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The evolution of waste-to-energy incineration: A review

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ABSTRACT

From the simple water wall incinerators of the late 19th century, the concept of waste-to-energy incineration has evolved dramatically. Initially, waste treatment had no energy recovery objective at all. To date, state of the art facilities exist and are coupled with not only mechanisms to recover heat and energy in combined heat and power plants, but sophisticated mechanisms to clean flue gas, utilize wastewater, and assimilate diverse streams of waste with high efficiency. This paper reviews the evolution of waste-to-energy incineration with the prime objective of evaluating progress made in solving problems, past and present concerns and future prospects in the industry. The review shows that waste-to-energy incineration has played a significant role in reducing the global waste problem and by maximizing its potential today, much more can be achieved. Nevertheless, the root problem notably the growing waste volume in today's society has not been fully addressed. An understanding of this evolution capacitates players in the waste-to-energy industry to better understand problems and formulate practical solutions which will steer waste to energy incineration towards more growth in the interim and devise lasting solutions for the distant future.

1. Introduction

The volume of municipal solid waste (MSW) generated globally from urban areas is increasing rapidly as a result of expanding human population and rapid urbanization [26,61,67]. The World Bank estimates that solid waste generated from urban areas globally will increase from roughly 3.5 million tonnes per day currently generated to 6.1 million tonnes per day by 2025 [67]. MSW incineration (MSWI) plays a pivotal role in not only managing this expanding volume of waste but also in recovering energy that can be used to supplement traditional supplies [11,16]. With more than 80% of the global primary energy share being met from fossil fuels [2,23] MSWI can play a crucial role in offsetting fossil fuel consumption and increasing the renewable energy share while at the same time assisting with waste treatment [53,65]. To date, approximately 1179 MSWI plants around the world exist with a total capacity in excess of 700,000 metric tonnes per day (hereafter written as MT/d) [33]. Currently, most plants are located in the EU, the US and East Asia [33]. Many African and Latin American countries also perform incineration to inertize medical and hazardous waste albeit without energy recovery [44]. The development of MSWI was not without its own challenges. Lessons learned from past failures helped shape the global outlook of today's WtE[1] landscape [58]. Today the WtE industry is financially rewarding, earning in excess of US$20 billion every year [62]. Despite such tremendous growth, some fundamental questions still arise: will the popularity of MSWI continue to grow? Will global waste management policies remain in favor of WtE? Is the root problem that led to the birth of MSWI being adequately addressed? In this paper, literature is reviewed in order to closely analyze the evolution of MSWI in an attempt to answer these questions and give an understanding of the evolving concerns and future prospects around WtE. The objective of the paper is to give an overview of the development of MSWI, with particular emphasis on the major achievements made around combustion technology and air emissions control in order to bring to light unresolved problems and the likely future direction of WtE. In the arrangements of sections of this paper, first, a historical overview surrounding the advent of MSWI plants is presented. Secondly, an effort is made to describe the path through which modern MSWI technology was developed with a particular focus on combustion technology and air pollution control (APC) systems. Finally, current concerns and future prospects around MSWI are discussed with the aim of highlighting challenges that remain unresolved and recommendations that may be useful in tapping optimal gains from

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[1] While waste-to-energy also refers to conversion by biochemical processes, in this paper the term will primarily refer to waste-to-energy via incineration.

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MSWI as an option for waste management. It is expected that the knowledge shared is useful in shaping both current and future prospects within the WtE sector as well as waste management in general.

2. Historical perspective and the development of MSWI

2.1. The 'Throw Away' society

The birth of formal MSW management systems was initiated by problems that arose from continued population growth within early towns and cities soon after the industrial revolution [43]. Science had shown that diseases were closely linked to bacteria (referred to as 'germs' during that era) and other microorganisms found in air, soil, and water [17]. The practice of dumping refuse in the open as well as on river banks was rampant [43]. A realization that the dirtier environments created conducive conditions for the growth of these disease-causing agents pushed the public to demand action from the city and town administrators [43,57]. Knowing the political consequences of failure to solve the citizens' problems, the responsible authorities yielded to the pressure. Soon, clean water supply and sewerage reticulation services were provided and by the turn of the 19th century, formal collection and disposal of garbage had begun [31]. This turn of events would not stop there. The volume of waste continued to rise, newer strategies to fight existing challenges were developed and newer problems emerged [43]. In the course of time, responsible authorities realized that the public had a role to play in reducing the waste disposal problem and began imposing regulations which primarily restricted locations where waste could be dumped [57]. In the US, the first regulations to be formulated by the Federal Government were issued in 1929 in which dumping of waste on river banks was prohibited [43].

The term 'Throw Away society' was coined from an article published on 1 August 1955 in an American magazine that ran under the name, 'Life' [57]. It generally denotes a society with an excessively high consumption pattern and wastage of resources thereby generating huge volumes of refuse. The waste volumes did not only expand with growing population but also evolved in characteristics (Fig. 1). [43]. This presented newer challenges to already implemented management strategies. For example, with an increasing proportion of product packaging as shown in Fig. 1, the use of pigs in large-scale farms to consume the garbage only resulted in an excessive build-up of rejected plastics as the pigs could only consume food waste. Responsible authorities had to devise new solutions.

2.2. The advent of waste recovery plants

During the last quarter of the 19th century, it had become evident that the rising waste volumes could be dealt with by incinerating part of the waste and recovering some of the materials present in the waste streams. The first batch of plants in the US and Europe were the ordinary refractory incinerators which were later replaced by the water-wall and modular incinerators of the late 19th century [58]. Focus of these early incinerators was on waste management alone with no intention to make use of the generated heat. There was growing realization that landfills would soon fill up and land to construct new ones would soon run out owing to pressure from rapid urbanization. The first MSW incinerator in the UK was built in 1870 [33] while in the US the first MSW incinerator without energy recovery was built in 1885 in New York City [16]. Heat recovery from incinerators began prior to the 20th century in Europe. In the US, it was not until halfway through the 20th century that rising oil prices prompted the need to utilize heat from the incinerators so as to generate steam and electricity [58]. This ultimately put heat recovery at the helm of primary waste treatment systems design. Initial WtE plants were in the form of simple water-wall and modular incinerators which lacked flue gas treatment mechanisms [58]. Methane recovery through co-digestion of refuse and sewage sludge as well as refuse derived fuel (RDF) production was later initiated. The potential for long-term markets for steam further catalyzed growth in thermal MSW treatment with heat recovery. It was not long before new problems began to emerge. The MSWI plants had technical problems which caused regular plant shut down and excessive rundown hours [58]. At the same time, resource recovery plants were also set up with the US's first commercial plant being commissioned in 1971 [58]. The initial objective was to recover the ferrous and non-ferrous materials especially iron, aluminium, glass and paper fibre [58]. Prevailing policies were inadequate in supporting resource recovery and as a result expected economic gains were not being realized. Pollution from the WtE incinerators was becoming a growing concern and public opposition began to mount. In the 1960s particulate matter was the only regulated pollutant but by 1980 regulations required control of acid gases too [37]. Incineration of a heterogeneous mix of MSW coupled with poor handling of ash created more public skepticism [46]. The bad reputation earned by these early WtE incinerators grossly affected public opinion and stirred opposition [46]. Increasing public pressure drove location of new plants away from towns but also too far from the consumers of generated heat and steam [58]. That development made infrastructural design for supplying heat and steam more complex and expensive. This new host of problems led to the decline in thermal treatment as an alternative to landfilling. In the US, incineration dropped from 31% of the total MSW stream in the 1960s to 9% in mid 1980s [38]. With landfilling still being an option, MSW diversion began to dwindle.

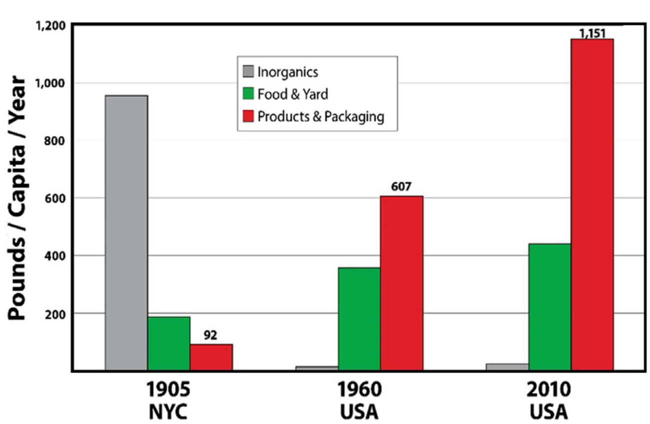

Fig. 1. Solid waste generation in the US and New York in 1905, 1960 and 2010. Adapted from [57].

3. Evolving MSWI technology

3.1. Combustion technology

Since the advent of WtE plants, the objectives of MSW treatment changed rapidly with more attention being directed towards heat recovery. Additionally, regulations governing the disposal of incineration ash as well as flue gas emissions were becoming more stringent. As a result, the adoption of MSWI as an option for waste management demanded the development of robust technology capable of achieving three things: volumetric reduction of the MSW, optimal recovery of heat and materials as well as cleaning the resulting flue gas to meet prevailing emission limits [43,66].

Early incinerators were categorized into continuous feed, batch-feed, ram-feed, metal conical and waste heat recovery incinerators [49]. Continuous feed incinerators were further grouped into traveling grate incinerators, reciprocating incinerators, rotary kilns and barrel-grate incinerators. They differed from batch-feed incinerators in that the latter used a system where refuse was fed at periodic intervals allowing the previously-fed batch to burn almost completely. That way, continuous feed incinerators had the capacity to handle larger amounts