Municipal Solid Waste (MSW) Incineration's Potential Contribution to Electricity Production and Economic Revenue in Taiwan

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ABSTRACT

This study deals with important waste and energy management issues; specifically, it examines municipal solid waste (MSW) incineration—a viable technology for energy recovery and electricity generation. Due to its limited available land space and natural resources, Taiwan has 24 waste-to-energy (WTE) plants in operation, the highest density of MSW incinertaors (number of MSW incinerators/land area) in the world. The total design power generation capacity of these 24 WTE plants is 558.5 MW. If this capcity was fully realized, it could generate a revenue of over US$167 million/year. Taiwan's MSW has high calorific value (1,873 kcal/kg) and low water content (53.4%), making it a valuable source of renewable energy. Approximately 6.5 million metric tons/year of MSW is currently being incinerated for energy recovery and waste reduction. This study applies the R1 formula to the WTE plants in Taiwan and finds that design power generation, capacity, and waste low heating value (LHV) are important design parameters for incineration facilities. This analysis of the energy production of these plants should be useful to others considering similar applications.

Keywords: Economic revenue, Municipal solid waste, R1 formula, Waste-to-energy

1. Introduction

Rapid industrialization and economic development over the past decades have led to adverse environmental effects, such as air quality deterioration, water pollution, and illegal dumping of solid wastes. The generation of municipal solid waste (MSW) has increased in parallel with rapid industrialization and population growth (Chakraborty *et al*., 2013; Ng *et al*., 2014; Singh *et al*., 2011), which is expected to reach 9.5 billion by 2050 (FAO, 2009). MSW is waste discarded in urban areas. It is predominantly household waste with a minor portion of commercial waste (Hossain *et al*., 2014). Globally, about 1.3 billion metric tons of MSW are produced each year (Hoornweg and Bhada-Tata, 2012). As the amount of MSW increases, so do the human health problems that can be traced back to insufficient and/or improper treatment or disposal of MSW. However, properly managed MSW can also be a valuable source of recovered energy.

Making MSW environmentally safe is usually the primary goal of waste management (Leckner,

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2015). More recently, energy recovery from MSW has become an important consideration, and many technologies have been developed for energy recovery from MSW. MSW is usually processed in one of three ways: landfilling, biological treatment, or thermal treatment. Landfilling is the most common practice and accounts for approximately 95% of the total collected MSW worldwide (Foo and Hameed, 2009), but it poses threats to underlying aquifers and releases methane (CH_4) and carbon dioxide (CO_2) to the atmosphere (Kalyani and Pandey, 2014). Both CH_4 and CO_2 are potent greenhouse gases (GHGs), and CH_4 is 25 times more detrimental than CO_2 from the global warming perspective (IPCC, 2006). Annually, 2% of global GHGs are from landfill waste (Castaldi *et al*., 2013). Biological treatment is more environmentally friendly; it is based on the enzymatic decomposition of organic matter by microbial action (Tan *et al*., 2014). Typical thermal technologies for MSW treatment include incineration (combustion), gasification, and pyrolysis (Hossain *et al*., 2014). Thermal technologies have been developed and improved in recent years. However, it should be noted that incineration may produce toxic substances, such as heavy metals and dioxin, that have negative effects on the environment. From the environmental perspective, it is possible for a technology to yield positive effects in some areas, while generating negative influences in other areas (Rehl and Müller, 2011); an optimal solution for MSW treatment has not yet been fully established (Magrinho *et al*., 2006).

Waste-to-energy (WTE) processes often involve direct conversion of the energy content of MSW to steam or electricity (Castaldi *et al*., 2013), and WTE has been defined as a renewable source of electricity by the Energy Policy Act of 2005 (Castaldi *et al*., 2013). In 2003, the United States Environmental Protection Agency (US EPA) pointed out that WTE, as a renewable source of electricity, has less adverse environmental effects than other sources (ASME, 2008). WTE is also cost-effective and has been practiced in many counties, including Australia, Canada, Finland, China, Singapore, Japan, and the United States (Ablia, 2014; Hossain *et al*., 2014). The cost of WTE is approximately 10% of that of solar energy and 66% that of wind energy (Lim *et al*., 2014). The average efficiencies of WTE plants are about 18% for electricity generation and 63% for heat production (Leme *et al*., 2014). WTE technologies can minimize the negative effects of waste dumping and GHG emissions; therefore, they are promising alternatives for the management of MSW. Globally, over 800 WTE plants annually incinerate about 190 million metric tons of MSW to generate energy from waste (Stengler, 2005).

This study conducted a simple and reliable test to evaluate the energy efficiency and economic revenue of the WTE plants in Taiwan. Proper management of WTE plants can contribute to efficient resource use including waste prevention and energy recovery. The results of this study will help practitioners developing WTE systems or policy frameworks for MSW management strategies.

2. Experimental section

Energy content is often measured by lower or higher heating values (LHV or HHV, respectively). The LHV of MSW is the total quantity of sensible heat released during combustion, often called the net calorific value (NCV) (Kropáč *et al*., 2009). Most WTE plants that generate steam at 40 bar/400^{o}C can achieve an electrical efficiency of approximately 22~24% of the LHVs (Bogale and Viganó, 2014; Gohlke and Martin, 2007). The HHV is the LHV plus the latent heat contained in the water vapor released by combustion. The latent heat of water that corresponds to a phase change at 25°C is typically assumed to be 2,442 kJ/kg (Consonni *et al*., 2005; Consonni and Viganò, 2011). Knowledge of energy content and elemental composition is essential to determine the mass and energy balances for treatment processes such as incineration.

In 2008, the European Commission introduced a criterion, named the R1 formula, to determine if a plant is an energy recovery plant (Friege and Fendel, 2011; Maier and Oliveira, 2014). The formula differentiates the recovery of MSW from its disposal. Recovery can take place if R1 > 0.65 for plants built in 2009 or later (for older plants, R1 > 0.60). Plants with values below these limits are considered disposal plants. The criterion is expressed in the following formula (Grosso *et al*., 2010; Rouf, 2001):

$$\mathrm{R1} = (E_p - (E_f + E_i)) / (0.97\,(E_w + E_f)) \tag{1}$$

where E_p (GJ/year) is the annual fuel energy used to produce heat and electricity. It is calculated as the sum of the electricity (E_{el}) multiplied by 2.6, and the heat produced for commercial use (E_{th}) multiplied by 1.1, as follows:

$$E_p = 2.6 \times E_{el} + 1.1 \times E_{th} \tag{2}$$

E_f (GJ/year) is the annual fuel energy input to the system, which contributes to the production of steam; it is obtained by summing the products of each fuel flow by its NCV (GJ/year). E_i (GJ/year) is the annual imported energy, for instance, electricity or steam from other sources. E_w (GJ/year) is the annual energy contained in the treated waste, based on the NCV. The factor accounting for energy losses caused by heat in the bottom ash and radiation is 0.97.

This can be compared to the conventional efficiency for electricity production, which is as follows:

$$\eta = E_{pe} / E_w \tag{3}$$

where E_{pe} (=E_p / 2.6) (GJ/year) is the electrical energy corresponding to the fuel energy (E_p). If E_f, E_i, and the energy loss are small and negligible and the focus is on electricity production, then R1 = E_p / E_w = 2.6 × η, and η can be considered the actual efficiency of electricity production. An energy analysis helps to determine the most efficient way to recover the energy contained in MSW.

3. Results and discussion

3.1 MSW generation and management in Taiwan

An MSW's suitability for energy recovery varies according to several characteristics. As shown in Fig. 1, the total feed to the WTE plants in Taiwan is ca. 6.5 × 10^6 metric tons/year, and there has not been much increase since 2012. However, its composition has been gradually changed by increases in industrial wastes. The decrease in general waste reflects the success of the reuse, recycle, and recover (3R) policy for general wastes. Studies have determined that some industrial wastes can be incinerated without much pretreatment; consequently, five incinerators (Tianwaitian, Bali, Shuline, Chiayi City, and Yongkang Plants, tabulated in Table 1) have accepted industrial waste as part of their feed since 2006. Thus, the 24 WTE plants in Taiwan have the capacity to treat all of the waste generated, including both MSW and combustible industrial

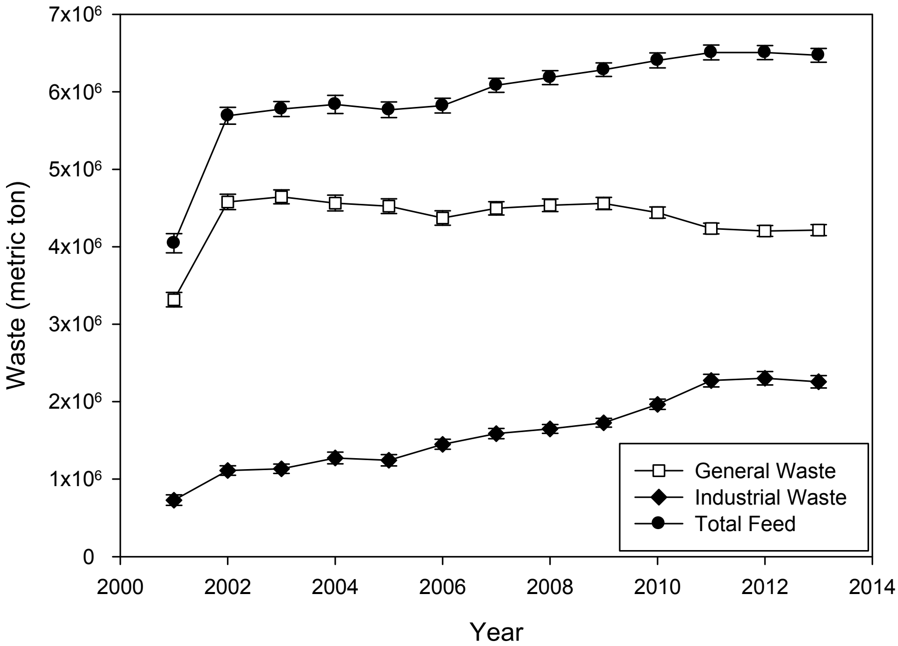

Fig. 1. Compositions of feed to the WTE plants. (Taiwan EPA, 2016)

waste.

The metabolization of MSW in Taiwan involves its production, throughput, and processing (Chen and Wu, 2015). Households and firms are legally obliged to dispose of their waste using waste cleaning teams or registered waste management companies. However, some MSW may be illegally collected by wastepickers who gather recyclable MSW and then sell it (Demaria and Schindler, 2016). Furthermore, uncollected MSW may be illegally dumped or burned in the open, polluting the environment (Talyan *et al.*, 2008). Both illegal activities decrease the feeding of WTE plants and affect their energy efficiency. Taiwan's MSW should be legally and properly managed according to its Waste Disposal Act.

MSW is generally collected without further separation, thus, it is made up of different organic and inorganic fractions. The composition, proximate analysis, and energy content of MSW in Taiwan are tabulated in Table 2. In 2015, paper (34.7%) and food waste (40.4%) were the dominant fractions, followed by plastics (15.6%), textiles (4.7%), wood and garden waste (1.6%), glass (1.0%), and iron (0.3%). Thus, typical MSW contains many valuable materials such as paper, plastics, glass, wood, and textile products that can be recycled. Recovery of such material at the source would reduce the amount of waste and favorably reduce the moisture content and increase the heating value of MSW (Leckner, 2015). In addition, the recycling of paper and plastics has greatly contributed to energy savings (Chen, 2016). It has been found that Taiwan's MSW contains a relatively high heating value (greater than 1,200 kcal/kg) and low moisture content (~50%), which are favorable characteristics for direct incineration.

3.2 WTE plants in Taiwan

There are 24 large-scale MSW incineration facilities in operation in Taiwan, which has one of the highest, if not the highest, density (number of MSW incinerators/area) of MSW incinerators in the world. Therefore, the design capacity, design power generation capacity, and LHV of these WTE plants can be indicators of WTE plants in general

Table 1. Design capacity, design power generation capacity, and LHV of WTEs in Taiwan (Taiwan EPA, 2014)

No.	Location		Design Capacity (Metric ton MSW/day)	Design Power Generation (MW)	Design LHV (kcal/kg)	Modified R1 results	Promotion Type	Year in Line
1	Keelung City	Tianwaitian plant	600	15.8	2,400	1.10×10^{-5}	OT	2006/03
2	Taipei City	Beitou plant	1,800	48.0	2,400	1.11×10^{-5}	POO	1999/05
3	Taipei City	Muzha plant	1,500	13.5	1,600	0.56×10^{-5}	POO	1995/03
4	Taipei	Neihu plant	900	6.0	1,350	0.49×10^{-5}	POO	1992/01
5	New Taipei City	Xindian plant	900	14.6	1,553	1.04×10^{-5}	OT	1994/11
6	New Taipei City	Shuline plant	1,350	22.3	1,533	1.08×10^{-5}	OT	1995/07
7	New Taipei City	Bali plant	1,350	35.8	2,305	1.15×10^{-5}	OT	2001/07
8	Taoyuan County	-	1,350	35.1	2,300	1.13×10^{-5}	BOO	2001/10
9	Yilan County	Lize plant	600	14.7	2,300	1.07×10^{-5}	OT	2006/04
10	Hsinchu City	-	900	23.7	2,300	1.14×10^{-5}	OT	2001/02
11	Miaoli County	Jhunan plant	500	11.8	2,300	1.03×10^{-5}	BOT	2006/02
12	Taichung City	Wenshan plant	900	13.0	1,500	0.96×10^{-5}	OT	1995/12
13	Taichung City	Houli plant	900	22.6	2,300	1.09×10^{-5}	OT	2000/08
14	Taichung City	Wuri plant	900	26.2	2,300	1.27×10^{-5}	BOT	2004/09
15	Changhua County	Hsichou plant	900	22.6	2,300	1.09×10^{-5}	OT	2001/01
16	Chiayi City	-	300	2.3	1,350	0.57×10^{-5}	OT	1998/11
17	Chiayi County	Lutsau plant	900	25.0	2,500	1.11×10^{-5}	OT	2001/12
18	Tainan City	Chengxi plant	900	14.3	1,600	0.99×10^{-5}	OT	1999/08
19	Tainan City	Yongkang plant	900	22.5	2,400	1.04×10^{-5}	OT	2008/03
20	Kaohsiung City	Central region	900	25.5	1,900	1.49×10^{-5}	POO	1999/09
21	Kaohsiung City	Southern region	1,800	49.0	2,500	1.09×10^{-5}	POO	2000/01
22	Kaohsiung City	Jenwu plant	1,350	33.7	2,400	1.04×10^{-5}	OT	2001/12
23	Kaohsiung City	Gangshan plant	1,350	38.0	2,500	1.13×10^{-5}	OT	2001/04
24	Pingtung County	Kanding plant	900	22.5	2,200	1.14×10^{-5}	OT	2001/12

Table 2. Composition, proximate analysis, and energy content of the MSW in Taiwan (Taiwan EPA, 2016)

Properties	2010	2011	2012	2013	2014	2015
Composition (% by weight on a dry basis)						
Paper	39.6	38.3	38.9	41.7	39.4	34.7
Textiles	2.5	2.0	2.5	2.4	2.3	4.7
Garden/trimmings	1.7	1.4	1.5	1.3	1.3	1.6
Food waste	35.7	39.2	38.3	35.1	37.6	40.4
Plastics	16.6	15.7	15.6	16.6	16.6	15.6
Leather/rubber	0.5	0.2	0.2	0.4	0.1	0.5
Iron	0.3	0.2	0.3	0.3	0.2	0.3
Other metal	0.3	0.3	0.2	0.2	0.3	0.2
Glass	1.5	1.3	1.3	0.7	0.8	1.0
Others	1.2	1.4	1.3	1.5	1.3	1.1
Proximate Approximate analysis (% by weight on a wet basis)						
Combustibles	42.2	40.2	41.1	41.4	39.4	39.3
Ash	5.2	4.7	5.0	4.5	5.5	6.0
Moisture	52.7	55.1	54.0	54.1	55.2	54.8
Energy content (as discarded)						
HHV (kcal/kg)	2,417	2,359	2,451	2,514	2,354	2,478
LHV (kcal/kg)	1,896	1,854	1,941	2,012	1,865	1,972

(Table 1). All of the 24 WTE plants in Taiwan have been operational since 2008.

3.2.1 Operation of the WTE plants

As shown in Table 1, these 24 WTE plants can be classified into four modes: Public-Own-Operate (POO), Build-Operate-Transfer (BOT), Build-Operate-Own (BOO), and Operate-Transfer (OT). The five WTE plants in the two main provincial cities (Taipei City and Kaohsiung City) are in the POO mode, and are owned and operated by the government. The POO arrangement usually has heavier financial burdens and is suitable only for municipalities with stable incomes. Most of the other WTE plants (16 incinerators) are operated according to the OT arrangement, which means that the government builds the facilities and the private sector operates them. Under the OT arrangement, the government retains ownership of the plants. The OT arrangement is suitable for waste management at the county level, with arrangements made by the local government. WTE operators find that this type of arrangement suits the characteristics of MSW and financing.

The WTE plants with over 1,000 metric tons/day capacity are located in major cities, such as Taipei, New Taipei, and Kaohsiung (Table 1). The capacity of the Taoyan plant (#8) is 1,350 metric tons/day, as it is designed to accommodate MSW from the nearby Taipei and New Taipei Cities, when needed. Using the data from Table 1, Fig. 2 illustrates the design capacities of the 24 WTE plants relative to the local population densities using two-dimensional Arc GIS9.2. As shown, higher population densities generate more MSW, as mentioned. The LHV of the MSW is also a critical parameter in the design of WTE facilities. The design LHV range is from 1,350 to 2,500 kcal/

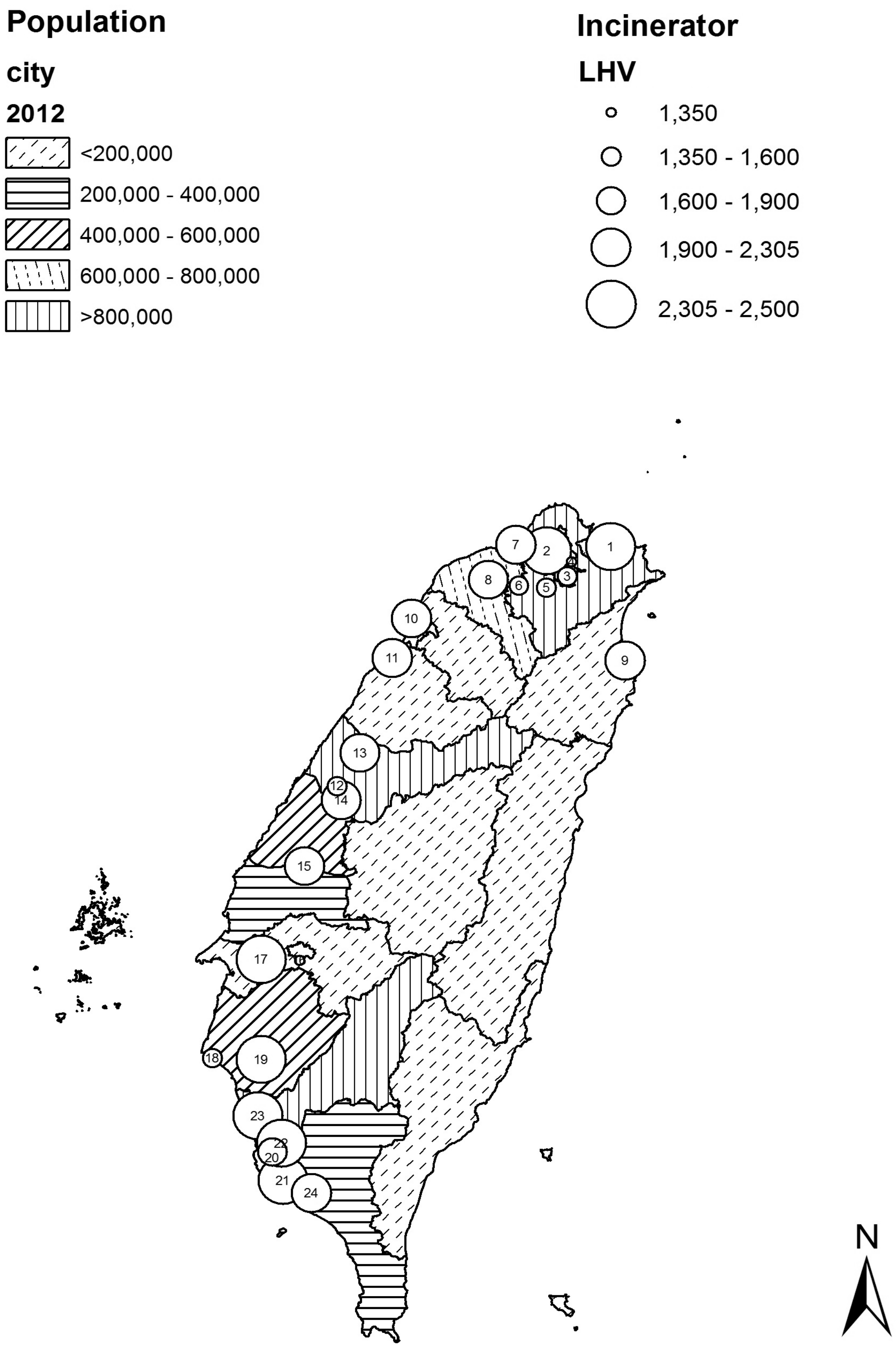

Fig. 2. Designed capacities of the 24 plants relative to the population densities using two-dimensional Arc GIS9.2 (National Statistics, 2016)

kg, which is suitable for the MSW in Taiwan. (The LHVs of MSW in Taiwan are shown in Table 2.)

3.2.2 Processes used in WTE plants

The typical treatment processes used in

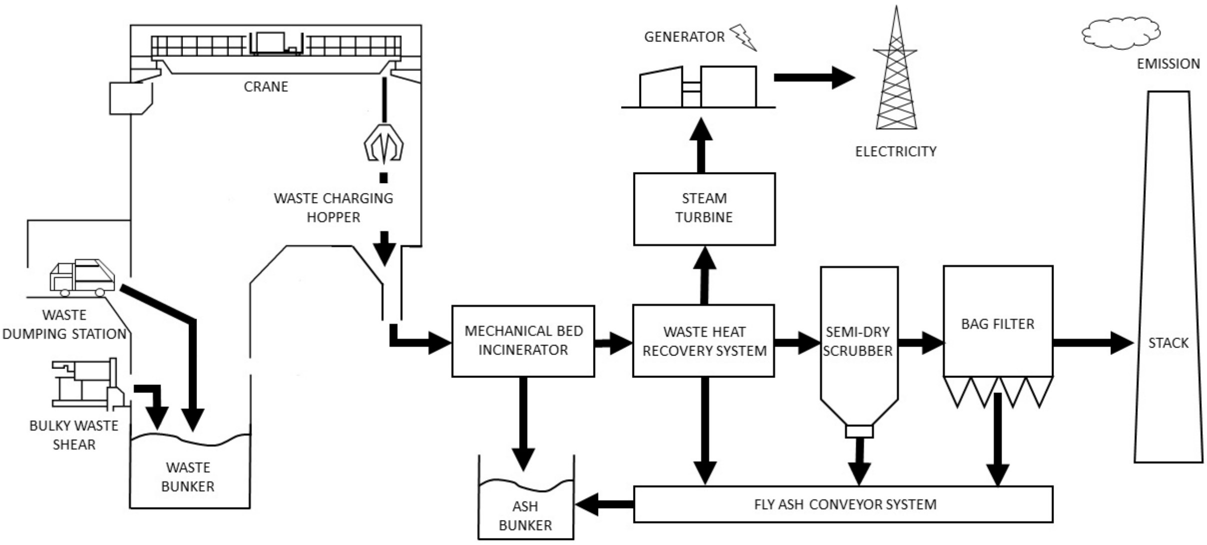

Fig. 3. Typical treatment processes of WTE plants (by authors).

WTE plants in Taiwan are shown in Fig. 3. MSW is collected by municipalities and independent haulers and brought to the WTE plants. Each truck is weighed at the scale house as it enters the facility and weighed again as it exits. Trucks unload the collected waste into the holding bunker. A larger in-door crane then transfers the trash into the combustor. Waste is burned and the remaining ash is collected at the bottom of the incinerator. The combustion heat is fed into a boiler to produce steam. The steam drives a turbine that generates electricity. The exhaust gas passes through a semi-dry scrubber and bag filters before being discharged into the atmosphere through the stack.

Due to the potential boiler corrosion problem, the steam operational parameters in typical WTE plants are limited to 40 bar/400°C (Bogale and Viganò, 2014; Brunner and Rechberger, 2015; Leckner, 2015). For a typical thermodynamic balance, the efficiency of energy conversion increases with higher steam temperature and pressure. The heat converted in a steam turbine can be used as an energy source for generating steam and electricity. Increasing steam temperature in the cycle improves the net electricity efficiency of WTE plants (Bogale and Viganò, 2014). The back-pressure steam turbines with lower efficiency in the Neihu Plant (#4), Chiayi City (#16), and Central Region Plant (#20) actually generate less electricity per year than other WTE plants. In comparison, the extraction condenser steam turbines in the Beitou Plant (#2), Wenshan Plant (#12), Hsichou Plant (#10), and Jenwu Plant (#22) have better electricity generation efficiencies. More sophisticated designs and better operation parameters account for the improved efficiencies of the latter WTE plants.

3.3 Results from using the R1 formula

As mentioned in Section 2, the R1 formula can be used to judge the efficiencies of an energy recovery plant. If E_f, E_i, and the energy loss are negligible, and the focus is on electricity production, the R1 formula can be modified as in Eq. (4) (Leckner, 2015):

$$\mathrm{R1} = E_p / E_w \tag{4}$$

This indicates that energy efficiency is proportional to the annual energy produced as heat or electricity, but inversely proportional to the annual energy contained in the treated waste, as calculated from its NCV. In this study, the annual energy produced and the treated waste mass (m_{waste}) are assumed to be related to the original design capacity, and the LHV is equal to NCV, such that

$$E_w = m_{waste} \times NCV_{waste} \approx E_{dc} \times LHV_{waste} \quad (5)$$

E_{dc} is the design capacity (metric tons/day) and LHV_{waste} reflects the design LHVs (kcal/kg), which are given in Table 2. The R1 formula fits the original design parameters as,

$$\text{R1} \approx E_{dp} / (E_{dc} \times LHV_{waste}) \quad (6)$$

where E_{dp} is the design power generation (MW). According to these calculations, the Central Region Plant (#20) in Kaohsiung City (1.49×10^{-5}) has the highest energy efficiency, followed by the Wuri Plant (#14) in Taichung City (1.27×10^{-5}), and the Bali Plant (#7) in New Taipei City (1.15×10^{-5}) (Table 1). The Central Region Plant (#20) in Kaohsiung City has a higher value of design power generation combined with lower design capacity and LHV, leading to the highest energy efficiency in our sample. The higher designed LHV in the Wuri Plant (#14) results in lower energy efficiency than in the Central Region Plant (#20). For the Bali Plant (#7), higher designed capacity and LHV lead to the third highest energy efficiency, although its value of design power generation is high. These data show that the design power generation, capacity, and waste LHV are important design parameters for incineration facilities. A WTE plant with higher design power generation, lower design capacity, and lower waste LHV has higher energy efficiency.

3.4 Economic revenue from WTE plants

The electricity generated from the incinerating facilities can offset the operation and maintenance costs of WTE plants. The total design power generation capacity of the 24 WTE plants in Taiwan is 558.5 MW, which could generate revenues of over US$167 million/year if the capacity is fully utilized. Figure 4(a) shows the average annual amount of electricity sold and the average annual income of the WTE plants in the past decade. The amount of electricity sold shows a steady value of around 2 million kWh. However, the revenues of the WTE plants have been increasing due to an increase in the price of electricity. The electricity price also varies seasonally (highest in summer). Consequently, each year the WTE plants generate higher revenues from June to September (Fig. 4(b)). The higher revenue in summer months can compensate for the lower revenues in other months. The electricity price structure in Taiwan is divided into three segments within the day: peak hours, semi-peak hours, and off-peak hour. Some WTE plants prefer to generate electricity during the peak hours to generate a better revenue, whereas others produce electricity for in-plant or local usages and offer heated swimming pools to nearby residents at a discounted price. On average, the 24 WTE plants incinerate 6.5 million metric tons of MSW each year, generating over 2,000 million kWh electricity and earning over US$167 million/year.

4. Conclusion

This study evaluates the potential of MSW for energy generation in WTE plants in Taiwan. These WTE plants play a vital role in producing renewable energy that supplies electricity during peak electricity demand periods and in reducing the amount of waste sent to the diminishing landfill space. The 24 WTE plants have been in operation in various cities in Taiwan since 2008. The 24 WTE plants in Taiwan have enough capacity to treat

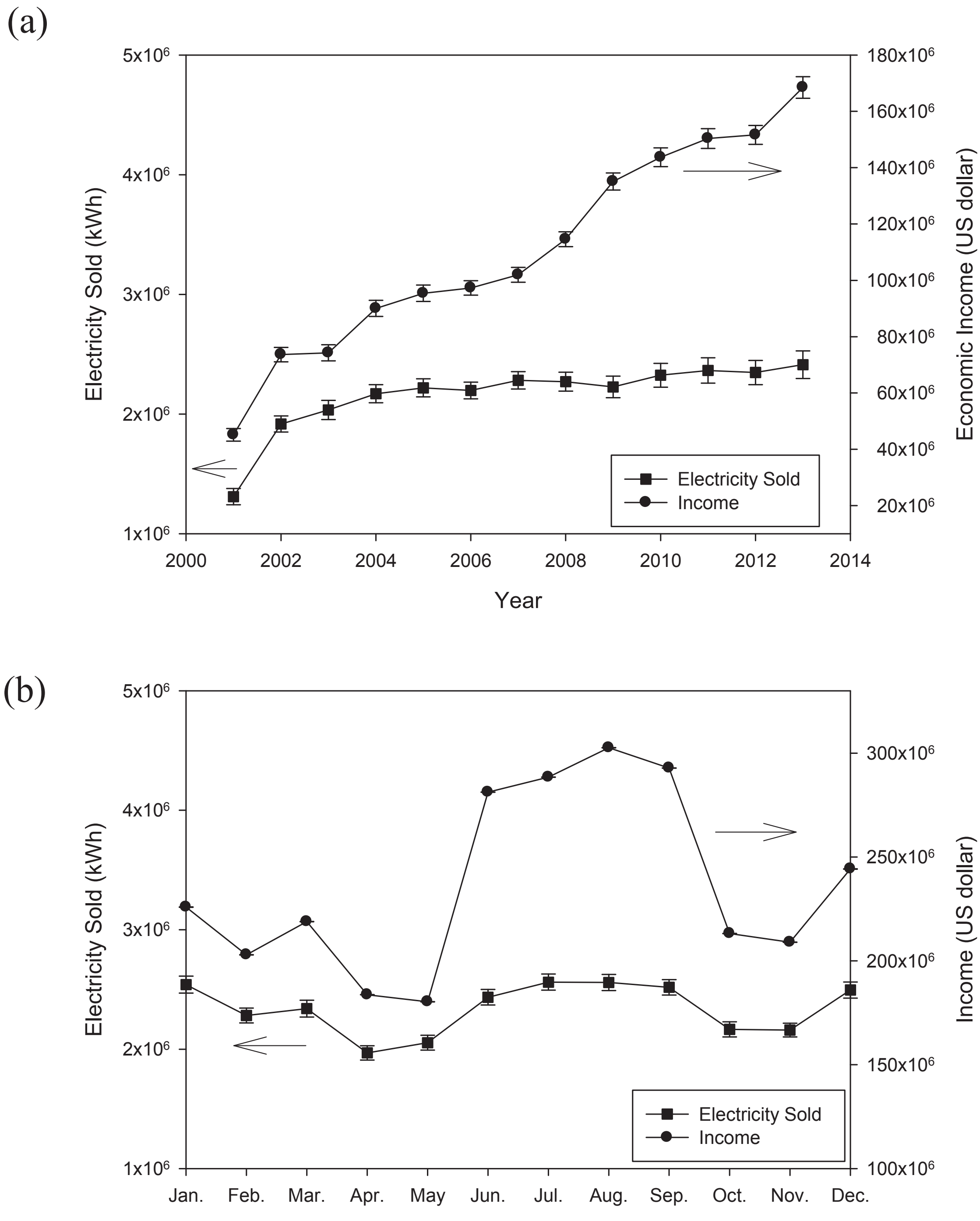

Fig. 4. Average monthly electricity sold and income for the past decade. (Taiwan EPA, 2016)

all of the waste generated, including both MSW and combustible industrial waste. Approximately 6.5 million metric tons of MSW are incinerated every year in Taiwan for energy recovery and waste reduction. Due to its high calorific value (greater than 1,200 kcal/kg) and low water content (~50%), the generated MSW is suitable for power generation through incineration. Using two-dimensional Arc GIS9.2, this study shows that higher population densities generate more MSW. The LHV of the MSW is also a critical parameter for the design of WTE facilities. In the treatment processes typically used in WTE plants, the back-pressure steam turbines with lower efficiency actually generate less electricity per year than the extraction condenser steam turbines, which have better electricity generation efficiencies. The results of the R1 formula show that the Central Region Plant (#20) in Kaohsiung City (1.49×10^{-5}) has the highest energy efficiency, followed by the Wuri Plant (#14) in Taichung City (1.27×10^{-5}), and the Bali Plant (#7) in New Taipei City (1.15×10^{-5}). The design power generation, capacity, and waste LHV are important design parameters for incineration facilities. The results of our analysis of these WTE plants should be useful for other bodies considering the beneficial uses of MSW. Future studies could study in detail the effects of different categories of MSW on the energy efficiency of WTE plants. In addition, the accuracy of the experimental results would be improved by the use of actual data from WTE plants.

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臺灣都市固體廢棄物之發電與經濟效益潛勢

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摘 要

本研究探討都市固體廢棄物(municipal solid waste, MSW)及其能源管理策略，將MSW焚化產生之能量轉製電力，發展「廢棄物轉製能源(waste to energy, WTE)」技術，其為備受認可之高應用性能源回收及發電技術。臺灣因土地與自然資源有限，現行運轉中24座大型WTE焚化廠，其建設密度比(WTE焚化廠/土地面積)位居世界最高。前述24座大型WTE焚化廠總設計發電裝置容量為558.5百萬瓦，預期可產生每年167百萬美金之經濟效益(能源效率100%狀態下)。臺灣產生之MSW兼具高熱值(1,873 kcal/kg)且低含水率(53.4%)之特性，其有利於直接以焚化處理，發展WTE再生能源技術。臺灣每年約有6.5百萬噸之MSW焚化產生再生能源，並可有效減少MSW體積。本研究引用歐盟R1公式計算國內24座大型WTE焚化廠之能源效率，發現焚化廠之設計發電量、發電裝置容量及MSW之低位發熱量(low heating value, LHV)為影響WTE焚化廠能源效率之重要參數。本研究結果可應用於改善國內現行WTE焚化廠之能源效率提升，並適用其他國家WTE焚化廠營運管理之策略建議。

關鍵詞：經濟效益、都市固體廢棄物、R1公式、廢棄物轉製能源

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