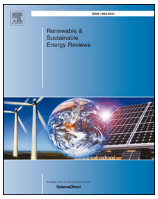
Renewable and Sustainable Energy Reviews 98 (2018) 163–178

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



# Harvest green energy through energy recovery from waste: A technology review and an assessment of Singapore

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## ARTICLE INFO

*Keywords:*
Waste to energy
AD
Gasification
CHP
Incineration

## ABSTRACT

The increasing challenge in waste disposal and high dependency on imported fossil fuel has compelled Singapore to make continuous efforts in advancing waste to energy (WTE) technology, which could ensure sustainable development on one hand and energy resilience on the other hand. This paper summarizes the current WTE practices and research trends in Singapore, covering anaerobic digestion (AD), gasification, combustion-based biomass combined heat and power (CHP) production, and incineration, with the aim to define future perspectives of Singapore WTE application. Among the different aspects assessed, source-separated food waste (FW) and brown water present the biggest energy potential if AD is adopted instead of incineration. Given that the purity of source separated waste determines the extent of recovered energy, suggestions are made to increase the participating rate in source separation among Singapore residents, such as environmental education through social media and phone apps and proper facilities installation at household and community. Moreover, additional benefits can be credited to WTE system if the waste to material practice is also conducted on top of energy production.

## 1. Outlook on Singapore energy consumption

Occupying a land area of 719.1 $km^2$, Singapore by 2015 accommodated 5.5 million populations, which were projected to be 6.9 million by 2030 as outlined in the latest Population White Paper [1]. Singapore today ranks among the world's strongest and most competitive economies, and energy undoubtedly plays an important role in the 50 years of continuous development and growth. However, Singapore has limited natural resource and relies heavily on the import of fuels from other countries. In 2015, the total electricity generation in Singapore was around 50 TWh, 97.2% of which was contributed by the imported fossil fuel (Fig. 1). The remaining 2.8% of electricity demand was met by local energy sources, such as municipal solid waste (MSW), biomass and photovoltaic panel. [2].

According to methodologies recommended by the Intergovernmental Panel on Climate Change (IPCC), it was calculated that the grid $CO_2$ emission factor for 1 kWh net electricity generation was 0.4313 kg [2]. In addition, 0.00213 kg methane was released upstream, as methane escaped into atmosphere during producing, processing and transporting of natural gas. In total, 1 kWh Singapore grid

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*Abbreviation:* AD, Anaerobic digestion; ADOS, Anaerobic digestion of organic slurry; APC, Air pollution control; BOD, Biological oxygen demand; BW, Brown water; CGE, Cold gas efficiency; CFD, Computational fluid dynamics; CHP, Combined heat and power; COD, Chemical oxygen demand; EF, Electrical conversion efficiency; FA, Fly ash; FB, Fluidised bed; FW, Food waste; GW, Global warming; GUI, Graphical user interface; HHV, High heating value; HM, Horse manure; IBA, Incineration bottom ash; IP, Incineration plant; IPCC, Intergovernmental panel on climate change; IWMF, Integrated waste management facility; LHV, Low heating value; MOF, Ministry of finance; MSW, Municipal solid waste; NEA, National environment agency; NTU, Nanyang Technological University; NUS, National university of Singapore; O&M, Operation and Maintenance; PPP, Public-Private-Partnership; R3C, Residue and resource reclamation centre; SCR, Selective catalytic reduction; SNCR, Selective non-catalytic reduction; TMTS, Tuas marine transfer station; TS, Totol solid; TWRP, Tuas water reclamation plant; VFA, Volatile fatty acid; VOCs, Volatile organic compounds; VS, Volatile solid; WRP, Water reclamation plant; WTE, Waste to energy; WTTP, Wastewater treatment plant

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https://doi.org/10.1016/j.rser.2018.09.009
Received 21 September 2017; Received in revised form 30 August 2018; Accepted 5 September 2018

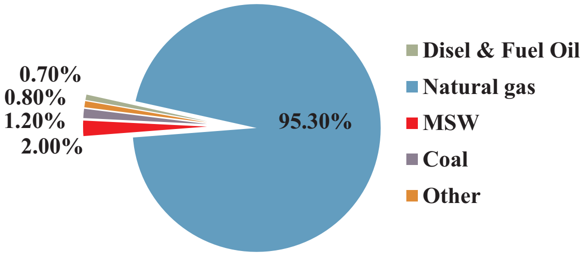

**Fig. 1.** Percentage contribution of different energy resources in Singapore electricity mix.

electricity would exert a global warming impact of 0.48455 kg $CO_2$eq. To fight for climate change as part of the international efforts, Singapore is seeking strategies to limit its greenhouse emissions with the aim of peaking around 2030 at the equivalent of about 65 million tonnes of carbon dioxide [3]. Use of renewable resources such as biomass, wind and solar energy, can be one way to reduce the nation's electricity carbon foot print. Meanwhile, allowing entry of various energy options into the country electricity market, especially indigenous source, could diversify the fuel mix and reduce Singapore's dependency on imported fossil fuel.

## 2. Singapore waste management challenge

With the increase in population and affluence over the past decades, the amount of MSW generated each year keeps rising in Singapore. Fig. 2 shows the amount of disposed domestic, disposed industrial waste and waste recycled from year 2006 to 2015 [4]. In waste treatment hierarchy, the priority is given to waste material recycling. Singapore has been actively promoting waste minimization and recycling since the early 1990s [4]. The overall national recycling rate shows increasing tendency from 51% in 2006 to 61% in 2015, heading towards the target recycling rate of 70% by 2030. The remaining unrecycled waste is disposed either by incineration or landfill. Over the last 10 year, the total annual generation of MSW had increased steadily from 7.8 million tonnes in 2006–10.7 million tonnes in 2015 with an average annual increasing speed of 5%. However, owing to the upward changes in the recycling intensity, the annual growth in disposed waste was just 2% (Fig. 2) from 2.6 million tonnes in 2006–3.0 million tonnes in 2015.

The disposed MSW in Singapore can be classified into two major categories: domestic and non-domestic refuse [5]. The first category refers to garbage collected from households, markets, food centres, hotels, restaurants, and shops, while the latter category is dominated by non-toxic and non-hazardous garbage from industrial premises and also contains small portion contributed by institutional facilities, such as government and statutory board installations, and public development projects. Based on the number of Singapore population including citizens and permanent residents, it was calculated that the disposed domestic waste per capita per day varied in the narrow range between 0.83 kg and 0.87 kg in the nearest eight years (Table S1). It was comparable with the data from the other developed cities, such as Tokyo (1.03 kg/capita/day), Seoul (1.08 kg/capita/day), and Berlin (0.88 kg/capita/day) [6], reiterating the find from Zhang et al. [7] that population growth alone was most probably the major cause of the growth of MSW in Singapore. By 2030, Singapore's total population escalates to range between 6.5 and 6.9 million [1]. Assuming no changes in waste generation per capita in the following year, the total disposed domestic waste could reach 5.4–6.0 million tonnes in 2030. The non-domestic waste generation is highly dependent on the economy growth [8]. A linear increment in GDP could be expected for Singapore's economic development (Fig. S1), while waste generation per dollar demonstrated a decline trend (Fig. S2) due to the increasing GDP share of Finance, Insurance and Business service, which produced less solid waste per dollar than traditional manufacturing and retail trade [9]. Assuming these patterns remained valid for the next fifteen years, the total disposed non-domestic waste was projected to be approximately 1.6 million tonnes in 2030. Overall, the domestic and non-domestic disposed waste was estimated to amount up to 7.3 million tonnes in 2030, which was more than double of that in 2015.

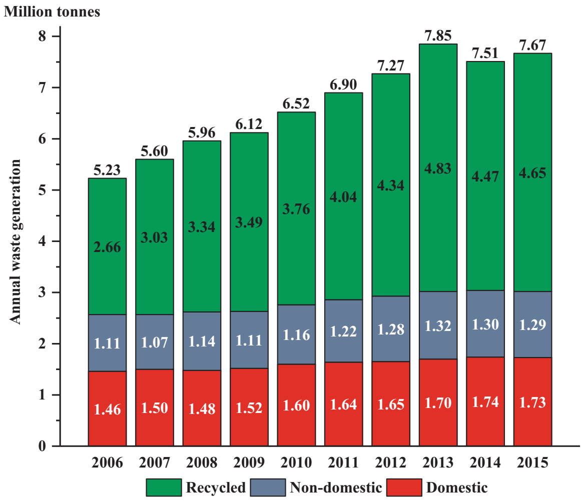

**Fig. 2.** Annual waste generation in Singapore. (Disposed waste refers to the remaining waste after recycling, which is the sum of non-domestic and domestic waste in this figure.).

## 3. Seeking renewable energy from MSW

Singapore has continuously spent efforts on raising the contribution of renewable energy in the national energy mix to reduce dependency on imported fossil fuels. Renewable energy source includes solar energy, tidal energy and energy from biomass. Although they are unlikely to replace natural gas power plant to meet the high electricity demand, they can help to enhance energy resilience and environmental sustainability [10]. Among the renewable energy available, energy from waste is of great interest due to its ability to tackle waste management problem and yield sustainable energy addressing both concerns simultaneously. Energy from biogenic MSW, such as paper, cardboard, food waste, horticultural waste, wood, and animal manure, is considered as carbon-neutral and environmental friendly [11]. The carbon dioxide emission associated with biomass exploitation is commonly not assumed to contribute to global warming impacts, since the amount of $CO_2$ released during biomass utilization is offset by the $CO_2$ eliminated from the atmosphere by photosynthesis during the growth of biomass [12].

After waste generation, waste material recycling is preferred to energy recovery. The unrecycled waste is first considered for energy recovery by technologies other than incineration. The physico-chemical nature of the waste dictates the choice of the technology appropriate for treating such waste stream. Food waste, putrescible and high in water content (around 80% by weight), is suitable for anaerobic digestion [13]. Horticultural waste, with moisture content less than 45% and a calorific value in the range of 8 MJ/kg to 13 MJ/kg [14], is amenable for use as an alternative fuel for power and heat supply. Waste demolition wood featuring lower water content (i.e. 30%) could be converted to energy at a higher efficiency in gasifier. Waste plastic, consisting of polymers, is a favourable feedstock for pyrolysis to yield high calorific value fuel as well as petroleum refining comparable products [15].

This study reveals the current industrial practices in the field of waste-to-energy. This review focuses on various conversion technologies to summarize the current development stage, identify the encountered problems and foresee the future trends.