Resources, Conservation and Recycling xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

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

Full length article

Efficient energy recovery through a combination of waste-to-energy systems for a low-carbon city

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ARTICLE INFO

Article history:
Received 31 March 2016
Received in revised form
27 September 2016
Accepted 22 November 2016
Available online xxx

Keywords:
Energy recovery
Waste-to-energy
Industrial symbiosis
Waste management
Methane fermentation

ABSTRACT

Innovative and efficient use of municipal solid waste as a source of energy is an important way to promote the transition to low-carbon cities. One key strategy to improve energy efficiency is to create a network of multiple sectors that can produce and utilize energy from waste. This mechanism has already been adopted at the urban scale in several developed countries as a way to enhance environmental efficiency and reduce adverse impacts. However, to use waste efficiently, it is necessary to examine the supply chain of wastes as a source of materials with potential to generate energy. Such an examination can inform the design of an efficient waste-to-energy process that will create a symbiosis between industry and the waste management sector. In this paper, we describe a model that evaluates energy recovery efficiency by considering the costs and benefits of an innovative waste-to-energy system. In the model, we also consider the material and energy flow of wastes in accordance with the quantity and quality of waste emissions, the separation system, treatment technologies and combinations thereof, and energy recovery and use in other sectors. The scenario was designed by identifying waste management options, including waste quantity/quality; the separation system; the treatment technology model for wet or dry methane fermentation; incineration; a combined system that involves superheating with exchanging heat between the incineration plant and fermenter; and use of refuse paper and plastic fuel (RPF). The results revealed that energy recovery efficiency was most dependent on the effective use of RPF with a relatively high lower heating value and superheating of boiler steam by methane gas in the combined system. An important conclusion was that the most efficient system was a combined system in which paper, plastic, and RPF were separated from 80% of the waste, and 20% of the waste was incinerated and used for wet methane fermentation. The amounts of energy recovered from that system was 54.5 kWh/t, and the efficiency was 33.4%. Analytical results indicated that it is possible to create the critical technology and to develop policy insights needed to make efficient waste management systems for the transition to low-carbon cities.

1. Introduction

Improving energy efficiency by creating networks of waste by-products, electricity and heat between multiple sectors has been adopted at the city scale throughout the world for mitigation of the adverse effects of climate change, resource depletion, issues related to the disposal of wastes, and the hollowing-out of industries (Geng et al., 2016). Innovative and efficient utilization of municipal solid waste as energy sources is a critical measure to promote low-carbon city transition, since examination of the supply chain of wastes as sources of materials and heat (Iakovou et al., 2010), which has the potential to connect industrial sectors, has revealed waste-to-energy (WtE) technologies that could facilitate networking, including alternative fuels (refuse paper and plastic fuel, RPF) and materials for energy-intensive industries, incineration, gasification with energy recovery, treatment of biodegradable waste, and the supply of heat to industrial, residential, and other building sectors (White et al., 2012). An appropriate combination of technological options and implementation can improve the energy recovery efficiency of the urban and industrial system and

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http://dx.doi.org/10.1016/j.resconrec.2016.11.018
0921-3449/

Please cite this article in press as: Ohnishi, S., et al., Efficient energy recovery through a combination of waste-to-energy systems for a low-carbon city. Resour Conserv Recy (2016), http://dx.doi.org/10.1016/j.resconrec.2016.11.018

contribute to the realization of low-carbon cities. Although several studies have reported comparative analyses of technologies for waste management (Fruergaard and Astrup, 2011), academic insights should be accumulated to identify integrative effects that result from networking through waste separation systems, treatment technologies, and consistent energy recovery from waste management in the urban area and materials-to-fuels supplies in the industrial area.

The technology of energy recovery from waste has evolved to the point that the system produces energy efficiently; meets requirements for public health, a clean environment, and air quality; and reduces the required number of dumping sites (Keim, 2008). In addition to these conventional issues, WtE can help to resolve the urgent issue of energy security. In Japan, the Fukushima nuclear accident has posed a challenge to society; all stakeholders have sought to formulate a post-Fukushima energy transition strategy (Vivoda, 2012; Hayashi and Hughes, 2013b). That accident has also impacted global energy security by reconfiguring the fossil fuel supply chain and causing a loss of public acceptability of nuclear power (Hayashi and Hughes, 2013a). The result has been policy changes and increasing awareness of energy security, not only in Japan but also in, inter alia, Korea (Park and Ohm, 2014), China (Ren and Sovacool, 2015), and Europe (Wittneben, 2012). Under such circumstances, the government of Japan promulgated its fourth strategic energy plan in April 2014. The plan calls for extensive institutional reforms and evaluated WtE technologies as sources of renewable energy in a distributed energy system, the goal being to ensure a certain amount of energy supply, even with an accident at a large power source.

In addition to improving energy recovery efficiency and energy security, decision makers should consider economic and social aspects when they plan and design waste management systems. Economic costs include waste collection and transportation, recovery processes and distribution processes; benefits would be the sales of recovered energy. The revenue of the waste management sector is quite high, accounting for 4.0% of total local municipal revenues in Japan in 2014 (Ministry of Internal Affairs and Communication, Japan, 2015). That is why the economic benefit from WtE has been expected to reduce the burden on the municipalities to organize their waste management systems. Additionally, social benefits to improve social–economic repercussions, cultural heritage, working conditions, governance etc. can attract local stakeholders and promote the installation of WtE systems (Ren et al., 2015). All types of WtE systems have strong and weak points to enhance sustainability from these perspectives, so evaluation of the systems by multi-criteria decision-making and sustainability assessment is important (Antonopoulos et al., 2014; Ren and Sovacool, 2015). However, this paper focuses only on the total energy recovery efficiency and total cost–benefit to reveal the feasibility of advanced WtE systems.

Several effective WtE technologies, including use of RPF, incineration, and treatment of biodegradable waste, have been used to recover energy from waste. These technologies have become widespread. RPF from plastic and paper waste have been used as substitutes for coal or heavy oil, especially in energy-intensive industries, by feedstock recycling and thermal recovery (Al-Salem et al., 2009; Okuwaki, 2004) with relatively high efficiency (Lee et al., 2014). This recycling process needs to be based on a sophisticated system in wider society, consisting of waste separation, collection, mechanical sorting, quality management, and market identification. We have proposed a "smart recycling system" to make the recycling process efficient, effective, and inexpensive (Fujii et al., 2012a,b; Fujii et al., 2014). Another technology to recover energy from waste is realized in cement production by substituting municipal solid waste (MSW) for part of the clay, coal, and lime (Choy et al., 2004; Geng et al., 2010; Uson et al., 2013). Such recycling processes could be characterized as "urban symbioses" that transform urban wastes into industrial materials and fuels in some cities (Van Berkel et al., 2009).

Incineration technology with power generation has been implemented as one of the most dominant treatment options, especially in developed countries. Power generation with boiler steam from incineration furnaces is a common technology that achieved an average generating efficiency of 11.7% in Japan in 2014 (Ministry of Environment, 2015), and a cogeneration system using steam from incineration would improve overall efficiency (Lombardi et al., 2015). However, this efficiency is relatively low compared to thermal power plants that had an average generating efficiency of 41.4% in Japan in 2014 (Sueyoshi and Goto, 2011). The reason for the gap between the efficiency of energy recovery via incineration and electricity production is caused by the mechanical and physical durability of the equipment versus the high pressures and temperatures with corrosive gas. To address this problem, Zwahr (2003) proposed a new technology: with nickel-coated tubes new WtE plants could be designed to accommodate more conventional steam parameters like 520 °C and 10 MPa, and the efficiency of electricity production could be raised to 30%. However, it is difficult to realize this technology due to technological limitations and economic hurdles. Further, the effect of scale is also a problem that affects the efficiency of power generation by an incineration plant. One of the strategies to improve efficiency is therefore to make the collection area wider. Another leading technological option is industrial symbiosis (Chertow, 2000; Chertow, 2007) involving the use of heat recovered from an incineration plant as the energy input to an industrial facility that is near the incineration plant. An example is a heat exchange business in Ulsan, Korea that has been reported to be a pioneer project between an incineration plant and a chemical company to save energy and enhance business competitiveness (Park and Park, 2014).

Technologies for recovering energy from organic waste such as food or agricultural waste have focused, in addition to incineration, mainly on bioethanol production by saccharification (Han and Shin, 2004), biodiesel production by catalyzed reactions (Kulkarni and Dalai, 2006), and fermentation to produce methane or hydrogen (Shin et al., 2004). Comparative analyses of these technologies have been reported (Kiran et al., 2014). A methane fermentation facility, compared with other technological options, is suitable for location near an incineration plant because exchange of materials and heat between the two facilities could take advantage of the opportunity to deal with waste and to recover energy. An example would be incineration of the residue from the fermentation process and use of the steam from incineration to heat the methane fermenter. Two technological options have been developed: (1) wet methane fermentation, in which food wastes separated from MSW and industrial food wastes are used as feedstock to a fermenter and (2) dry methane fermentation, in which wastes mechanically separated with food and paper are used in relatively high-temperature conditions (Nishio and Nakashimada, 2007). Recovered biogas would be used mainly for electricity generation and for fuels in the residential, industrial, and transportation sectors. The combined system would use biogas to heat steam recovered from the incineration boiler with separate superheating equipment that has been developed and implemented (Horio et al., 2009; Fujii et al., 2012a,b).

From the standpoint of thermodynamics, it is definitely efficient to recover energy from a waste management process and use it at the highest possible temperature when waste is utilized as heat rather than as material. Each waste management facility such as an incinerator, gasifier, or fermenter has limitations with respect to heat durability from mechanical, physical, technological, and financial restrictions. It is therefore a better strategy to harness energy from other existing facilities with high heat durability to improve

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