Journal of Cleaner Production 192 (2018) 262–269

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Evaluating greenhouse gas emissions and energy recovery from municipal and industrial solid waste using waste-to-energy technology

Ying-Chu Chen

Institute of Natural Resources Management, National Taipei University, No. 151, Daxue Rd., New Taipei City, 237, Taiwan, ROC

ARTICLE INFO

Article history:
Received 11 October 2017
Received in revised form
27 April 2018
Accepted 28 April 2018
Available online 1 May 2018

Keywords:
Energy
Greenhouse gas
Incineration
Industrial
Waste
Waste-to-energy

ABSTRACT

In recent years, considerable efforts have been devoted to developing waste-to-energy (WTE) technologies that can reduce the volume of waste and mitigate its negative effects on the environment. Waste is usually classified as municipal solid waste (MSW) or industrial solid waste (ISW). Both types (without hazards) can be treated by WTE technology, and both offer high potential rates of energy recovery. In Taiwan, five categories of general ISW—wood, cooking oil, plastic, lubricants, and rubber—are routinely recycled as auxiliary fuels in WTE plants. This study examined the potential for energy recovery and the extent of greenhouse gas (GHG) emissions from MSW and general ISW to evaluate the environmental performance of WTE technology using data normalization. Totals of $7,394.13 \times 10^9$ kWh/y and 340.15×10^9 kWh/y were recovered from incinerating MSW and general ISW, respectively, from 2014 to 2015. For MSW, the incineration of plastic waste produced the most GHGs (874.66 Gg CO_2-eq/y), followed by paper waste (53.92 Gg CO_2-eq/y) and textile waste (12.61 Gg CO_2-eq/y). Of the various types of general ISW, rubber waste had the highest potential to emit GHGs (11.42 Gg CO_2-eq/y). The incineration of MSW made a far greater contribution to total GHG emissions than did that of general ISW. Plastic MSW had the greatest environmental impact, and it should thus be treated carefully due to its greater potential for GHG emissions. The WTE technology has shown to improve waste management to treat both MSW and general ISW in Taiwan. These findings may be extrapolated for use in other countries.

1. Introduction

Urbanization and population growth have led to increased volumes of waste. Globally, the volume of waste is increasing faster than the rate of urbanization (Hoornweg and Bhada-Tata, 2012). In Asia, more than 1 Mt of municipal solid waste (MSW) is generated every day, and this amount is expected to increase to 1.8 Mt/d by 2025 (Hoornweg and Bhada-Tata, 2012). Waste is usually divided into two categories: MSW and industrial solid waste (ISW). MSW, which is waste discarded in urban areas, is composed predominantly of household waste with a minor amount of commercial waste (Hossain et al., 2014). ISW is waste produced by industrial activities. The 23 million people who live in Taiwan's relatively small land area (c.a. 36,000 km^2) generate about 8 Mt of MSW annually (Fig. 1(a)). About 55% of this MSW is general waste, 35% is recyclables and 10% is food waste (Taiwan EPA, 2017a). ISW is mainly categorized into "general" and "hazardous" forms in Taiwan. General ISW consists of all forms of industrial waste other than hazardous ISW. The volume of total ISW increased from 13 Mt in 2004 to 18.8 Mt in 2014 (Fig. 1(a)), an increase of 40.7% over 10 years. The volume of hazardous ISW generally represents between 5.8% and 9.0% of the total ISW (Fig. 1(b)). A fraction of the general ISW is considered suitable for incineration with little or no pretreatment (Chen and Wang, 2017). Consequently, in 2006, five WTE plants that only incinerate MSW began to accept general ISW. The 24 WTE plants in Taiwan have sufficient capacity to treat the entire volume of both MSW and general ISW.

In Taiwan, general ISW can legally be recycled as auxiliary fuels or materials or for other purposes. The recycling of general ISW as auxiliary fuel involves the implementation of WTE technology. In Taiwan, general ISW can be commissioned to be cleaned (15%), self-cleaned (5%) or exported (<1%) (Fig. 2). "Cleaned" means that registered waste-cleaning companies are entrusted to clean the ISW, whereas "self-cleaned" means that the industries that generate the ISW clean it themselves. If the registered waste-

---

E-mail address: ycchen@mail.ntpu.edu.tw.

https://doi.org/10.1016/j.jclepro.2018.04.260
0959-6526/

List of abbreviations

CV	calorific value
EPA	environmental protection agency
EU	European Union
GHG	greenhouse gas
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
ISW	industrial solid waste
LHV	lower heating value
MSW	municipal solid waste
NCV	net calorific value
PET	polyethylene terephthalate
WCO	waste cooking oil
WTE	waste to energy

List of Nomenclatures

CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
d	day
Eq	equation
Gg	gigagram
kg	kilogram
kJ	kilojoule
km	kilometer
kWh	kilowatt-hours
M	million
Mt	million ton
MW	millionwatt
N_2O	nitrous oxide
t	ton
y	year

cleaning companies or businesses have limited ability to clean the ISW, they may “export” the waste to other countries to be treated. Overall, 13 categories of general ISW can be recycled as auxiliary fuels (Taiwan EPA, 2015), but only 5 are routinely recycled by the industries (Table 1). Each form of recycled general ISW has its own code, with the prefix “R” indicating that the general ISW can be recycled. Industrial businesses must obtain certificates before recycling general ISW as auxiliary fuel.

WTE technology directly converts the energy content of waste into steam or electricity (Luz et al., 2015). The WTE technology in Taiwan mostly converts the energy content of waste into electricity (Chen and Wang, 2017). It is cost-effective, with an energy cost of approximately 10% of that of solar energy and 66% of that of wind energy (Lim et al., 2014). The average efficiency of WTE plants is about 18% for electricity generation and 63% for heat production (Leme et al., 2014). Globally, more than 600 WTE plants incinerate about 181 Mt of MSW each year to generate energy (Albores et al., 2016). WTE technology has been implemented in many countries, including Australia (13 plants) (Schwarzböck et al., 2016), Canada, Finland, China, Singapore, and Japan (1900 plants) (Tan et al., 2015), Switzerland (29 plants) (Harris et al., 2015) and the U.S. (300 plants) (Paleologos et al., 2016). Of these countries, those in the Asia-Pacific region, including Taiwan, are predicted to be the fastest growing users of WTE technology (World Energy Council, 2013).

A strong correlation has been found between waste generation and greenhouse gas (GHG) emissions (Hoornweg and Bhada-Tata, 2012). Globally, the total disposed waste is responsible for about 3%–4% of anthropogenic GHG emissions (IPCC, 2006). Waste minimization and recycling are also highly beneficial in terms of GHG reduction (Marzouk and Azab, 2014). Studies have evaluated the GHG emissions from waste incineration and demonstrated that waste incineration can serve as a GHG sink—in other words, energy recovery via the production of energy or electricity could mitigate GHG emissions from waste (Chen and Lo, 2016). An integrated WTE system could also bring about a significant decrease in GHG emissions and increase revenue from electricity sales (Zsigraiová et al., 2009). Many countries incinerate waste to recover energy to generate heat, steam and electricity. Hammond and Norman (2014) reported that the heat generated from incinerated ISW was technically recoverable and that this incineration saved 2.2×10^6 t CO_2-eq/y emissions compared with conventional waste disposal. Achieving reductions in GHG emissions requires improving the efficiency of energy recovery and resource disposal (Corsten et al., 2013). Several studies have discussed specific energy recovery or GHG emissions from waste, yet few have discussed both at the same time and normalized them to assess their environmental performance. Furthermore, studies related to ISW are less common.

This paper compares the levels of GHG emissions and energy recovery from treating MSW and general ISW with WTE technology. The potential for energy recovery and the extent of GHG emissions from WTE technology are evaluated. Finally, the environmental performance of WTE technology in treating both MSW and general ISW is evaluated using data normalization, as a technology with positive effects in some areas can have a negative influence in other areas (Rehl and Müller, 2001). An optimal approach to waste treatment has yet to be determined (Magrinho et al., 2006). The results of this study are helpful for countries that seek to improve energy recovery and mitigate GHG emissions from waste by managing different compositions of the wastes, as suggested in this paper.

2. Materials and methods

2.1. System boundary of this study

The system boundary of this study is shown in Fig. 3. The calculations were based on the energy recovery and GHG emissions from WTE plants in Taiwan, which has 24 WTE plants designed to generate 558.5 MW of power and to incinerate 24,650 t of waste every day (Chen and Wang, 2017). The WTE plants incinerate MSW containing paper, textiles, food waste, plastic, metals and glass as classified by the Taiwan Waste Disposal Act. The general ISW in the WTE plants is categorized as suitable for use as an auxiliary fuel in Taiwan. Industries routinely recycle five categories of general ISW including wood, cooking oil, plastic, lubricant and rubber as auxiliary fuels. Hazardous waste is not incinerated and was excluded from this study.

This study was limited to evaluate the energy recovery and GHG emissions within the WTE plants; the processes of transportation, pre-treatment and final disposal were not examined. In Taiwan, the certificates granted for the incineration of general ISW as an auxiliary fuel are valid for only 2 years. Thus, the data used in this study are for 2014 to 2015 and the average values were used. The data of MSW and ISW was collected from yearly statistics and the Recycling Management System (RMS) published by Taiwan EPA. Other data sources were cited in tables and figures' captions.