential in arid countries: case study of Bahrain. Waste Manag. Res. 38, 1110–1118. https://doi.org/10.1177/0734242X20933338.

Fair, G.M., Moore, E.W., 1932. Heat and energy relations in the digestion of sewage solids: II. Mathematical formulation of the course of digestion. Sewage Works J 428–443.

Fu, D., Huang, Y., Zhang, X., Kurniawan, T.A., Ouyang, T., 2017. Uncovering potentials of integrated TiO_2(B) nanosheets and H_2O_2 for removal of tetracycline from aqueous solution. J. Mol. Liq. 248, 112–130. https://doi.org/10.1016/j.molliq.2017.10.020.

Fu, D., Kurniawan, T.A., Li, H., Wang, L., Chen, Z., Wang, H., Li, W., Wang, Y., Li, Q., 2019. Applicability of HDPC-supported Cu nanoparticles composite synthesized from unused waste digestate for octocrylene degradation in aqueous solutions. Chem. Eng. J. 355, 650–660. https://doi.org/10.1016/j.cej.2018.08.188.

Fu, D., Kurniawan, T.A., Avtar, R., Xu, P., Othman, M.H.D., 2021a. Recovering heavy metals from electroplating wastewater and their conversion into Zn_2Cr-layered double hydroxide (LDH) for pyrophosphate removal from industrial wastewater. Chemosphere 271, 129861. https://doi.org/10.1016/j.chemosphere.2021.129861.

Fu, D., Kurniawan, T.A., Lan, L., Yaqiong, L., Avtar, R., Othman, M.H.D., 2021b. Arsenic removal from aqueous solution by FeS_2. J. Environ. Manag. 286, 112246 https://doi.org/10.1016/j.jenvman.2021.112246.

Fu, D., Kurniawan, T.A., Li, H., Wang, H., Wang, Y., Li, Q., 2021c. Co-oxidative removal of As(III) and tetracycline (TC) from aqueous solutions based on a heterogeneous Fenton's oxidation using Fe nanoparticles (Fe NP)-impregnated solid digestate. Environ. Pollut. 290, 118062 https://doi.org/10.1016/j.envpol.2021.118062.

Fu, D., Kurniawan, T.A., Li, Q., Gui, H., Othman, M.H.D., 2022a. Treatment of As(III)-contaminated water using iron-coated carbon fiber. Materials 15, 4365. https://doi.org/10.3390/ma15124365.

Fu, D., Kurniawan, T.A., Gui, H., Li, H., Wang, Y., Li, Q., 2022b. Role of Cu_xO-anchored pyrolyzed hydrochars on H_2O_2-activated degradation of tetracycline: effects of pyrolysis temperature and pH. Ind. Eng. Chem. Res. 61, 8847–8857. https://doi.org/10.1021/acs.iecr.2c01100.

Ghisellini, P., Ripa, M., Ulgiati, S., 2018. Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. J. Clean. Prod. 178, 618–643. https://doi.org/10.1016/j.jclepro.2017.11.207.

Gillingham, K.T., Huang, P., Buehler, C., Peccia, J., Gentner, D.R., 2021. The climate and health benefits from intensive building energy efficiency improvements. Sci. Adv. 7, eabg0947 https://doi.org/10.1126/sciadv.abg0947.

Godefroy, A., Perier-Muzet, M., Mazet, N., 2019. Thermodynamic analyses on hybrid sorption cycles for low-grade heat storage and cogeneration of power and refrigeration. Appl. Energy 255, 113751. https://doi.org/10.1016/j.apenergy.2019.113751.

Gu, B., Jiang, S., Wang, H., Wang, Z., Jia, R., Yang, J., He, S., Cheng, R., 2017. Characterization, quantification and management of China's municipal solid waste in spatiotemporal distributions: a review. Waste Manage. (Tucson, Ariz.) 61, 67–77. https://doi.org/10.1016/j.wasman.2016.11.039.

Gu, B., Wang, H., Chen, Z., Jiang, S., Zhu, W., Liu, M., Chen, Y., Wu, Y., He, S., Cheng, R., Yang, J., Bi, J., 2015. Characterization, quantification and management of household solid waste: a case study in China. Resour. Conserv. Recycl. 98, 67–75. https://doi.org/10.1016/j.resconrec.2015.03.001.

Handayani, K., Filatova, T., 2021. Greening energy supply in the light of SDGs and Covid-19. IOP Conf. Ser. Earth Environ. Sci. 753, 012035 https://doi.org/10.1088/1755-1315/753/1/012035.

Hong, J., Shen, G.Q., Feng, Y., Lau, W.S.T., Mao, C., 2015. Greenhouse gas emissions during the construction phase of a building: a case study in China. J. Clean. Prod. 103, 249–259. https://doi.org/10.1016/j.jclepro.2014.11.023.

Hosseini, S.S., Yaghmaeian, K., Yousefi, N., Mahvi, A.H., 2018. Estimation of landfill gas generation in a municipal solid waste disposal site by LandGEM mathematical model. Global J. Environ. Sci. Manage. 4, 493–506. https://doi.org/10.22034/GJESM.2018.04.009.

Kalyani, K.A., Pandey, K.K., 2014. Waste to energy status in India: a short review. Renew. Sustain. Energy Rev. 31, 113–120. https://doi.org/10.1016/j.rser.2013.11.020.

Kaynakli, O., Kilic, M., 2007. Theoretical study on the effect of operating conditions on performance of absorption refrigeration system. Energy Convers. Manag. 48, 599–607. https://doi.org/10.1016/j.enconman.2006.06.005.

Kaza, S., Yao, L., Bhada-Tata, P., Van Woerden, F., 2018. What a Waste 2.0: a Global Snapshot of Solid Waste Management to 2050. World Bank, Washington.

Khan, A.H., López-Maldonado, E.A., Khan, N.A., Villarreal-Gómez, L.J., Munshi, F.M., Alsabhan, A.H., Perveen, K., 2022. Current solid waste management strategies and energy recovery in developing countries-State of art review. Chemosphere 291, 133088. https://doi.org/10.1016/j.chemosphere.2021.133088.

Kurniawan, T.A., Lo, W., Chan, G., 2006. Degradation of recalcitrant compounds from stabilized landfill leachate using a combination of ozone-GAC adsorption treatment. J. Hazard Mater. 137, 443–455. https://doi.org/10.1016/j.jhazmat.2006.02.020.

Kurniawan, T.A., Lo, W., Sillanpää, M., 2011. Treatment of contaminated water laden with 4-chlorophenol using coconut shell waste-based activated carbon modified with chemical agents. Separ. Sci. Technol. 46, 460–472. https://doi.org/10.1080/01496395.2010.512030.

Kurniawan, T.A., Oliveira, J.P., Gamaralalage, P.J.D., Nagaishi, M., 2013. City-to-city level cooperation for generating urban co-benefits: the case of technological cooperation in the waste sector between Surabaya (Indonesia) and Kitakyushu (Japan). J. Clean. Prod. 58, 43–50. https://doi.org/10.1016/j.jclepro.2013.08.002.

Kurniawan, T.A., Lo, W., Singh, D., Othman, M.H.D., Avtar, R., Hwang, G.H., Shirazian, S., 2021a. A societal transition of MSW management in Xiamen (China) toward a circular economy through integrated waste recycling and technological digitization. Environ. Pollut. 277, 116741 https://doi.org/10.1016/j.envpol.2021.116741.

Kurniawan, T.A., Singh, D., Avtar, R., Othman, M.H.D., Hwang, G.H., Albadarin, A.B., Shirazian, S., 2021b. Resource recovery from landfill leachate: an experimental investigation and perspectives. Chemosphere 274, 129986. https://doi.org/10.1016/j.chemosphere.2021.129986.

Kurniawan, T.A., Singh, D., Xue, W., Avtar, R., Othman, M.H.D., Hwang, G.H., Shirazian, S., 2021c. Resource recovery toward sustainability through nutrient removal from landfill leachate. J. Environ. Manag. 287, 112265 https://doi.org/10.1016/j.jenvman.2021.112265.

Kurniawan, T.A., Avtar, R., Singh, D., Xue, W., Othman, M.H.D., Hwang, G.H., Iswanto, Kern, A.O., Albadarin, A.B., 2021d. Reforming MSWM in Sukunan (Yogjakarta, Indonesia): a case-study of applying a zero-waste approach based on circular economy paradigm. J. Clean. Prod. 284, 124775 https://doi.org/10.1016/j.jclepro.2020.124775.

Kurniawan, T.A., Liang, X., Singh, D., Othman, M.H.D., Goh, H.H., Gikas, P., Shoqeir, J. A., 2022a. Harnessing landfill gas (LFG) for electricity: a strategy to mitigate greenhouse gas (GHG) emissions in Jakarta (Indonesia). J. Environ. Manag. 301, 113882 https://doi.org/10.1016/j.jenvman.2021.113882.

Kurniawan, T.A., Othman, M.H.D., Singh, D., Avtar, R., Goh, H.H., Setiadi, T., Lo, W.H., 2022b. Technological solutions for long-term management of partially used nuclear fuel: a critical review. Ann. Nucl. Energy 166C, 108736. https://doi.org/10.1016/j.anucene.2021.108736.

Kurniawan, T.A., Liang, X., O'Callaghan, E., Goh, H.H., Othman, M.H.D., Avtar, R., Kusworo, T.D., 2022c. Transformation of solid waste management in China: moving towards sustainability through digitalization-based circular economy. Sustainability 14, 2374. https://doi.org/10.3390/su14042374.

Kurniawan, T.A., Othman, M.H.D., Hwang, G.H., Gikas, P., 2022d. Unlocking digital technology in waste recycling industry in Industry 4.0 era: a transformation towards digitalization-based circular economy in Indonesia. J. Clean. Prod. 357, 131911 https://doi.org/10.1016/j.jclepro.2022.131911.

Kurniawan, T.A., Maiurova, A., Kustikova, M., Bykovskaia, E., Othman, M.H.D., Goh, H. H., 2022e. Accelerating sustainability transition in St. Petersburg (Russia) through digitalization in waste recycling industry: a strategy to promote carbon neutrality in era of Industry 4.0. J. Clean. Prod. 363, 132452 https://doi.org/10.1016/j.jclepro.2022.132452.

Larson, S.L., Martin, W.A., Şengör, S.S., Wade, R., Altamimi, F., 2021. Amendment for increased methane production rate in municipal solid waste landfill gas collection systems. Sci. Total Environ. 772, 145574 https://doi.org/10.1016/j.scitotenv.2021.145574.

Li, D., He, J., Li, L., 2016. A review of renewable energy applications in buildings in the hot-summer and warm-winter region of China. Renew. Sustain. Energy Rev. 57, 327–336. https://doi.org/10.1016/j.rser.2015.12.124.

Li, L., Chen, K., 2017. Quantitative assessment of carbon dioxide emissions in construction projects: a case study in Shenzhen. J. Clean. Prod. 141, 394–408. https://doi.org/10.1016/j.jclepro.2016.09.134.

Li, Y., Li, J., Deng, C., 2014. Occurrence, characteristics and leakage of polybrominated diphenyl ethers in leachate from municipal solid waste landfills in China. Environ. Pollut. 184, 94–100. https://doi.org/10.1016/j.envpol.2013.08.027.

Liang, X., Goh, H.H., Kurniawan, T.A., Zhang, D., Dai, W., Liu, H., Liu, J., Goh, K.C., 2022. Utilizing landfill gas (LFG) for promoting digitalization of data center in China: a novel approach to facilitate sustainable energy transition in era of Industrial Revolution 4.0. J. Clean. Prod. 370, 133297 https://doi.org/10.1016/j.jclepro.2022.133297.

Lin, Y., Kurniawan, T.A., Yi, Z., Albadarin, A., Walker, G., 2017. Enhanced photocatalytic degradation of acetaminophen from wastewater using $WO_3/TiO_2/SiO_2$ composite under UV-VIS irradiation. J. Mol. Liq. 243, 761–770. https://doi.org/10.1016/j.molliq.2017.08.092.

Lo, H.M., Kurniawan, T.A., Sillanpää, M., Pai, T.Z., Liu, M.H., Banks, C.J., Wang, S.C., Wu, K.C., 2010. Modeling biogas production from organic fractions of MSW co-digested with MSWI incinerator ashes in anaerobic bioreactors. Bio Technol. 101, 6329–6335. https://doi.org/10.1016/j.biortech.2010.03.048.

Lou, Z., Wang, M., Zhao, Y., Huang, R., 2015. The contribution of biowaste disposal to odor emission from landfills. J. Air Waste Manage. Assoc. 65, 479–484. https://doi.org/10.1080/10962247.2014.1002870.

Ma, J.J., Du, G., Zhang, Z.K., Wang, P.X., Xie, B.C., 2017a. Life cycle analysis of energy consumption and CO_2 emissions from a typical large office building in Tianjin. China. Build. Environ. 117, 36–48. https://doi.org/10.1016/j.buildenv.2017.03.005.

Ma, X., Liu, X., Liu, G., Yang, L., 2017b. Macro factors analysis and development trend scenario forecast on building energy consumption in Shenzhen. Heat. Vent. Air Cond. 47, 15–20.

Maiurova, A., Kurniawan, T.A., Kustikova, M., Bykovskaia, E., Othman, M.H.D., Goh, H. H., 2022. Promoting digital transformation in waste collection service and waste recycling in a smart city: applying circular economy in Moscow (Russia) to mitigate climate change effects on the environment. J. Clean. Prod. 354, 131604 https://doi.org/10.1016/j.jclepro.2022.131604.

Manasaki, V., Gikas, P., 2014. Landfill gas to electric energy: pros and cons of available technologies. In: International Solid Waste Association (ISWA) World Congress, pp. 8–11.

Manasaki, V., Palogos, I., Chourdakis, I., Tsafantakis, K., Gikas, P., 2021. Techno-economic assessment of landfill gas (LFG) to electric energy: selection of the optimal technology through field-study and model simulation. Chemosphere 269, 128688. https://doi.org/10.1016/j.chemosphere.2020.128688.

Menikpura, S.N.M., Sang-Arun, J., Bengtsson, M., 2016. Assessment of environmental and economic performance of waste-to-energy (WTE) facilities in Thai cities. Renew. Energy 86, 576–584. https://doi.org/10.1016/j.renene.2015.08.054.

Ministry of Ecology and Environment of the People's Republic of China, 2020. Annual Report on Prevention and Control of Environmental Pollution by Solid Waste in Large and Medium City in China. http://www.mee.gov.cn/ywgz/gtfwyhxpgl/gtfw/202012/P020201228557295103367. pdf.

Mondejar, M.E., Andreasen, J.G., Pierobon, L., Larsen, U., Thern, M., Haglind, F., 2018. A review of the use of organic Rankine cycle power systems for maritime applications. Renew. Sustain. Energy Rev. 91, 126–151. https://doi.org/10.1016/j.rser.2018.03.074.

Mozaffari, N., Mozaffari, N., Elahi, S.M., Vambol, S., Vambol, V., Khan, N.A., Khan, N., 2021. Kinetics study of CO molecules adsorption on Al_2O_3/zeolite composite films prepared by roll-coating method. Surf. Eng. 37, 390–399. https://doi.org/10.1080/02670844.2020.1768628.

Mukherjee, S., Mukhopadhyay, S., Hashim, M.A., Sen Gupta, B., 2015. Contemporary environmental issues of landfill leachate: assessment and remedies. Crit. Rev. Environ. Sci. Technol. 45, 472–590. https://doi.org/10.1080/10643389.2013.876524.

Nuñez-Cacho, P., Górecki, J., Molina-Moreno, V., Corpas-Iglesias, F.A., 2018. What gets measured, gets done: development of a circular economy measurement scale for building industry. Sustainability 10, 2340. https://doi.org/10.3390/su10072340.

Osra, F.A., Ozcan, H.K., Alzahrani, J.S., Alsoufi, M.S., 2021. Municipal solid waste characterization and landfill gas generation in Kakia landfill, Makkah. Sustainability 13, 1462. https://doi.org/10.3390/su13031462.

Premakumara, D.G.J., Canete, A.L.M.L., Nagaishi, M., Kurniawan, T.A., 2014. Policy implementation of the republic act (RA) No. 9003 in the Philippines on MSW management: a case study of Cebu city. Waste Manag. 34, 971–979. https://doi.org/10.1016/j.wasman.2013.10.040.

Pot, V., Portell, X., Otten, W., Garnier, P., Monga, O., Baveye, P.C., 2022. Accounting for soil architecture and microbial dynamics in microscale models: current practices in soil science and the path ahead. Eur. J. Soil Sci. 73, e13142 https://doi.org/10.1111/ejss.13142.

Reshadi, M.A.M., Bazargan, A., McKay, G., 2020. A review of the application of adsorbents for landfill leachate treatment: Focus on magnetic adsorption. Sci. Total Environ. 731, 138863 https://doi.org/10.1016/j.scitotenv.2020.138863.

Scheehle, E.A., Kruger, D., 2006. Global anthropogenic methane and nitrous oxide emissions. Energy J. https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI3-2.

Shea, R.P., Ramgolam, Y.K., 2019. Applied levelized cost of electricity for energy technologies in a small island developing state: a case study in Mauritius. Renew. Energy 132, 1415–1424. https://doi.org/10.1016/j.renene.2018.09.021.

Shi, Q., Chen, J., Shen, L., 2017. Driving factors of the changes in the carbon emissions in the Chinese construction industry. J. Clean. Prod. 166, 615–627. https://doi.org/10.1016/j.jclepro.2017.08.056.

Susorova, I., Tabibzadeh, M., Rahman, A., Clack, H.L., Elnimeiri, M., 2013. The effect of geometry factors on fenestration energy performance and energy savings in office buildings. Energy Build. 57, 6–13. https://doi.org/10.1016/j.enbuild.2012.10.035.

Su, Z., Ouyang, T., Chen, J., Xu, P., Tan, J., Chen, N., Huang, H., 2020. Green and efficient configuration of integrated waste heat and cold energy recovery for marine natural gas/diesel dual-fuel engine. Energy Convers. Manag. 209, 112650 https://doi.org/10.1016/j.enconman.2020.112650.

Tehrani, A.M., Bahrami, A., Leili, M., Poorolajal, J., Zafari, D., Samadi, M., Mahvi, A.H., 2020. Investigation of seasonal variations and probabilistic risk assessment of BTEX emission in municipal solid waste transfer station. Int. J. Environ. Anal. Chem. https://doi.org/10.1080/03067319.2020.1814269.

Vilve, M., Vilhunen, S., Vepsäläinen, M., Kurniawan, T.A., Lehtonen, N., Isomäki, H., Sillanpää, M., 2010. Degradation of 1,2-dichloroethane from contaminated water laden with ion-exchange resin using Fenton's oxidation. Environ. Sci. Pollut. Res. 17, 875–884. https://doi.org/10.1007/s11356-009-0291-5.

Wang, J.J., Yang, K., Xu, Z.L., Fu, C., 2015. Energy and exergy analyses of an integrated CCHP system with biomass air gasification. Appl. Energy 142, 317–327. https://doi.org/10.1016/j.apenergy.2014.12.085.

Weber, B., Stadlbauer, E.A., 2017. Sustainable paths for managing solid and liquid waste from distilleries and breweries. J. Clean. Prod. 149, 38–48. https://doi.org/10.1016/j.jclepro.2017.02.054.

Wijekoon, P., Koliyabandara, P.A., Cooray, A.T., Lam, S.S., Athapattu, B.C., Vithanage, M., 2022. Progress and prospects in mitigation of landfill leachate pollution: risk, pollution potential, treatment and challenges. J. Hazard Mater. 421, 126627 https://doi.org/10.1016/j.jhazmat.2021.126627.

Xu, J., Luo, E., Hochgreb, S., 2021. A thermoacoustic combined cooling, heating, and power (CCHP) system for waste heat and LNG cold energy recovery. Energy 227, 120341. https://doi.org/10.1016/j.energy.2021.120341.

Yi, Z., Zhuo, Z., Haiying, Z., Xiangrong, M., Jian, W., 2009. Study on cleaning technology of municipal solid waste landfill gas (LFG). In: 3rd International Conference on Bioinformatics and Biomedical Engineering. https://doi.org/10.1109/ICBBE.2009.5163465.

Yu, H., Engelkemier, S., Gençer, E., 2021. Process improvements and multi-objective optimization of compressed air energy storage (CAES) system. J. Clean. Prod. 130081 https://doi.org/10.1016/j.jclepro.2021.130081.

Zaman, A.U., 2016. A comprehensive study of the environmental and economic benefits of resource recovery from global waste management systems. J. Clean. Prod. 124, 41–50. https://doi.org/10.1016/j.jclepro.2016.02.086.

Zhu, M., Kurniawan, T.A., You, Y., Othman, M.H.D., Avtar, R., Fu, D., Hwang, G.H., 2020a. Fabrication, characterization, and application of ternary magnetic recyclable Bi_2WO_6/BiOI@Fe_3O_4 composite for photodegradation of tetracycline in aqueous solution. J. Environ. Manag. 270, 110839 https://doi.org/10.1016/j.jenvman.2020.110839.

Zhu, M., Kurniawan, T.A., You, Y., Othman, M.H.D., Avtar, R., 2020b. 2D Graphene oxide (GO) doped *p-n* type BiOI/Bi_2WO_6 as a novel composite for photodegradation of bisphenol A (BPA) in aqueous solutions under UV vis irradiation. Mater. Sci. Eng., C 108, 110420. https://doi.org/10.1016/j.msec.2019.110420.

Zhu, M., Kurniawan, T.A., Avtar, R., Othman, M.H.D., Ouyang, T., Yujia, H., Xueting, Z., Setiadi, T., Iswanto, 2021. Applicability of TiO_2(B) nanosheets@hydrochar composites for adsorption of tetracycline from contaminated water. J. Hazard Mater. 405, 123999 https://doi.org/10.1016/j.jhazmat.2020.123999.

Zhu, M., Kurniawan, T.A., Liang, D., Song, Y., Hermanowicz, S.W., Othman, M.H.D., 2022. Advances in Bi*OX*-based ternary photocatalysts for water treatment and energy storage applications: a critical review. Rev. Environ. Sci. Bio/Technol. 21, 331–370. https://doi.org/10.1007/s11157-022-09617-0.