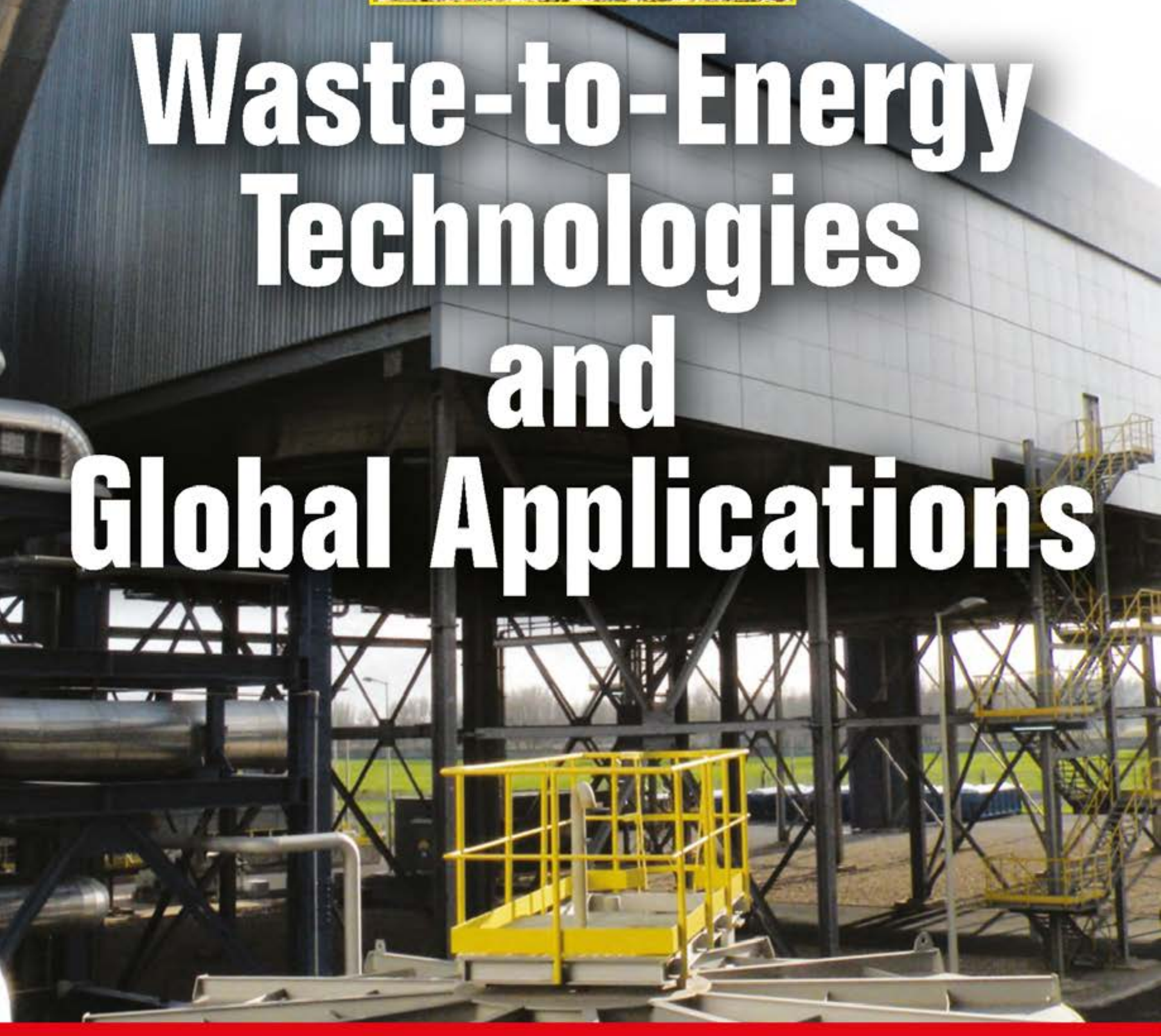

Waste-to-Energy Technologies and Global Applications

Efstratios N. Kalogirou

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The current book is dedicated to my family, my wife,
Rea Evangelatou, and my children, Eleftheria-Maria and Nikolaos.
I really missed them a lot while traveling around the globe to visit more
than 40 waste-to-energy worldwide plants within the last 15 years.

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Preface

The main objective of this business-oriented book is to present state-of-the-art waste-to-energy (WTE) technologies and their global applications for the twenty-first century and, at the same time, educate the reader in predesign and pre-evaluation of new waste-to-energy plants through a multiparameter waste-to-energy tool/model, in each region around the globe. Emphasis is given to the combustion process of municipal solid waste with energy recovery (production of electricity, district heating/cooling) since the combustion process represents the majority of more than 2000 waste-to-energy plants globally, treating approximately 250 million tons of waste annually.

The first chapter covers a general introduction to developing state-of-the-art, sustainable waste management and waste-to-energy worldwide.

The second chapter analyzes legislation, which is crucial to developing sustainable waste-to-energy projects.

The third chapter, one of the basic and main chapters of the book analyzes the current global situation of waste-to-energy technologies, combustion processes, gasification, plasma gasification, and pyrolysis. Emphasis is mainly on the combustion process, since it is the dominant technology (and especially the use of moving grates) in the majority of existing worldwide waste-to-energy plants.

Chapters 4–7 are the core chapters—presenting real, worldwide waste-to-energy case studies. They analyze the technical data/specifications and basic financial data (with many on-site photographs taken by the author) of 35 worldwide waste-to-energy plants that the author has visited within the last 10 years around the globe, in almost all continents: Europe, the United States, Asia, and Africa.

Chapter 8 describes the environmental aspects of waste-to-energy plants. The new WTE plants are often situated in the center of metropolitan cities due to state-of-the-art flue gas cleaning systems, which are covered in Chapter 3.

Chapter 9 is also a very important chapter. It describes the waste-to-energy tool/business model that precalculates and predesigns waste-to-energy plants worldwide, taking into consideration multiparameters such as the composition and calorific value of the input waste, local climate conditions, the gross domestic product (GDP), social/financial conditions, and so on.

First, I want to express my warmest regards to my close colleague, MSc. Environmental Engineer Antonios Sakalis who contributed much to this work and to the final presentation of the abovementioned chapters.

I want to thank my other colleague, Mechanical Engineer, MBA, Manolis Klados who contributed to Chapter 3 and especially to the WTE business tool/model presentation in Chapter 9.

I also want to thank Emeritus Professors from KU Leuven, Dr. Carlo Vandecasteele and Dr. Chantal Block, for Chapter 8 on environmental aspects.

Finally, I want to thank Professor Emeritus, Dr. Nickolas J. Themelis of the Earth Engineering Center of Columbia University and Chair (founder) of the Global Waste-to-Energy Research and Technology Council (WTERT).

I believe that this book is an important tool for academics, university staff and undergraduate and graduate alike students, engineers, companies (both public and private sectors), governmental authorities, public administration, NGOs, especially policy/decision makers that want to develop waste-to-energy projects and plants around the globe.

The book is also a very useful tool for citizens around the globe who can include in their touristic attractions some of the new state-of-the-art waste-to-energy plants while traveling/visiting metropolitan megacities. After reading this book, the NIMBY syndrome (Not in My Backyard) will be replaced as everyone will be happy to have a state-of-the-art waste-to-energy plant in their neighborhood since the real emissions and environmental effects would really be negligible. Many will want to convert these plants from industrial buildings to very attractive, touristic places like the ones in this book.

Waste-to-energy facilities are an integral part of worldwide sustainable waste management, in harmonic cooperation with the recycling of municipal solid waste at the source and composting of preselected organic material (without any contradiction). Combustion processes with energy production (electricity/district heating and, in some cases, district cooling) represent the most dominant and proven technology in the majority of more than 2000 worldwide WTE plants. The current worldwide capacity of WTE plants today is approximately 250 million tons annually and the estimation from ISWA and UNEP for the next decade is expected to highly increase.

Dr. Efstratios N. Kalogirou
Athens, Greece
E-mail: ozone.greece@gmail.com

Author

Efstratios N. Kalogirou, PhD, is the co-founder and first Chair of Waste-to-Energy Research and Technology Council (WTERT) Greece (Synergia, www.wtert.gr) and also the first Vice Chair of the Global WTERT Council, headquartered in the Earth Engineering Center of Columbia University (www.wtert.org). He is a permanent member of the ISWA Working Group on Energy Recovery (ISWA-WGER, www.iswa.org). He graduated from the Department of Chemical Engineering from Aristotle University of Thessaloniki, Greece and has a PhD from the National Technical University of Athens, School of Chemical Engineering. He is an international expert on waste management, specializing in state-of-the-art waste-to-energy (WTE) novel technologies. His major scientific fields include energy from waste, potable water resources, and ozone sterilization technologies. Dr. Kalogirou is involved in many environmental projects worldwide (especially in WTE feasibility studies, preliminary studies, etc.). He is the author of many scientific and technical papers, especially on WTE, and coordinates worldwide intensive courses/seminars on advancing state-of-the-art sustainable waste management and waste to energy as a renewable energy source contributing to green development and carbon credits, in close cooperation with policy/decision makers, local governmental authorities, local industry, and universities. He is experienced in advancing sustainable waste management courses and projects in developing and transitional nations worldwide. He has integrated technical site visits of many worldwide WTE plants (in all continents around the globe) within the last 15 years with simultaneous experience and expertise in conducting specific WTE pre-feasibility and preliminary techno-economical studies and relevant business plans worldwide. Finally, he is a peer reviewer for worldwide high-level scientific journals and relevant research programs.

He is also the author of a Greek book titled: *Drinking Water and Human Health* (*Trace Elements and Trace Organics*), published in 1994 (Second Edition in 1999) by Papasotiriou Books Corporation. This book is part of the university course, "Quality Characteristics and Water Treatment," which has been taught since 1995 as an environmental course (6 months in duration) at the Department of Chemical Engineering in Aristotle University of Thessaloniki, Greece.

Dr. Kalogirou has 2 years of experience in the installation and commissioning of the waste water treatment plant of Argos, Naflpio, N Kios (Greece), 2 years of experience at the Business Center for Attica Air Pollution (mathematical modeling for dispersion of atmospheric pollution, MIUU, UAM), and 4 years of experience in the design, construction, and optimization of the operation of a state-of-the-art compact system for drinkable water and internal air purification-sterilization with ozone technology KFT-X88-C (in cooperation with a Shanghai-based, Chinese company specialized in ozone applications, www.cftcn.com). The compact machine is certified according to European Union Certificates (CE, RoHS & ISO 9001/2000).

He also has 5 years of experience as a Chemical Engineer Supervisor in the Electromechanical Engineering Department of INTRACOM S.A., Multinational Telecommunications and IT Industry, 1997–2002, https://www.intracom.com/.

Dr. Kalogirou served for 11 years as Environmental Projects Director for the Construction Company INTRAKAT S.A., 2002–2013, http://www.intrakat.gr/en/. He has been an expert of Greek court appraisals in chemistry, chemical engineering, and environmental engineering (water, wastewater, and municipal solid waste treatment with an emphasis on waste-to-energy, marine lubricants, and oils), since 2000. He was appointed by the Greek Court in 2013 for the Special Greek appraisement/expertise in the operation of dewatering and mechanical thickening and further treatment of produced sludge in the largest European wastewater treatment plant of Psitaleia, Piraeus, Greece.

1 Introduction

1.1 GENERAL

Today, an estimated 250 million tons of municipal solid waste (MSW) are worldwide thermally treated annually to produce electricity and heat. This relevant global industry is usually called waste-to-energy (WTE) and is rapidly growing: an estimated 250 WTE facilities were built during the first 15 years of the twenty-first century, mostly in Europe and East Asia. The great majority of these WTE plants are based on grate combustion of as-received or post-recycling MSW, and produce electricity and heat. There are also several gasification processes, implemented mostly in Japan; however, a recent compilation of all Japanese WTE facilities showed that 84% of Japan's MSW is treated in grate combustion plants. Several small-scale WTE plants (<5 tons/hour) are operating in Europe and Japan and are based both on grate combustion and gasification technologies. However, the trend is toward very large facilities based on the principle of combustion on a moving bed.

There was little academic interest in WTE technology in the United States until the formation of the Waste-to-Energy Research and Technology Council (WTERT) in 2002. WTERT is a collaboration between the Earth Engineering Center (EEC) of Columbia University and the Energy Recovery Council (ERC—previously IWSA), the latter being the association of WTE companies and plants. By now, WTERT has expanded to international level, and comprises 17 national organizations worldwide.

1.2 ADVANCING SUSTAINABLE WASTE MANAGEMENT WORLDWIDE

Since the beginning of our history, humans have generated solid waste and disposed of them in a variety of ways, such as makeshift waste dumps or incineration. After the Industrial Revolution (which began near the end of the eighteenth century), the amount of goods used and discarded by people increased so dramatically that it became necessary for cities to provide landfills and old-style incinerators for disposing wastes. The management of urban waste, or MSW, became problematic during the mid-twentieth century as the consumption of goods and the corresponding generation of MSW saw a manifold increase. A waste management logistics and transport system is shown in Figure 1.1. It represents the Vienna Plant.

In response, the most advanced countries developed various means and technologies for dealing with solid waste. These range from reducing waste by designing more efficient products and packaging to recycling of usable materials, composting of green wastes, combustion with energy recovery (which falls under the category of WTE), and sanitary landfilling that prevents aqueous and gaseous emissions into

FIGURE 1.1 Waste management logistics and transport (Vienna, Austria).

the environment. Recycling is a key component of modern waste reduction and is the third component of the "Reduce, Reuse, Recycle" waste hierarchy, according to the Directive 2008/98/EC.

Figure 1.2 shows one of the most picturesque WTE facilities in Europe, the Havre WTE plant in France.

It has been estimated that the recorded post-recycling MSW amounts to over 1.4 billion tons per year, of which 1.2 billion tons are placed in a landfill and 0.25 billion tons are treated by various WTE technologies. Also, only 20% of the landfilled MSW is disposed of in sanitary landfills that reduce aqueous and gaseous emissions into the environment. Figure 1.3 shows the situation on an unsanitary landfill in a developing nation.

1.3 THERMAL TREATMENT TECHNOLOGIES USED GLOBALLY

There are currently about 2000 WTE facilities worldwide; an estimated 250 WTE facilities were built during the first 15 years of the twenty-first century, mostly in Europe and Asia, with booming rates in East China. Now, WTE plants are operating globally and providing electricity or heat to their surrounding local communities.

FIGURE 1.2 The WTE plant in Havre, France.

A list compiled by the EEC shows that 250 plants began operations after the turn of this century (see www.wtert.org for a master list of WTE Plants). Table 1.1 summarizes the installed annual capacities of the various WTE technologies.

Figures 1.4 and 1.5 show images from the construction phase and photorealistics of the new state-of-the-art WTE plant in Byggeplads Amager Bakke, Copenhagen, Denmark, which opened during the first quarter of 2017.

FIGURE 1.3 A nonsanitary landfill in Lebanon. (From ISWA, 2016, *A Roadmap for Closing Waste Dumpsites*, Vienna, Austria.)

TABLE 1.1
Feedstock, Energy Product, and Total Capacity of Existing WTE Technologies (2012)

WTE Process	Feedstock	Energy Product	Estimated[a] Annual Capacity (tons)	Continents/ Countries Where Applied
Combustion on moving grate	As-received MSW	High pressure steam	<200 million	Asia, Europe, America
Rotary kiln combustion	As-received MSW	High pressure steam	>2 million	Japan, USA, EU
Energy Answers Process (SEMASS)	Shredded MSW	High pressure steam	>1 million	USA
RDF to grate combustion	Shredded and sorted MSW	High pressure steam	>5 million	USA, EU
Circulating fluidized bed (CFB)	Shredded MSW or RDF	High pressure steam	>15 million	China, Europe
Ebara fluidized bed	Shredded MSW or RDF	High pressure steam	>0.8 million	Japan, Portugal
Bubbling fluidized bed	Shredded MSW or RDF	High pressure steam	>0.2 million	USA
Mechanical biological treatment (MBT or BMT)	Shredded and bioreacted MSW	RDF to cement kilns and coal power plants	>5 million	EU
Direct smelting process	RDF	High pressure steam	>0.9 million	Japan
Thermoselect gasification	As received MSW	Syngas (CO, H_2,CO_2)	>0.8 million	Japan
Plasma-assisted gasification	Shredded MSW	Syngas (CO, H_2,CO_2)	>0.2 million	Canada, Japan, France
Global WTE capacity			<230 million	

[a] Based on data compiled by the EEC of Columbia University (earth@columbia.edu).

1.4 MATERIALS THAT CAN BE PROCESSED BY GRATE COMBUSTION

The feedstock to the WTE plant can include all nonradioactive and nonexplosive materials such as

- Residential and commercial wastes remaining after projected recycling and composting
- Combustible industrial wastes that are currently disposed of in regulated or nonregulated landfills mixed with the MSW in the storage bunker
- Post-recycling combustible construction and demolition wastes
- Sludge cake generated by the wastewater treatment plant of the municipality

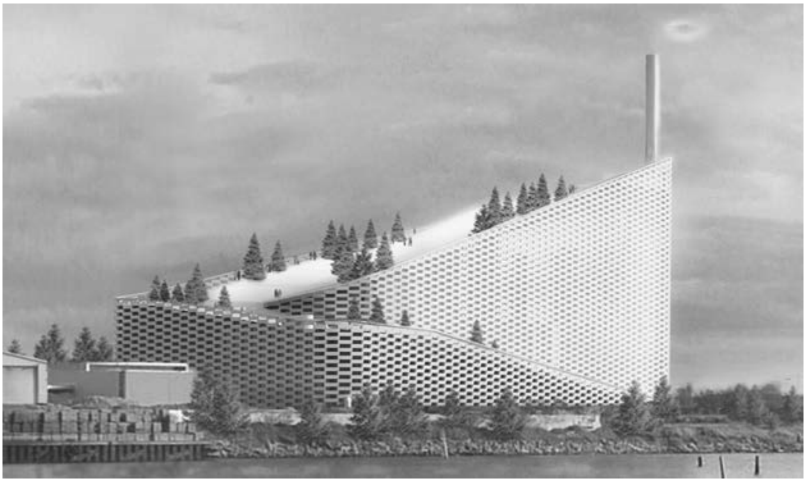

FIGURE 1.4 Photorealistic image of the state-of-the-art new WTE plant in Byggeplads Amager Bakke, Copenhagen, Denmark.

- Shredded rubber tires, mattresses, and post-recycling furniture
- Hospital wastes contained in thick, sealed plastic bags, such as those used in medical combustors

Materials processed during grate combustion that are being transferred are shown in Figure 1.6 (the photograph is from the technical visit by the author to the New Jersey WTE plant).

FIGURE 1.5 The new WTE plant in Byggeplads Amager Bakke, Copenhagen, Denmark under construction (May 2014).

FIGURE 1.6 Materials used in grate combustion (New Jersey WTE plant).

1.5 GRATE COMBUSTION AND GASIFICATION TECHNOLOGIES IN JAPAN

Japan has been a leader in developing and implementing novel thermal treatment technologies. This nation generates about 65 million tons of MSW, thermally treats over 40 million tons of MSW, and recycles the rest.

As further analyzed in Chapter 3 (Section 3.2.1), 84% of the 37.8 million tons of MSW in Japan are mainly processed in relevant moving grate combustion plants.

The WTE processes known as gasification are a combination of partial oxidation and volatilization of the organic compounds within the waste. Gasification in the first furnace is followed by combustion of the volatile gases and steam generation in a second furnace, or by use of syngas in a gas engine or turbine.

Japan is the largest user of MSW gasification in the world; there are over 100 thermal treatment plants based on relatively novel processes such as direct smelting (practiced by steel producers such as JFE and Nippon Steel), the Ebara fluidization process, and the Thermoselect gasification and melting process. The emissions from these processes are as low as the conventional WTE combustion process and produce a vitrified ash that can be used beneficially outside landfills. However, gasification has a higher energy consumption (for more details refer Section 3.2).

A definite advantage of gasification processes is their ability to vitrify the ash, which explains the large number of such plants in Japan. However, plants with capacities of over 500 tons/day utilize grate combustion furnaces that are backed by a second furnace for vitrifying ash. Also, the Syncom grate combustion process, as applied at plants in Sendai, Japan and Arnoldstein, Austria (analyzed in Chapter 4), uses oxygen-enriched air to produce a semi-vitrified ash (see also Section 3.2).

Transportation of as-collected MSW from one municipality to another is not allowed in Japan. As a result, many WTE facilities are relatively small. Also, in some cases, the MSW of several communities is processed to a refuse-derived fuel (RDF) in local RDF facilities and is then transported to a central thermal treatment plant that serves several communities. WTE plants are required to vitrify their ash after combustion by means of an electric furnace, thermal plasma melting, or other means.

1.6 THE EEC AND THE GLOBAL WTERT COUNCIL

The mission of the EEC of Columbia University is to identify and develop the most suitable means for managing various solid waste research and disseminate this information by means of publications, the Web, and technical meetings. This research effort has engaged many MS and PhD students on all aspects of waste management. Since 2000, the EEC has produced more than 30 MS and PhD theses and published nearly 100 technical papers. In 2002, the EEC co-founded WTERT along with the ERC (ERC; www.wte.org), which is now the foremost research organization on the recovery of energy and metals from solid waste in the United States.

In the course of its studies, the EEC established the following:

- 1.2 billion tons of MSW is landfilled each year
- Landfilling will continue to be used in the foreseeable future
- Nearly 80% of the world's landfills are not equipped to capture landfill gas (LFG) and protect surface and ground waters from contamination

Therefore, in 2008, the EEC proposed the expanded the Hierarchy of Waste Management (Figure 1.7) that differentiates between traditional and sanitary landfills.

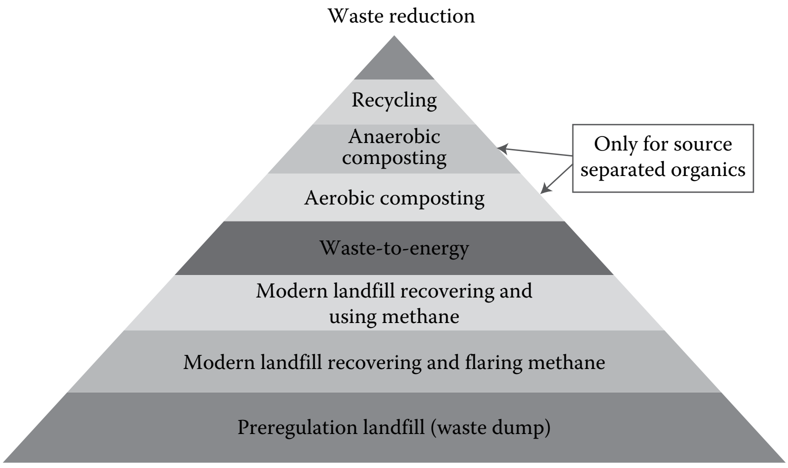

FIGURE 1.7 The EEC Hierarchy of Waste Management.

WTERT is a nonprofit scientific and research organization that coordinates the actions of all 17 worldwide sister organizations, located in Greece, Germany, the United Kingdom, France, Italy, the United States, Canada, Brazil, Mexico, China, the Republic of Korea, Japan, India, and Singapore; affiliates in Colombia, Chile, and Cuba are in development. These organizations share one common goal: the application of state-of-the-art sustainable waste management worldwide via direct contact with policy makers and governmental authorities in order to develop local environmental legislation and promote research of all waste treatment technologies, the main focus being on WTE as a renewable energy source that contributes to green development and carbon credits worldwide.

The principal tool for disseminating information from the United States and other members of WTERT is the Internet. The web addresses used all include the acronym WTERT (www.wtert.org, www.wtert.eu, www.wtert.gr, etc.), the advantage being that when one searches, for example, "WTERT-Italy" in Google or another search engine, one is immediately linked to WTERT organizations in different countries. Thus WTERT has become a valuable brand name and can be very helpful to people seeking information on waste management in a particular country (e.g., Greece) by using the acronym "WTERT" and the name of the country or its acronym (e.g., "gr").

1.7 WTERT'S MISSION

The mission of WTERT is outlined below:

- To identify the best available technologies for the treatment of various waste materials
- To conduct additional academic research as required
- To disseminate this information by means of publications, the WTERT web pages, and periodic meetings

In particular, WTERT strives to increase the global recovery of materials and energy from used solids by means of recycling, composting, WTE, and sanitary landfilling with landfill gas utilization. The guiding principle is that responsible waste management must be based on science and state-of-the-art technology, rather than affordability, as inexpensive solutions today could become expensive issues in the future.

Figure 1.7 shows the previously accepted Hierarchy of Waste Management. However, WTERT understands that for practical or economic reasons it may not be possible to follow this hierarchy at all times and at all locations. For example, WTE requires a larger initial investment than a landfill and therefore may not be attainable at a certain stage of economic development of a community; in such a case, a sanitary landfill with LFG recovery would be the next most preferable option.

Waste management solutions vary from region to region. Hopefully, through the new and powerful tool of the Internet, a global platform will be created to facilitate the sharing of experience, expertise, and information that will advance the goals of sustainable waste management worldwide. Also, the education of local communities, universities, NGOs, and policy makers is very important in order to explain to all stakeholders how to advance relevant sustainable waste management in developing nations around the globe. Therefore, the role of workshops, seminars, conferences, intensive courses, and so on, is crucial.

1.8 WTE'S ROLE IN ADVANCING SUSTAINABLE WASTE MANAGEMENT

WTE is an established option for municipal solid waste treatment, motivated both by the necessity to minimize the environmental stresses of landfilling and the aim of increasing the share of renewable energy (Athanasiou et al., 2015; Gohlke, 2009). European Directive 2008/98/EC (European Commission, 2008) classifies WTE in the recovery category of the conceptual hierarchy of waste management (see Figure 1.7) options when the R1 criterion for energy efficiency is fulfilled (Athanasiou et al., 2015).

During the past decade, WTE plants have been criticized for causing negative impacts on the environment and public health, but in reality they are equipped with sophisticated air pollution control (APC) systems in order to minimize air pollutant emissions, which are strictly monitored (CEWEP, 2015). Directive 2000/76/EC on the incineration of waste made WTE one of the most stringently regulated and controlled industrial activities.

A study in the United States (Dwyer and Themelis, 2015) showed that, by 2012, the dioxin emissions of the U.S. WTE industry have been reduced to 0.54% of all controlled sources. Three major noncontrolled sources are responsible for 89% of total dioxin emissions: landfill fires, forest and brush fires, and backyard burning.

In the last two decades, the WTE industry in Europe, North America, and Asia has developed technologies that are currently among the cleanest sources of thermoelectric energy. The dominant WTE technology by far is grate combustion of as-received or post-recycling MSW for the production of electricity and heat. This method is practiced in over 2000 plants in over 45 nations. However, alternative processes, such as the circulating fluidized bed (CFB), are constantly under development. It is possible that one of more of these techniques may result in lower capital costs per ton of MSW processed than grate combustion. Therefore, proposals to build WTE plants should be open to all technologies, provided they meet the total required environmental criteria.

The contractual arrangement for the construction of a WTE project must include the ironclad commitment of the general contractor that the plant will operate at the specified plant availability (i.e., 8000 hours per year at full capacity), deliver the specified rate of electricity per ton of MSW processed to the grid, and continuously meet the specified environmental standards. The host municipality is also contractually committed to collect and provide the specified daily and annual tonnage of MSW to the WTE plant (this material must also be within the specified range of calorific values).

It is strongly recommended that national governments place sustainable waste management higher up on their list of essential infrastructure projects, in addition to services such as waste removal, electricity, and wastewater treatment.

The construction of the first WTE plant in a nation can motivate other cities to apply for WTE projects. Often, WTE projects are not viewed as economically profitable to private investors in the short term; however, WTE projects can develop into economic booms in the long-term, in terms of job creation, the addition of a local source of renewable energy, the enormous amount of land conserved over hundreds of years, and the environmental and greenhouse gas advantages of WTE over landfilling. Therefore, it becomes prudent for national or regional governments to participate in a public-private partnership that will allow the nation to move towards more sustainable waste management.

The development of WTE facilities in nearly 45 nations across the globe has had a positive track record on improving the environment in the areas where these plants operate. The first WTE project in a city or nation should be viewed as a genuine positive development with very beneficial impacts environmentally, financially, and socially.

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2 Legislation

2.1 WASTE-TO-ENERGY'S ROLE IN EU ENERGY POLICY AND CIRCULAR ECONOMY

The European Union Legislation for Sanitary Landfills (1999/31/EC) imposes a decrease in the biodegradable waste fraction which is landfilled. Hence, thermal treatment methods of municipal solid waste (MSW), along with recycling at the source and composting a pre-sorted fraction of waste, are nearly the only solutions to such problems. Additional advantages include the volume and weight reduction of MSW and energy production (with the possibility for district heating, for industrial heating, or for cooling waste-to-energy [WTE] plants).

The main relevant European Union directives for incineration of waste are 2000/76/EC and 2010/75/EC, while the regulation on renewable energy sources (RES, Directive 2001/77/EC) includes the biogenic fraction of wastes. Also, the European Union defined the optimum hierarchy for waste treatment methods through the 2008/98 EU Directive. According to this directive, reduction, reusing, and recycling are the first stages, followed by efficient energy recovery methods, which have been upgraded in the hierarchy list.

The European Union, via the directives that it issues, indirectly promotes the application of thermal treatment methods (combustion, gasification, and pyrolysis), along with recycling at the source and composting of preselected waste from the organic fraction of the source, as effective methods of reducing the quantities of MSW that are deposited in sanitary landfills, while simultaneously producing energy in the form of heat and electricity by exploiting the heating value of MSW. With fossil fuel reserves decreasing dramatically, the utilization of MSW as a fuel source looks even more promising.

Waste-to-energy plants thermally treat waste not suitable for recycling and that would otherwise be consigned to landfills. They produce reliable baseload energy from residual waste and help reduce the use of (limited) fossil fuels, which would otherwise be used to produce energy. Energy from waste contributes to diversifying the EU's energy mix by boosting the share of renewable energy and reducing greenhouse gas (GHG) emissions and dependence on fossil fuel imports.

Especially in Europe, waste-to-energy plants generate sustainable energy of which approximately 50% is renewable (this percentage can slightly vary locally, due to the variation of the estimated biodegradable/biogenic fraction). The other 50% would be lost in landfills so, although not renewable, it still replaces fossil fuels such as coal, lignite, diesel, pet coke, petroleum, and so on. Waste-to-energy plants produce a reliable and secure baseload energy, while at the same time providing vital environmental services for residual waste that is not suitable for reuse or recycling, all in line with the waste hierarchy. They provide energy to households and industries, particularly through district heating and cooling networks as well as process steam. Some plants generate electricity only. Most waste-to-energy plants in Europe are equipped to provide combined heat and power (CHP).

Waste-to-energy provides synergy between the circular economy and energy union goals, helping to reduce dependence on landfills and their greenhouse gas emissions, while replacing fossil fuels used by conventional power plants.

The Confederation of European Waste-to-Energy Plants (CEWEP, www.cewep.eu) promotes investment in the energy efficiency of the plants in order to generate as much sustainable energy as possible from the residual waste. The European Commission's (EC) "Energy efficiency first" principle should be properly considered in the design of a sustainable energy market. An example of this principle is the synergy between energy-consuming industrial activities and energy providers, where the energy produced is a by-product of other industrial activities. European waste-to-energy plants provide such synergy by treating residual waste and, at the same time, producing energy. They play an important twofold role in waste management and energy systems.

Moreover, waste-to-energy provides secure and clean energy that can be used as a baseload supply, therefore helping to stabilize the variability of the grid. Waste-to-energy plants are considered most efficient if they are located close to consumers of heat and steam. This is often not the case due to negative public perception of emissions from these plants. Informing the public about the benefits of waste-to-energy, and particularly the huge progress that has been made in antipollution equipment of waste-to-energy plants, is of utmost importance.

Today, waste-to-energy is one of the most stringently regulated and controlled industrial activities and achieves very low emissions. It complements recycling by treating waste that could not be avoided and thereby diverting it from landfills.

In the major cities of Europe, the combustion of post-recycling MSW is applied with great success. Using thermal treatment, steam and electricity are produced and the weight of MSW is reduced by up to 70%–80%, whereas the volume is reduced by up to 90%. With an emphasis on the major advantages of weight and volume reduction, the absence of pathogenic substances, and the very small land area requirements, in parallel with the steam and electricity production, thermal treatment of MSW is increasingly applied. The dominant WTE technology is combustion in moving grates because of its simplicity and relatively lower capital cost.

The combustion of MSW is an old and well-proven process that includes the development of high temperatures, with the presence of flame for the oxidation of the MSW. The target of this complicated physicochemical operation is the evaporation, the degradation, the destruction of organic elements of the MSW with the presence of oxygen (in stoichiometric proportion or in surplus), and the reduction of the weight and volume of MSW. The products of the combustion process include gaseous compounds (e.g., CO_2, NO_x, acid gases, PAHs, etc.), which need to be further treated in the state-of-the art flue gas cleaning system before their final emission into the atmosphere. The relatively inert solid residues (mainly bottom ash, fly ash, and usually the small portion of typically hazardous waste), which represent in total the 23%–30% of the initial feed (MSW quantity) of the WTE plant, and possibly contain some important inorganic pollutants including heavy metals, also need to be further treated. After stabilization and solidification, the fly ash can be disposed of in a sanitary landfill for residuals, while the bottom ash is relatively inert (usually after the toxicity characteristic leaching procedure (TCLP) test) and can most commonly be used for construction applications (in roads, earthworks, mines, aggregates, etc.).

The big advantage of the previously mentioned combustion-based WTE plants using moving grates, is that they can directly treat and burn MSW, without any pretreatment of the MSW before it enters the combustion chamber. Therefore, the operation of such a waste-to-energy plant is relatively simple. For the exploitation of the produced heat from the combustion and the recovery of energy, modern combustors are superior to special boilers for steam production. Then, the produced steam is used either directly for heating applications or via a suitable steam turbine and generator for the production of electricity (these are described in detailed in Section 3.1).

In Figure 2.1, a typical MSW combustion/WTE plant for energy production is presented.

The most important process in such a WTE plant is the state-of-the-art flue gas cleaning system (air pollution control (APC)) for the chemical cleaning of the produced gaseous pollutants. The major systems are dry, semi-dry or wet, semi-wet scrubbers, electrostatic precipitator (ESP) filters, fabric bag filters and cyclones, activated carbon filters, selective non-catalytic reduction (SNCR) or selective catalytic

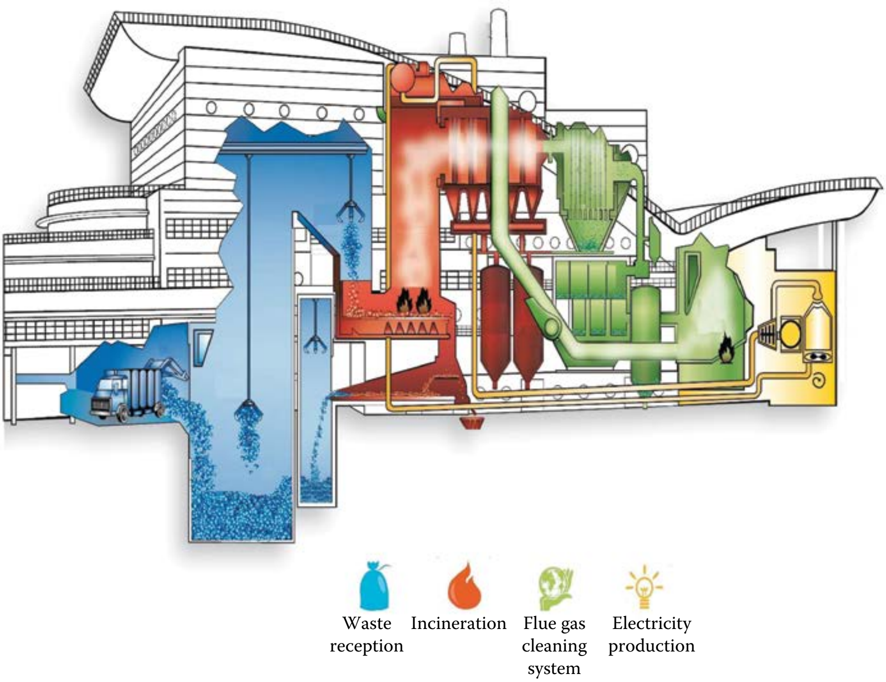

FIGURE 2.1 A typical MSW combustion/WTE plant with electricity production. (From SEVEDE, 2007, *Annual Report 2007*, Paris, France.)

reduction (SCR), and chemicals (like NH_3, CaO, $Ca(OH)_2$, etc.). The optimum selection of the flue gas cleaning system is based on the composition of the gaseous pollutants under treatment (depending also on the composition of the feed of MSW), on the maximum admissible limits of the emissions of all the plants into the atmosphere, and on the possible produced liquid waste, according to the directives 2000/76/EU and 2010/75/EU.

2.2 EMISSION LEVELS IN WASTE-TO-ENERGY FLUE GASES

The best available techniques (BATs) for antipollution during the whole thermal treatment process of the MSW, (e.g., via the very strict emission limits of the 2000/76/EU and 2010/75/EU Directives and also similar limits in the United States and other countries) lead to the environmental acceptance of the MSW relevant WTE plants worldwide. These techniques also result in promoting this combustion process as more friendly for the environment compared to other typical human activities, like traffic and industrial pollution.

Today, it is well known that, according to the important European Union directive 2008/98, landfilling is discouraged. The further construction and use of sanitary landfills will be legal in the future, only for the disposal of the residuals after treatment. Pioneer countries in the application of waste-to-energy (thermal treatment methods for MSW) are Switzerland, Sweden, Netherlands, Denmark, Germany, France, Belgium, Austria, and Norway in Europe; Japan, South Korea, and China in Asia; and the United States.

In Europe, the contribution of dioxins produced by MSW/WTE plants is less than 0.7% of total dioxin emissions, as shown in Table 2.1 of the relevant study (Bilitewski, 2006).

For example, in Brescia (Italy) there is a WTE plant with an annual capacity of around 340,000 tons MSW (two lines for the combustion of household waste began operation in 1998) and 170,000 tons of biomass (one line began operation in 2004), producing 50 MW of electrical power and 100 MW of thermal power for district heating. This plant is only within 300 meters of the first row of houses in Brescia (which is located halfway between Milan and Padua in Northern Italy).

TABLE 2.1
Dioxin Emissions

Modern WTE plant	1	0.01 ng/m^3
Modern WTE plant for hazardous waste	1	0.01 ng/m^3
Noncontrolled incineration (i.e., fireplaces)	1000	10 ng/m^3
Fireworks	10,000	100 ng/m^3
Burning landfill	100,000	1000 ng/m^3

Source: Bilitewski, B., 2006, *Proceedings Venice 2006: Biomass and Waste to Energy Symposium*, November 29–December 1, Venice, Italy.

TABLE 2.2
Stack Emissions from Brescia WTE Plant

Values Referred to Dry Gas, Normal Conditions, 11% O_2	Plant Authorization Limits 1993	Plant Design Data 1994	European Union Limits 2000	Actual Operating Data
Particulate matter	10	3	10	0.4
Sulfur dioxide	150	40	50	6.5
Nitrogen oxides (NO_x)	200	100	200	<80
Hydrochloric acid (HCl)	30	20	10	3.5
Fluorine acid (HF)	1	1	1	0.1
Carbon monoxide	100	40	50	15
Heavy metals	2	0.5	0.5	0.01
Cadmium (Cd)	0.1	0.02	0.05	0.002
Mercury (Hg)	0.1	0.02	0.05	0.002
Polycyclic aromatic hydrocarbon (PAH)	0.05	0.01		0.00001
Dioxin (TCDD Teq)	0.1	0.1	0.1	0.002

Note: All values in mg/Nm3 (except for dioxin, ng/Nm3).

From Table 2.2 it is well-understood that the gaseous emissions from the relevant stack are much lower than the accepted maximum limit values of the European Union Directive for the incineration of waste (2000/76/EC), (Figure 2.2).

In Europe today, there are approximately 470 WTE plants operating. There were over 90 MSW WTE plants in Germany in 2016.

FIGURE 2.2 WTE plant in Brescia, Italy.

2.3 WASTE-TO-ENERGY AS AN INTEGRAL PART OF SUSTAINABLE WASTE MANAGEMENT WORLDWIDE

Especially for MSW management, it is recognized that the most efficient, dominant, integrated, and proven waste management system is recycling at the source and composting preselected organic waste, followed by thermal treatment (recovery of energy from waste through the combustion process) of MSW, as implemented in the majority of the currently operating 2000 WTE plants worldwide.

WTE is a proven, environmentally sound process that provides reliable electricity and steam generation and sustainable disposal of post-recycling MSW. WTE technology is used extensively in Europe and the United States as well as in other developed nations such as China, South Korea, Japan, Singapore, and Taiwan.

Thermal treatment methods affect climate change. Energy recovered from thermal treatment of waste contributes to the reduction of greenhouse gases in two ways:

1. Prevents the production of methane CH_4 (21 times more potent as greenhouse gas than CO_2) and other emissions from landfill sites and
2. Emits less CO_2 compared to fossil fuels, which it replaces (i.e., lignite, mazout, etc.). In thermal treatment plants, it is possible to co-combust industrial waste of similar composition to municipal waste, sludge from waste water treatment plants, and biomass.

2.4 WASTE-TO-ENERGY TECHNOLOGY AS A RENEWABLE ENERGY SOURCE

New policies encouraging WTE can help reduce the world's greenhouse gas emissions. In fact, world-wide use of WTE technologies can become one of the leading contributors to planned reduction of greenhouse gas emissions.

WTE can also have an impact on reducing fossil fuel usage and increase energy production using renewable sources. Combusting the biogenic fraction of WTE is considered renewable by the environmental departments in most developed countries. As landfilling is the most common waste management method currently used in many countries, there is a significant potential to increase energy production from WTE. Each ton of MSW combusted produces the energy equivalent of one-third of a ton of coal or one barrel of oil.

Also, through the recovery of metals during the waste-to-energy process, additional environmental benefits are achieved, as mining operations are reduced. According to the Confederation of European Waste-to-Energy Plants (CEWEP), WTE is classified as a renewable energy source, depending on the percentage of the biodegradable fraction of the incoming waste (the renewable energy output is estimated 50%).

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3 Waste-to-Energy Technologies

3.1 COMBUSTION

3.1.1 Introduction

The combustion process is considered today to be the most dominant and proven waste-to-energy (WTE) technology, with more than 2000 well operating plants/references worldwide. Globally, WTE facilities treat more than 250 million tons annually, and forecasts from both the International Solid Waste Association and the United Nations Environment Programme estimate this capacity to increase 500% in the next decade as many of the worldwide developing nations embrace WTE technology to strongly reduce their reliance on landfills and dumpsites.

Especially in high populated metropolitan cities like Paris, Frankfurt, Lisbon, Turin, Vienna, Copenhagen, Seoul, Shanghai, Beijing, Tokyo, WTE plants based on the combustion process are situated almost in the center of the city and comply to the most strict environmental maximum admissible limits, as described in previous chapters. These WTE plants provide a final integrated solution, advancing state-of-the-art sustainable waste management for the municipal solid waste (MSW) treatment and simultaneously producing electricity and district heating/cooling.

In Figure 3.1 an indicative relevant WTE flowchart (process flow diagram) is described.

3.1.2 Plant Layout

An indicative combustion-based WTE plant layout is shown in Figure 3.2.

The main departments of the indicative WTE plant are

1. Bunker
2. Combustion chamber
3. Boiler
4. Steam turbine/generator
5. Air pollution control (APC)
6. Stack

3.1.3 Reception

Incoming vehicles enter the plant via weighbridges, which record various data about waste load. These data are transferred to a computer in the control room and usually include the origin of the vehicles and waste, net and gross tonnage, as well as time and date of the delivery.

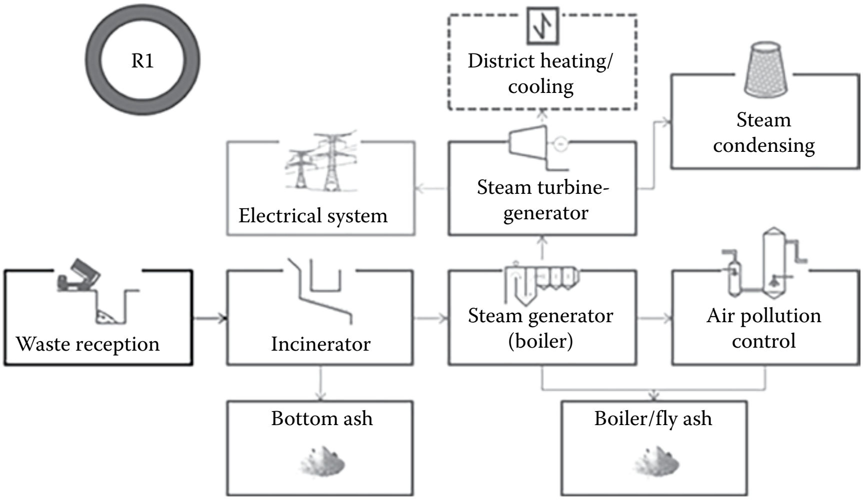

FIGURE 3.1 Indicative WTE process flow diagram.

From the weighbridge, vehicles proceed to the tipping hall to discharge their load into the waste bunker. There are tipping bays into which the vehicles reverse. The bays are demarcated with bollards and raised kerbs to allow the vehicles to reverse safely.

The tipping hall is fitted with a roller shutter door to minimize fugitive emissions of odor. This door remains closed when no waste deliveries are occurring. The tipping hall is also maintained at a low pressure in order to further minimize odor emissions, and it is cleaned periodically. A sloping floor allows wastewater produced by cleaning activities to be collected for further treatment.

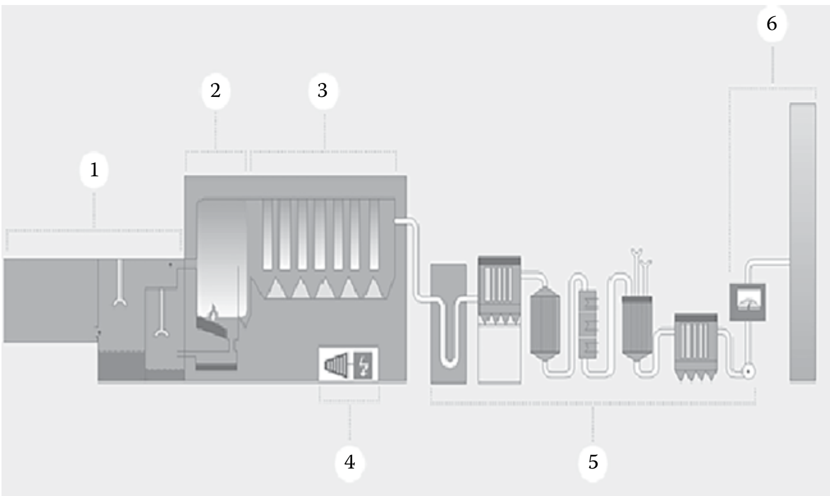

FIGURE 3.2 Indicative WTE plant layout.

Above the waste bunker, there are installed sets of automatic control grabs mounted on traveling cranes. They are operated by crane operators seated in the control room overlooking the waste bunker. Control can be manual, semi-automatic or fully automatic. In addition to feeding the charging hoppers, cranes mix the waste in the bunker. Mixing of the waste ensures good consistency and improves combustion. The capacity of the grab is sufficiently large to feed the charging hoppers while operating at full capacity. The weight of the waste in the grab is recorded automatically, and the data are fed back to the control room.

The waste bunker also serves as a temporary storage area during periods of maintenance or shutdown. The bunker usually has the capacity to store 4–7 days worth of waste at normal operating capacity. In case of prolonged shutdown, waste can be transferred from the bunker back into lorries for safe disposal in a licensed facility.

During normal operation, the bunker is emptied in a rotation sequence to prevent long periods where waste remains in certain parts, which could result in waste degradation and odor production. The bunker is equipped with a system for continuous monitoring of excessive heat within the waste. This consists mainly of an infrared camera mounted within the bunker.

Usually the control room of the plant is placed in the same room as the crane operator. As a minimum, the following processes usually take place in the control room:

- Monitoring, recording, and logging of plant status and process parameters
- Provision of operator information regarding the plant status and process parameters
- Provision of operator controls to affect changes to the plant status
- Automatic process control and batch/sequence control during start-up, normal operation, and shutdown
- Detection of unusual operations

These functions are normally provided by alarm protection and process control systems. The human interface may comprise a number of input and output components, such as controls, keyboard, mouse, indicators, annunciators, graphic terminals, mimics, audible alarms, and charts.

The plant interface comprises inputs (sensors), outputs (actuators), and communications (wiring, fiber optic, analogue/digital signals, pneumatics, fieldbus, signal conditioning, barriers, and trip amplifiers). The logic elements may be distributed and linked by communications or marshaled together. They may be in the form of relays, discrete controllers or logic (electronic, programmable, or pneumatic), distributed control systems (DCSs), supervisory control and data acquisition (SCADA), computers (including PCs), or programmable logic controllers (PLC). The logic elements may perform continuous control functions, batch, or change of state (e.g., start-up/shutdown) sequences.

Figure 3.3 shows an indicative bunker for waste reception; in Figures 3.4 and 3.5 the crane and the bunker (from the control room) are shown. In Figure 3.6 the bunker is shown from the operator’s perspective. In Figure 3.7 an indicative control room is shown from inside.

FIGURE 3.3 Indicative waste reception (bunker).

FIGURE 3.4 Indicative waste reception (bunker) and the crane.

FIGURE 3.5 Indicative waste reception (bunker) as shown from the control room.

FIGURE 3.6 Crane operator.

FIGURE 3.7 Control room view.

3.1.4 Combustion Chamber

Cranes, as described in the previous section, transfer waste from the waste bunker into the feed system, which consists of feeding hoppers and chutes that feed the combustion chamber. The aim of the charging hopper is to feed the waste continuously and smoothly in order to ensure steady combustion conditions.

The following three combustion chamber/systems are applicable in WTE plants, with the first one being the most prevailing and most popular due to simplicity of operation:

1. Moving grates
2. Rotary kiln
3. Fluidized bed

3.1.4.1 Moving Grate Combustion

Conventional moving grate combustion consists of a layer on the grate transporting material through the furnace. While on the grate, the waste is dried and burned at high temperatures with air supply. The ash (including noncombustible fractions of waste) leaves the grate as slag/bottom ash through the ash chute.

The grate forms the bottom of the furnace. The moving grate, if properly designed, efficiently transports and agitates the waste and evenly distributes the combustion air. The grate may be sectioned into individually adjustable zones, and the combustion air can usually be preheated to accommodate variations in the lower calorific value of the waste.

There are several different grate designs—including forward movement, backward movement, double movement, rocking, and roller. Other alternatives may be suitable as well.

Grates are designed for the combustion of waste with a calorific value of 7800 kJ/kg to 12,500 kJ/kg, without the need for auxiliary fuel.

There are four main components that make up the combustion grate:

- *The feeder*: A pusher-type feeder is used to feed the waste onto the grate. The waste layer breaks into smaller pieces as it falls between the feeder and the drying grates. Any moisture in the waste evaporates on the drying grate.
- *The drying grate*: The drying grate and burning grate are inclined for efficient transport of the waste and enhanced mixing. The movement of the alternating fixed and moving grate bars has the effect of continuously stoking and mixing the burning mass of waste. This enables a homogeneous fuel bed to be formed.
- *The burning grate*: Combustion takes place on the burning grates. The combustion air is uniformly supplied to the entire width of the grate so that the waste can be brought into uniform and efficient contact with the air to maximize the efficiency of combustion.

  The combustion air is distributed, depending upon the combustion characteristics, by dividing the hoppers into several compartments to the waste flow direction. The quantity and temperature of the combustion air are controlled depending on combustion characteristics and waste property, respectively.
- *The burn out grate*: The remaining unburned combustibles fall between the combustion grate and the burnout grate and break into smaller pieces. Sufficient retention time is given to ensure unburned combustibles are completely transformed to ash. The bottom ash (or slag) falls from the end of the grate through a chute into the bottom ash discharge system. Slag is quenched into a water bath and discharged by a hydraulically operated ram extractor, a device specifically designed for this purpose. The water bath also provides a gas seal to the furnace and prevents ingress of air and egress of dust and fumes.

3.1.4.1.1 Grate Bars

Individual hydraulic drives push each of the grates. This allows the thickness of the waste and ash layers to be controlled by adjusting the speed of each of the drives. The grate bar elements are designed to carry out their function reliably and with long service life. They are made of high-grade chrome steel alloy castings and are capable of withstanding high temperatures while maintaining close tolerance to ensure a close fit between adjacent bars and proper air distribution across the grate. The air flowing through the grate also ensures cooling of the grate bars.

3.1.4.1.2 Combustion Chamber

The combustion chamber is made up of membrane water tube walls with refractory lining that are completely integrated within the steam boiler to reduce heat loss and avoid air leaks. The external body of the combustion chamber consists of air-sealing steel plates and refractory materials designed to prevent air leaks. The exterior structure is heat insulated in order to prevent heat loss.

The general consideration of the design of the combustion chamber is to control combustion, reduce carbon monoxide (CO) production, and ensure a minimum residence time of 2 seconds at a minimum temperature of 850°C or 1100°C, depending on the chlorine content.

WTE plants are designed, built, equipped, and operated in such a way so as the produced gas is raised at a temperature of 850°C, in a controlled and homogenous manner. The measurements occur for two seconds, near the inner wall or at other representative points in the combustion chamber, according to the guidelines of the competent authority. If hazardous wastes, with a content of more than 1% of halogenated organic substances, expressed as chlorine, have to be combusted, the temperature has to be raised to 1100°C for at least 2 seconds.

3.1.4.1.3 Air Distribution System

The air distribution system consists of primary and secondary air fans, air preheaters, and air dusts. The combustion air fan consists of a primary and a secondary air fan, which supply air to the grate and the secondary combustion chamber, respectively. Approximately two-thirds of combustion air is supplied to the grate; the remaining one-third is diverted to the secondary combustion chamber. The primary air fan takes air from the waste bunker. After heating the air, the primary air is sent to the air plenum below the grate through a ductwork system with adjustable control dampers. The secondary air fan takes air from the boiler hall and sends it to the side walls of the secondary combustion chamber, through air preheaters and manually preset dampers. Primary air temperature is adjusted to the waste calorific value. The air preheaters are supplied with low and medium pressure steam, depending on the required temperature.

Secondary air is supplied at the top of the combustion chamber to fully combust any CO present. The geometry of the combustion chamber and location of the secondary air injection nozzles are carefully designed to ensure optimized combustion conditions.

3.1.4.1.4 Auxiliary Firing System

An auxiliary firing system is needed to ensure that the furnace temperature is maintained above 850°C (or 1100°C if needed) while there is waste on the grate and to preheat the furnace to the same temperature at start-up, prior to the waste introduction onto the grate. Oil-fired burners are more commonly used as the auxiliary firing system. During shutdown, the burners are used to slowly decrease temperature and prevent a sharp variation in temperature, which could cause the nonburning of the residual waste in the grate.

3.1.4.2 Rotary Kiln Combustion

Combustion based on a rotary kiln consists of a layered burning of the waste in a rotating cylinder. The material is transported through the furnace by the rotations of the inclined cylinder.

The rotary kiln is usually refractory-lined but can also be equipped with water walls. The cylinder may be 1–5 meters in diameter and 8–20 meters long. The capacity may be as low as 2.4 t/day (0.1 t/hour) and up to approximately 480 t/day (20 t/hour).

The excess air ratio is well above that of the moving grate combustor and even the fluidized bed. Consequently, the energy efficiency is slightly lower and may be up to 80%.

As the retention time of flue gases is usually too short for a complete reaction in the rotary kiln itself, the cylinder is followed by, and connected to, an afterburning chamber, which can be incorporated in the first part of the boiler.

The rotary kiln may also be used in combination with a moveable grate, where the grate forms the ignition part and the kiln forms the burning-out section. This results in a very low level of unburned material in the slag. The slag leaves the rotary kiln through the ash chute.

3.1.4.3 Fluidized Bed Combustion

Fluidized bed combustion is based on a principle whereby solid particles mix with the fuel and are fluidized by air.

The reactor (scrubber) usually consists of a vertical, refractory-lined steel vessel, containing a bed of granular material such as silica sand, limestone, or a ceramic material. The fluidized bed technology has a number of appealing characteristics in relation to combustion technique: reduction of dangerous substances in the fluidized bed reactor, high thermal efficiency, flexibility regarding multifuel input, and cost.

A main disadvantage of the fluidized bed for waste combustion is the usually demanding process of pretreating waste before the fluidized bed so as to meet the rather stringent requirements for size, calorific value, ash content, and so forth. Because of the heterogeneous composition of MSW, it can be difficult to produce a fuel that meets the requirements at any given point.

Figure 3.8 shows the view of a moving grate combustion. A rare view of a moving grate during maintenance is shown in Figure 3.9. An indicative furnace diagram is illustrated in Figure 3.10, whereas a moving grate diagram is shown in Figure 3.11. More information about moving grates is shown in Figure 3.12. Finally, Figure 3.13 shows a combustion chamber during the combustion process.

FIGURE 3.8 Moving grate during combustion.

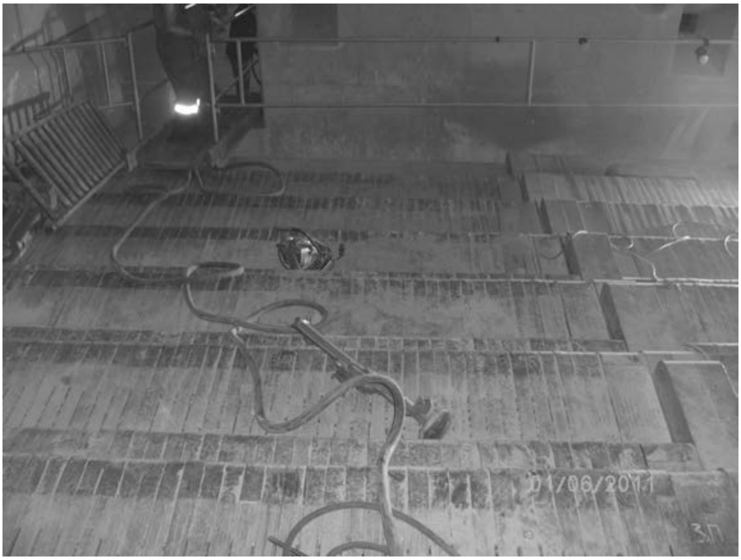

FIGURE 3.9 Moving grate during maintenance.

3.1.5 Boiler

Energy is released from combustion and leaves the furnace as flue gas at a temperature of approximately 1000–1200°C. The flue gases are cooled through a boiler, where the energy released from combustion is initially recovered as hot water or steam.

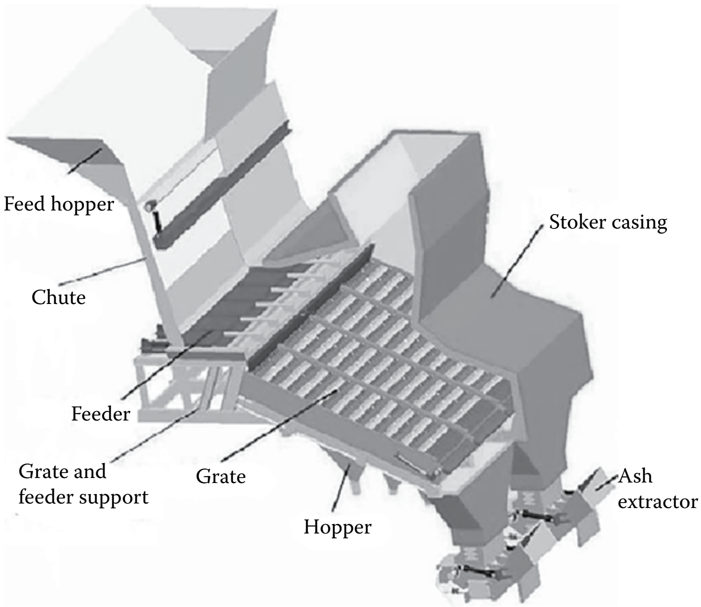

FIGURE 3.10 Indicative furnace diagram.

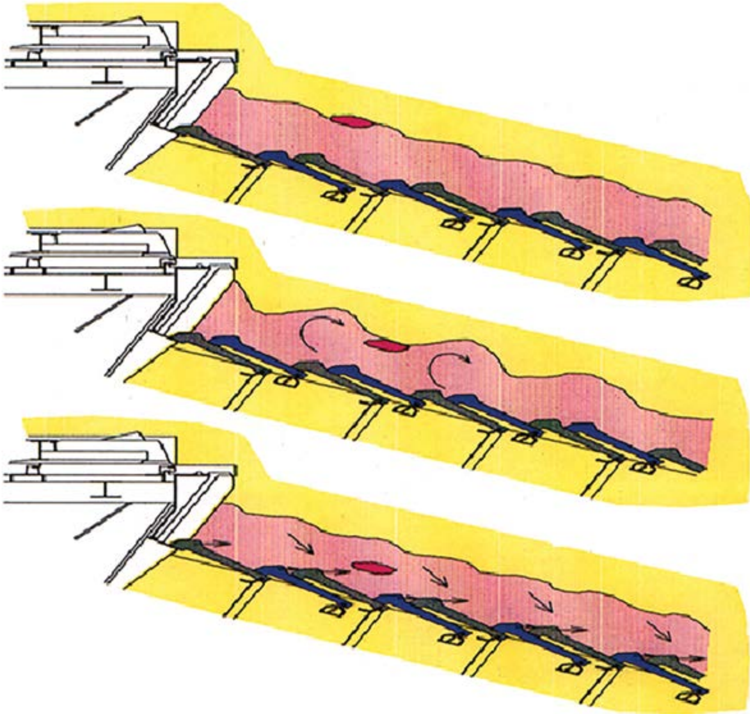

FIGURE 3.11 Diagram showing waste movement on moving grate.

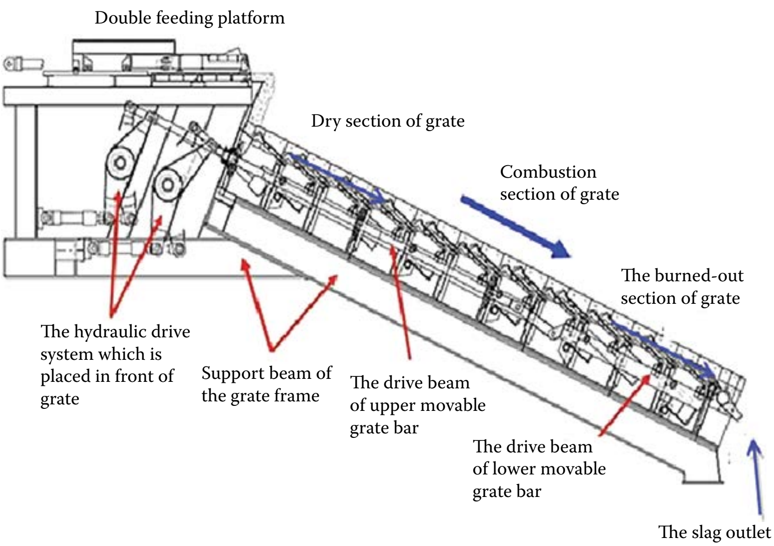

FIGURE 3.12 Diagram explaining a moving grate's parts.

FIGURE 3.13 Furnace during combustion.

The end use possibilities of power, district heating, or steam depend on the type of boiler. The boilers are divided into three broad categories, as follows:

- The hot water-producing boiler produces heat only (hot water).
- The low pressure-producing boiler produces low-pressure steam only.
- The steam-producing boiler generates power and combines power and process steam or heat.

3.1.5.1 Hot Water Boiler

The energy from the hot flue gas is transferred via a hot water boiler to an internal circuit of water, which passes the energy to the end-user circuit (district heating system) in order to heat homes and public buildings. Hot water (approximately 110°–160°C) may be produced. It can be heated to higher temperatures depending on the operating pressure level of the boiler. A boiler efficiency of up to approximately 80% can be achieved. The recovery is limited by the temperature of the returning cooling water. The hot water boiler is fairly simple in design, accommodation in building arrangements, finance, operation, and maintenance. Technically, special attention should be paid to the corrosive nature of the flue gases produced by waste combustion.

3.1.5.2 Low-Pressure Steam Boiler

If a district heating network is not available and there is a demand for process steam, a low-pressure boiler may be an alternative to the hot water boiler. The low-pressure boiler is similar to the hot water boiler in terms of complexity, accommodation in building arrangements, financing, operation, and maintenance, although the design requires more attention because the flue gases are so corrosive.

Depending on the operating pressure level of the boiler and the extent of superheating, the steam may be approximately 120° to 250°C. A steam pressure of up to approximately 20 bar may be relatively low. This allows saturated steam to be at approximately 210°C. A certain amount of superheating may be necessary, depending on the vicinity of the end users—as uses for low-pressure steam depend on its energy content. A boiler efficiency of up to approximately 80% can be achieved.

3.1.5.3 High-Pressure Steam Boiler

A steam boiler requires more attention in design than the hot water-producing or low pressure steam boiler because of the highly corrosive nature of the flue gas. It also requires more attention for its operation and more space.

The steam boiler is divided into one to three open radiation passes and a convection part. The radiation part includes the evaporator where saturated steam is produced. After passing the radiation part, the flue gases enter the convection heating surfaces. There, they first transfer heat to superheaters and then to economizers and after that pass to the flue gas cleaning system.

The superheater aims to increase the temperature of the condensed steam coming from the evaporator. The temperature of the flue gases that head to the superheater does not exceed 630°C. The heating surface of the superheater is divided into three sections with intermediate water injection between the stages (desuperheaters) in order to control steam temperature (max 400°C). The last section of the economizer aims to preheat the feed water prior to entering the boiler steam drum but also to decrease gas temperature down to 160–220°C.

The radiation part of the boiler requires a room of up to 30–40 meters in height. The convection part of the boiler can be arranged either horizontally or vertically. The horizontal arrangement takes up approximately 20 meters more space than the vertical arrangement in the longitudinal direction. The arrangement of the convection section can significantly affect building costs and should be determined as early as possible.

The waste-fired plant cannot be designed with steam parameters similar to those of traditional power plants fired with coal, gas, or oil. This is because waste differs from fossil fuel, particularly in terms of the content of chlorine, which—combined with sulfur—may lead to high-temperature corrosion, even at relatively low temperatures. The risk of corrosion and erosion can be reduced by observing a number of specific design criteria and by designing the boiler for moderate steam parameters (pressure and temperature).

The primary features to minimize fouling and corrosion are as follows:

1. Optimized combustion chamber dimensions and low gas velocity to reduce ash entrainment
2. Long gas residence time in the radiation pass before entering the convective pass
3. Horizontally, flue gas flows in the convective pass, which has higher thermal efficiency
4. Online cleaning systems in the convective pass made of mechanical rapping devices rather than soot blowers
5. Wide tube spacing in the horizontal pass, including free space for additional heating surface

Some combustion processes may, furthermore, have a risk of CO corrosion. The corrosive nature of the flue gas from waste combustion usually limits the steam parameters to a maximum temperature of approximately 400°C and a pressure of approximately 40 bar. The temperature of the water returning to the boiler (feed water) is maintained at a minimum of 125–130°C to limit the risk of low-temperature corrosion in the coldest part of the boiler.

Hoppers are provided under the vertical and horizontal passes to collect boiler ash. Collected dust is discharged by mechanical conveyors into the ash silos. Boiler ash is considered to be part of the produced fly ash.

The energy recovery from a steam-producing boiler is conventionally known as the Rankine process. The Rankine process allows energy outputs in the form of power, steam, and combinations of power, steam, and hot water.

The energy from the hot flue gases is recovered through the boiler and passes to the internal circuit of steam. The steam energy may be converted to power by a turbine and a generator set. The superheated and high-pressurized steam of the boiler is expanded in the steam turbine, which transforms the energy content of the steam to kinematic energy, which is further transformed to electrical energy by the generator. The excess heat of the low-pressure steam is converted to hot water within the heat exchanger (condenser) and either passed to a district heating network or cooled away.

Condensate from the condenser is returned to the feed water tank and the deaerator, in order to have suitable heating and degassing. The feed water tank and the deaerator are made of a cylindrical horizontal storage tank. It is fitted with baffles and steam distribution nozzles in the bottom and a dome in the upper part of the tank equipped with spray nozzles. To compensate for continuous boiler blowdown, demineralized water is transferred to each feed water tank through makeup water pumps. The boiler water is supplied to the boiler from the feed water tank and the deaerator by high pressure feed water pumps. Chemicals are used to raise pH levels

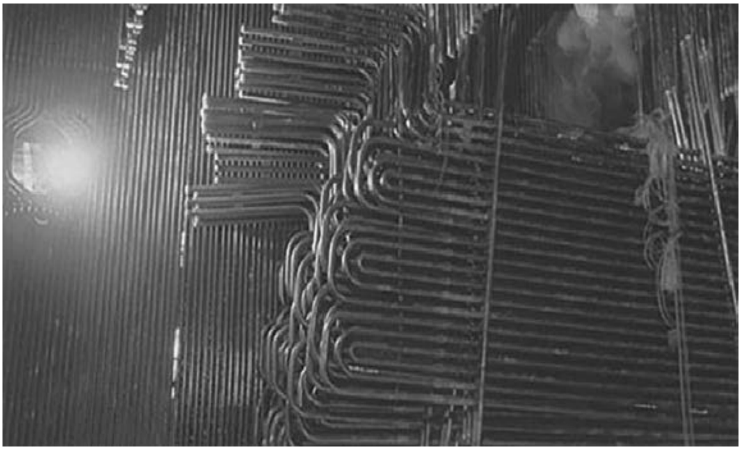

FIGURE 3.14 Boiler view: Superheater part.

FIGURE 3.15 Boiler view.

to prevent the boiler's corrosion and scaling. A deoxidizer, which decreases dissolved oxygen, is used in order to prevent corrosion of the boiler.

Part of the superheater in the boiler is shown in Figure 3.14. Another view of the boiler is shown in Figure 3.15. Finally, Figure 3.16 shows an indicative boiler during maintenance.

FIGURE 3.16 Boiler during maintenance.

3.1.6 Steam Turbine: Condenser

3.1.6.1 Steam Turbine

In WTE plants, electricity is produced through a steam turbine generator set. When producing electrical power, it is possible to recover only up to 35% of the available energy in the waste as power. The surplus heat has to be cooled in a condenser or a cooling tower. This option is attractive if the plant is situated far from consumers who require heat. When only power is produced, a fully condensing turbine is used. The excess heat is produced at such a low temperature in this condenser that it is not attractive for recovery.

A steam turbine is a rotary type of steam engine that consists of a stationary set of blades (called nozzles) and a moving set of adjacent blades (called buckets or rotor blades) installed within a casing. Steam from nozzles or guide passages is directed continuously against the two sets of blades in such a way that the steam turns the shaft of the turbine and the connected load (i.e., the generator). The stationary nozzles expand steam to a lower pressure, resulting in steam's velocity acceleration. A rotating bladed disc changes the direction of the steam flow, thereby creating a force on the blades that, because of the wheeled geometry, manifests itself as torque on the shaft on which the bladed wheel is mounted. The combination of torque and speed is the output power of the turbine.

The turbine's shaft is connected to a generator so that the generator spins around with the turbine blades. As it spins, the generator converts kinetic energy from the turbine to alternating current electrical energy by using a rotating magnetic field.

The difference in the various types of steam turbines is due to different methods of using the steam, depending upon the construction and arrangement of the nozzles, steam passages, and buckets.

In the *impulse* type of steam turbine, the expansion and consequent change in the pressure of the steam occurs entirely within the nozzles, which direct the steam in jets against the moving buckets. Inasmuch as the expansion of steam takes place in the nozzles, the clearance between the rotating and stationary surfaces is greater than in the reaction type of steam turbine.

In the *reaction* type of steam turbine, the expansion and consequent change in pressure of the steam occurs entirely in the blading where the steam is directed against the moving buckets or blading by guide valves or orifices. The expansion of the steam takes place through both the stationary and moving guide vanes, and therefore the clearance space between the stationary and moving surfaces is very small, to cut the pressure drop by leakage between stages down to a minimum.

The thermodynamic cycle for the steam turbine is the Rankine cycle. The cycle is the basis for conventional power-generating stations and consists of a heat source (boiler) that converts water to high-pressure steam. In the steam cycle, water is first pumped to an elevated pressure, which is medium to high pressure depending on the size of the unit and the temperature to which the steam is eventually heated. It is then heated to the boiling temperature corresponding to the pressure, boiled (heated from liquid to vapor), and then most frequently superheated (heated to a temperature above that of saturated steam). The pressurized steam is expanded to lower pressure in a multistage turbine, then exhausted either to a condenser at vacuum conditions or into an intermediate temperature steam distribution system that delivers the steam to the industrial or commercial application. The condensate from the condenser or from the industrial steam utilization system is returned to the feed water pump for continuation of the cycle.

3.1.6.1.1 Types of Steam Turbines

Steam turbines used for electricity production exclusively are called condensing turbines, while steam turbines used for combined heat and power (CHP) can be classified into two main types: noncondensing and extraction.

- *Condensing Turbine*: The primary type of turbine used for central power generation is the condensing turbine. These power-only utility turbines exhaust directly to condensers that maintain vacuum conditions at the discharge of the turbine. An array of tubes, cooled by river, lake, or cooling tower water, condenses the steam into (liquid) water. The condenser vacuum is caused by the near ambient cooling water creating condensation of the steam turbine exhaust steam in the condenser.

  The condensing turbine processes result in maximum power and electrical generation efficiency from the steam supply and boiler fuel. The power output of condensing turbines is sensitive to ambient conditions.
- *Noncondensing (Backpressure) Turbine*: The noncondensing turbine (also referred to as a backpressure turbine) exhausts its entire flow of steam to the industrial process or facility steam mains at conditions close to the process heat requirements.

  Usually, the steam sent into the mains is not much above saturation temperature. The term "backpressure" refers to turbines that exhaust steam at atmospheric pressures and above. The discharge pressure is established by the specific CHP application. The lower pressure is most often used in small and large district heating systems, and the higher pressure is most often used in supplying steam to industrial processes. Significant power-generating capability is sacrificed when steam is used at appreciable pressure rather than being expanded to vacuum in a condenser.
- *Extraction Turbine*: The extraction turbine has openings in its casing for extraction of a portion of the steam at some intermediate pressure. The extracted steam may be used for process purposes in a CHP facility or for feed water heating as happens in most utility power plants. The rest of the steam is condensed.

  The steam extraction pressure may or may not be automatically regulated depending on the turbine design. Regulated extraction permits more steam to flow through the turbine to generate additional electricity during periods of low thermal demand by the CHP system. In utility-type steam turbines, there may be several extraction points, each at a different pressure corresponding to a different temperature at which heat is needed in the thermodynamic cycle.

  The facility's specific needs for steam and power over time determine the extent to which steam in an extraction turbine will be extracted for use in the process or be expanded to vacuum conditions and condensed in a condenser.

  An indicative steam turbine is shown in Figure 3.17. Figure 3.18 shows a backpressure steam turbine.

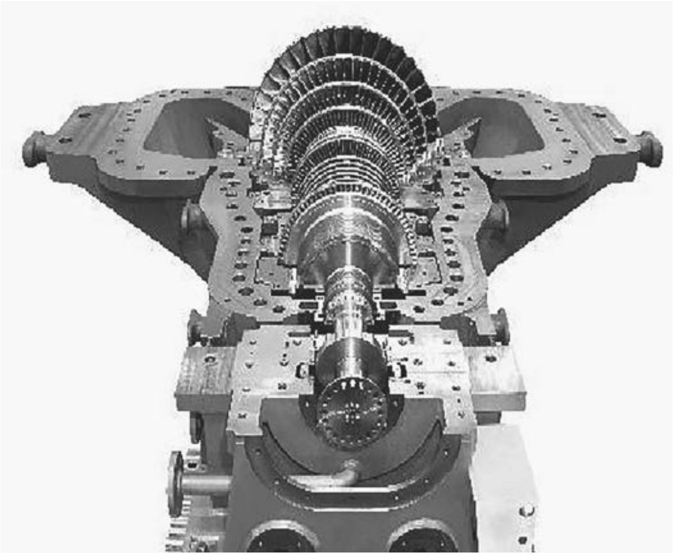

FIGURE 3.17 Indicative steam turbine.

3.1.6.2 Steam Condensing (Cooling)

A steam condenser is a device in which the exhaust steam from steam turbine is condensed by means of cooling water. The main purpose of a steam condenser in the turbine is to maintain a low backpressure on the exhaust side of the steam turbine. The cooling water absorbs the latent heat of steam released during condensing. The

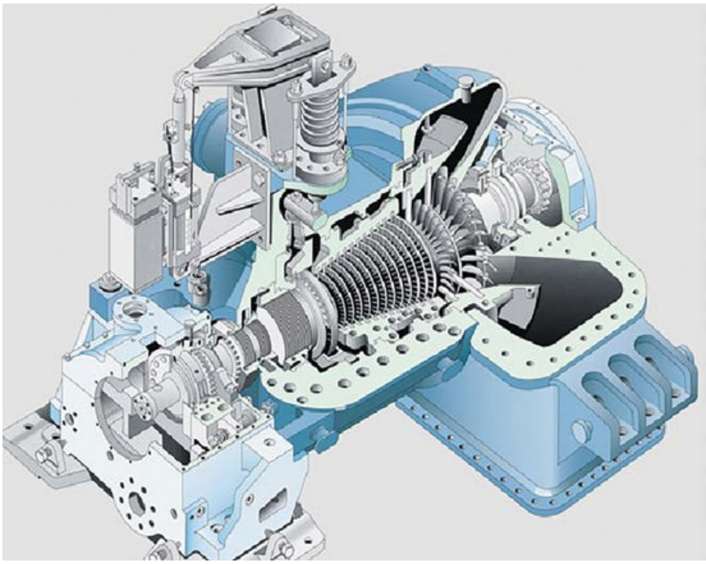

FIGURE 3.18 Backpressure steam turbine.

condensed water returns to the boiler (through the deaerator) for steam reproduction, while the cooling water heads to cooling towers for the release of the absorbed heat at the environment. A cooling tower uses water as a cooling medium and emits steam.

If cooling water is not available, a fan-mounted air cooler can serve the purpose, although it is less energy-efficient. Moreover, an air-cooler is less appropriate in hot environments as the cooler dimensions are increased with the ambient air temperature.

3.1.6.2.1 Cooling Towers

Cooling towers are used to reject heat through the natural process of evaporation. Warm recirculating water is sent to the cooling tower where a portion of the water is evaporated into the air passing through the tower. As the water evaporates, the air absorbs heat, which lowers the temperature of the remaining water. The amount of heat that can be rejected from the water to the air is directly tied to the relative humidity of the air. Air with a lower relative humidity has a greater ability to absorb water through evaporation than air with a higher relative humidity, simply because there is less water in the air. As an example, consider cooling towers in two different locations: one in northern Europe and another in southern Europe. The ambient air temperature at these two locations may be similar, but the relative humidity in southern Europe on average is much lower than that of northern Europe. Therefore, the cooling tower in southern Europe will be able to extract more process heat and will run at a cooler temperature because the dry air has a greater capacity to absorb the warm water.

An indicative illustration of the operation of a cooling tower is shown in Figure 3.19.

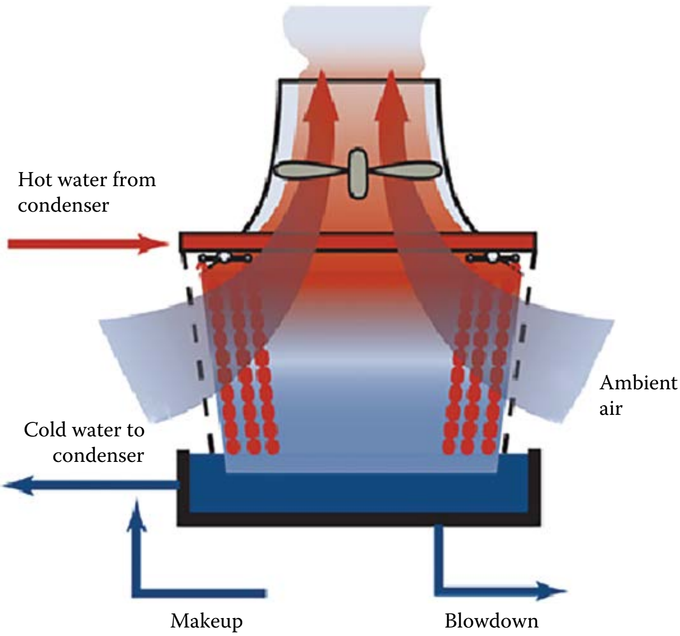

FIGURE 3.19 Indicative cooling tower.

Cooling towers can be split into two distinct categories: open circuit (direct contact) and closed circuit (indirect) systems. In open circuit systems, the recirculating water returns to the tower after gathering heat and is distributed across the tower where the water is in direct contact with the atmosphere as it recirculates across the tower structure. Closed circuit systems differ in the circulation of the return fluid (often water, or sometimes water mixed with glycol). The latter circulates through the tower structure in a coil, while cooling tower water recirculates only in the tower structure itself. In this case, the return fluid is not exposed directly to the air.

3.1.6.2.2 Air-Cooled Condenser

In the case of air-cooled condensers, the condensation system consists of vacuum heat exchangers cooled by ambient airflow. Exhaust steam from turbine is fed directly to the heat exchanger piping network of the air-cooled condenser. Ambient air passing through the condenser's tubes acts as the cooling mean that absorbs latent heat from steam and transfers it to the environment. Condensed water flows by gravity to the condensate tank located below; it is then fed back to the deaerator by condensate pumps.

An indicative illustration of the operation of an air-cooled condenser is shown in Figure 3.20.

The air-cooled condenser is a multicell unit, with each cell comprising of tube bundles mounted in an inverted "V" arrangement and a cooling fan placed horizontally

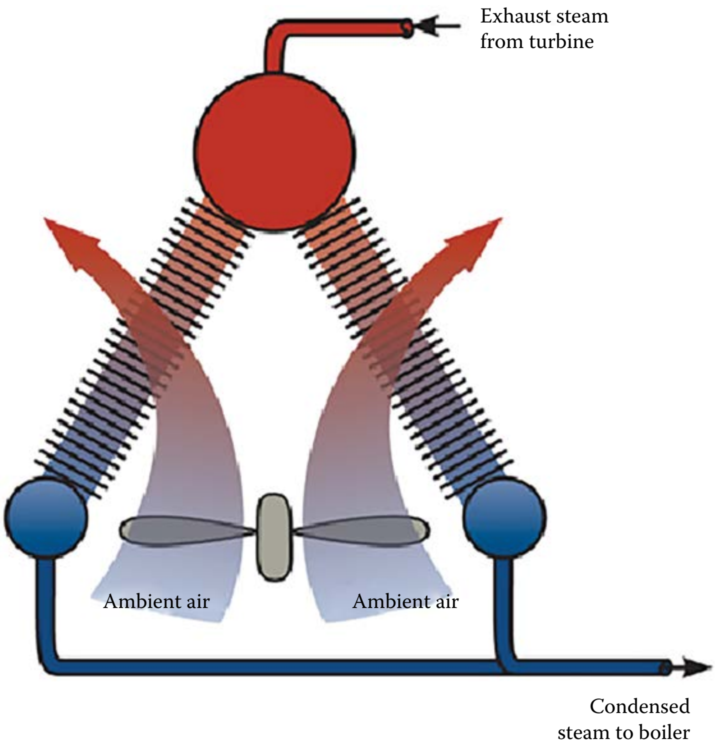

FIGURE 3.20 Indicative air-cooled condenser.

FIGURE 3.21 Air condenser view.

beneath the heat exchange surface to provide a forced draught air discharge over the extended surface tube banks. The diameter and speed of the cooling fans are specifically selected to provide low operating noise levels. An air-cooled condenser is made of modules arranged in parallel rows. Each module contains a number of finned tube bundles. An axial flow, forced-draft fan located in each module forces the cooling air across the heat exchange area of the finned tubes.

An indicative air condenser from a WTE plant is shown in Figure 3.21. A panoramic photograph of an air condensing unit is shown in Figure 3.22. Figure 3.23 shows the fan operation of the air condensing unit. Finally, the feeding pipe of an air condensing unit is shown in Figure 3.24.

3.1.7 Teleheating: Electrical System

3.1.7.1 Teleheating

CHP is the simultaneous production of heat and power from a single fuel or energy source at or close to the point of use. An optimal CHP system is designed to meet the heat demand of the energy user—whether at building, industry, or citywide levels—since it costs less to transport surplus electricity than surplus heat from a CHP plant. By using the heat output from the electricity production for heating or industrial applications, CHP plants generally convert 75%–80% of the fuel source into useful energy. For this reason, CHP WTE plant is quite crucial since it has to be close enough to its consumers of heat.

CHP has a long history within the industrial sector, which has large concurrent heat and power demands in the heating district sector of countries with long heating

FIGURE 3.22 Panoramic view of the air condensing unit.

seasons. It can cover heat demands in residential, public, and commercial buildings as well as process steam demands in industrial users.

3.1.7.1.1 Combined Heat and Power Generation

When producing a combination of heat and power, it is possible to use up to 80% of the energy of the waste. With a boiler designed for waste combustion (moderate steam parameters), an output of electricity of 20%–25% and an output of heat of 60% can be

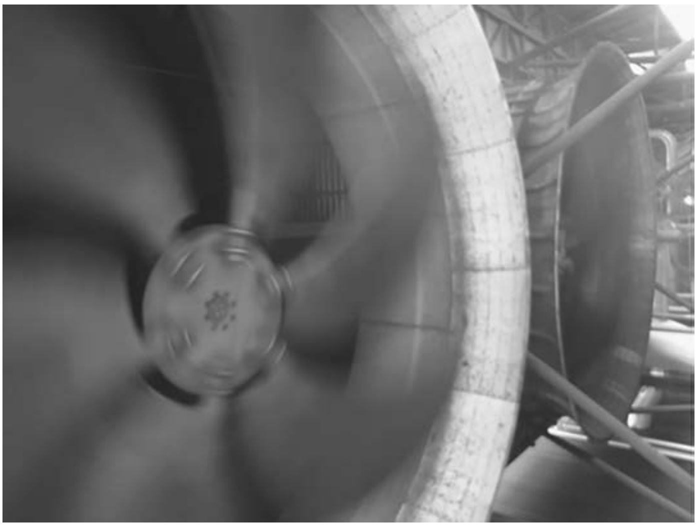

FIGURE 3.23 Fan operation of the air condensing unit.

FIGURE 3.24 Air condensing unit feeding pipe.

achieved. When a combination of power and district heating is produced, a so-called backpressure turbine is used. The backpressure is determined by the temperature and the flow of the coolant, which is usually water from a district heating network.

A heat exchanger serves as interface between the district heating network and the building's own radiator and hot tap water system, so the hot water used in the district heating system is not mixed with the water of the customer's network. A district heating piping network consists of feed and return lines, which transfer hot water via well-insulated pipes to the customer premises.

In countries with lower heat demands but higher cooling demands in a given year, supplementary district cooling solution is preferred. District cooling is the centralized production and distribution of cooling energy, which is a sustainable alternative to conventional electricity or gas-driven air conditioning systems. Chilled water is delivered via an underground, insulated pipeline to office, industrial, and residential buildings to lower the temperature of air passing through the building's air conditioning system. Absorption chillers use district heating as an energy source to cool a district heating circuit. Large units can be placed centrally to supply large district cooling systems, while small units can be located in buildings that require cooling, and connected to a local cooling system.

3.1.7.1.2 Combined Process Steam and Power Generation

When producing both process steam and power, the electrical output may be between 20% and 35%, depending on the amount of process steam extracted from the turbine, with values varying between those of power production only and CHP production. During this process, a minimum amount of steam has to pass all the way through the turbine. This means that at least 10% of the low-pressure steam has to be cooled away. When power and process steam are produced, an extraction turbine is used, which may operate as a fully condensing turbine cooled by seawater or air. When needed, steam can be extracted from a bleed in the turbine at relevant parameters (pressure and temperature). To prevent extensive heat loss and avoid expensive pipelines, the industries that need process steam should be located near the plant.

3.1.7.1.3 District Heating Piping Network

District heat is transmitted from production plants to clients as hot water in a closed network consisting of two pipes (flow and return pipes). District heating pipes are laid in the ground, usually at a depth of 0.5–1 meter. Pipes consist of a steel pipe, an insulating layer, and an outer casing. The insulating material typically used is polyurethane foam or something similar, while the outer casing is usually high-density polyethylene (HDPE). They can currently be built up to around 30 km from the generating plant, and distribution networks can be hundreds of kilometers long. The network distance is also easily extended by simply adding more providers of heat, or "heat sources," along the way. On an average, heat losses in the distribution network account for less than 10% of the energy transmitted in the pipes. The return pipe conveys the water back to the production plant for reheating. The temperature of returned water from clients to the production plants ranges in best cases between 25°C and 50°C.

Figure 3.25 shows the construction of a district heating network. The insulated pipes of this network before installation are shown in Figure 3.26.

3.1.7.2 Electrical System

An electrical substation is a subsidiary station of the WTE plant, where voltage is transformed from low to high using transformers. Electrical energy produced in a generator is used to power plant equipment (accounted for 10%–20% of total production, depending on the plant's capacity), while the surplus is stepped up, usually to medium voltage, by the main transformer and sent out to the grid. The main transformer is usually immersed in oil and located near the substation.

FIGURE 3.25 District heating network during construction.

FIGURE 3.26 Insulated pipes for district heating.

Substations generally have switching, protection, and control equipment and one or more transformers. In a large substation, circuit breakers are used to interrupt any short-circuits or overload currents that may occur on the network. Smaller distribution stations may use recloser circuit breakers or fuses for protection of distribution circuits. Other devices, such as power factor correction capacitors and voltage regulators, may also be located at the substation. The substations are placed on open surfaces in fenced enclosures, underground, or located in special-purpose buildings.

In case of turbine shutdown, it is possible to import electricity from the grid through the substation's transformer. Power is stepped down to low voltage (690V to 415V to 230V) by each distribution transformer and fed to electrical loads in the plant. Each distribution transformer has the capability to be backed up by another one.

Uninterruptable power supply equipment is also available and capable of supplying all direct current consumers, but mainly providing power supply security to the DCS in case of failure of the main circuits, ensuring that the plant is properly controlled and supervised even in the case of power failure.

An emergency diesel generator is provided for emergency loads in order to shut down the plant safely. The emergency diesel generator can be started automatically within 15 seconds of the network's loss; return to the network will be manually performed. The main loads to be backed-up by the diesel generator are

- Furnace fans
- Feed water and condensate pumps
- Turbine generator control panels and oil systems
- Burners
- Continuous emission monitoring systems
- Some of the building services

An electric substation of a WTE plant can be viewed in Figure 3.27. Transformers of this substation are shown in Figure 3.28.

FIGURE 3.27 Substation view.

FIGURE 3.28 Transformer view.

3.1.8 Bottom Ash

The noncombustible fraction of the waste charged to the furnace forms a residue (ash) remaining on the grate at the completion of the combustion cycle. This material is generally referred to as bottom ash but is also called grate ash, slag, or clinkers.

Bottom ash is generated at a rate of approximately 20%–25% by weight of the waste combusted (or more if there is a high amount of ash or other noncombustible material in the waste) but only 5%–10% by volume. It is similar in appearance to a porous, greyish, silty sand with gravel and contains small amounts of unburned organic material and chunks of metal. The bottom ash stream consists primarily of glass, ceramics, ferrous and nonferrous metals, and minerals.

Bottom ash must be taken out of the furnace in such a way that maintains control over the combustion process. A seal on the furnace is normally provided by a column of water. The water bath also serves to extinguish any remaining combustibles and cool the ash. Furthermore, large pieces of clinker fracture when quenched, reducing their size. The bottom ash leaves the furnace wet, thereby minimizing fugitive dust emissions.

The grain size distribution of bottom ash is largely determined by the composition of the waste and the combustor type. The grain size distribution is important for the mechanical properties of the bottom ash and has to imitate the grain size of natural gravel. Screening, which in some cases is followed by crushing, might be carried out in order to make ash suitable for some applications, such as cement and concrete. Also, lumps of ferrous and nonferrous metal are separated from ash through the use of magnets and eddy current separators.

Bottom ash is exposed to atmosphere to allow metal oxides and hydrates to react with water and carbon dioxide (CO_2) to form carbonate. These reactions reduce the leachability of the metals and reduce the potential impact on the environment. Reactions with water can cause the materials to swell; therefore, weathering is essential. Weathering (maturation) is normally achieved by leaving the ash in a stockpile to allow rainfall and time to complete the reactions. For the new generation of combustors, a weathering time of at least 3–4 months is required. The leachate produced during storing/weathering requires appropriate disposal as it may contain high concentrations of highly soluble salts and minor amounts of metals, especially copper, chlorides, and sulphates.

Weathering is sometimes followed by cement stabilization, which is typically carried out on the construction site by mixing the bottom ash with cement or other puzzolanic materials to form a monolithic material that effectively excludes moisture (physical encapsulation). In addition, the cement environment provides a highly buffered environment that limits the solubility of most trace metals by maintaining a high pH. For some trace metals, however, the high pH provides higher solubility.

Bottom ash can either be landfilled or utilized. The legislation and boundary conditions regarding the utilization of bottom ash appear to be different throughout the countries of the European Union, United States, and Canada. Since a large quantity of solid waste combustion bottom ash is generated, the impact of byproduct utilization is large (both economically, environmentally, and related to public acceptance).

In many countries there is simultaneously an increasing shortage of suitable natural aggregate, lack of available landfill space, and increase in the amounts of bottom ash. This is the principle motivation for utilization of bottom ash. In all countries, however, a portion of the bottom ash is landfilled.

If bottom ash is not managed properly, it constitutes a possible environmental hazard. Therefore, proper legislation for reuse is essential to ensure that the

FIGURE 3.29 Bottom ash from furnace.

environmental impact of contemplated land uses is restricted to an acceptable level. In western Europe, the legislation is mainly based upon leachate limit values according to EC decision 2003/33 (in U.S. toxicity characteristic leaching procedure tests).

The mechanical properties of bottom ash have been studied in several countries, concluding that bottom ash can replace not only sand but also natural gravel in unbound layers (subbase) if the content of organic matter is kept low. The most abundant elements in municipal waste combustor ash are silica, calcium, and iron. Although ash composition can be expected to vary from facility to facility, these elements are present within relatively predictable ranges. The presence of a relatively high salt content and trace metal concentrations, including such elements as lead, cadmium, and zinc, in municipal waste combustor ash (compared with conventional aggregate materials) has raised concerns in recent years regarding the environmental acceptability of using ash as an aggregate substitute material.

Figure 3.29 shows the bottom ash from the combustion process, and Figure 3.30 shows the collection of bottom ash. Scrap metals and other metal products can be extracted as seen in Figure 3.31. The weathering process of bottom ash follows, and is shown in Figure 3.32.

3.1.9 APC: Fly Ash

3.1.9.1 Air Pollution Control

Combustion of MSW generates large volumes of flue gas. The flue gases carry residues from incomplete combustion and a wide range of harmful pollutants. The pollutants and their concentration depend on the composition of the waste incinerated

FIGURE 3.30 Collection of bottom ash.

FIGURE 3.31 Scrap metal produced from bottom ash.

FIGURE 3.32 Bottom ash transferred for weathering.

and the combustion conditions. However, these gases always carry ash, heavy metals, and a variety of organic and inorganic compounds.

The pollutants are present as particles (dust) and gases such as hydrochloric acid (HCl), hydrogen fluoride (HF), and sulfur dioxide (SO_2). Common composition of flue gases follows:

- *Particulate pollutants*: Fly ash, including the heavy metals of antimony (Sb), arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni), thallium (Tl), and vanadium (V)
- *Gaseous pollutants*: HCl mainly from the combustion of polyvinyl chloride, SO_2 from combustion of sulfurous compounds, HF from combustion of fluorine compounds, and nitrogen oxides (NO_x) from part of the nitrogen in the waste and N_2 in the air

Some harmful compounds such as mercury, dioxins, and NO_x can be fully removed only through advanced and costly chemical treatment technologies. Primary and secondary measures can help reduce emission of pollutants. Primary measures—which are initiatives that actually hinder the formation of pollutants, especially NO_x and organic compositions such as dioxins—must be applied as much as possible.

Primary measures comprise an efficient combustion process (such as long flue-gas retention time at high temperature with an appropriate oxygen content, intensive mixing and recirculation of flue gases, etc.), pre-precipitation of ashes in the boiler, and short flue gas retention time at intermediate temperatures. The content of CO and total organic carbon (TOC) excluding CO in the raw flue gas before inlet to the cleaning system is a good indicator of the efficiency of the combustion process.

TABLE 3.1
Combustion Flue Gas Treatment Technologies

Parameter	Used Abatement Technology
Particulate matter	Cyclones
	Electrostatic precipitator (wet/dry)
	Bag filters
Acid gases	Dry sorption
	Semi-dry sorption
	Wet scrubbers
Nitrogen oxides	Selective non-catalytic reduction
	Selective catalytic reduction

Secondary measures consist of the APC system that precipitates, adsorbs, absorbs, or transforms the pollutants. An APC system is comprised of electrostatic precipitators (ESPs); baghouse filters; dry, semi-dry, semi-wet, and wet acid gas removal systems; catalysts; and the like. The selection of APC system depends primarily on actual emission limits or standards, if any, and the desired emission level. In this context, the different APC systems can be grouped as basic, medium, or advanced emission control.

Table 3.1 provides an indication of the technologies used for the treatment of waste combustion flue gases.

3.1.9.1.1 Semi-Dry Scrubber

Dry and semi-dry scrubbing processes are simple and cheap concerning their investment and are thus used in many plants all over the world. In most cases the adsorbent is either injected directly into the gas duct or into a spray dryer downstream of the boiler in dry form (dry process) or as a slurry (semi-dry process). In most cases, the scrubbing products are removed from the flue gas by a fabric filter.

As flue gases enter the dry scrubber lime milk is sprayed to cool them down and to react with acids like HCl and SO_2, while partial mercury-capturing occurs. Liquids evaporate in the vertical scrubber; thus the reaction products appear as a dry dust in the flue gas. Larger particles fall to the bottom of the scrubber and then are removed. The reactant used is proposed to be lime milk (suspension of fine $Ca(OH)_2$ in water).

Semi-dry scrubbers offer several advantages, such as:

- At least 50% removal of mercury and cadmium when combined with other materials such as activated carbon
- No wastewater production

These advantages balance the disadvantage of slightly larger quantities of fly ash.

3.1.9.1.2 Wet Scrubber

In wet scrubbers, SO_2 is reduced by reaction with a NaOH solution or a $CaCO_3$ suspension. Due to excess oxygen in the flue gas, the reaction products are a sodium sulfate (Na_2SO_4) solution and a gypsum ($CaSO_4{,}2H_2O$) suspension, respectively.

If NaOH is applied, the scrubber system must have an additional water treatment plant in which the sulfate ions of the Na_2SO_4 solution are precipitated as gypsum by Ca ions—for example, by mixing in the $CaCl_2$ solution from the treatment of the water from the HCl removal. If $CaCO_3$ is used, the gypsum is formed directly and may be removed as a sludge by settling or in a hydrocyclone and dewatered.

The gas from the SO_2 scrubber is reheated in the gas or gas heat exchanger and led to a baghouse filter. Before this, activated carbon or a mixture of lime and activated carbon is injected into the duct. Thus, the bags are powdered, and when the gas penetrates them, Hg and dioxins are removed to concentrations below the limit values of the advanced control level. In addition, dust, HCl, HF,SO_2, and the other heavy metals are further reduced. None of these processes, however, have any effect on NO_x.

3.1.9.1.3 Powdered-Activated Carbon Injection

Powdered-activated carbon (PAC) is used to remove heavy metals and organic compounds. The system includes a PAC silo, a feeder, an injection blower, and an in-pipe reactor with injection nozzle and injection valve.

PAC is transferred pneumatically from the silo to the exit pipe of the scrubber and is injected in the entrained reactor between the semi-dry scrubber and the bag filter.

The silo consists of a cylinder and two feeding funnels (cone shaped) made of special steel. In order to allow inspection, two sliding doors are situated at the lower part. The feeder should continuously supply PAC to the injection system. The amount of PAC is determined according to the flue gas flow after the bag filters (i.e., through a dosing screw).

For good system operation at least three injection blowers are installed (one spare). At the exit of the blowers, pressure gauges should be installed for measuring pressure. Pressure transmitters should be located at the main injection lines for monitoring air input pressure.

Mercury, cadmium, thallium, and (partially) arsenic are removed by the activated carbon while molecules of these metals become adjacent to the small dust particles captured at the bag filters. Other heavy metals also cling onto dust particles and are removed.

Activated carbon also "captures" volatile organic compounds (VOCs), dioxins/furans, and polycyclic aromatic hydrocarbons (PAH), while the PAC dust is removed in the bag filters. Residues from the bag filters are stored in the fly ash silo and are transferred outside the plant for proper management.

3.1.9.1.4 Electrostatic Precipitators

An ESP is a particle control device that uses electrical forces to move the particles out of the flowing gas stream and onto collector plates. The particles are given an electrical charge by forcing them to pass through a corona, a region in which gaseous ions flow. The electrical field that forces the charged particles to the walls comes from electrodes maintained at high voltage in the center of the flow lane.

Once the particles are collected on the plates, they should be removed from the plates without re-entraining into the gas stream. This is usually accomplished by knocking them loose from the plates, allowing the collected layer of particles to slide down into a hopper from where they are evacuated. Some precipitators remove the particles by intermittent or continuous washing with water.

3.1.9.1.5 Bag Filters

Bag filters ensure very efficient collection of dust, while at the same time they further absorb the acidic residue. For the attainment of this further absorption, it is important that a layer of dust be maintained on the fabric as it collects particles with diameters smaller than micrometers (μm). In this way, heavy metals and dioxins, usually smaller particles are removed efficiently.

The automatic system of controlling and cleaning the filters (activated by a detected pressure difference of filters) ensures the presence of a continuous dust layer on the bags/filters. The cleaning process is programmed to take place when these are in operation (it is not necessary to isolate the filter part being cleaned) and not influence the process of cleaning.

Gases flow through bag filters from the outside of the bag toward the inside, and dust is collected on the outside. Gases reach the bag filters through a pipe and are distributed via openings to various filter sections. A special pipe ensures smooth flow of the gases; in this way, removal is optimized and the lifetime of the filters is extended.

Fly ash is captured on the dust layer formed on the bags and the filter itself. Clean gases flow through the upper openings of the compartment outlet damper and via the outlet pipe through the induced draft fan. They then reach the chimney and finally the atmosphere.

The dust layer increases the bag filter efficiency while remaining quantities of lime react with acidic compounds. Dioxins and the rest of VOCs are absorbed by the activated carbon, and the PAC particles are captured by the dust layer. When pressure of the filter is increased up to a certain point, this means that the dust layer has become too thick and the cleaning process should be activated.

The fly ash that stays at the outer surface of the filter bags is periodically removed by an air pulse and blown into the bag from the inner side. This cleaning releases the particles, which fall into the discharge hopper.

Under each filter station an air tank equipped with plunger valves is positioned. Compressed air is blown at the lower inner part of the bags in a very short pulse, no more than 0.1 s. The entire process, which takes place while the bag filter is in operation, should require minimum amounts of energy.

3.1.9.1.6 NO_x Removal

The production of NO_x may be prevented with the following measures:

- Continuous mixing of wastes in the bunker to ensure a better fuel mixture
- Good mixing of secondary air through ideal position of the secondary air nozzles so as to create turbulence in the combustion chamber that subsequently causes good mixing of combustion gases and smooth flow
- Use of low NO_x burners
- Use of natural gas

As an end-of-pipe measure for NO_x removal, the selective non-catalytic reaction (SNCR) is proposed. In SNCR, ammonia (NH_3) or urea ($CO(NH_2)_2$) is injected into the furnace to reduce NO_x emissions. The NH_3 reacts most effectively with NO_x

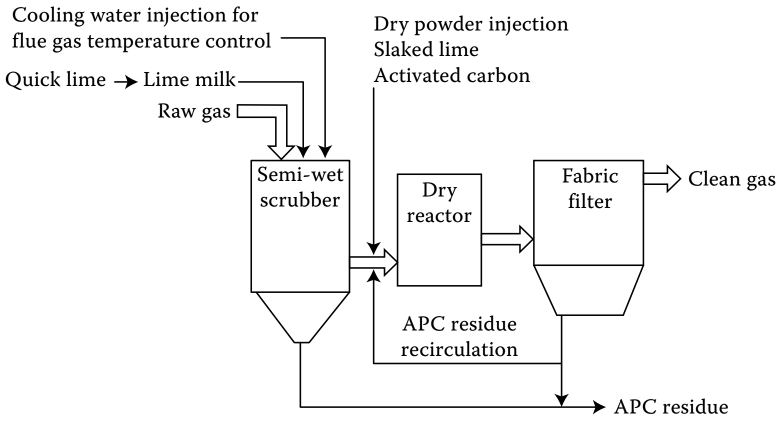

FIGURE 3.33 Semi-wet indicative process diagram.

between 850 and 950°C, although temperatures of up to 1050°C are effective when urea is used. If the temperature is too high, a competing oxidation reaction generates unwanted NO_x. If the temperature is too low, or the residence time for the reaction between NH_3 and NO_x is insufficient, the efficiency of NO_x reduction decreases and the emission of residual ammonia can increase: This is known as NH_3 slip. Some ammonia slip will always occur because of chemistry reaction. Additional NH_3 slip can be caused by excess or poorly optimized reagent injection.

Enough nozzles are placed to ensure ammonia sprays through the radiation zone, thus enabling good contact and less residual ammonia. The number and position of the operating nozzles should be controlled based on the furnace temperature, which should be measured with advanced devices like infrared pyrometers or acoustic systems.

The volume of injected ammonia solution is determined by NO_x concentrations measured at the chimney. The ammonia solution will be diluted with water coming from the boiler (blowdown water) before it turns into droplets with the use of compressed air.

An indicative diagram for the semi-wet process is shown in Figure 3.33.

3.1.9.2 Fly Ash

Fly ash in WTE plants consists mainly of APC residues, usually mixed with boiler ash. This mixture amounts to 2%–3% by weight of the original waste. It consists of mineral particles, variably soluble salts (for example, NaCl), and heavy metal compounds (of which $CdCl_2$ is readily soluble). The grain size is very fine; thus fly ash is very dusty.

Fine, noncombustible particles of incinerated waste pass with the flue gas out of the furnace and into the boiler. Since the flue gas velocity in the boiler is lower than in the furnace, some of the particles settle as boiler ash and are removed from the bottom hoppers of the boiler. The finest particles, however, pass on to the APC installation. When the flue gas cools in the boiler, various gaseous compounds—for example, evaporated heavy metals and their compounds, including zinc, lead, and cadmium chloride ($ZnCl_2$, $PbCl_2$, and $CdCl_2$) formed from hydrogen chloride (HCl) in the flue gas—condense on particles to form fly ash. Fly ash is either collected alone, perhaps in an ESP, or together with the reaction products of APC processes.

APC residues from waste combustion facilities exist in a number of different varieties, depending on the type of combustor/WTE plant and the type of flue gas cleaning equipment installed. The chemical composition of the residues also depends on the waste combusted. Typically, however, APC residues are a very fine-grained powder, ranging from light grey to dark grey.

Overall, two different types of residues exist, which cover most modern waste combustors/WTE plants worldwide:

1. *Dry and semi-dry residue systems*: Slaked lime is injected into the flue gas, either in dry form or as slurry. This is done to neutralize acidic components in the flue gas, typically before removing the fly ash from the flue gas. Fly ash, reaction products, and unreacted lime are typically removed in fabric filters. Activated coal may be injected for dioxin removal and removed together with the fly ash. Dry and semi-dry systems usually generate a single residue. Maximum byproducts are 3%–5% per mass of MSW feed.
2. *Semi-wet and wet residue systems*: Fly ash is typically removed before neutralizing acidic components. After this, the flue gas is scrubbed in one, two, or a multistage arrangement of scrubbers. The scrubber solutions are then treated to produce sludge and gypsum. Wet systems typically generate more than one residue. Maximum byproducts are 2%–3% per mass of MSW feed.

The main problem related to APC residues is the potential release of contaminants to the environment. This release may potentially occur by several routes but the primary route is by leaching from the residues landfilled or placed at their final destination. On modern plants the residues are generally handled and transported in closed systems or under moist conditions to avoid dusting. Therefore, these activities are not considered important from an environmental perspective.

The main environmental concern with respect to APC residues is leaching of:

1. *Easily soluble salts such as chloride (Cl) and sodium (Na)*: Although they are not toxic for humans in typical concentration levels, these components may significantly affect ecosystems and pollute drinking water resources.
2. *Heavy metals such as cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn)*: Heavy metals and trace elements can potentially be in concentrations harmful for humans as well as for ecosystems.
3. *Dioxins*: Although dioxins and furans do not easily leach, release of these contaminants is of major concern because of their toxicity.

In order to minimize impacts on the environment, the release of these contaminants should be reduced as much as possible. Available techniques of reducing leaching produced by residues after final placement may be grouped according to the main principle of operation, as follows:

- *Extraction and separation*: Processes involving extraction and removal of specific components in the residues.

- The main advantage of extraction and separation processes is the use of relatively simple techniques. The main disadvantage is the generation of metal and salt containing process water; this may, however, be utilized for further recovery.
- *Chemical stabilization with phosphate, sulfuric acids, and so on*: Processes involving binding and immobilization of contaminants by chemical reactions.
  - The main advantage of chemical stabilization processes is a significant improvement of the leaching properties of the residues and the use of relatively simple techniques. The main disadvantage is the generation of process water containing metal and salt.
- *Solidification*: Processes involving physical binding and encapsulation of residues, and in some cases also chemical stabilization.
  - The main advantages of solidification techniques are the decrease of leaching and the improvement of the mechanical properties. Solidification techniques often also make use of relatively simple technology. The main disadvantages are that the physical integrity of the product may, depending on the choice of binder, deteriorate over time and mass and volume increases with the treatment.
- *Thermal treatment*: Processes involving heating of the residues and changes of the physical and chemical characteristics.
  - The main advantage of thermal treatment processes is the production of a very dense and stable product with good leaching properties. Another very important aspect is destruction of persistent organic pollutants (POPs) such as dioxins. The main disadvantages are high energy demands for the process and generation of flue gas containing volatile metals. Three major types of thermal treatment exist: plasma gasification/vitrification, melting, and sintering. Also pyrolysis solution is under research.

The overall aim has been to treat residues so that landfill acceptance criteria are fulfilled, but various material-related criteria may also have to be fulfilled, for example with utilization. The techniques above reflect different approaches to meet these goals. Differences in local traditions, regulations, market conditions, and political focus have led to the development of these different types of techniques, rather than using a single process worldwide.

However, even after the most sophisticated treatment process, a risk of leaching, and thereby future release of contaminants from the processed residues, remains. To minimize such a risk, the treated fly ash should be safely landfilled under controlled conditions (in a special cell/ash monofill). Only a limited number of recovery and utilization solutions for fly ash exists today. The main reason for the lack of commercially available recovery and utilization technologies is likely difficulties related to achieving satisfactorily technical qualities of products based on APC residues (due to high content of salts and heavy metals) compared to readily available virgin materials.

An external silo for fly ash collection is shown in Figure 3.34. Figure 3.35 shows the collection silo for fly ash inside a WTE plant. The state-of-the-art fly ash stabilization plant in Langøya is shown in Figure 3.36.

FIGURE 3.34 External silo for fly ash.

FIGURE 3.35 Collection silo for fly ash.

FIGURE 3.36 Langøya fly ash stabilization with sulfuric acid producing gypsum.

3.1.10 Stack

An induced draught fan is needed to overcome the pressure drop across the flue gas treatment system and maintain a certain pressure in the furnace. This is normally placed at the rear of the flue gas treatment train and is furnished with a silencer. The flue gas is passed into the stack. The stack height is decisive for the dilution of the flue gases in the environment, depending on the emission control level applied and other factors. A minimum height is required to prevent the plume from reaching the ground or entering tall buildings. This minimum height will depend on the local atmospheric conditions, the topography (flat or hilly), and the height of the buildings within a radius of at least 1.0 km. The stack height should be decided on the basis of computer modeling, but as a rule of thumb, stack height should be twice the height of the tallest building within 1.0 km or at least 70 meters high.

An indicative ESP is shown in Figure 3.37, followed by the view of a dosimetric system for chemical additives in Figure 3.38.

3.1.11 Results: R1

WTE plants generate electricity and heat through the thermal treatment of MSW. In 2003, the European Court of Justice stated that a particular WTE plant was a disposal operation because its main purpose was to treat waste. This did not take into account the energy produced and exported by WTE plants, their contribution to the

FIGURE 3.37 Electrostatic precipitator.

FIGURE 3.38 Dosimetric system for chemical additives.

national energy supply, resources savings (primary fuel savings), or the corresponding reduction of CO_2 emissions (greenhouse gases, climate relevance).

The situation was clarified by the Waste Framework Directive (WFD) 2008/98/EC by including in Annex II a calculation formula to determine when a waste combustion installation is a recovery operation (R1: use principally as a fuel or other means to generate energy) or, when it does not meet the R1 efficiency criteria threshold, a disposal operation (D10: combustion on land).

The "R1 criterion" or the "R1 formula" is a nondimensional figure based on the first law of thermodynamics (energy input = energy output) combined with political objectives (minimizing demand for primary fuels). The R1 formula is:

$$R1 = \frac{(E_p - (E_f + E_i))}{(0.97 \times (E_w + E_f))} \tag{3.1}$$

where:

The threshold value is 0.6 for plants operational before December 31, 2008 and 0.65 for plants beginning operations after December 31, 2008.

E_p is the annual energy produced as heat or electricity. It is calculated with energy in the form of electricity being multiplied by 2.6 and heat produced for commercial use multiplied by 1.1.

E_f is the annual energy input to the system from fuels contributing to the production of steam.

E_i is the annual energy imported excluding E_w and E_f.

E_w is the annual energy contained in the treated waste.

The main objective of the R1 formula is to promote the efficient use of energy from waste in WTE plants. It takes into account the plant's effectiveness in recovering the energy contained in waste as well as the effective uses of energy as electricity, heating and cooling, and processing steam.

Annex II of the WFD restricts the scope of the formula to "combustion facilities dedicated to the processing of Municipal Solid Waste," so it does not apply to plants that are dedicated to combustion or co-incineration of hazardous waste, hospital waste, sewage sludge, or industrial waste.

It is also crucial that the formula is applied to the correct parts of the Energy from Waste (EfW) process and that the "system boundaries" are set correctly. The system boundaries used will have considerable implications on the energy streams that are calculated as E_f, E_w, and E_i in the efficiency calculation. Therefore, the "system boundaries" are clearly defined in the guidance as the "functional combustion unit" and not the installation according to the International Plant Protection Convention permit. The functional combustion unit is set as the combustion oven(s), the boiler(s), and the combustion flue gas cleaning system. Often, energy transformation and recovery equipment, such as heat exchangers feeding a district heating or cooling network and/or turbine generator, are also taken into account.

The most significant issues regarding the R1 formula follow:

- *Climate*: The use of heat instead of electricity significantly increases the R1 value achieved. The ability of an installation to use the heat produced is very much dependent on climate.
- *Location*: An installation located in a rural area is unlikely to find efficient use for its produced heat. However, industrialized areas are unvaryingly consumers of heat, so plants located in urban or industrialized areas have a far higher probability of finding a heat client and improving their R1 rating.
- *Size*: Larger plants are often more efficient due to economies of scale.

However, Article 38.1 of the WFD states that with regard to the R1 formula, local climatic conditions may be taken into account, such as the severity of the cold and the need for heating, insofar as they influence the amounts of energy that can be technically used or produced in the form of electricity, heating, cooling, or processing steam.

With the introduction of the R1 formula, WTE plants are now being classified as recovery rather than disposal; thus the R1 formula will facilitate WTE moving up the waste hierarchy. The R1 formula is applicable only in European countries, and it should not be mixed with the efficiency ratio (η) of the plant (a relevant example of R1 calculation is presented in three case studies in Chapter 9).

A new correction factor for the R1 formula entered into force on July 31, 2016, as provided by Directive 2015/1127/EU.

All member states are required to align their regulation to European directive from that date forward. The climate correction factor (CCF) multiplies the value of the energy efficiency as calculated in the annotation to the item R1 of Annex II of Directive 2008/98/CE. This addition was necessary in order to "achieve a level playing field in the Union" and "compensate WTE facilities affected by the impact of local climatic conditions" on their energy production and therefore on the achievement of recovery qualification.

The CCF is calculated based on heating degrees day (HDD)—thus it has a strong local connotation—and its formula differs depending on date of authorization. Therefore, installations in operation and authorized before September 1, 2015 that work at a low average seasonal temperature (HDD $\geq$ 3350) experience an increase in their energy efficiency of up to 1.25, equal to the maximum correction factor (for further information see Directive 2015/1127/EU).

3.2 ALTERNATIVE THERMAL TREATMENT TECHNOLOGIES

3.2.1 Introduction

Pyrolysis and gasification are integral sub-processes of the combustion of waste in grate systems that start with drying, continue at higher temperature with pyrolysis and gasification, and ends with combustion of the waste. The technologies described here are also in combined processes strictly separated from each other. Pyrolysis is a process for disintegration of organic substances at elevated temperatures under inert

TABLE 3.2
Reaction Conditions and Products of Pyrolysis and Gasification Processes

		Pyrolysis	Gasification
Reactor	**Unit**	**Rotary Drum**	**Shaft Furnace/Fluidized Bed**
Temperature	°C	250–700	800–1600
Pressure	mbar	<1000	1000–45,000
Reactant		None	O_2, H_2O, air
Stoichiometry	–	0	<1
Main products		C_nH_m, H_2, CO, pyrolysis oil, H_2O	H_2, CO, CH_4, CO_2
Solid residues		Ash	Ash/slag

Source: Vehlow, J., 2016, Overview of the pyrolysis and gasification processes for thermal disposal of waste. IRRC 2016 Congress, Vienna.

atmosphere. The technically preferred reactor is a heated rotary drum. The products are, depending on the operation temperature and the feed composition, gaseous organic compounds, oils, water, and coke-rich ashes. The term gasification denotes the partial combustion of an organic substance at high temperatures. The reactor is usually a fluidized bed or a shaft furnace. Primary products are hydrogen (H_2), CO, and CO_2. The solid residues are in almost all cases molten slags. Table 3.2 describes the main reaction conditions and the products of pyrolysis and gasification.

The gaseous products of both processes can be used as feedstock in the chemical industry (for example, for production of transportation fuels). In most technical implementations, all products are, after some conditioning, either burned in directly coupled combustion chambers or transferred into power plants respectively industrial furnaces.

3.2.2 Pyrolysis

Pyrolysis can be defined as the thermal decomposition of organic material through the application of heat without the addition of extra air or oxygen. Some authors define it as the thermal decomposition "in the absence of oxygen." However, sometimes air can be trapped in the waste or the chemical composition of waste may also include oxygen. Although pyrolysis can be considered as an alternative to reduce waste volume and a method for obtaining energy from wastes, it appears to be best suited for processing organic feedstocks with a high heating value. In Figure 3.39, a pyrolysis plant from the Indian company PYROCRAT is presented (isometric view for capacity 5 tpd).

At a temperature of around 450°C and under no addition of air, the hydrocarbon content of the waste reacts and generates pyrolysis products, such as pyrolysis gas, pyrolysis coke, and tar. The pyrolysis process can be see in Equation 3.2. The produced fuel gas, consisting mainly of CO and hydrogen, is suitable for either electricity generation or to provide heat in boiler applications.

$$C_aH_bO_c + \text{heat} \rightarrow H_2O + CO_2 + H_2 + CO + CH_4 + C_2H_6 + CH_2O + \text{tar} + \text{char} \tag{3.2}$$

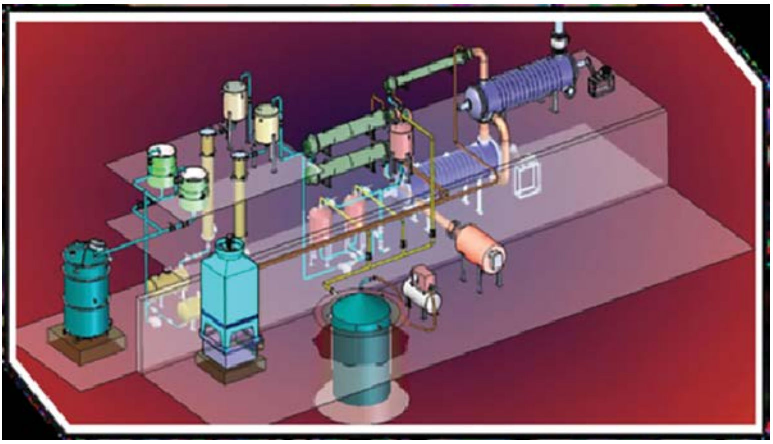

FIGURE 3.39 A 5 tpd Pyrocrat pyrolysis plant: Isometric view.

The solid products of the pyrolysis process consist of metals, sand, glass, and pyrolysis coke, which contains residual carbon that is not converted to gas in the process. Although the pyrolysis coke can be further processed to release the energy content of the carbon or utilized in other thermal processes, often there is no solid market for the pyrolysis coke. In addition, pyrolysis is an endothermic process, meaning that it does not generate heat but instead requires heat for the reaction to be sustained.

The EU intends to increase the reuse and recycling rates of paper, plastics, and biowaste streams. Such an increase will mean that WTE plants based on pyrolysis and gasification technologies may not be able to operate profitably, as their feedstock is rich on these types of waste.

Therefore, it requires a much higher initial investment of electricity than gasification, where part of the heat needed for gasification is provided by partial combustion of the wastes. Because of this factor, pyrolysis is not suitable, and has not been applied on an industrial scale, to the processing of MSW that contains about 2.8 MWh of thermal energy per ton of MSW.

In contrast to combustion, pyrolysis is the thermal degradation of a substance in the absence of oxygen. This process requires an external heat source to maintain the temperature required. Typically, lower temperatures of between 300°C and 850°C are used during pyrolysis of materials such as MSW. Raw municipal waste is usually not appropriate for pyrolysis and typically would require some mechanical preparation and separation of glass, metals, and inert materials (such as rubble) prior to processing the remaining waste. In general, pyrolysis processes tend to prefer consistent feedstocks, and there is a very limited track record of commercial scale pyrolysis plants accepting municipal-derived wastes in the world. The products produced from pyrolysing materials are a solid residue and a synthesis gas (syngas). The solid residue (sometimes described as a char) is a combination of noncombustible materials and carbon. The syngas is a mixture of gases (combustible constituents include CO, hydrogen, methane, and a broad range of other VOCs). A proportion of these can be condensed to produce oils, waxes, and tars. The syngas typically has a net calorific value (NCV) of between 10 and 20 MJ/Nm^3. If required, the condensable fraction can be collected by cooling the syngas, potentially for use as a liquid fuel. One key issue for use of syngas in energy recovery at alternative thermal treatment facilities are the problems related to tarring. The deposition of tars can cause blockages and other operational challenges and has been associated with plant failures and inefficiencies at a number of pilot and commercial scale facilities. Tarring issues may be overcome by higher temperature secondary processing, as referred in the gasification process.

However, pyrolysis can be applied to source-separated plastic wastes that contain about 8 MWh of thermal energy per ton. Therefore, some of that energy can be expended for pyrolysis of the wastes. At this time, most plastic wastes (90% in the United States) are not recycled for practical reasons, so instead of being landfilled, they could be combusted or subjected to pyrolysis.

Several processes for the pyrolysis of plastic wastes have been investigated, and some were found to be technically and economically viable. However, these processes are not suitable for mixed MSW but only for tires and plastics.

Especially in the case of such feedstock, the pyrolysis oil, a hydrocarbon liquid that is generated by de-polymerization of plastic waste, may have the following properties. More specifically, the final produced pyrolysis oil may have the physicochemical properties and specifications of an industrial diesel grade fuel superior to fuel oil grade, as described here:

1. Using tires as feedstock:
   a. Flash point: 40°C
   b. Pour point: −21°C
   c. Calorific value: 10,150 Kcal/Kg
2. Using plastics as feedstock (mixed plastics, including HDPE, low-density polyethylene (LDPE), polyethylene (PE), polypropylene (PP), nylon, Teflon, polystyrene (PS), acrylonitrile butadiene styrene (ABS), fiber-reinforced plastic (FRP):
   a. Flash point: 60°C
   b. Pour point: −4°C
   c. Calorific value: 10,000 Kcal/Kg

3.2.2.1 Applications

The produced pyrolysis oil can be utilized in electric generators, boilers, diesel pumps, furnaces, hot water generators, hot air generators, thermic fluid heaters, industrial burners, electricity generators, furnaces, boilers, steam generators, hot mix plants, and so on.

3.2.3 Gasification and Plasma Gasification

Gasification is a process that converts carbonaceous materials, such as coal, petroleum, biofuel, or biomass, into CO and hydrogen by reacting the raw material with a controlled amount of oxygen and/or steam at high temperatures. The resulting gas mixture is called synthesis gas or syngas and is itself a fuel. Gasification is a method for extracting energy from many different types of organic materials. The advantage of gasification is that using the syngas is potentially more efficient than direct combustion of the original fuel because it can be combusted at higher temperatures or even in fuel cells, so that the thermodynamic upper limit to the efficiency defined by Carnot's rule is higher or not applicable.

The produced syngas may be burned directly in internal combustion engines, used to produce methanol and hydrogen, or converted via the Fischer–Tropsch process into synthetic fuel. Gasification can also begin with materials that are not otherwise useful fuels, such as biomass or organic waste.

In addition, the high-temperature combustion refines out corrosive ash elements such as chloride and potassium, allowing clean gas production from otherwise problematic fuels. Gasification of fossil fuels like lignite is currently widely used on industrial scales to generate electricity. However, almost any type of organic material can be used as the raw material for gasification, such as wood, biomass, or even plastic waste. Gasification relies on chemical processes at elevated temperatures (>700°C), which distinguishes it from biological processes, such as anaerobic digestion, that produce biogas.

In principle, gasification can proceed from just about any organic material, including biomass and plastic waste. The resulting syngas can be combusted. Alternatively, if the syngas is clean enough, it may be used for power production in gas engines, gas turbines, or even fuel cells, or converted efficiently to dimethyl ether (DME) by methanol dehydration, methane via the Sabatier reaction, or diesel-like synthetic fuel via the Fischer–Tropsch process.

In many gasification processes most of the inorganic components of the input material, such as metals and minerals, are retained in the ash. In some gasification processes (slagging gasification) this ash has the form of a glassy solid with low leaching properties, but the net power production in slagging gasification is low (sometimes negative) and costs are higher.

Power consumption in the gasification and syngas conversion processes may be significant and may indirectly cause CO_2 emissions; in slagging and plasma gasification, the electricity consumption may even exceed any power production from the syngas.

Combustion of syngas or derived fuels emits exactly the same amount of CO_2 as would have been emitted from direct combustion of the initial fuel. Biomass gasification and combustion could play a significant role in a renewable energy economy because biomass production removes the same amount of CO_2 from the atmosphere as is emitted from gasification and combustion. While other biofuel technologies, such as biogas and biodiesel, are carbon neutral, gasification in principle may run on a wider variety of input materials and can be used to produce a wider variety of output fuels.

Gasification can be considered a process between pyrolysis and combustion in that it involves the partial oxidation of a substance. This means that oxygen is added but the amounts are not sufficient to allow the fuel to be completely oxidized and full combustion to occur (since a sub-stoichiometric portion of air is used in that process). The temperatures employed are typically above 650–800°C. The process is largely exothermic (heat producing), but some heat may be required to initialize and sustain the gasification process.

Raw municipal waste is usually not appropriate for gasification and typically would require some mechanical preparation, homogenization and separation of glass, metals, and inert materials (such as rubble), prior to processing the remaining waste. The main gasification product is a syngas, which contains CO, hydrogen, and methane. Typically, the gas generated from gasification will have an NCV of 4–10 MJ/Nm^3. For reference, the calorific value of syngas from pyrolysis and gasification is far lower than natural gas, which has a NCV of around 38 MJ/Nm^3. As mentioned earlier, one key issue for using syngas in energy recovery at alternative thermal treatment facilities are the problems related to tarring. The deposition of tars can cause blockages and other operational challenges and has been associated with plant failures and inefficiencies at a number of pilot and commercial scale facilities. The application of a higher temperature secondary processing phase may be used to "crack" the tars and clean up the syngas prior to application in energy recovery systems. This process is sometimes referred to as "gas clean up" or "polishing" and could enable higher efficiency energy recovery than applicable through other waste thermal treatment processes.

It should be noted, however, that most commercial gasification facilities processing MSW-derived feedstocks (like refuse-derived fuel [RDF] and solid-recovered fuel [SRF]) utilize a secondary combustion chamber to burn the syngas and recover energy via a steam circuit, seeking to achieve high energy. While this is not combustion, the differences between the processes in practical and efficiency terms are much more modest. The other main product produced by gasification is a solid residue of noncombustible materials (ash) that contains a relatively low level of carbon.

Some plasma gasification technologies are examples of where a high-temperature (electric arc) method is applied potentially at various stages of the gasification process (in different configurations). Plasma, or other very high-temperature thermal processing, can be applied to fuse the ash from the process into an inert (vitreous or glassy) residue and crack the tars to generate a relatively clean syngas. There are several initiatives seeking to achieve high energy recovery efficiencies using gas engines and hydrogen fuel cells linked to gasifiers.

The WTE processes called gasification are in fact a combination of partial oxidation and volatilization of the contained organic compounds. Gasification in the first furnace is followed by combustion of the volatile gases and steam generation in a second furnace, or by use of the syngas in a gas engine or turbine. Japan is the largest user of MSW gasification in the world. However, even in Japan, the principal technology used is grate combustion of "as received MSW," but there are more than 100 thermal treatment plants based on relatively novel processes such as direct smelting (JFE, Nippon Steel), the Ebara fluidization process, and the Thermoselect gasification and melting process. These processes have emissions as low as the conventional WTE combustion process and produce a vitrified ash that can be used beneficially outside landfills.

Transportation of "as collected" MSW from one municipality to another is not allowed in Japan. As a result, the grate combustion facilities are relatively small. Also, the MSW of several communities is processed to RDF in local RDF facilities and is then transported to a central WTE plant that serves several communities.

Also, all WTE plants are required to vitrify their ash after combustion, by means of electric furnace, thermal plasma melting, or other means. These regulations allow for the introduction of such novel thermal treatment processes that would be considered uneconomic in other developed nations.

In the following sections, some indicative gasification and plasma gasification processes are briefly described.

3.2.4 The JFE Direct Melting Process

The JFE direct melting reactor resembles a small iron blast furnace where the feed particles are fed through the top of a vertical shaft. Several direct melting WTE plants have been built by JFE and also, in a similar version, by Nippon Steel. MSW is shredded and converted to RDF, drying the organic fraction in a rotary kiln and then extruding the product under pressure into 20-mm long by 15-mm diameter cylindrical particles. The material produced in several RDF facilities is then transported to a regional direct melting facility, where it is combusted and energy is recovered. For example, the Fukuyama direct melting plant is supplied by seven RDF facilities located at municipalities served by the direct smelting (DS) facility.

The RDF is fed by means of a corkscrew feeder on top of the shaft furnace. As the feed descends through the furnace, it is gasified and its inorganic components are melted to slag and metal, which are trapped at the bottom of the shaft. The gas product is combusted in an adjoining boiler to generate steam that is used to generate electricity in a steam turbine, same as in conventional WTE. Air is introduced into the furnace through primary, secondary and, tertiary tuyeres located along the height of the shaft. The primary air, near the bottom of the shaft, is enriched to about 30% oxygen in order to generate the high temperatures required to melt slag and metal at the bottom of the furnace.

The RDF-DS combination can handle up to 65% water in the MSW (the usual allowable range is 40%–50%), which in the drying kiln is reduced to 5%–6%. The process requires the addition of coke (about 5% of RDF), which is added along with the RDF at the top of the shaft, as well as sufficient lime to form a fluid slag at the bottom of the furnace. The JFE process produces slag and metal globules (10% of RDF) that are used beneficially and fly ash (2% of RDF) that contains volatile metals and is landfilled. The slag and metal overflow from the furnace are quenched in a water tank to form small spherical particles of metal and slag. The copper content of the metal fraction is apparently too high to be used in steelmaking and too low to be suitable for melting copper; its main use is as a counterweight in cranes and other ballast applications.

3.2.5 The Energos Grate Combustion and Gasification Process

The Energos grate combustion and gasification technology is currently in operation at six plants in Norway, one in Germany, and one in the U.K. Energos is part of the ENER-G group, headquartered near Manchester. This technology was developed in Norway in the 1990s in order to provide an economic alternative to grate combustion WTE with equally low emissions to the atmosphere and flexibility in feedstock.

All operating plants treat MSW plus additional streams of commercial or industrial waste. The current operating plants range in capacity from 10,000 to 78,000 tons per year.

The feedstock to an Energos plant is post-recycling MSW mixed with a smaller amount of other waste streams. These include industrial wastes and residues from materials recovery facilities (MRF). Prior to thermal treatment, the materials are shredded in a high-torque, low-rpm shredder and then ferrous metals are removed magnetically. In the first chamber of the Energos process, the feedstock is partially oxidized and gasified on a moving grate at sub-stoichiometric oxygen conditions (air to fuel ratio, k = 0.5–0.8); combustion of the fixed carbon on the grate results in TOC of <3% in the WTE ash. The volatile gases generated in the gasification chamber are then combusted fully in an adjoining chamber, and the heat in the combustion gases is transferred to steam in a heat recovery system. Temperatures reach up to 900°C in the gasification chamber and up to 1000°C in the oxidation chamber. Formation of NO_x is kept relatively low (at about 25% of the EU limit), any dioxins in the feed are destroyed in the combustion chamber, and the rapid cooling achieved in heat recovery steam generator minimizes formation of dioxins. A schematic diagram of the gasifier and combustion chamber is shown in Figure 3.40.

After the heat recovery steam generator (Figure 3.40), the flue gas enters the dry flue gas cleaning system, which consists of dry scrubbing with lime, activated carbon injection, a bag filter, and a filter dust silo. The lime absorbs acidic compounds in the flue gas, and the activated carbon adsorbs dioxins and heavy metal molecules. Emissions are monitored continuously. Table 3.3 shows typical emission measurements at the Averoy plant of Energos in Norway. These measurements were

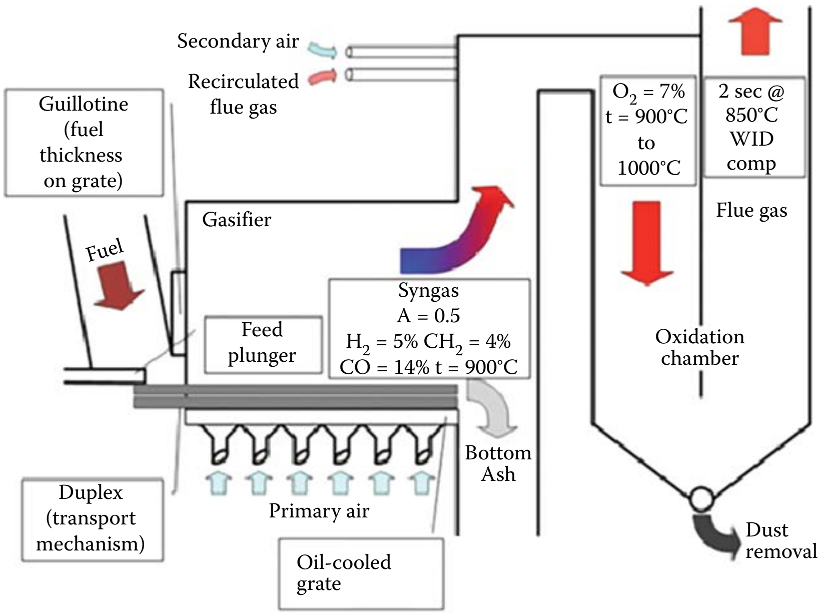

FIGURE 3.40 Flowchart of an indicative Energos plant.

TABLE 3.3
Averoy Plant Emissions (at 11% Oxygen)

Parameter	EU Limits (mg/Nm³)	Energos, Averoy
Particulate matter	10	0.24
Hg	0.05	0.00327
Cd + Ti	0.05	0.00002
Metals	0.5	0.00256
CO	50	2
HF	1	0.02
HCl	10	3.6
TOC	10	0.2
NO_x	200	42
NH_3	10	0.3
SO_2	50	19.8
Dioxins (ng/Nm³ TEQ)	0.1	0.001

taken by an independent agency (TUV NORD Umweltschtz) for the Norwegian Environmental Agency and are reported at 11% oxygen.

The reported availability of the Energos plants is about 90% (8000 hours per year similar with typical combustion WTE plants). The feedstock, annual capacity, and other information on the seven operating plants is shown in Table 3.4.

Over the years, the Energos plants have reported treated more than 1.8 million tons of post-recycling wastes and produced 3800 GWh of mostly thermal energy. These plants provide district heating to the host communities as well as steam to local industries, including chemical, pharmaceutical, paper, and food processing plants. For example, the Forus plant that serves Stavanger, Norway, is a CHP system; during periods of low heat demand, steam is used to produce electricity that is sold to the grid.

As shown in Table 3.4, these plants range in annual capacity from 10,000 to 78,000 tons. As would be expected, the smaller plants were costlier to build, per ton of annual capacity. The Sarpsborg plant, with capacity of 78,000 tons per year, was reported by Energos to cost $525 per annual ton of capacity, which is at the low end of the capital cost of much larger grate combustion plants (about $600 per annual ton of capacity). At the low capacity end, the Averoy plant cost about $1000 per annual ton of capacity.

3.2.6 The Ebara Fluidized Bed Process

The Ebara process (Figure 3.41) consists of partial combustion of debagged and shredded MSW in a fluidized bed reactor followed by a second furnace where the gas produced in the fluidized bed reactor is combusted to generate temperatures up to 1350°C such that the ash is vitrified to slag. There is no oxygen enrichment. The largest application of the Ebara process is a three-line, 900 tons per day plant in Spain.

The ash overflow from the fluidized bed is separated from the sand used in the reactor for fluidization. Separation is by means of an inclined vibrating screen with 3–4 mm openings through which sand particles can pass while glass and metal

TABLE 3.4
Energos Plants Worldwide

Plant Location (Startup Year)	Feedstock	Annual Capacity in Tons (Number of Lines)	Approximate Site Area (m^2)	Thermal Energy Produced (MWh/yr)	MWh per ton	Capital Investment in Millions	Investment in ton of Annual Capacity
Ranheim, Norway (1997)	Paper mill rejects + various commercial wastes	10,000 (1)	N.A.	25,000	2.5	$14	$1350
Averoy, Norway—Nordmore region (2000)	MSW + commercial wastes	30,000 (1)	6000	69,000	2.3	$31	$1033
Hurum, Norway (2001)	MSW + commercial waste from airport + paper rejects	39,000 (1)	6000	105,000	2.7	$26	$657
Minden, Germany (2001)	MSW + RDF (paper and plastic waste)	39,000 (1)	6000	105,000	2.7	$26	$673
Forus, Norway—Stavanger region (2002)	Post-recycling MSW (18,000 tons) + industrial wastes (21,000 tons)	39,000 (1)	6000	105,000	2.7	$32	$825
Sarpsborg #1, Norway (2002)	MSW + commercial wastes	78,000 (2)	9000	210,000	2.7	$41	$525
Sarpsborg #2, Norway (2010)	MSW + commercial wastes	78,000 (2)	9000	256,000	3.3	$41	$525

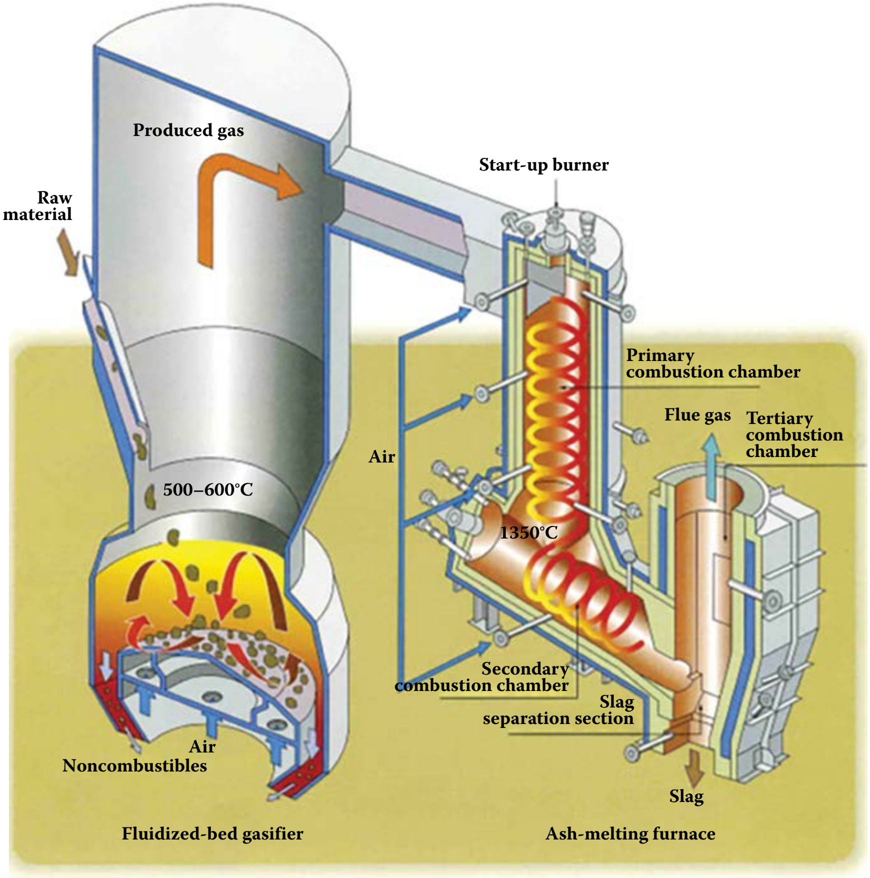

FIGURE 3.41 The Ebara fluid bed gasification process.

particles cannot. Bottom ash in Japan cannot be used for applications such as road construction and therefore has to be melted into slag, which is the final solid product and can be used in construction. The Spanish plant of the Ebara process produces a net of about 560 kWh per ton of RDF.

3.2.7 The Thermoselect Gasification and Melting Process

The JFE steel company of Japan operates many plants, ranging from grate combustion to the JFE direct smelting process described earlier, and also seven JFE Thermoselect plants with a total capacity of 2000 tons per day. The syngas produced in the Thermoselect furnace is quenched and cleaned before it is used in gas turbines or engines to generate electricity. The amount of process gas per ton of MSW is much lower than in conventional grate combustion. However, cleaning a reducing gas is more complex than for combustion process gas. Also, the Thermoselect process uses some of the electricity it generates to produce the industrial oxygen used for partial oxidation and gasification of the MSW. The expectation is that the syngas product can be combusted in a gas turbine to generate electricity at a much higher thermal efficiency than is possible in a conventional WTE plant using a steam turbine.

3.2.8 Plasma-Assisted Gasification WTE Processes

In recent years, there has been a lot of interest in plasma-assisted gasification of MSW. A plasma torch is a device for transforming electricity to heat by passing current through a gas flow.

Increasing interest is focusing on plasma-assisted gasification applied to the treatment of MSW, especially as it may be a new way to increase WTE worldwide. Plasma technology has been used for a long time for surface coating and for destruction of hazardous wastes, but its application to MSW has not been explored. Plasma-assisted gasification in the WTE process combines the use of plasma with partial oxidation of the hydrocarbons in MSW.

Relatively high voltage, high current electricity is passed between two electrodes, spaced apart, creating an electrical arc. Inert gas under pressure is passed through the arc into a sealed container of waste material, reaching temperatures as high as 13,900°C in the arc column. The temperature a few feet from the torch can be as high as 2760–4427°C. At these temperatures, most types of waste are broken into basic elemental components in a gaseous form, and complex molecules are separated into individual atoms. This arc breaks down waste primarily into elemental gas and solid waste (slag) in a device called a plasma converter. The process is intended to be a net generator of electricity, depending on the composition of input wastes, and a reducer of the volumes of waste being sent to landfill sites.

A scientific study of this technology was conducted by the Earth Engineering Center of Columbia University under the supervision of Professor Nickolas J. Themelis. Plasma technology has been used for a long time for surface coating and also for the destruction of hazardous materials, such as asbestos, hospital and toxic waste.

In the case of MSW processing, plasma torches are used to gasify the solids, to crack the volatile gases, and to vitrify the ash to slag and metal globules. The syngas product is combusted in a gas engine or turbine generator to produce electricity, or it can be used to produce synthetic fuels. The technologies investigated in the previously mentioned EEC study were Westinghouse Plasma, owned by Alter NRG, Plasco Energy Group, Europlasma, and the InEnTec process of Waste Management, Inc. The main advantage over grate combustion is the dramatic decrease in process gas flow (up to 75%). Also, the reducing atmosphere in the gasification process should result in lower NO_x emissions than in the grate combustion process. However, this study showed that the capital cost per ton of capacity was of the same magnitude as in grate combustion. Because of the use of electricity for high-temperature gasification, it is expected that the energy production per ton of feedstock will not be higher than in the case of grate combustion. For example, the Alter NRG gasification process is expected to generate about 0.6 MWh/ton of MSW. Finally, the availability of these plants is not similar to the combustion process WTE plants (8000 hours annually).

3.2.9 Application of Various WTE Processes in Japan

It can be seen from the previous discussion that Japan has been a leader in developing and implementing traditional and novel thermal treatment technologies. This nation generates about 65 million tons of MSW, thermally treats 40 million tons, and recycles the rest. Table 3.5 was prepared for the IDB Guidebook and lists all the types of WTE technologies used in Japan. It can be seen that despite the abundance of other technologies, 84% of the 37.8 million tons of MSW listed in Table 3.5 are processed in grate combustion plants.

In closing the gasification section, it should be noted that it is often assumed that gasification processes will encounter less resistance by environmental groups who are opposed to "incineration," that is, grate combustion with energy recovery. In fact, in the recent past, the same groups have opposed gasification, which they call "disguised incineration."

TABLE 3.5
Thermal Treatment Technologies Used in Japan

	Number of Plants	All Plants, Tons/Day	Average Tons/Day per Plant	Percentage of WTE Capacity of Japan
Martin reverse acting grate (66 plants)[a]	66	71,500	1083	62%
JFE Volund grate (stoker; 54 plants)[a]	54	10,100	187	9%
Martin horizontal grate (14 plants)[a]	14	7454	532	7%
Nippon Steel direct melting (28 plants)	28	6200	221	5%
JFE Hyper Grate (stoker; 17 plants)[a]	17	4700	276	4%
Rotary kiln (15 plants)	15	2500	167	2%
JFE Thermoselect (gasification; 7 plants)	7	1980	283	2%
All other fluid bed (15 plants)	15	1800	120	2%
Ebara fluid bed (8 plants)	8	1700	213	1%
JFE Direct Melting (shaft furnace, 14 plants)	14	1700	121	1%
Hitachi Zosen fluid bed (8 plants)	8	1380	173	1%
JFE fluid bed (sludge and MSW; 9 plants)	9	1300	144	1%
All other direct melting (9 plants)	9	900	100	1%
Fisia Babcock (2 forward, 1 roller grate)[a]	3	710	237	1%
Babcock and Wilcox air-cooled grate (43)[a]	43	690	16	1%
Total	**310**	**114,614**		**100%**
Total tons/year (at 330 days-24 h/year)		37,822,620		
% of total MSW to grate combustion plants[a]				84%

Source: Ganfer N., Recovering energy from waste, EEC thesis, Columbia University, August 2011, New York.

[a] Grate combustion plants.

Finally, the major challenges for the produced syngas are the optimization of the cleaning process, the high relevant operating costs, and the explosive conditions that may occur due to hydrogen and CO presence (that complex operational problem does not exist in typical combustion WTE plants). In conclusion, all of these novel alternatives to combustion WTE technologies are not yet fully applied commercially in big capacities of mixed MSW, so very few such WTE plants are fully operational today (only combustion process WTE plants have an availability of 8000 hours annually).

3.2.10 Technical Visit in an Alternative WTE Process Plant

The author integrated a technical visit of a pilot plasma gasification and vitrification (PGV) plant on October 20, 2011. It has a capacity of 10 tpd of as-received MSW and is located in Cheongsong, South Korea (8000 hours of annual operation since January 2009).

The technology is based on plasma torch systems and produces synthetic gas for various applications like high purity (20 m^3/hr, 99.99%) hydrogen or, alternatively, diesel, power, ethanol, or steam. It is the first hollow cathode plasma torch in South Korea. The nontransferred plasma torch (200 kW $\times$ 2 units) and cyclonic plasma gasification and vitrification technology produces 50 kW fuel cell power. The capital expenditure was \$3 million, and the operational cost was around \$200/ton. The furnace temperature is 1430°C, pressure is 10 mmH_2O (−0.1 bar), and temperature in post combustion chamber is 920°C.

Finally, there is a plan to develop an 110 tpa PGV plant with feed refuse plastic fuel (RPF) in order to supply heat and steam in the vicinity through CHP generation.

Figure 3.42 shows the plasma torches at PGV GS Platech plant. Figure 3.43 presents the impressive plasma arch, and finally Figure 3.44 shows the vitrificated ash produced at the plant.

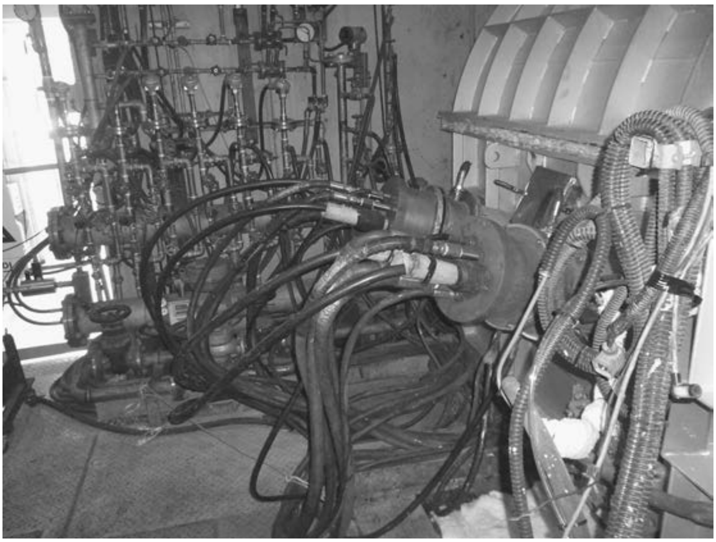

FIGURE 3.42 Plasma torches at PGV GS Platech plant.

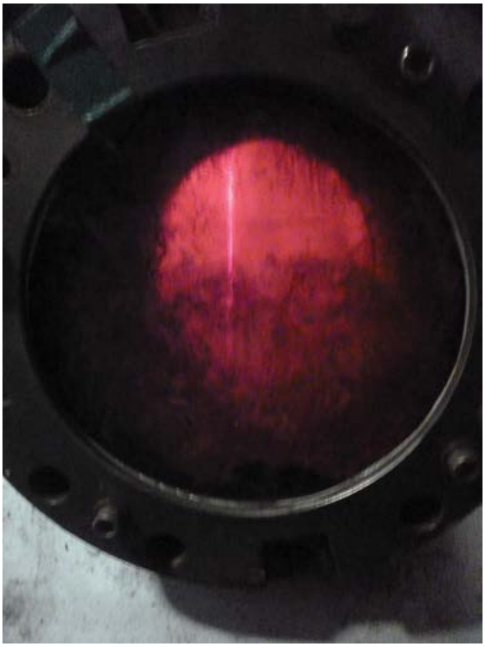

FIGURE 3.43 Plasma arch at PGV GS Platech plant.

FIGURE 3.44 Vitrificated ash produced at PGV GS Platech plant.

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4 Waste-to-Energy in Europe

In the current chapter, technico-economic data for 24 WTE plants are presented. The data are based on reports created by the author after his relevant site visits.

4.1 SPAIN

Waste management in Spain is mainly dominated by landfilling (60%), while recycling and composting represents 29% of waste management activities and WTE represents only 11%. There are currently ten WTE plants in Spain, with a total annual capacity of 3 million tons. Four of these WTE plants are located in Catalonia and have a total capacity of 800,000 tpa.

The landfill gate fees are significantly low, ranging from 13–25 USD/t, which, along with the financial crisis in Spain, affect the development of new WTE projects. The central government has no unique and integrated municipal solid waste strategy, resulting in autonomous waste management in each district. The gate fees of the Spanish WTE plants range from 35–90 USD/t.

In the following sections, the author describes and provides information about the TERSA WTE plant in Barcelona and the Mataró WTE plant in Maresme.

4.1.1 TERSA WTE Plant, Barcelona

The TERSA WTE plant in Barcelona started operating in 1974 with two lines; recently, a third line was installed. The plant treats 21% of the total MSW that is produced in the metropolitan area of Barcelona with a population of roughly 680,000. The plant annually produces 150 GWh of electricity and 75,000 tons of steam for district heating and cooling. Figure 4.1 shows a view of the TERSA WTE plant.

Main technical details

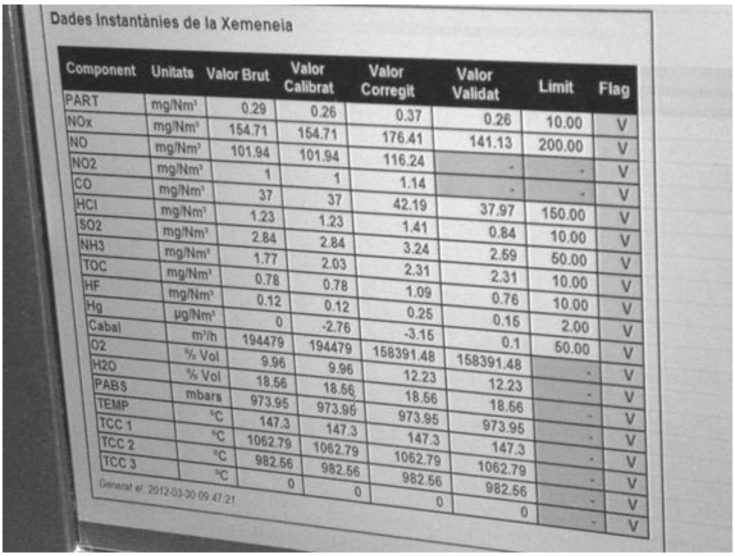
- The plant is equipped with three combustion lines with a capacity of 16.5 tph per line (385,000 tpa)
- The total area of the plant is 40,000 m^2 (10 acres), and it operates 8000 hours annually
- The grate technology used in the plant is from Hitachi Zosen Inova
- The flue gas cleaning system uses a semi-dry scrubber, a bag filter, SNCR, and an activated carbon injection system
- Bottom ash produced after the combustion of MSW is reused for road construction
- Fly ash is treated as hazardous waste (i.e., exported)
- The gate fee is around 33 USD/t, the lowest in Europe
- The selling price of the produced electricity is 77 USD/MWh

FIGURE 4.1 TERSA WTE plant in Barcelona.

- The plant is equipped with continuous monitoring devices to measure flue gas emissions according to the European standards (Directive 2000/76/EC)

In Figure 4.2, the emissions in the stack are presented in real time.

The turbine exhaust steam of the TERSA WTE plant is used for district heating and cooling, as described in the following section.



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Component	Unitats	Valor Brut	Valor Calibrat	Valor Corregit	Valor Validat	Limit	Flag
PART	mg/Nm³	0.29	0.26	0.37	0.26	10.00	V
NOx	mg/Nm³	154.71	154.71	176.41	141.13	200.00	V
NO	mg/Nm³	101.94	101.94	116.24	-	-	V
NO2	mg/Nm³	1	1	1.14	-	-	V
CO	mg/Nm³	37	37	42.19	37.97	150.00	V
HCl	mg/Nm³	1.23	1.23	1.41	0.84	10.00	V
SO2	mg/Nm³	2.84	2.84	3.24	2.59	50.00	V
NH3	mg/Nm³	1.77	2.03	2.31	2.31	10.00	V
TOC	mg/Nm³	0.78	0.78	1.09	0.76	10.00	V
HF	mg/Nm³	0.12	0.12	0.25	0.15	2.00	V
Hg	µg/Nm³	0	-2.76	-3.15	0.1	50.00	V
Cabal	m³/h	194479	194479	158391.48	158391.48	-	V
O2	% Vol	9.96	9.96	12.23	12.23	-	V
H2O	% Vol	18.56	18.56	18.56	18.56	-	V
PABS	mbars	973.95	973.95	973.95	973.95	-	V
TEMP	°C	147.3	147.3	147.3	147.3	-	V
TCC 1	°C	1062.79	1062.79	1062.79	1062.79	-	V
TCC 2	°C	982.56	982.56	982.56	982.56	-	V
TCC 3	°C	0	0	0	0	-	V

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FIGURE 4.2 Emissions exiting the stack at the TERSA WTE plant.

FIGURE 4.3 Districlima district heating and cooling data at the TERSA WTE plant.

4.1.1.1 The Districlima District Heating System

The Districlima network (district heating and cooling in cooperation with ENGIE) consists of 13.1 km of pipeline and has a total investment value of USD55 million. It is used by 60 clients (hotels, hospitals, office/commercial buildings, residential areas, shopping malls, etc.). The contracted heating power is 44.45 MW and the contracted cooling power is 68.29 MW. The main advantages of this system are potable water savings, reduced noise pollution, and a lack of visual impact on buildings. The heating and cooling network runs through the city streets and is composed of four parallel pipelines, two for hot water (pumped at 90°C and sent back at 60°C) and two for cold water (pumped at 5.5°C and sent back at 14°C), which carry energy from the production plant to the substations of energy exchange points at designated building sites. Saturated steam from the WTE plant measuring 174°C is used in adsorption coolers.

Figure 4.3 shows the technical data for district heating and cooling. In Figure 4.4, district heating and cooling equipment is presented. The central pumping station is shown in Figure 4.5.

4.1.2 The Mataró WTE Plant (Maresme Integrated Waste Management Center)

Mataró is a touristic seaside municipality in Catalonia that covers an area of 22.5 km^2 and hosts 124,280 inhabitants, resulting in a high population density of more than 5500 inhabitants per km^2. Waste management in the municipality exemplifies the

FIGURE 4.4 Districlima equipment at the TERSA WTE plant.

effective combination of source collection, recycling, and WTE recovery (Salesa Mirabet, 2014, 2015).

The whole area is served by the Maresme Integrated Waste Management Center. The total budget of the updated WTE investment was estimated at USD100 million (Salesa Mirabet, 2014, 2015).

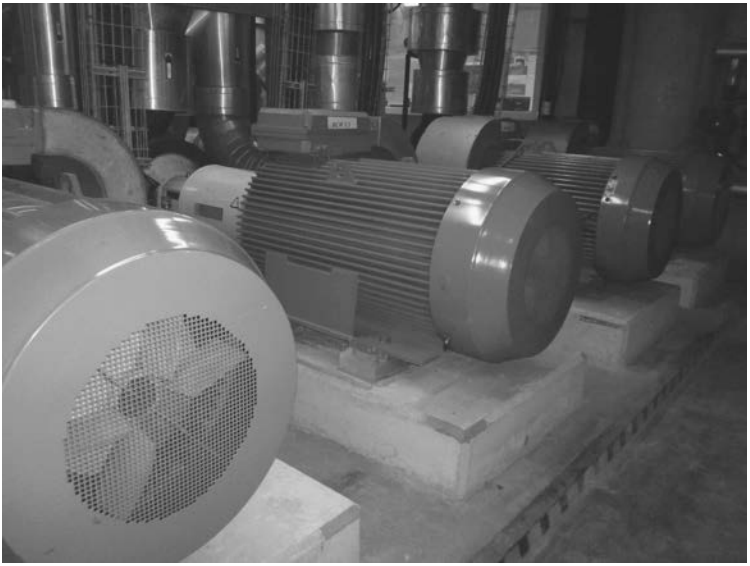

FIGURE 4.5 Districlima central pumping station at the TERSA WTE plant.

FIGURE 4.6 Aerial photo of the Maresme Integrated Waste Management Center.

In Figure 4.6, an aerial photo of the Mataro WTE plant is shown.

4.1.2.1 The Maresme Integrated Waste Management Center History

First generation: Early plant in 1985. In 1985, the Consorci was formed to serve 17 towns of the Maresme area and the Diputació de Barcelona. A recycling and composting plant was established, with the objective of sorting out the recoverable subproducts and compost the organic matter.

Second generation: Construction of the WTE plant in 1994. During the period of strong economic growth from 1985 to 1990, the generation of waste in Maresme increased by 5% yearly. These circumstances increased the membership of the Consorci to 27 towns, the Diputació de Barcelona, and the Consell Comarcal del Maresme. The increase in membership warranted a similar increase in the plant's capacity and therefore prompted the need to build a new WTE plant. The combination of the existing recycling and composting plant and the new WTE plant was called the Centre Integral de Valorització de Residus del Maresme (CIVRM).

Third generation: Construction of the MBT plant in 2010. The new CIVRM was framed within the land sectorial plan of infrastructures for the management of municipal waste, approved by a Generalitat de Catalunya decree on February 16, 2010. The new center included the following facilities for waste treatment:

- A mechanical biological treatment (MBT) plant for the mixed waste fraction

- A treatment line for bulky waste
- Transfer stations for different fractions collected separately
- The already existing facility for energy recovery with improvements

The total budget of the investment was estimated at USD100 million, value-added tax (VAT) included.

Main technical data

- Contract treatment capacity: 154,000 tpa
- Number of lines: Two
- Combustion system: Reverse-acting grate
- Unit thermal capacity: 4,000,000 kcal/h
- Unit steam generation ratio: 33 tph
- Steam pressure:
    - Boiler: 67 bar
    - Superheater: 62.5 bar
    - Turbine: 61 bar
- Steam temperature:
    - Boiler: 283°C
    - Superheater: 385°C
    - Turbine: 380°C
- Flue gas treatment system:
- NO_x reduction SNCR type with urea in combustion chamber
    - Semi-dry absorber
    - Dry contact reactor
    - Active carbon injection
    - Fabric filters
- Condensation type: Air-cooled condensers
- Generation power: 13.55 MW (11.25 MW + 2.3 MW)
- Energy production: 115,000 MWh/year
- Energy self-consumption: 30,000 MWh/year
- Electricity sold: 85,000 MWh/year

4.1.2.2 Air Pollutant Emissions at the Stack

Tables 4.1 and 4.2 present the annual average air pollutant emissions from the flue gas stack. It is undeniable that the modern air pollution control (APC) systems of the WTE plant aid in the achievement of its environmental goals, with all measurements falling below the strict requirements of the new Directive 2010/75/EC for incineration.

This demonstrates the effectiveness of BATs in the protection of the atmospheric environment, which dramatically minimized the dioxin/furan emissions (concentrations) and emission rates.

Figure 4.7 shows the plant equipment.

In the Mataró WTE plant, there is a unique education center. A 3-D cinema room presents the route of an end-life product through the Maresme waste management system.

TABLE 4.1
Annual Average Air Pollutants Concentration Exiting the Stack

Year	CO (mg/m^3)	NO_2 (mg/m^3)	SO_2 (mg/m^3)
EU Legislation Standards (Directive 2010/75/EC – Annex VI)	50	200	50
2006	20.73	148.87	9.59
2007	32.74	146.25	22.10
2008	31.28	152.50	20.56
2009	24.81	154.62	20.07
2010	21.47	118.50	14.27
2011	23.28	109.55	26.94
2012	19.26	133.22	12.99
2013	13.56	139.32	9.74
2014	18.40	133.24	9.84
2015	19.86	141.11	7.40

Source: Sakalis, A., 2016, Technical visit in Mataró, WTE Plant, October 18.

TABLE 4.2
Dioxin and Furan Emissions at the Exit of the Stack

Dioxins and Furans	Emissions (ng/m^3)	Comparison with EU Standards (%)
2000	0.0165	16.50
2001	0.0199	19.90
2002	0.0187	18.70
2003	0.0417	41.70
2004	0.0205	20.50
2005	0.0068	6.80
2006	0.0044	4.40
2007	0.0015	1.50
2008	0.0038	3.80
2009	0.0046	4.60
2010	0.0058	5.80
2011	0.0066	6.60
2012	0.0062	6.20
2013	0.0079	7.90
2014	0.0038	3.80
2015	0.0148	14.80

Source: Sakalis, A., 2016, Technical visit in Mataro, WTE Plant, October 18.

FIGURE 4.7 View in front of the Mataró WTE plant.

4.2 ITALY

The waste management in Italy is based mainly on landfilling (44%), while recycling and composting represents 39% of waste management activities and WTE represents 17%. The annual production of waste is 34 million tpa (580 kg/inhabitant). There are currently 50 WTE plants in Italy, with the majority of them (34), situated in North Italy. Eighteen of these WTE plants utilize online measurement of mercury and dioxins (on a voluntary basis).

The gate fees of Italy's WTE plants are within the range of 55–120 USD/t and the feed-in electricity tariff falls between 65–120 USD/MWh. Under the new political landscape in Italy, there is opposition to the development of new WTE plants, which is why there is a delay in the integration of additional WTE plants in Naples and in Parma.

4.2.1 Turin WTE Plant

The Turin WTE plant put one combustion line into operation in April 2013 and two others in 2014. The plant has a nominal capacity of 580,000 tpa and serves the metropolitan area of Turin (equivalent of 1,750,000 people). It annually produces 350 GWh of electricity for roughly 175,000 families of three families and 170,000 MWh of district heating for 17,000 houses (each averaging 100 m^2).

The plant has an excellent design by the famous architect Bertone (the designer of several Maserati sports cars).

Main technical details

- The plant is equipped with three combustion lines, with a total capacity of 74.2 tph per line and a lower heating value (LHV) of 11 MJ/kg. The total area of the plant is 70,000 m^2 (17.5 acres), and the buildings cover 16,000 m^2. It operates 7800 hours annually.
- Steam parameters: 450°C, 65 bar, 110 MWe (55.5 MW district heating).
- Net electrical efficiency: 29% (use of cooling towers).
- The grate technology used in the plant is by Martin GmbH.
- The flue gas cleaning system uses a dry scrubber (sodium bicarbonate and an activated carbon injection system), ESP, a bag filter, and SCR.
- Bottom ash produced after combustion of MSW (21%) is reused for bituminous applications.
- Fly ash (3.5%) is treated as hazardous waste (exported).
- The gate fee is 120 USD/t.
- The selling price of the produced electricity is 83 USD/MWh.
- The plant is equipped with continuous emission monitoring devices for measuring flue gas emissions, as per the European standards (Directive 2000/76/EC).
- The height of the stack is 125 m (higher than usual but typical for northern Italy).

4.2.2 Piacenza WTE Plant

The WTE plant within the small city of Piacenza is operated by the Italian company Tecnoborgo. The plant was constructed by CNIM in 2003.

Figure 4.8 shows the stack of the Piacenza WTE plant.

Main technical details

- The plant is equipped with two combustion lines with a daily capacity of 200 tons of MSW each. The total area of the plant is 40,000 m^2 (4 ha), and it operates 8000 hours annually.
- The grate technology used in the plant is the moving grate provided by MARTIN GmbH.
- The plant's input consists of 80,000 tpa MSW, 44,000 tpa of industrial waste, and 2200 tpa of hospital waste; the average lower calorific value (LCV) is 10.9 MJ/kg.
- Firing: Grate firing at 1100°C–1200°C; flue gas retention time in the combustion chamber at $T > 1100°C$: >2 s.
- The flue gas cleaning system consists of dry scrubbers, fabric filters, an activated carbon injection system, and a combination of SNCR/SCR.
- Only electricity is produced. The gross power production is 11.6 MWe, and the net production is 10 MWe. Gross electrical efficiency of the plant is

FIGURE 4.8 The flue stack of the Piacenza WTE plant.

24%, and the net is 22%, R1 is 0.66 (meets the EU legislation Directive 2008/98/EC).

- The thermodynamic characteristics of the produced steam are 390°C and 39 bar.
- Bottom ash produced after the combustion of MSW (19%) is used after aging as a substitute for cement manufacturing in a cement plant located next to the WTE plant. The ferrous and nonferrous metals are recovered via magnetic and eddy current separation.
- Fly ash (4.7%) is solidified at a cost of around 185 USD/t.
- The gate fee of the plant is 115 USD/t.
- The selling price of electricity is 110 USD/MWh.
- The total investment in the plant was USD90 million.
- The plant is equipped with continuous emission monitoring devices to measure flue gas emissions according to the European standards (Directive 2000/76/EC).
- The stack height is 70 m.

Figure 4.9 shows a conveyor in the plant. Figure 4.10 depicts a pile of scrap that was removed from bottom ash.

FIGURE 4.9 A conveyor in the Piacenza WTE plant.

FIGURE 4.10 Scrap removed from the bottom ash at the Piacenza WTE plant.

4.2.3 Brescia WTE Plant

The Brescia WTE plant is operated by the Italian company A2A.

Main technical details

- The plant is equipped with three combustion lines with a daily capacity of 880 tons of MSW each, mainly from the surrounding areas; the total area of the plant is 70,000 m^2 (7 ha), and it operates 8000 hours annually.

- The first two lines were constructed in 1999, and the third was constructed in 2004.
- The grate technology used in the plant is the moving grate provided by MARTIN GmbH.
- In each line, two-thirds of waste is mixed MSW and one-third is biomass, the average LCV is 10 MJ/kg.
- Firing: Grate firing at 850°C–1000°C. Flue gas retention time in the combustion chamber at T > 850°C: >2 s.
- The flue gas cleaning system consists of dry scrubbers, fabric filters, an activated carbon injection system, and a combination of SNCR/SCR.
- CHP is produced. The power production is 80 MWe, and district heating is also provided to the community. The gross electrical efficiency of the plant is 28%; R1 is greater than one.
- The thermodynamic characteristics of the produced steam are 450°C and 60 bar.
- Bottom ash produced after the combustion of MSW is treated on-site for maturation. The iron and nonferrous materials (aluminum, copper, zinc, etc.) are recovered via magnetic separation and used in the cement industry (at a cost of 50 USD/t, including transportation).
- Fly ash is exported to Germany as hazardous waste, which costs around 220 USD/t.
- The gate fee of the plant is 77 USD/t.
- The selling price of the productive electricity is 107 USD/MWh.
- The total investment in the plant was USD440 million.
- The plant is equipped with continuous emission monitoring devices to measure flue gas emissions that are calibrated according to the European standards (Directive 2000/76/EC); dioxin and furan emissions from the plant fall between 0.002–0.005 ng/Nm^3.

A view of the equipment inside the facility is shown in Figure 4.11. Figure 4.12 shows the fabric filters used in the antipollution system. Finally, Figure 4.13 shows the data from the steam turbine.

4.2.4 Acerra WTE Plant, Naples

Campania has an MSW production of 7700 tons per day (approximately 2.9 million tpa). Due to MSW treatment problems that occurred in Naples in the past, there are around 7.7 million tpa MSW in bales in the surrounding area. The WTE plant in Acerra was built by Fisia Babcock Environment and is operated by the Partenope Ambiente (a subsidiary of A2A, which also operates the Brescia WTE plant). Operation of the Acerra WTE plant started on January 14, 2010.

Figure 4.14 shows the entrance of the plant. Figure 4.15 presents the crane in the bunker. The air condensing unit is shown in Figure 4.16. In Figure 4.17, the reader can see the flue gas treatment equipment. Finally, in Figure 4.18, the impressive stack of the plant is shown.

In the Acerra WTE plant, MSW is lightly pretreated before feeding begins.

FIGURE 4.11 View of the equipment at the Brescia WTE plant.

FIGURE 4.12 View of the fabric filter at the Brescia WTE plant.

FIGURE 4.13 Technical characteristics of the steam turbine at the Brescia WTE plant.

Main technical details

- Three boilers, capacity 89 tph (712,000 tpa)
- 418 tph of steam at a temperature of 500°C and pressure of 90 bar
- 107.8 MWe gross electrical power and 91.8 MWe net
- Temperature of the flue gases is around 1040°C

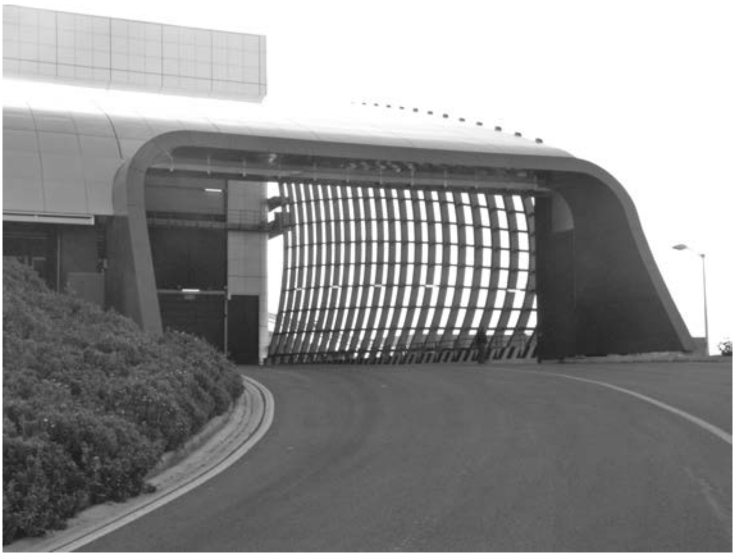

FIGURE 4.14 Entrance to the Acerra WTE plant in Naples.

FIGURE 4.15 The crane during operation at the Acerra WTE plant.

- Moving grates are water cooled and integrated with the boiler
- White wash injection system
- Semi-dry absorption reactor to eliminate acidic gases
- Powder-activated carbon injection system
- Filter sleeve to remove light ash and micropollutants

FIGURE 4.16 The air condensers of the Acerra WTE plant.

FIGURE 4.17 Flue gas treatment equipment at the Acerra WTE plant.

- Mixed reagent injection system (mix $Ca(OH)_2$/activated carbon)
- $DeNO_x$ SCR to remove nitrogen oxides
- Extractor fan
- Emissions-monitoring system for chimney stack
- The bottom ash (20% in total) is fully recovered and used as aggregate for asphalt, the fly ash (5% in total) is stabilized and exported to salt mines in Germany
- Although it produces only electrical power, R1 is high due to the excellent thermodynamic characteristics of the produced steam
- Dioxin and furan emissions are estimated at 0.025 ng/Nm^3, NO_x at 85 mg/Nm^3
- The plant supplies electricity for 230,000 families
- The gate fee is around 55 USD/t, and the electricity sale price is 88 USD/MWh. The gate fee does not include the cost of the MSW pretreatment of the MSW (MBT)
- The plant experiences higher maintenance costs because of increased corrosion at high temperatures

The investment cost was USD390 million. A second, smaller-capacity plant is scheduled to be opened in Naples.

FIGURE 4.18 The stack of the Acerra WTE plant.

4.3 POLAND

Six new Polish WTE plants with a total design capacity of approximately 1 million tpa were put into operation in the years 2015 and 2016. According to the Eurostat statistics, in 2014 the share of municipal waste incineration in Poland reached approximately 9%—achieved mainly by co-combustion in the cement industry—and it is expected to rise at the end of 2017 to approximately 20%. The growing share of recycling results in a significant decrease in the share of waste landfilling.

Cities and regions in which new WTE plants operate are now able to meet a number of EU requirements—for example, to reduce by 2020 the amount of biodegradable waste by 65% compared to 1995 totals since January 1, 2016, regulations imposing a ban on the landfilling of combustible waste.

New Polish WTE plants will pave the way for the construction of other combustion plants in Poland, although there is no intention of building a large number of new ones. Priority will be given to plants that produce refuse-derived fuels (RDF), such as solid recovered fuels (SRF), as there is a significant overproduction of this type of waste in Poland.

4.3.1 Poznań WTE Plant

In April 2011, the city of Poznań, the fifth largest city in Poland, announced the launch of a procurement procedure to select a private partner to design, build, finance and operate a large WTE facility for the recovery of residual waste from a population of about 750,000 residents of Poznań and its neighboring communities. Due to the complexity of the project and the lack of experience in developing public–private partnerships (PPP), the city decided to organize a competitive dialogue with five pre-qualified bidders in order to develop the technical, financial, and contractual arrangements for the project. The dialogue started at the end of 2011 and was completed one year later, at which point bidders were able to submit their final proposals, paving the way to the first waste-related PPP project in Poland ever to reach financial targets. An additional pioneering characteristic of the project was the ability to combine private financing (in the form of capital and long-term credits) and EU cohesion funds, both to be disbursed during the construction phase.

The selected bidder (SITA Zielona Energia), a special purpose company (SPC) formed by SITA Polska (part of SUEZ) and the Marguerite Fund, contracted a consortium of Hitachi Zosen Inova and Hochtief Polska to design and build the WTE facility on a turnkey basis for a contract value of USD187 million. Construction started in April 2014 and has since progressed perfectly in line with the schedule, commercial operation started in January 2017. The plant, which includes two combustion lines with a capacity of 15 tph, will recover 230,000 tons of MSW per year and deliver both power and heat to the district heating network. The plant will be operated for 25 years by SITA Zielona Energia and handed back to city at the end of the PPP contract.

As is the case with most large PPPs and concession contacts, the project is funded according to the principles of project finance, that is, using a combination of equity and/or subordinated debt contributed by the SPC sponsors and a long-term credit facility to be reimbursed by the SPC from the project's future cashflows (in this case, a 20- to 22-year maturity credit facility of 800 million zlotys obtained from a syndicate of three prime Polish banking institutions). Part of the debt financing was prepaid in 2015, after the decision of the European Commission to allocate USD90 million to the project. Thanks to a specially designed contractual mechanism, the future remuneration of the SPC was immediately adjusted to reflect its reduced financial obligations.

From the start of operation, the private partner is to receive an availability-based compensation (i.e., independent of the waste delivered to the facility), subject to the plant achieving defined performance standards. Due to uncertainties as to the level of feed-in tariffs for renewable energy in Poland after 2017, it was decided that all revenues obtained by the private partner from the sale of heat and power would be passed onto the city and decrease the net cost of project.

The Poznań WTE project is proof that waste PPPs, which are usually considered complex to structure and finance, are not the exclusive privilege of countries with a long tradition of concessions and similar models, but rather can be successfully developed in new EU member or candidate countries. However, a key success factor is to achieve a fair allocation of risk and obligation between the private and public partners with the overarching objective of creating a bankable and affordable project.

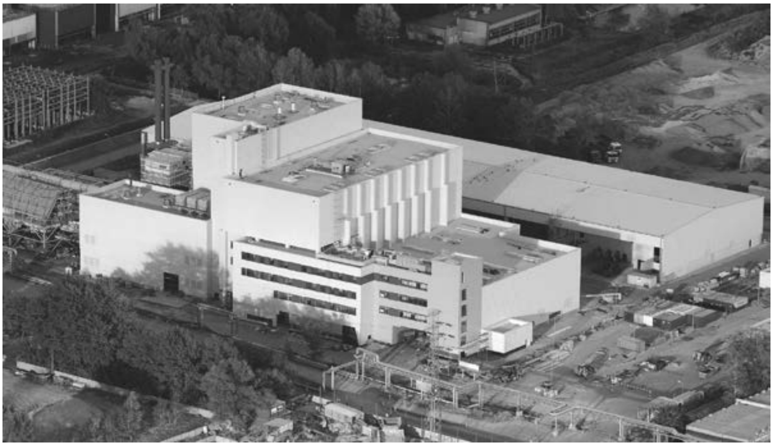

FIGURE 4.19 Aerial view of the Poznań WTE plant.

Figure 4.19 shows an aerial view of the Poznań WTE plant.

General project data

- Owner: Sita Zielona Energia Sp. z o.o.
- Operator: Sita Energia z Odpadów Sp. z o.o.
- Commissioned: 2016
- Total investment: PLN 725 million

Main technical details

- Annual capacity: 236,000 t
- Number of lines: Two
- Throughput per line: 15 tph (nom)–16.5 tph (max)
- Calorific value of waste: 6.0 MJ/kg (min)–12.1 MJ/kg (max)
- Thermal capacity per line: 31.5 MW
- Waste type: Municipal and commercial solid waste
- Combustion system: Grate type, Hitachi Zosen Inova grate
- Grate size: Length = 10.8 m, width = 5.2 m
- Grate cooling: Air cooled
- Boiler type: Four-pass boiler, vertical
- Steam quantity per line: 42.3 tph
- Steam pressure: 61.5 bar(a)
- Steam temperature: 422°C
- Flue gas treatment: DyNOR® concept, SNCR $DeNO_x$, HZI SemiDry® system
- Flue gas volume per train: 66,000 m^3/h
- Flue gas temperature: 145°C (at stack)
- Energy recovery: Extraction condensing turbine
- Electric power generation: 17.6 MW (max)
- District heating output: 34 MW (max)
- Residues: Bottom ash treatment and fly ash stabilization on-site

- Bottom ash: 71.500 tpa
- Flue gas treatment residues: 10.000 tpa (including fly ash and boiler ash)

4.4 NORWAY

4.4.1 The Klemetsrud Plant, Oslo

In Figure 4.20, the technical equipment at the Klemetsrud plant is presented.

The WTE plant at Klemetsrud has three lines, two old and one newly opened (2011). The facility was constructed by Hitachi Zosen Inova. Carbon capture from renewable energy at Klemetsrud Plant AS is one of the major initiatives encompassed by Oslo's new climate and energy action plan, and the city council plans to make Klemetsrud a national industrial pilot project. This type of project would be a significant contribution toward reaching Oslo's ambitious goal of reducing greenhouse gas emissions. The Norwegian Parliament (Stortinget) has decided to establish at least one full-scale plant for CO_2 capture by 2020, and in their prefeasibility study of 2015, Gassnova recommended the Klemetsrud plant as one of three possible candidates. Oslo municipality's WTE agency (EGE) started a feasibility study on assignment from Gassnova in the fall of 2015. The study was concluded in the summer of 2016, and provides the basis for an application to establish a full-scale plant by the year 2020. The plant will be in operation continuously throughout the year and will still be operating after 40 years, even if ownership changes hands over time. It therefore provides an excellent base for technological development. The plant provides flexible energy, supplying both heat and electricity (Stuen, 2016).

Carbon capture storage (CCS) from waste combustion will be of major global interest. A number of new WTE plants are being planned, or are currently under

FIGURE 4.20 The technical equipment of the Klemetsrud WTE plant.

construction, in accordance with the EU's upcoming landfill restrictions for degradable waste.

Oslo is working toward an increasing amount of material recovery from waste. Renewable energy is the best alternative for the final stage of waste processing, after recycled material has been sorted out. Use of CCS will reinforce the principles of sustainability in cycle-based waste management.

The Klemetsrud plant is well situated for CCS, since it is located relatively close to Oslo Harbour, and boat transport of liquid CO_2 from Oslo Harbour will be feasible. The establishment of an infrastructure for transportation and storage of CO_2 must be a governmental task. Renewable energy from waste is strictly regulated by EU environmental legislation. A Norwegian pilot plant could pave the way for greater emphasis on CCS in tendering procedures and criteria, and for future requirements regarding CCS at WTE plants within the EU. Oslo has a unique opportunity to further develop its status as a European pioneer in the area of environmental and climate efforts and to have a leading role in the development of technology related to the capture and storage of CO_2 emissions from WTE plants. This hinges on political will and implementation ability, as well as a national investment in technology and logistics for capture and storage (Klemetsrud-Anlegget, 2016).

Main technical details

- Line capacity: 11 tph each (older lines), 165,000 tpa (newer line)
- CHP production: 55.4 MWth (300 GWh annually, district heating for 40,000 households) and 10.5 MWe (70 GWh electricity for 20,000 households)
- Boiler capacity: One boiler, 22 tph (165,000 tpa)
- Steam temperature: 360°C
- Steam pressure: 40 bar
- 300 GWh annually district heating, 70 GWh electricity
- Moving grates
- Wet scrubber to eliminate acidic gases
- Wastewater treatment plant for the liquid waste from wet scrubber
- Powder-activated carbon injection system
- Bag filters, ESP
- $DeNO_x$ SCR to remove nitrogen oxides (with urea)
- The bottom ash (20% in total) is fully recovered and used as aggregate for asphalt
- The fly ash (3% in total) is stabilized with sulfuric acid–producing gypsum at NOAH on the island of Langøya (which receives and treats different kinds of hazardous waste and contaminated soil): All waste material is stabilized before being deposited below sea level in a former limestone quarry and the gate fee for the fly ash stabilization treatment on the island is 88 USD/t of fly ash
- The gate fee is 55 USD/t; the electricity sale price is 77–99 USD/MWh, and the district heating sale price is 22 USD/MWh
- The investment cost is approximately USD105 million

Figure 4.21 shows the frozen sea in the port of Klemetsrud before the visit to the Langøya. In Figure 4.22, the reader can see the stabilization pond of Langøya island.

FIGURE 4.21 The frozen sea in the port of Klemetsrud before the visit to Langøya Island.

FIGURE 4.22 Stabilization pond in Langøya.

4.5 DENMARK

Denmark has about 29 WTE plants, with the majority coproducing electricity and district heating. In April 2017, a new state-of-the-art WTE plant in Copenhagen will be operational and ready to host ski fans on a man-made slope from the roof to the bottom floor of the plant in the most impressive WTE design worldwide.

4.5.1 KARA/NOVEREN WTE Plant

KARA/NOVEREN is a waste management company founded on January 1, 2007, in a merger between the two waste management companies KARA and NOVEREN.

The company is owned by nine municipalities situated west and south of Copenhagen. The main purpose of the company is to solve the common task of general waste management for the nine municipalities. KARA/NOVEREN covers an area with approximately 400,000 citizens and 20,500 companies.

The major part of the residual waste is treated at the company's WTE facility in Roskilde. The annual capacity of the facility before 2013 was 270,000 tpa. When the new line was inaugurated in 2013, the capacity grew to 385,000 tpa.

With the new WTE plant completed in 2014, the city of Roskilde in Denmark now has a second towering landmark, besides the UNESCO World Heritage–listed cathedral. The plant handles the combustion of waste from nine surrounding municipalities and from many places abroad and produces electricity and heat power for the whole region of Roskilde.

Figure 4.23 shows the installation of the flue gas equipment during construction.

The design presents an iconic expression for the otherwise functional architecture of the local waste management company KARA/NOVEREN's next generation WTE plant. The facade consists of two layers: The inner layer provides the actual climatic barrier, allowing the second, outer one to be treated more freely. The outer layer consists of raw umber-colored aluminum plates with an irregular pattern of laser-cut circular holes.

The design is based on simple construction details combined with cutting-edge manufacturing technology, clever processing, and repetition for the production of the aluminum facade panels. Due to its large scale, the WTE plant is destined to become an outstanding structure in the wide and open landscape of the Roskilde area and represents a hypermodern and sustainable energy plant, where waste will be turned into power.

The new WTE plant in Roskilde is created specifically to add value to an otherwise purely industrial complex. Enriching the skyline of this small Danish city, once the Danish capital, the silhouette of the plant also provides a comment on its historic surroundings. The lower part of the building resembles the angular roofs of surrounding factories, but the impressive 97-meter spire and its materialization is the modern counterpart of the city's prime historical monument, the Roskilde Cathedral (van Egeraat, 2013).

KARA/NOVEREN in Roskilde is the first WTE plant to receive the authorities' approval since 2002 and has now established a new USD190 million WTE unit

FIGURE 4.23 Installation of the flue gas equipment during construction of the KARA/NOVEREN WTE plant.

capable of meeting the capacity demands for thermal treatment of waste generated in its municipalities.

4.5.1.1 The Energy Tower

The plant, dubbed the Energy Tower, is built, financed, owned, and operated by KARA/NOVEREN. KARA/NOVEREN is a nonprofit intermunicipal company based on a cost coverage principle. The gate fee at the WTE facility is one of the lowest in Europe and amounts to only DKK200 (30 USD) per ton of waste (excluding taxes and VAT). The low gate fee is attributable to the efficiently operated facility on the one hand and to the extensive energy recovery on the other.

The electricity produced at the WTE facility is sold to the national grid, and the heat is sold to the district heating network owned by the Copenhagen district heating transmission company, VEKS, which supplies heat and hot water to the equivalent of 150,000 families. In the summer, the entire consumption of heat and hot water in VEKS's transmission area is covered by KARA/NOVEREN and one other WTE facility in Copenhagen.

The suppliers of the Energy Tower are MARTIN GmbH (grate and boiler), LAB SA (flue gas treatment system) and MAN Diesel & Turbo (turbine). The large, outspoken, amber-colored facade is designed by Dutch architect Erick van Egeraat, and at night the backlighting of the perforated facade transforms the spire into an illusion of a glowing beacon, symbolizing the energy production inside the facility. Rambøll has been the main consultant to KARA/NOVEREN for many years.

4.5.1.2 Focus on Energy Optimization

The energy content of waste at the Energy Tower is transformed into steam, which is subsequently converted to electricity as well as district heating. Earlier generations of WTE facilities stopped the energy recovery process at this point. However, the installation of flue gas condensation raises the temperature of the district heating water returning from the city, and heat production is increased by approximately 10%. The plant goes even further by incorporating a component cooling system that is driven by district heating, thereby reducing the amount of electricity required to operate the plant.

With a total energy efficiency rate of almost 100% and an increase in energy recovery of 35% compared to the facility's old units, the Energy Tower is one of the most modern and efficient WTE facilities in Europe. The Energy Tower produces electricity corresponding to the consumption of some 44,000 households, while the production of district heating corresponds to the consumption of about 26,000 households.

Main technical details (Ramboll, 2013)

- Capacity: 385,000 tpa
- Waste: MSW and commercial waste
- Energy performance: 20 MWe and 60 MWth
- Steam parameters: 50 bar, 425°C
- Energy recovery: Turbine with district heating condensers, flue gas condensation
- Flue gas treatment: Primary dust removal in bag filter followed by four-stage wet scrubbing system (SNCR)
- Commissioned: 2013

A photo of the WTE plant's construction is shown in Figure 4.24.

4.6 PORTUGAL

4.6.1 Lipor Integrated Waste Management System

Lipor (Intermunicipal Waste Management of Greater Porto) is the entity responsible for the management, valorization, and treatment of MSW produced by eight associated municipalities. These are Espinho, Gondomar, Maia, Matosinhos, Porto, Póvoa de Varzim, Valongo, and Vila do Conde. Lipor was originally created as an association of municipalities in 1982, and it has since come to implement an integrated management of waste.

Lipor treats around 550,000 tpa of MSW, produced by 972,000 inhabitants, per year. Sustaining modern MSW management concepts such as the adoption of integrated systems and minimizing disposal in landfills, Lipor has developed an integrated treatment, valorization, and confinement strategy for MSW based on three main components: multimaterial valorization, organic valorization, and energy recovery. These components are complemented by a sanitary landfill for the final disposal of residuals.

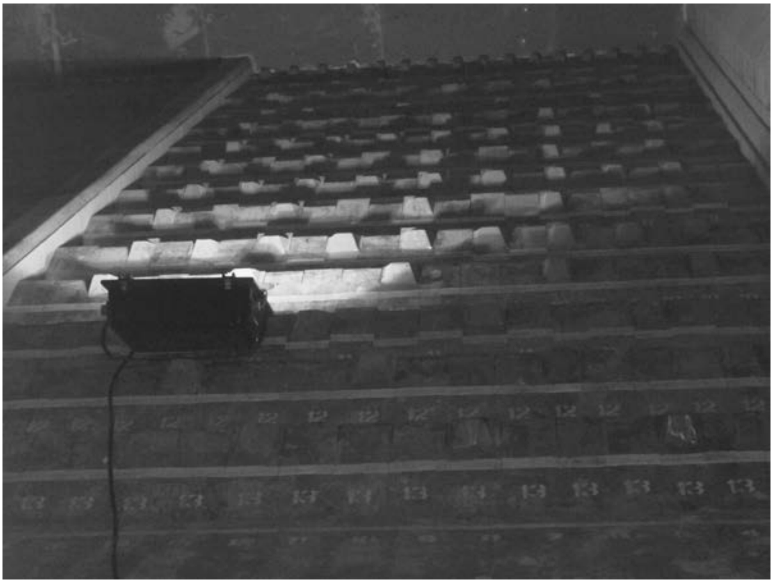

FIGURE 4.24 Moving grates in the KARA/NOVEREN WTE plant in Denmark.

4.6.1.1 Visit to Lipor's Recycling Circuit

In a tour of the Lipor Multimaterial Recycling Circuit, the whole process was observed, from deposition in the eco-containers and drop-off sites to passage by the Sorting Plant, where materials are sorted and baled for recycling. Lipor's Sorting Plant is prepared to treat 38,500 tpa of waste coming from selective collection sites.

4.6.1.2 Visit to Lipor's Organic Recovery Circuit

The Organic Recovery Circuit included a visit to the Home Composting Center—Horta da Formiga—and a visit to the Composting Plant, where the organic waste is processed to be transformed into compost for agricultural use. The Composting Plant has the capacity to treat about 66,000 tpa of organic waste and produces about 22,000 tpa of high-quality compost. Any residuals produced from nonorganic material found in the waste, such as paper, plastics, and so on, is sent to the Energy Recovery Circuit.

The Lipor recycling facility is shown in Figure 4.25.

4.6.1.3 Visit to Lipor's Energy Recovery Circuit–Maia

The tour of the Energy Recovery Circuit and Sanitary Landfill included a visit to the Energy Recovery Plant, located 8 kilometers from the center of Porto, and to Lipor's sanitary landfill. The plant, with two lines of treatment capable of continuous and almost automatic production, combusts nearly 1000 tons of waste a day, producing 25 MWe of electrical power, enough to supply a population of around 150,000.

FIGURE 4.25 Lipor recycling facility.

The Lipor Landfill of Maia, located next to the Energy Recovery Plant, was designed under strict environmental control and protection standards. The amount of residue and ash deposited on this landfill is estimated at about 83,000 tpa.

Main technical details

- Capacity: 1100 tons per day MSW × 330 days
- 10 years of operation
- 26 MWe, 66 tph steam × 2 lines
- Combustion temperature on the grate at the time of the visit was 1050°C, and flue gas temperature was 950°C–970°C. Normal operating temperatures on the grate are 1000°C–1200°C
- Gate fee: 44 USD/t
- Electricity selling price: 88 USD/MWh
- Semi-wet scrubbers, SNCR (levels of NO_x emissions: 150–190 mg/Nm^3)
- Fly ash is solidified with cement on-site (0.2 ha) and then driven to the landfill
- Bottom ash is inert and is driven either to the landfill or utilized in road construction
- The plant was constructed by CNIM (grate type: MARTIN GmbH) and is operated by a subsidiary company of Veolia
- The total leachates from all ashes are biologically cleaned through ultrafiltration and reverse osmosis

Figure 4.26 shows the electrical substation of the Lipor WTE plant. Figure 4.27 presents the cement production unit for the on-site solidification of fly ash. Figures 4.28 and 4.29 show the fly ash before and after solidification.

FIGURE 4.26 The Lipor WTE plant electrical substation.

FIGURE 4.27 Cement production for the solidification of fly ash on-site at the Lipor WTE plant.

FIGURE 4.28 Fly ash before treatment at the Lipor WTE plant.

FIGURE 4.29 Solidified fly ash at the Liport WTE plant.

4.6.2 Valorsul WTE Plant

The Valorsul WTE plant is located at about 6 kilometers from the center of Lisbon. The plant receives approximately 2200 tons of waste daily and produces enough energy to supply a city of 150,000 inhabitants. It occupies an area of 4 ha and has a nominal processing capacity of 728,000 tpa (90% availability). A complete environmental-monitoring program is in place in order to evaluate the impact of the plant on the surrounding area.

Main technical details

- Technological process: Mass burning with energy recovery
- Location: São João da Talha, municipality of Loures
- Area occupied: 4 ha
- Origin of MSW: Mixed collection by municipalities or private entities
- Nominal processing capacity: 728,000 tpa (90% availability)
- Calorific value of the MSW: Nominal 7820 kJ/kg
- Firebox grid: Detroit Stoker's reverse-acting stoker
- Steam production boilers: Two units with natural circulation of a water panel with superheating
- Steam discharge in the turbine: 244 tph
- Superheated steam: 52.8 bar
- Gross electrical production: 525.71 kWh/t of MSW
- Electrical self-consumption: 71.13 kWh/t of MSW
- Nitrogen oxides removal system: SNCR
- Acid gases removal system: Semi-dry process through injection of lime wash
- Dioxins and furans removal system and heavy metals removal system: Injection of activated carbon
- Particle removal system: High-performance baghouse filters

The Valorsul sanitary landfill is used to deposit waste that cannot be combusted, as well as the mixed waste collection at times when the WTE processing plant is not operating. It is made up of cells with impervious linings to retain the leached materials. There are also specific cells in which stabilized fly ash is deposited. In the landfill, there is a biogas extraction and burning network and a bottom ash recovery plant that receives the ash of the WTE plant and separates ferrous and nonferrous metals from the ash. The metal is led to recycling, and the inert material may be used in civil construction. The ferrous metal recovered is stated to be enough to manufacture 16,500 vehicles a year. The total amount of materials deposited in the Valorsul landfill is estimated to be 143,000 tpa for bottom ash occupying an area of 2.8 ha.

4.7 FRANCE

France is the country with most WTE plants worldwide (129 facilities in the country). However, most of them have lower capacities than those in other European countries like Germany, Italy, and so forth.

4.7.1 Oréade–Le Havre WTE Plant

Plant identity

- Area: 10 ha
- Commissioned: May 13, 2004
- Client: SEVEDE
- Nominal capacity: 210,000 tpa
- Waste treated: MSW, industrial solid waste

Main technical details

- Two lines with a capacity of 13.2 tph
- Line constructor: CNIM
- Boilers: 2 × 42.7 tph
- Steam parameters: 45 bar, 400°C, constructed by CNIM
- Turbine/generator: 17 MW, constructed by Alstom
- Flue gas treatment: Dry scrubber, constructed by CNIM
- Gross electricity production: 126,000 MWh/year
- Net electricity production: 110,000 MWh/year
- Bottom ash production: 46,000 tpa
- Fly ash production: 2,600 tpa
- Personnel: 27
- Operation: 362 days/year

Figure 4.30 shows a wide view of the plant facilities.

4.7.2 Créteil WTE Plant

The Créteil WTE plant treats the waste generated by 615,000 residents of the 19 member municipalities of the Intercommunal Syndicate for Urban Mixed Waste Treatment in Val-de-Marne (ISMWTUVM).

FIGURE 4.30 Wide-angle view of the Le Havre WTE plant.

The total capacity of the plant is 267,000 tons for both household waste and waste from healthcare activities with infectious risks.

4.7.2.1 Characteristics of the Plant

This unit is equipped with two lines with a capacity of 16.5 tph, for an average calorific value of 9210 kJ/kg of waste processed. The primary air drawn into the pit is injected under the gates and allows the burning of waste. The secondary air is introduced above the grate at the entrance of the first term (or part) of the boiler.

Two boilers recover the energy released by combustion of waste previously transformed into steam, which is superheated to 360°C and 45 bar. This steam is oriented toward a generator, which can produce in operation 115,000 MWh of electricity per year, corresponding to the power consumption of 150,000 inhabitants.

To supply heat to the heating system, the Créteil plant has established an exchange substation with a capacity of 18 MW. These exchangers recover one-third of sub-drawn steam issued from the turbine and produce 93,000 MWh/year, delivered to the palace boiler room via a network connection based on two pipes. This new heat source supplies the urban heating system and satisfies one-third of the city's heating needs in the winter and 100% of domestic hot water needs in the summer.

The service is provided continuously throughout the year, including during maintenance phases. Regarding waste from healthcare activities with infectious risks, the treatment capacity is 42,000 tpa. These wastes are inserted into a dedicated line and are also coincinerated in furnaces intended for treating household waste (SUEZ, 2008).

Figure 4.31 shows the weighbridge at the entrance of the plant. In Figure 4.32, the flame from the combustion chamber is presented. Figures 4.33 and 4.34 show two

FIGURE 4.31 View of the weighbridge at the entrance of the Créteil WTE plant.

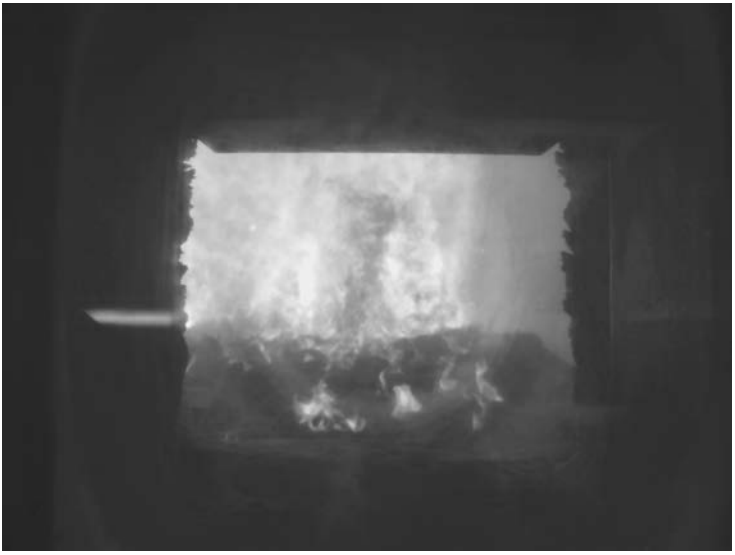

FIGURE 4.32 Combustion chamber of the Créteil WTE plant.

FIGURE 4.33 Air condensing unit of the Créteil WTE plant.

main departments of the facility, the air condensing unit and the flue gas treatment equipment, respectively.

4.8 GERMANY

There are approximately 90 WTE plants in Germany.

FIGURE 4.34 Flue gas treatment equipment in the Créteil facility.

4.8.1 MVB WTE Plants and AVG Hazardous WTE Plant, Hamburg

Figure 4.35 shows the MVB WTE plants and the AVG hazardous waste-to-energy plant.

4.8.1.1 MVB WTE (Units 1 and 2)

Main technical details

- The WTE plant was commissioned in 1994 and acquired at an investment cost of USD200 million
- There are two combustion lines, treating an overall waste capacity of 358,000 tpa (LHV 9 MJ/kg), of which 92% is MSW, 4% is commercial waste, and 4% is bulky refuse
- The shareholders are 85.5% the Vattenfall Europe New Energy GmbH and 14.5% the EEW Energy from Waste GmbH
- The flow rate of the produced steam is 77 tph per line, at 19 bar and 380°C
- The main energy product is heat which is supplied to the municipal district system of Hamburg
- In 2009, the plant functioned for 315 days and delivered 736,340 MWh of steam energy
- The plant is also equipped with a small steam turbine producing 3 MW for the plant's internal needs
- The filtration part of the plant is equipped with SNCR technology, baghouse filters, and HCl and SO_2 scrubbers

FIGURE 4.35 MVB WTE plant (units 1, 2, and 3) and the AVG hazardous waste plant.

- The plant's residuals are 67,900 tpa bottom ash (19% of the initial feed), 9000 tpa fly ash (2.5% of the initial feed), and 10,000 tpa scrap metals (2.8% of the initial feed)

The plant's emissions are shown in Tables 4.3 and 4.4.

4.8.1.2 MVB Wood Residuals and Waste Wood (Biomass) Energy Recovery Plant (Unit 3)

Main technical details

- The biomass energy recovery plant was commissioned in 2005 and acquired at an investment cost of USD46 million

TABLE 4.3
Continuously Measured Emissions of MVB Units 1 and 2

Continuously Measured Emissions	NO_x	CO	Dust	HCl	SO_2	Hg
Average 2009 (mg/m^3)	98.3	7.4	0.3	0.2	5.5	0.0038
Legal limits (mg/m^3)	200	50	10	10	50	0.03

TABLE 4.4
Discontinuously Measured Emissions of MVB Units 1 and 2

Discontinuously Measured Emissions	HF	Cd + Tl	Sb-Sn	As-BaP	PCDD/F
Average 2009 (mg/m^3)	0.045	0.0006	0.0066	0.0017	0.0085
Legal limits (mg/m^3)	4	0.05	0.5	0.05	0.1

- The overall biomass capacity is 174,000 tpa (LHV 13 MJ/kg) and is treated in one combustion line. Of the total annual capacity, 65% is category A1–A3 waste wood and the remaining 35% is category A4 (defined as follows):
  - *Category A1*: Natural or only mechanically treated waste wood (not more than insignificantly contaminated with foreign substances).
  - *Category A2*: Glued, varnished, coated, painted, or otherwise treated waste wood without organic halogen compounds and without wood protection agents.
  - *Category A3*: Waste wood coated with organic halogen compounds, without wood protection agents.
  - *Category A4*: Waste wood treated with wood protection agents such as railway sleepers, line poles, hop poles, vine stakes, and other types of waste wood.
- The distribution of shareholders is similar to that of Units 1 and 2. The applied boiler technology is a circulating fluidized bed with an efficiency rate of 92.24%
- The flow rate of the produced steam is 99 tph per line, at 90 bar and 500°C
- The plant is equipped with a steam turbine of 20 MWe
- In 2009, the plant functioned for 330 days and delivered 159,420 MWh of electrical energy
- The filtration part of the plant is equipped with cyclones, calcium hydroxide activated carbon, and baghouse filters
- The plant's residuals are 7060 tpa fine combusted bed ash (4% of the initial feed), 5500 tpa rough combusted bed ash (3.15% of the initial feed), and 7700 tpa flue dust (4.4% of the initial feed)

The plant's emissions are shown in Tables 4.5 and 4.6.

TABLE 4.5
Continuously Measured Emissions of MVB Unit 3

Continuously Measured Emissions	NO_x	CO	Dust	HCl	SO_2	Hg	HF
Average 2009 (mg/m^3)	86	13	0.6	2.0	2.7	0.1	0.1
Legal limits (mg/m^3)	200	50	10	10	50	0.03	4

TABLE 4.6
Discontinuously Measured Emissions of MVB Unit 3

Discontinuously Measured Emissions	Cd + Tl	Sb-Sn	As-BaP	PCDD/F
Average 2009 (mg/m^3)	0.0008	0.011	0.0023	0.0012
Legal limits (mg/m^3)	0.05	0.5	0.05	0.1

Source: Boness, M., 2016, *SICK, CEMS for AVG Hamburg WTE Plant*, Hamburg, Germany.

4.8.1.3 AVG WTE Recovery Plant for Hazardous Materials

Main technical details

- The AVG plant was established in 1971. Between 1994 and 1997, USD220 million was spent on its reconstruction
- There are two combustion lines (hazardous waste incinerators) with an overall capacity of 176,000 tpa, from which 40% is international waste (originating outside of Germany's borders)
- The two combustion lines are equipped with rotary kilns, in which hazardous wastes remain for 2 s at a temperature greater than 1100°C (up to 1250°C)
- The high-temperature combustion plant is equipped with storage units that allow for separation according to the kind of waste, chemical-physical treatment units, separation units, and temporary storage needs
- Between 750 and 840 different kinds of hazardous waste (according to European waste catalog [EWC]) are accepted for treatment in the AVG plant. These hazardous wastes mainly fall into the following categories:
  - Residues from the production and off-spec products from pharmaceutical, chemical, and other industries
  - Organic and inorganic laboratory wastes
  - Hospital wastes
  - Pesticides
  - Paints, varnishes, and resins
  - PCB oils
  - Wastes containing dioxin
  - Wastes containing halogen
  - Contaminated filter materials and absorbent materials
  - Soil from contaminated sites
- The flow rate of the produced steam is 37 tph per line at 20 bar and 380°C
- The main energy product is heat, of which 70% is supplied to the municipal district system of Hamburg and the remaining 30% covers internal needs
- The filtration part of the plant is equipped with an electrostatic precipitator, HCl and SO_2 scrubbers, and activated carbon filters

The plant's emissions are shown in Tables 4.7 and 4.8.

TABLE 4.7
Continuously Measured Emissions of AVG Hazardous WTE Recovery Plant

Continuously Measured Emissions	NO_x	CO	Dust	HCl	SO_2
Average 2009 (mg/m^3)	<95	<45	<8	<5	<30
Legal limits (mg/m^3)	200	50	10	10	50

Source: Boness, M., 2016, *SICK, CEMS for AVG Hamburg WTE Plant*, Hamburg, Germany.

TABLE 4.8
Discontinuously Measured Emissions of AVG Hazardous WTE Recovery Plant

Discontinuously Measured Emissions	Cd + Tl	Sb-Sn	PCDD/F	Hg	HF
Average 2009 (mg/m^3)	<0.01	<0.2	<0.05	<0.02	<0.1
Legal limits (mg/m^3)	0.05	0.5	0.1	0.03	4

Source: Boness, M., 2016, *SICK, CEMS for AVG Hamburg WTE Plant*, Hamburg, Germany.

4.9 AUSTRIA

4.9.1 Arnoldstein WTE Plant

The Arnoldstein plant is located in the town of Arnoldstein in the district of Villach-Land in the Austrian state of Carinthia (within the borders of Austria, Slovenia, and Italy). It is the southernmost state of Austria, with a population of 560,000 inhabitants. The plant serves the whole state, processing almost 27% of the state's waste.

The plant commenced operations during the spring of 2004. It was constructed by MARTIN GmbH, Siemens, Austrian Energy and Environment, and Porr Technobau und Umwelttechnik. The operator is KRV, which consists of Verbund-Beteiligungs GmbH (40.85%), KELAG (42.85%), and Porr Infrastruktur (14.3%). The original investment cost was USD73 million, and the final budget reached approximately USD82 million. The plant has 29 people on its technical and managerial staff, divided into three shifts, with 8000 operational hours per year. The technical characteristics of the plant are listed below.

Waste reception

- The waste is delivered by trucks coming from all over Carinthia; each truck has a mean capacity of 4.5 tons; the trucks unload the waste into one of the four tipping halls available
- The waste is moved from the waste bunker to the combustion chamber using cranes

Figure 4.36 shows the waste reception from the waste trucks to the waste bunker of the plant.

Combustion process

- The combustion chamber consists of a single line with two moving grates, with a total capacity of 100,000 tpa MSW and an LHV of 10 MJ/kg
- The combustion process takes place with air enriched in oxygen at percentages of 24%–35% (SYNCOM process, MARTIN GmbH)
- Flue gas temperature is 1100°C–1200°C. Flue gases are recirculated for better combustion

FIGURE 4.36 Waste reception in the Arnoldstein WTE plant.

- Due to the fact that the air is enriched by oxygen, the combustion is more efficient and there is almost a complete destruction of dioxins; dioxin monitoring is done online

Air pollution control
The plant's APC system consists of the following:

- Semi-dry scrubbers with hydrated lime to reduce SO_2, HCl, and hydrogen fluorides
- Filters to reduce dust particles, heavy metals, and organic pollutants
- Activated carbon filters
- SCR to reduce NO_x in the flue gases

Electricity and steam production
- The flow rate of the produced steam is 11–14 tph at 40 bar and 400°C
- There is a market for teleheating and for hot water usage
- The gross power is rated at 7 MWe, the net power is rated at 5.2 MWe, and the R1 formula is above 0.65
- Self-consumption is higher than normal because of the oxygen production (∼95%) to enrich the combustion air
- Energy production is 500 KWh/t. Electricity is sold at a price of approximately 40–65 USD/MWh with 50% biomass and 30% bioenergy

Residuals treatment
- The produced bottom ash is 25% and is of good quality due to the increased combustion efficiency. In order to avoid leaching, the bottom ash is sintered

- Boiler ash is recirculated for a more uniform product
- Bottom ash is landfilled in an ash monofill at a price of 55 USD/t
- Fly ash is stabilized with lime and cement within the landfill area, and then it is landfilled; the transfer takes place via railway

4.9.2 Spittelau WTE Plant

The Spittelau WTE plant is probably the most popular worldwide WTE plant, located almost in the city center of Vienna. The plant received its name from the district Spittelau in the city of Vienna. The plant is adjacent to the homonymous underground station.

History

- 1969–1971: Construction of Spittelau district heating plant with integrated waste combustor to ensure heat supply of Vienna General Hospital
- 1987: Major fire that almost completely destroyed the plant
- 1989–1992: Recommission and facade redesign by the famous artist Friedensreich Hundertwasser

Figure 4.37 shows the incredible blending of the Spittelau WTE plant with the urban environment of Vienna.

FIGURE 4.37 Spittelau WTE plant view from the Danube Bridge in the center of Vienna.

Technical Data—Status

Capacity

- Two combustion lines: 2 × 31.25 MWth
- Waste throughput: 2 × 16.5 tph, heating value: 7.5 MJ/kg
- Actual capacity: 275,000 tpa
- Heating network: 1212.5 km
- Customers: 353,860

Equipment

- MARTIN GmbH two-track reverse-acting stoker grate
- Boiler: 33 bar, 240°C (saturated steam)
- Flue gas cleaning:
  - Two electrostatic precipitators
  - Two-stage flue gas scrubbing
  - Electrodynamic venturi system
  - Catalytic $DeNO_x$ system (SCR)

Energy generation

- Saturated steam backpressure turbine: Power output 13.2 MW (3.7 MW for self-consumption and grid feed-in)
- Annual feed-in of district heating to the network of Wien Energie: 58 MW
- Grate/boiler steam parameters: 400°C, –40 bar

Figure 4.38 shows the entrance and waste reception area of the Spittelau WTE plant. Figure 4.39 shows the district heating equipment of the facility.

FIGURE 4.38 Entrance to the Spittelau WTE plant and a view of the artistic stack.

FIGURE 4.39 District heating equipment at the Spittelau WTE plant.

4.10 FINLAND

4.10.1 Vaasa Westenergy WTE Plant

Westenergy Oy Ab owns and operates a modern WTE plant that utilizes source-separated combustible waste as fuel. The WTE plant is located in Mustasaari, near the city of Vaasa in Finland, and has been in operation since 2012.

The Westenergy WTE plant is an important part of a well-functioning waste management system, as the plant allows energy to be extracted from nonrecyclable waste in an efficient, safe, and clean way.

Westenergy's cooperation partner Vaasan Sähkö Oy uses the steam produced in the plant to produce electricity and district heating. More than one-third of the district heating needed in the Vaasa region is produced in the plant.

Westenergy Oy Ab is owned by five municipal waste management companies (Lakeuden Etappi Oy, Ab Stormossen Oy, Vestia Oy, Botniarosk Oy, and Ab ja Millespakka Oy, north west Finland around city of Vaasa). The shareholders operate in an area covering approximately 50 municipalities and more than 400,000 inhabitants.

The Westenergy WTE plant was completed in December 2012 and began processing 165,000 tpa of household waste from 400,000 inhabitants, coproducing 15 MW electricity and 45 MW heat.

It took six months longer than usual to build the facility, as it was built on solid rock.

The energy produced at the facility is equivalent to the electricity demand of 7000 households and covers 25% of the district heating demand in the city of Vaasa (Westenergy, 2013).

4.10.1.1 Main Suppliers and Cooperation Partners

- *Grate and boiler:* The plant's boiler, including auxiliary equipment, is supplied by a Swiss-Japanese company, Hitachi Zosen Inova AG, which has experience with similar plants. The grate is a water-cooled furnace grate with a fuel input of 61 MW. The steam pressure is 40 bar, and the temperature of the steam is 400°C (typical of a WTE plant). The plant capacity is 22 tph.
- *Flue gas treatment:* The flue gas treatment system is supplied by a French company, LAB S.A. The flue gas treatment system uses a semi-dry process, in which the flue gases are cleaned by adding lime and activated carbon. The remaining particles are absorbed by a fabric filter.
- *Turbine and generator:* The turbine and generator are supplied by a German company, MAN Diesel & Turbo SE. The turbine was manufactured at the company's plant in Hamburg.
- *Consultant:* The project's main consultant was a Danish company, Rambøll Denmark A/S. The architectural and structural design was made by Rambøll's subcontractor Citec Engineering Ltd. from Vaasa, Finland.

Flue gases are cleaned in several stages in the plant, and the emissions are continuously analyzed and measured, as is required by the environmental permit. The residues formed in the plant are also further treated accordingly (Westenergy, 2013).

4.10.1.2 Combustion Process

The temperature on the grate is over 1000°C, a temperature at which lower-quality fuel is also combusted efficiently. The plant is supervised 24 hours a day, and the process is adjusted in order to keep it clean and safe. The technology used in the plant represents BAT. Modern WTE plants all over Europe use similar equipment, which means that the technology used in the plant has already been thoroughly tested in practice.

The flue gases are carefully cleaned in a multiphase process. After the combustion, the temperature of the flue gases is held at a minimum of 850°C to prevent the formation of toxic gases. Nitrogen oxides are neutralized by adding ammonia. Ammonia infusion is controlled by a sophisticated computer-operated system. Based on temperature and computer models, the chemical is added only when and where necessary, minimizing the amount of ammonia used as well as the ammonia residue in the flue gases. The remaining hazardous compounds are absorbed into fabric filters using lime and activated carbon. The advantage of this system is that no effluents requiring further treatment are formed in the plant. The composition of the flue gases is constantly monitored and controlled in order to ensure that no hazardous substances will get into the air. Information obtained from continuous monitoring of the flue gases is used to adjust the operations of the boiler.

4.10.1.3 Residues Treatment

There are different kinds of ashes formed in the plant.

FIGURE 4.40 Entrance to the Westenergy WTE plant.

Bottom ash is discharged from the grate, just like ash from a fireplace at home. The composition of the bottom ash is thoroughly analyzed, and potential alternatives for utilization are evaluated. Until the means of utilization has been confirmed, the bottom ash will be placed at a landfill.

Boiler ash is formed as the hot flue gases are led up through the boiler. There are ash flakes in the hot flue gases, and as the flue gases cool down, the ash gets stuck to the heat-exchange surfaces of the boiler. The surfaces are cleaned regularly, and, just as with the bottom ash, the contents of the ash will be analyzed for utilization purposes. Before utilization, the ash will be stabilized and placed at a landfill suitable for hazardous waste.

Flue gas treatment residue is the residue of the flue gas treatment process. Lime and activated carbon are added into the flue gases. The hazardous compounds of the flue gases, such as heavy metals, adhere to the lime and activated carbon particles. These particles in turn are absorbed by fabric filters, somewhat similar to a vacuum cleaner bag. The flue gas treatment residue is temporarily stored in its own silo. It is stabilized using cement and safely disposed at a landfill especially built for this purpose (the typical solidification process for fly ash in Europe) (Westenergy, 2013).

Figure 4.40 shows the entrance of the Westenergy WTE plant. Figure 4.41 illustrates an artistic view of the stack from the base of the plant.

4.11 UNITED KINGDOM

Many county WTE plants are under construction in the United Kingdom (mainly combustion based process). Over the years, the country has developed what may be the largest number of gasification plants in Europe.

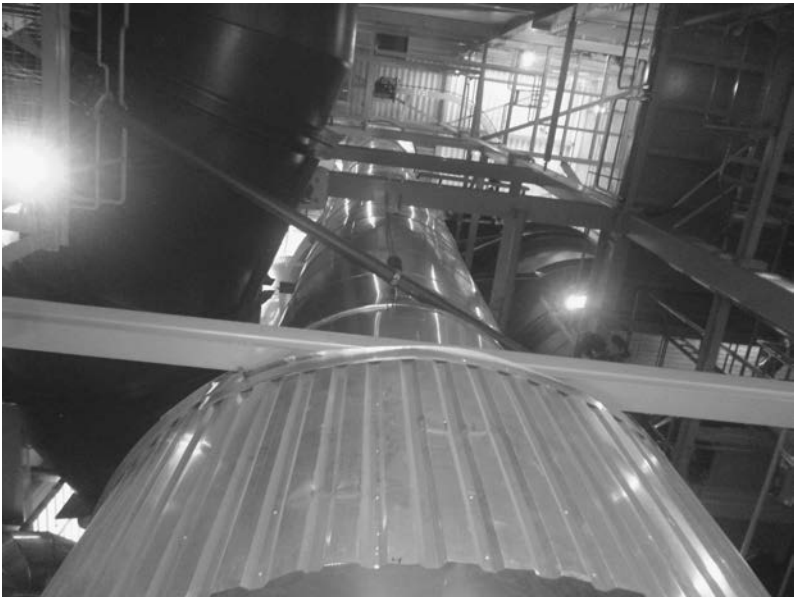

FIGURE 4.41 View from the base of the stack at the Westenergy WTE plant.

4.11.1 Isle of Man WTE Plant

The Isle of Man is an island belonging to Great Britain. In 2007, the production of municipal and commercial waste reached 72,000 tons, and the WTE plant fulfilled 5.2% of the electricity needs of the island. It is one of the smallest WTE plants in the world.

Figure 4.42 shows a view from outside the plant on the Isle of Man.

Main technical details

- First line: 66,000 tpa for municipal and commercial waste
- Second line: 6000 tpa for animal, medical, and oil wastes
- The feeding area (bunker) is designed to meet the storage needs of the plant for 16 days
- Production of electricity: 5.5 MW gross (1.5 MW for self-consumption), 4 MW net
- In 2006, approximately 30,642 MWh were exported to the grid; 22,314 MWh were exported in 2007, as there was a damage to the turbine

Data from 2007

- Total of 62,914 tons combusted, with the following breakdown:
  - Urban: 58,300 tons
  - Wood: 2,870 tons
  - Tires: 160 tons
  - Packaging: 370 tons

FIGURE 4.42 The Isle of Man WTE plant.

- Construction materials: 1,060 tons
- Miscellaneous: 154 tons

Residues production
- Bottom ash: 16,500 tons (25%). In the United Kingdom, it is used to build roads; however, it is not economically advantageous to transport ash into the United Kingdom, so the operator plans to use the bottom ash for construction purposes on the island.
- Fly ash: 2750 tons (4%). Fly ash is moved to the United Kingdom for special treatment as hazardous waste. Metals: 1000 tons (1.4%), are recycled.
- The WTE plant has a state of the art flue gas cleaning system

In 2007, the plant had 30 employees.

4.12 IRELAND

4.12.1 Meath WTE Plant

For the first time in Ireland's history, 20,000 households in Meath County are provided with waste-powered electricity. Located some 40 kilometers north of Dublin, Ireland's first WTE plant began delivering electricity to the city's grid in November 2011. Indaver Ireland selected Babcock & Wilcox Vølund as a sub-contractor to develop and supply its most advanced, state-of-the art, waste-fired power plant technology. The total investment was USD143 million.

Figure 4.43 shows the facilities of the Meath WTE plant

Plant design data (per line)
- Waste capacity: 29.4 tph
- Heat value (lower): 8.0 MJ/kg

FIGURE 4.43 The entrance to the Meath WTE plant.

- Steam output: 91 tph
- Steam temperature: 400°C
- Steam pressure: 43 bar
- Thermal input: 69.3 MW
- Thermal efficiency: 86.9%
- Total organic carbon, bottom ash: 3%
- Feed water temperature: 130°C
- Boiler outlet flue gas temperature: 190°C

Emissions before flue gas treatment (out of the boiler) (B&W Volund, 2012)

NO_x[a]:	160 mg/Nm^3
CO[b]:	150 mg/Nm^3
NH_3[a]:	10 mg/Nm^3

All values refer to 11% O_2 dry gas.
[a] Daily.
[b] Per 30 min.

The presented values are before flue gas cleaning.

The plant's limit values comply with the EU Directive on waste incineration. Naturally, the plant is equipped with a modern flue gas cleaning system.

Figures 4.44 and 4.45 present the air-cooled moving grates and the combustion chamber. Finally, Figure 4.46 shows the stack of the plant.

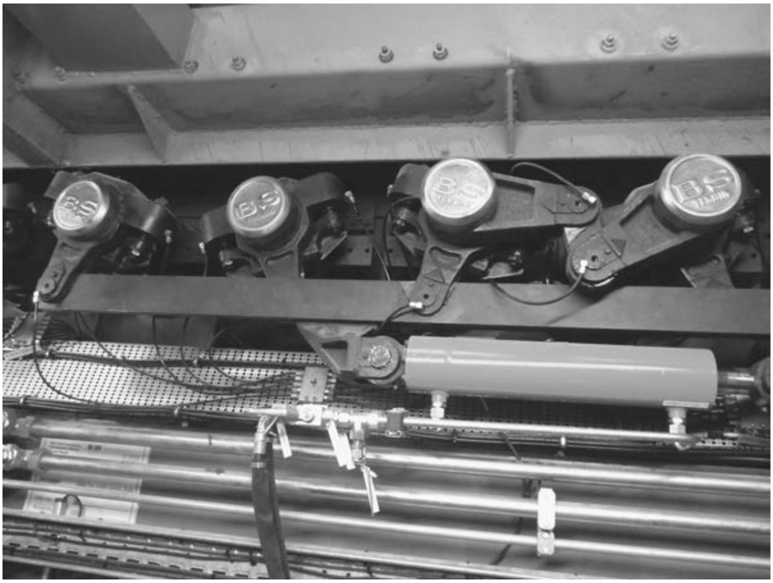

FIGURE 4.44 The air-cooled moving grates at the Meath WTE plant.

FIGURE 4.45 The combustion chamber of the Meath WTE plant.

FIGURE 4.46 The Meath WTE plant's stack.

4.13 BELGIUM

4.13.1 ISVAG WTE Plant

ISVAG is one of the oldest WTE plants in Belgium. Figures 4.47 and 4.48 show the exterior of the ISVAG WTE plant.

Main technical data (ISVAG, 2008)

- Two lines × 9 tph, total 165,000 tpa
- Operated since 1975, upgraded in 2005.
- Production ∼11–12 MWe, providing enough electricity for 20,000 inhabitants.
- The ISVAG furnace consists of two identical furnace lines that can each process around 10 tph of waste, 24 hours per day, all year round. In this way, the employees handle about 140,000–150,000 tpa. The entire treatment process is computerized and automated.

FIGURE 4.47 View of the ISVAG WTE plant's stack.

FIGURE 4.48 View of the ISVAG WTE plant from a distance.

- During the combustion process, the heat is channeled via a separate boiler, in which steam is produced. This steam drives the blades of a turbine, which is connected to an alternator. This alternator produces electric energy. It provides enough electricity for 20,000 households all year round. That alternative energy creates considerable fuel savings (33,000 tons of coal or 20,000 tons of oil) (ISVAG, 2008).
- Gate fee: 100 USD/t
- The percentage of fly ash is 2.5%, and is exported.
- The flue gas cleaning system consists of an electrostatic precipitator, semi-wet scrubbers, baghouse filters, and wet scrubbers. In a large reaction tank, lime milk removes harmful substances. This also cools the flue gases to 170°C.
- The bottom ash first passes through a water bath to cool it and is then passed via a vibrating table to a separate storage bunker. But first a large rotating band magnet takes out the iron which is reused in the steel industry. The remaining ash is fully reused in road construction.
- The plant was operated solely by the intermunicipal company ISVAG from 1975 to 2005. In 2005, the intermunicipal company IGEAN joined the operation as a partner.
- The plant was constructed by Keppel Seghers.
- The NO_x emissions are reduced through SNCR to approximately 130 mg/Nm^3.
- Total area: ~3.5 ha.
- Emissions data are constantly available online at www.isvag.be.

4.14 RUSSIA

4.14.1 EVN WTE Plant

A technical visit to EVN's thermal waste utilization plant in Moscow was scheduled for the author. This plant (MSZ3) incinerates a part of the household waste accumulated by the population of Moscow.

Moscow produces 9 million tons of solid household waste, most of which was previously dumped. At the throughput capacity of 400,000 tpa (the total for three lines), ENV's WTE plant in Moscow makes a considerable contribution to the plans for ecological household waste treatment.

Figure 4.49 shows the stack from the entrance of the EVN WTE plant.

Basic data of the plant

- The project will remain in private interests until 2019 and afterwards will become the property of the city of Moscow.
- The WTE plant project involved an investment of USD210 million (BOOT model).
- The gate fee is 55 USD/t, guaranteed by the government.
- The WTE plant is located in the Biryulyovo industrial zone in the south of Moscow on a site 2.5 ha in length.

FIGURE 4.49 View of the EVN WTE plant's stack.

- The previous facilities were built in 1983 and were reconfigured using state-of-the-art combustion technology with an all-encompassing flue gas cleaning system.
- The waste yields a calorific value of about 7.5 MJ/kg, which produces steam at the rate of 127 tph. This corresponds to the output from 10,000 litres of fuel oil per hour, which can be saved through the combustion of solid waste.
- The energy extracted from the waste supplies 48,000 households in Moscow with clean energy for heating and hot water.

Main technical data

- Location: Podolskikh Kursantov Str., Biryulyovo Industrial Zone, Southern District
- Plot size: 2.5 ha
- Capacity: 400,000 tpa
- Firing: Grate firing at 850°C–1000°C
- Flue gas retention time in the furnace at $T > 850°C$: >2 s

Response to the composition of solid household waste in the city of Moscow: Effective combustion of solid household waste is possible regardless of moisture, composition, and season for the following reasons:

- Combustion air is heated up, bunker waste water is evaporated, afterburner zone is lined with approximately 400 mm bricking, and the furnace is lined with refractory concrete of low heat conductivity
- Flue gas cleaning takes place in three stages as follows: injection of activated carbon in the flue gas flow for absorption, quasi-dry absorber conveys and sprays hydrated lime to absorb acidic gases, fabric filter is utilized to precipitate fly ash and dust and deNO_x the plant
- Emission rates measured: CO, O_2, HCl, HF, NO_x, SO_2, dust, dioxins, furans, CO_2, H_2O, Corg, Hg, and Hg compounds
- Combustion and gas cleaning control: Automated control system that prevents feeding of solid household waste before the furnace temperature reaches 850°C
- Exploitation of the energy potential included in solid household waste: ~370,000 Gcal/year in heat and ~38,000 MWhr/year in electricity (5 MWe)

Figures 4.50 and 4.51 present the maintenance operation in the combustion chamber. In Figure 4.52, the reader has the opportunity to see the southern part of Moscow from the roof of the plant.

FIGURE 4.50 Entrance to the combustion chamber of the EVN WTE plant (during maintenance).

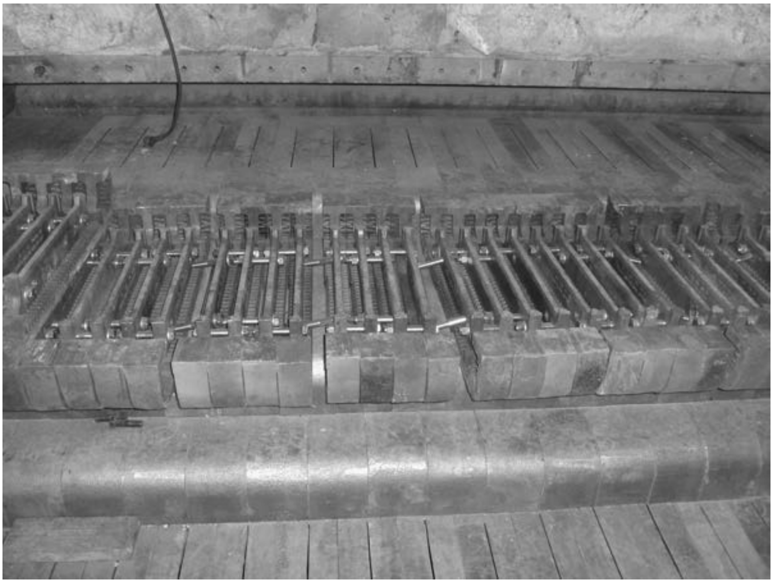

FIGURE 4.51 Maintenance of the moving grate at the EVN WTE plant (inside the combustion chamber).

FIGURE 4.52 View of southern Moscow from the roof of the EVN WTE plant.

4.15 THE NETHERLANDS

Amsterdam has the biggest WTE capacity in the world (1.5 million tpa). A plant with a similar capacity is under construction plant in Shenzhen, China. The details regarding the Alkmaar WTE plant presented here are based on an older site visit by the author.

4.15.1 Alkmaar WTE Plant

Main technical data

- Four combustion lines process approximately 730,000 tpa of residual waste
- Heat generation: 50 MW (enough for heating 16,000 houses)
- Electricity generation: 68 MW (sufficient for a city of 130,000 residents)

4.15.1.1 WTE Plant in Alkmaar Delivers Heat to the AZ Football Club's Stadium

The heat is transported to the stadium via a district heating network and is used to provide hot water for the showers as well as to heat the stadium complex and the pitch. This makes AZ one of the few Dutch football clubs that can continue to train in the winter. Connecting all of the football club's buildings to the heat distribution network produces the same reduction in carbon dioxide emissions that would result if more than 38,000 solar panels were used. That is roughly ten football pitches full of solar panels.

4.15.1.2 Heating and Cooling Distribution Project in Alkmaar, Netherlands (Hvc Groep)

There are a large number of residential developments being built in Alkmaar. If the heat from the WTE plant were used to heat them it would save 660 tonnes of carbon dioxide for every 500 homes. Pipes will be laid from the plant to the center of Alkmaar. With these pipes, approximately 2500 dwellings in Overdie and the same number in Overstad will be connected to the network. Forty solar panels are required to make the equivalent savings in carbon dioxide emissions for one family using heat from the WTE plant during one year. The first phase of the main grid project has been accomplished (3 km pipeline connecting the WTE plant and the city). Since October 2010, a large local school uses the heat from the plant (1.5 MW), and in February 2011, the first dwellings were connected to the grid. At the end of 2011, another 300 dwellings were connected to the heating grid, with the final goal being to connect 10,000 dwellings (CEWEP, 2010).

Figure 4.53 shows the entrance to the Alkmaar WTE plant. In Figure 4.54, one of the plant's steam turbines is presented. Finally, a real-time temperature measurement of the combustion chamber is shown in Figure 4.55.

FIGURE 4.53 Entrance to the Alkmaar WTE plant.

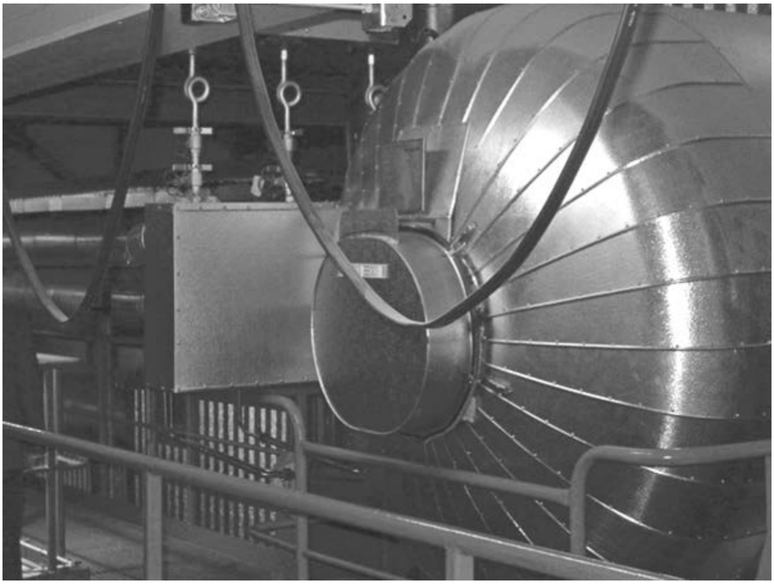

FIGURE 4.54 Steam turbine of the Alkmaar WTE plant.

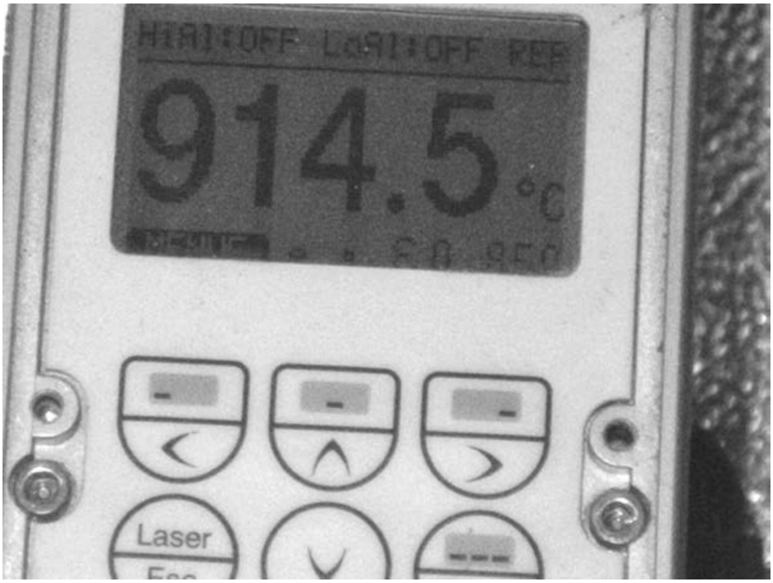

FIGURE 4.55 Real-time temperature indication in the combustion chamber of the Alkmaar WTE plant.

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5 Waste-to-Energy in the Americas

In the current chapter, technico-economic data for three waste-to-energy (WTE) plants are presented. The data are based in the reports made by the author after his relevant site visits.

5.1 UNITED STATES OF AMERICA

5.1.1 Union County, New Jersey

The Union County Resource Recovery Facility, operating as Covanta Union, LLC, is located on the banks of the Rahway River. It began commercial operation in June 1994 and serves the residents of Union County, New Jersey. The 22-acre facility processes approximately 1500 tons of solid waste each day into enough electrical energy to power some 30,000 homes and businesses. Designed and built by Covanta, the facility is owned by the Union County Utilities Authority and operated by Covanta under a long-term lease agreement.

Figures 5.1 and 5.2 show the entrance to the Union County, New Jersey, waste-to-energy (WTE) plant.

Facts and Figures (Covanta, 2009)

- Commercial operation: June 1994
- Plant capacity: 1500 tons per day
- Air pollution control equipment: Semi-dry flue gas scrubbers injecting lime, fabric filter baghouses, nitrogen oxide control system, mercury control system, and continuous emissions monitoring system
- Dams: Three 480 ton-per-day waterwall furnaces with MARTIN reverse-reciprocating grates and ash handling system
- Power generation (at rated capacity): Up to 42 MW from one condensing steam turbine generator

Figures 5.3 through 5.5 show integral parts of the plant: the combustion chamber, the air condensing units, and the stack.

5.1.2 West Palm Beach, Florida

The Solid Waste Authority (SWA) of Palm Beach County is the operator of the plant. Babcock and Wilcox is the constructor of the plant. Figures 5.6 and 5.7 show the entrance of the facility and the impressive vegetation of the Florida flora from the roof of the Palm Beach County WTE plant.

FIGURE 5.1 Outside the Union, New Jersey WTE plant.

FIGURE 5.2 Entrance to the Union County, New Jersey WTE plant.

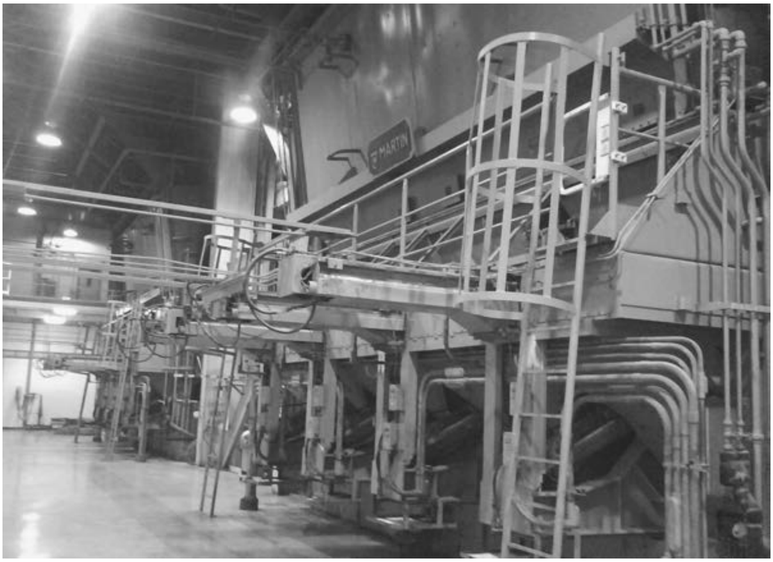

FIGURE 5.3 Combustion chamber of the Union County, New Jersey WTE plant.

FIGURE 5.4 Air condensers of the Union County, New Jersey WTE plant.

FIGURE 5.5 Stack and electrical grid of the Union County, New Jersey WTE plant.

FIGURE 5.6 Entrance to the Solid Waste Authority of Palm Beach County, Florida WTE plant.

FIGURE 5.7 View from the headquarters of the Solid Waste Authority of Palm Beach County, Florida WTE plant.

The facility is capable of processing 3000 tons of municipal solid waste (MSW) per day to produce electricity and significantly reduce the amount of waste sent to landfills. The project scope includes the installation of a metals recovery system to maximize the recovery and recycling of aluminum, steel and other metals. The new plant is located on 24 acres adjacent to the SWA's existing WTE plant, Palm Beach Renewable Energy Facility (PBREF) No. 1, which was also designed and built by B&W.

Process description: MSW, collected from homes and businesses in Palm Beach County, is delivered to transfer stations. Trucks then transport the MSW to the Palm Beach Renewable Energy Park where it is distributed to either PBREF No. 1 or the newly constructed PBREF No. 2. For PBREF No. 2, MSW is unloaded into a large pit located in the refuse building. Crane operators, housed within the control room, manage the waste deliveries by clearing the area where the trucks drop the waste and remove any large objects that could potentially jam the processing equipment. MSW is delivered to the boilers through charging hoppers and is fed onto B&W Vølund DynaGrate traveling grates where it is combusted. The heat generated by the combustion reaction is used to boil water inside the boilers to produce steam. Steam is delivered to the facility's turbine generator, where the energy is converted to up to 95 gross MW of electricity that is sold to Florida Power and Light. Flue gases generated by the combustion reaction are then processed by the emissions control system to remove air pollutants. The emissions control system provided by B&W is designed to remove acid gases, heavy metals, and particulates from the flue gas stream before exiting the stack. The SCR system is the first to be installed in a WTE power plant in the United States. The cold-side SCR arrangement utilizes a unique heat recovery system to maximize power production without burning natural gas.

FIGURE 5.8 The main WTE plant building of the Solid Waste Authority of Palm Beach County, Florida.

TABLE 5.1
Plant Design Data (Total Values for 3 Lines)

Process Parameters	Guaranteed Values[a]	Units
Waste capacity	113.4	t/h
Steam output	386.2	t/h
Steam temperature	443	°C
Steam pressure	63	Bar
Gross electric output	95.3	MW
TOC, bottom ash	3	%
Feed water temperature	149	°C
Boiler outlet flue gas temperature	179.44	°C
Flue Gas Values out of Boiler		
NO_X[b]	50 ppmv	Ng/Nm^3
CO[c]	100 ppmv	Ng/Nm^3
TOC	7 ppmv	%

[a] All values refer to 11% O_2 on dry gas.
[b] Daily.
[c] Half-hour.

FIGURE 5.9 The plant's combustion chamber.

A B&W KVB-Enertec continuous emissions monitoring system analyzes the flue gas to determine the concentration of regulated emissions on a continuous basis before the flue gas is sent to the stack. Bottom and fly ash by-products of the combustion process are delivered, along with any metallic items, to an ash management building via a series of conveying equipment. A rotary magnet removes the ferrous metals and an eddy current separator removes the nonferrous metals from the ash stream to be recovered for resale on the scrap metal market. The remaining ash is collected in bunkers where it is loaded onto trucks for transporting to a landfill (Babcock and Wilcox, 2016).

Figure 5.8 shows the main building of the facility as well as the flue gas stack. The plant's design data are presented in Table 5.1. Figure 5.9 shows the combustion chamber of the Palm Beach WTE plant. Figures 5.10 and 5.11 show the different grate-type cooling technologies used for the combustion process.

5.2 CANADA

5.2.1 Durham York Energy Centre

The Durham York Energy Centre (DYEC) is a waste management facility that produces energy from the combustion of garbage. The DYEC safely processes 154,000 tons per year of residential garbage that remains after maximizing waste diversion programs—reducing, reusing, recycling, and composting—in the Durham and York Regions. Councils from both Durham and York Regions endorsed WTE in 2006 as the best long-term, local and sustainable option for final disposal of residential garbage.

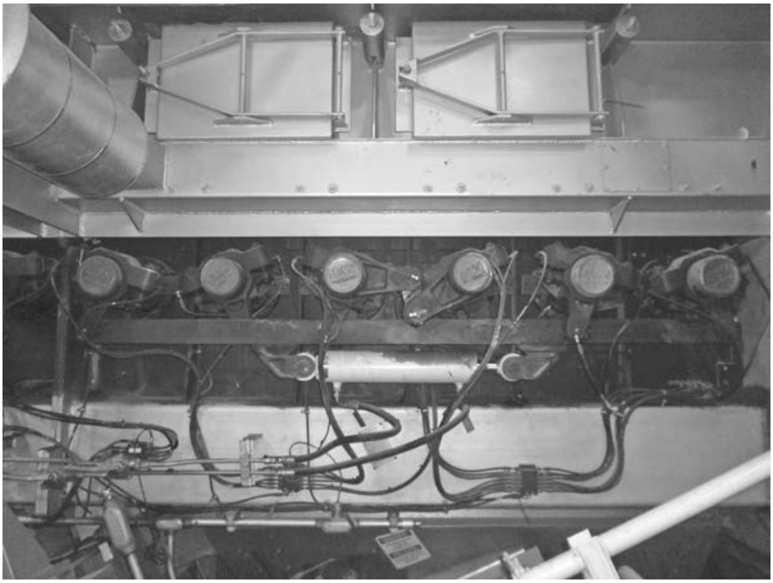

FIGURE 5.10 Air-cooled grates at the plant.

FIGURE 5.11 Water-cooled grates at the plant.

In the past, residential garbage collected by Durham and York Regions has been sent to landfills. Rather than just burying garbage, the DYEC processes it to recover valuable resources such as energy and additional metals first, then reducing the volume for landfill disposal.

Energy in the form of electricity is generated by the WTE process—enough to power approximately 10,000 homes—which helps to conserve fossil fuels. Additionally, the facility has the ability to use steam energy for district heating in the future.

By using state-of-the-air pollution control systems and proven, reliable WTE technology, the DYEC meets the most stringent environmental standards, reduces greenhouse gas emissions compared to the existing landfill option, and reduces the overall volume of garbage being sent to landfills by up to 90% (DYEC WTE Center, 2015).

Figure 5.12 shows the entrance to the DYEC WTE center.

The process flow diagram of the DYEC WTE plant is shown in Figure 5.13.

Main technical details

- Site size: 12 hectares
- Owners: 100% publicly owned by the Durham and York regions
- Operator: Covanta; first day of operation February 13, 2015
- Processing capacity: 154,000 tons of garbage/year (121,000 tons/year from the Durham region and 33,000 tons/year from the York region)

FIGURE 5.12 Entrance to the Durham York Energy Center.

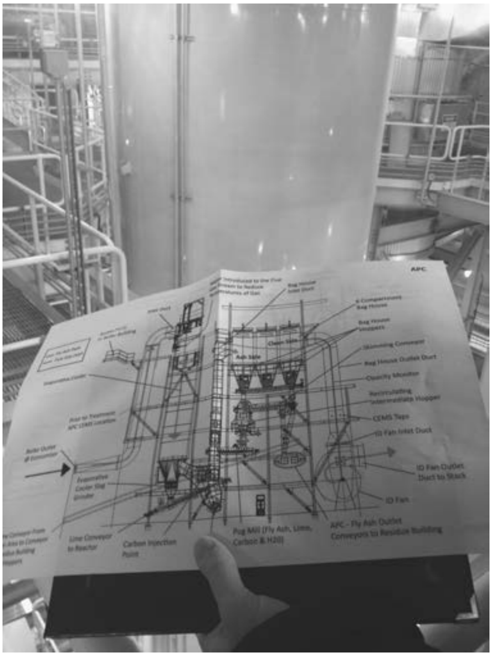

FIGURE 5.13 Process flow diagram of the Durham York Energy Center.

- Technology: Thermal mass burn with MARTIN moving grate combustion technology
- Boiler design:
  - Two municipal solid waste-fired combustors (MWCs) utilizing mass burn technology; each capable of processing 240 tons/day or 77,000 tons/year for a combined total of 480 tons/day or 154,000 tons/year
  - Steam parameters: 500°C, 91 bar
- Air pollution control equipment: Each boiler has its own dedicated air pollution control system consisting of
  - Selective noncatalytic reduction (SNCR) system for control of nitrogen oxides (NO_x)
  - Patented Very Low NO_x (VLN™) system for additional NO_x control
  - Evaporative cooling tower with dry lime reactor for acid gas control
  - Activated carbon injection system for mercury and dioxin control
  - Minimum temperature of 1000°C for volatile organic compounds (VOC), dioxin, and furan control
  - Fabric filter baghouse system for particulate matter control
- Emissions monitoring:
  - Continuous emissions monitoring (CEM) devices monitor stack emissions on a continuous basis to ensure compliance with stringent Ontario Ministry of the Environment and Climate Change air quality standards and Environmental Compliance Approval (ECA) limits

- Stack height: 87.6 meters
- Electrical energy generation:
  - GE turbine generator produces gross electrical output of 17.5 MW and a net output of approximately 14 MW
  - Electricity is sold to the provincial grid under a Power Purchase Agreement (PPA) with the Ontario Power Authority (OPA)
- Secondary materials recovery: Recovery of ferrous metals (e.g., iron and steel) and nonferrous metals (e.g., aluminum and copper)
- Wastewater discharge:
  - Zero wastewater discharge to the municipal sanitary sewer system (except for the office washrooms and kitchen facilities); all process water is reused within the facility
  - Fly ash and bottom ash (approx. 25%–28%): Construction usage daily landfill cover; on-site solidification of fly ash for cement block production
  - Metals (approximately 2% or 4400 tons per year) recovery (ferrous and nonferrous); DYEC recovers enough metal to build approximately 2500 cars annually

Gate fee: (80 USD/ton)
FIT (feed-in electricity tariff): (58 USD/MWh)

Total Capital expenses (CAPEX): (USD180 million)

Figure 5.14 represents the processed fly ash from the facility.

FIGURE 5.14 Processed fly ash from the Durham York Energy Center.

5.3 BRAZIL

Brazil, like most developing countries and emerging economies has thus far directed its collected waste to dumpsites or landfills, intensifying the long-lasting problems of poor sanitation and increasing levels of public diseases. Huge quantities of resources are disposed to dumpsites, with no proper reuse or recovery possibility, generating economic losses and also increasing the problems and costs of exploiting new natural resources. One possible solution to waste processing is given by Waste Processing Center (WPC) plants, especially those designed for developing countries and emerging economies that previously relied on manual sorting of recyclables and handling of water treatment.

In Brazil this work has been stimulated by the 2010 National Solid Waste Policy. Technical, financial, and social benefits have been achieved with this approach. The results highlight that

- WTE plants are economically feasible
- Taxation policies have significant influence on bottom lines
- Results are influenced by economies of scale
- A few municipalities generate most of the waste
- Bigger cities are able to finance their own plants, smaller cities should form consortiums or adopt cheaper alternatives suitable to each particular situation
- There is a huge potential for recovery of resources

5.4 CUBA

5.4.1 Special Conference Events in Cuba

Dr. Efstratios Kalogirou participated, as lecturer, in an intensive course held in Cienfuegos, Cuba, titled "Technologies for Sustainable Waste/Biomass management" and, as plenary speaker, at the first International Scientific Conference of Cienfuegos for Renewable Energy Sources and Cleaner Production held in Cienfuegos.

The intensive course/seminar ran from Monday, June 24 through Tuesday, October 25, 2016 in the Conference Center of the Hospital of Cienfuegos, in cooperation with the University of Cienfuegos, as a pre-conference course in preparation for the International conference.

Topics addressed by Kalogirou in his lectures included the grate combustion of municipal and similar solid waste with energy recovery; the pyrolysis/gasification/plasma gasification of MSW; the current situation of WTE worldwide; the potential for advancing sustainable WTE in Cuba; business models and case studies of worldwide WTE Projects; and the financial aspect Capital expenses/operation expenses (CAPEX/OPEX). Around 35 participants attended: doctoral students from the University of Cienfuegos; specialists from local governmental authorities; representatives from local industry (Empresa Azucarera/Sugarcane); members of the Laboratory of Combustion San Marine of Cienfuegos; and university professors, students and PhD students from departments from multiple universities in Cuba and abroad (University of Cienfuegos, the Universidad Tecnológica de la Habana José Antonio Echeverría (CUJAE), Universidad de Oriente, University de Sancti Spiritus, University of Guadalajara, Mexico, etc.).

Then, from October 26 to 28, Kalogirou participated in the first International Scientific Conference of Cienfuegos for Renewable Energy Sources and Cleaner Production and, additionally, in the Eighth International Conference of Energy and Environment, organized by Centro de Estudios de Energia y Medio Abiente (CEEMA) held in Hotel La Union, City of Cienfuegos, Cuba. Kalogirou presented the plenary address on the current situation of WTE worldwide and the potential of advancing sustainable WTE in Cuba. He participated in different interesting discussions with local participants and stakeholders from local universities, industry, and nongovernmental organizations (NGOs) such as Cuba Solar, on the abovementioned topics.

5.4.2 Technical Visit

On Saturday, October 30, an interesting technical site visit was held in the local laboratory of Combustion Dionisio San Roman, Cienfuegos, next to the city's power plant. Interesting pilot plant equipment (combustion chambers, a gasifier, a fluidized bed combustor, cyclones, etc.) can be utilized for further research on pretreated MSW and local biomass for energy production. A productive discussion with the local administration and engineers was held during the visit.

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6 Waste-to-Energy in Asia

In the current chapter, technico-economic data for six waste-to-energy (WTE) plants are presented. The data are based on reports made by the author after relevant site visits.

6.1 CHINA

Waste management in China is based mainly on landfills (80% of the waste) and WTE (20% of the waste). As of 2016, there were approximately 210 operating WTE plants in China and 60 plants under construction, while projections for the next five years indicate construction of another 250 WTE plants, making WTE a booming market in China. The rapid development of WTE has been greatly aided by the country's renewable energy policy. The gate fees range from 11 to 33 USD/ton of municipal solid waste (MSW) and in 2011 the Chinese government passed new legislation for permitted dioxin emissions in order to conform to European Union (EU) limits, changing it from 1 to 0.1 ng/Nm^3. Permitted emissions is noteworthy that the moisture content of Chinese MSW is relatively high, ranging from 50% to 55%, and the average caloric value is around 4–6 MJ/kgr. Therefore, the main operating problem is the handling of the leachate (around 30%) and the limited energy production (<280 Kwh/ton compared with 500–650 KWh/ton in Europe).

The rapid growth of the WTE industry has also been helped by the relatively low cost of capital, which is less than 300 USD/annual tons (about 33% to 50% of the capital costs of European and U.S. WTE plants).

Waste-to-energy plants in China are mainly of two types: stoker grate and circulating fluidized bed (CFB).

The biggest worldwide capacity WTE plant is under construction in Shenzhen.

6.1.1 Suzhou Everbright State Venus Industry Demonstration Park in Suzhou City

The Suzhou WTE plant is located in Suzhou city. It was built (Build Operate Transfer [BOT]) by China Everbright International. The Suzhou project will increase its designed daily household waste processing capacity from 2200 tons to 3500 tons, giving it one of the largest daily household waste processing capacities in the People's Republic of China (PRC), with the most advanced emission standards.

In Figure 6.1 the Suzhou plant and its access road are shown. Figure 6.2 shows the main screen in the control room.

Main technical details

- The plant's capacity is 1.1 million tons per year; producing 0.2 million MWh net electricity to the network
- Stoker technology

FIGURE 6.1 View of the Suzhou WTE plant.

- Power production of 25 MWe
- Selective non-catalytic reduction (SNCR) for reduction of nitrogen oxides (NO_x)
- Dioxin and furan emissions from the plant's operation range between 0.01 and 0.06 ng/Nm^3

FIGURE 6.2 The control room of the Suzhou WTE plant.

- The bottom ash (25% of feed MSW) is landfilled
- The fly ash is sent to special hazardous waste landfills at a cost of 110 USD/ton
- Gate fee for the plant is approximately 19 USD/ton
- The selling price of the electricity is 77 USD/MWh
- The total investment was around USD140 million
- All the emissions meet the requirements of EU Directive 2000/76

6.1.2 Gao-An-Tun WTE Plant in Beijing

The Gao-An-Tun WTE Plant in Beijing is one of the largest WTE plants in China and was built in BOT mode. Golden State Waste Management Corporation (GSWM) constructed and currently operates this plant.

Main technical details

- 2 lines × 880 tons per day (TPD), 590,000 tons per annum (TPA)
- SN-grate combustion technique from the Japanese company Takuma; stepped-forward moving grate (inclined and horizontal)
- Steam parameters of waste heat boiler: 400°C, 4 MPa (40 bar)
- Installed capacity of steam turbine 2 × 15 MW, 0.2 million MWh net electricity to the network
- Novel integrated desulfurization (NID) flue gas cleaning system from Alstom
- SNCR dentrification technique
- The bottom ash (25% of feed MSW) is landfilled
- Fly ash (3% of the feed of MSW) becomes inert after on-site solidification with cement
- Gate fee for the plant is around 24 USD/ton
- The selling price for the electricity is 77 USD/MWh
- The total investment was around USD99 million
- All the emissions comply with the requirements established by EU Directive 2000/76

6.1.3 Shanghai Pucheng Thermal Power Energy Co., Ltd., Pudong Yuqiao WTE Plant

The Yuqiao WTE Plant in Pudong was first put into operation in September 2002.

Figure 6.3 shows the front of the Shanghai Pucheng WTE plant. In Figure 6.4 the bottom ash management line is shown.

Main technical details

- The plant is equipped with three combustion lines, each of which has a daily capacity of 360 tons, feeding MSW from part of Pudong district
- The total area of the plant is 80,000 m^2 (20 acres)
- The plant operates for 7500 hours annually

FIGURE 6.3 Outside the Shanghai Pucheng WTE plant.

- The grate technology used is the SITY 2000 technology owned by MARTIN GmbH
- There are three gravity circulating water-wall boilers and each combustion-boiler line is coupled with a flue gas cleaning system with semi-dry scrubber, bag filter, and activated carbon injection system

FIGURE 6.4 Bottom ash management in the Shanghai Pucheng WTE plant.

- Steam produced from two turbine generators each with a normal capacity of 8.5 MW, so the nominal capacity of the two turbines is 17 MW
- Bottom ash produced after combustion of MSW is reused as material for bricks after special treatment
- Fly ash is transported to the Shanghai Solid Waste Treatment Center's special waste landfill, which costs around 90 USD/ton
- The thermodynamic characteristics of produced steam are 400°C and 40 bar pressure
- The gate fee is around 240 RMB 30 USD/ton
- The total investment was USD75 million
- The selling price for the electricity is 65 USD/MWh
- The plant is equipped with continuous emission monitoring devices for flue gas emissions calibrated according to the European standards directive 2000/76

6.1.4 Chongqing Sanfeng Covanta WTE Plant

The Tongxing WTE plant in Chongqing was first put into operation on March 28, 2005. It is a joint venture headed by Chongqing Steel which includes Sanfeng Covanta, one of many subsidiaries of the Chongqing Iron and Steel Co. The plant uses the Alstom SITY 2000 design from MARTIN GmbH. Nearly all of the equipment was fabricated locally to MARTIN GmbH specifications. The plant handles 50% of the waste generated in the Chongqing municipality.

Figure 6.5 shows some technical details of the plant.

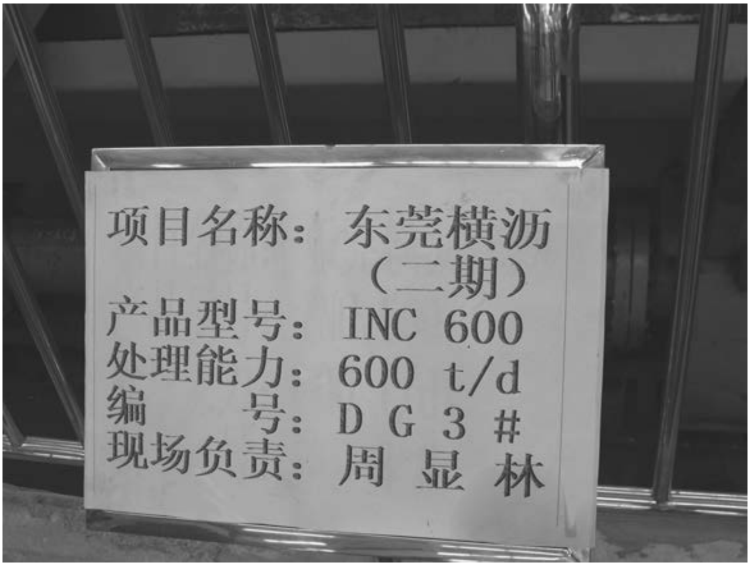

FIGURE 6.5 Technical details of the Chongqing WTE plant.

Main technical details

- The company has three aspects: Engineering, Procurement, Construction (EPC) contracts, core technology, and equipment and project operation
- Chongqing Sanfeng Covanta Environmental Industry Co., Ltd. has constructed and operates 25% of the WTEs in China
- The technology adopted by Sanfeng Covanta is suitable for high-water-content, low-heating-value municipal waste that could burn steadily without preselection and auxiliary fuel
- Plant capacity is 1320 TPD with the SITY 2000 inclined reverse grate; it is the model project of WTE for high-water-content and low-heating-value MSW
- High efficiency combustion with residence time over 2 seconds, gas temperature above 850°C
- The project uses two sets of 64.23 t/h steam boilers, a natural circulating system, 130°C feeding water, 210°C induced draft, 4.0 MPa (40 bar) steam pressure, and 400°C steam temperature
- Waste heat from the burning of waste is used for power generation from 220 to 250 kWh per ton of waste, adequate for 40,000 households
- Previously, the dioxin limit in China was 1.0 ng/Nm^3 but has now been reduced according to the EU 2000/76 directive to 0.1 ng/Nm^3; dioxin and furan emissions from the plant are 0.05 ng/Nm^3
- The bottom ash (25% of feed MSW) is used for road construction and fly ash (3% of the feed MSW) becomes inert after on-site solidification with cement
- The bottom ash is used for building material
- Wastewater will be recycled and, after three levels of treatment, used for watering the plant's landscaping
- Gate fee is around 11 USD/ton
- The total investment was USD37 million

6.2 AZERBAIJAN

The author coordinated a 5-day international WTE summit, entitled "Waste-to-Energy as an Integral Part of Sustainable Waste Management Worldwide: The Case of Baku City, Azerbaijan," organized in collaboration with Synergia (WTERT/Greece), the Earth Engineering Center of Columbia University, and the local waste management authority, Tamiz Shahar, from June 17 to 21, 2013 in the city of Baku, Azerbaijan.

6.2.1 Baku WTE

6.2.1.1 Introduction

Baku, the capital of the Republic of Azerbaijan, is the largest city of the Caucasus region. In addition to being the biggest industrial, scientific, and cultural center, it is also a large port in the Caspian Sea basin. Baku covers about 2130 km^2 of territory and occupies the main part of the Absheron Peninsula. Because Baku is a large, modern, industrial city, it has developed oil and gas, chemicals, mechanical engineering, and food industries.

6.2.1.2 The Past

According to international practices, if the operations relating to collecting, sorting, transporting, placing, using, neutralizing, processing, and burying wastes—the basic components of the waste management system—are carried out properly and systematically, reforms aimed toward ensuring efficient functioning of this system will prove themselves and achieve the expected efficiencies.

From this point of view, for the purpose of the establishment and management of the collection system, transportation, and neutralization of wastes, in the country's capital, in an organized manner, as well as meeting contemporary standards, and improving the environmental situation of the city, on August 6, 2008, the Instructive Order "On Improvement of the Waste Management System in Baku City" was signed by Mr. Ilham Aliyev, President of the Republic of Azerbaijan. According to the Instructive Order, all solid domestic waste generated on the territory of the capital would be collected by the Executive Power Authority of Baku city and handed over to the newly established waste management association of the state organization Tamiz Shahar, OJSC. This enterprise had to ensure complete utilization by carrying out placement and neutralization of wastes.

The France-based company CNIM S.A. (Constructions industrielles de la Méditerranée S.A.) won the announced international tender on designing, constructing, and managing the WTE plant.

At the end of 2008, the CNIM Group signed a USD385 million contract with the Ministry of Economic Development of the Republic of Azerbaijan for the construction of a WTE plant processing municipal waste for the capital city of Baku. The plant capacity is 550,000 tons per year and has been in operation since 2012.

The Baku Municipal WTE Plant covers an area of 10 hectares and consists of two technological facilities, each with an combustion capacity of 275,000 tons, and one turbine generating the electric power. Reportedly, on average, the annual waste generation per capita in Baku is 350 kg. The shortage of waste containers and specialized motor vehicles creates serious problems in the collection of waste in some areas. According to official information, 2540 waste collection points are functioning in the city and three agglomerations in the city's Sabunchu, Surakhani, and Garadagh districts. The largest of them is the Balakhani area, which has been functioning since 1963. Though the majority of urban waste is transported to those areas, there are numerous unauthorized waste dumps in suburban areas of Baku city.

According to surveys, there are several serious problems in the existing unauthorized areas. The problems include the need for the elimination of mixing of hazardous substances with subsoil waters, open waste discharge, self-combustion—and, the resulting spread of smoke containing combustion gases and different toxic substances and similar harmful products.

The waste is transported to the collection points without sorting. Because partial sorting of wastes according to category—paper, metal scraps, plastic, and glass—is carried out manually in refuse dumps, it creates a high risk for various infections. Therefore, assessment of current capacities of waste grounds for placement of waste by category is of critical importance.

Along with the establishment and launch of Tamiz Shahar mentioned in the Instructive Order, the construction of a solid domestic waste combustion plant (a WTE plant) in Balakhani (in the Sabunchu district) has been envisioned amongst the measures to be undertaken by the Ministry of Economic Development.

6.2.1.3 The Present

The inauguration of the facility, at which Mr. Ilham Aliyev, President of the Republic of Azerbaijan, was present, took place on December 19th, 2012. The opening of the state-of-the-art WTE plant for the disposal of solid domestic waste in Balakhani was a great event for Baku city.

Figure 6.6 shows the facility behind an oil extraction pump.

6.2.1.4 The WTE Plant

The plant includes two lines, for a total capacity of 550,000 tons/yr (1540 tons/day @ 8500 kJ/kg) of municipal waste and 11,000 tons/yr of clinical waste, with electric production.

The technology of the WTE plant focuses in particular on the following main equipment:

- The MARTIN GmbH grate, installed on several hundred WTE units in the world, and designed since its creation to be adapted to the evolutionary characteristics of the waste.
- The vertical single-drum boiler, of the suspended type, resulting in an assembly fully integrated with the grate.
- The optimized energetic valorization, which can be done either by electric energy production only or, if required in the future, by a combined

FIGURE 6.6 View of the plant behind the oil extraction platform.

heat and power supply. Although the optimization is done for the electrical power supply, this future possibility of combined heat and power production allows maximization of the energetic efficiency of the plant, according to the potential variable needs of future consumers.
- The flue gas treatment of the semi-dry type, completed by an efficient NO_x reduction treatment based on a proven SNCR technology.

6.2.1.5 Waste Reception and Handling

According to the existing waste collection system in Baku, the nature of the waste that will be delivered to the plant should be totally uneven and unsorted. For this reason, the waste reception process in the plant has been designed to address this existing constraint, with the possibility of progressive evolution according to modernization of the waste collection and, in particular, the installation of selective waste collection.

The waste reception process has therefore been adapted to address the waste reception, oversized waste management, and storage of the waste before treatment. The design, the result of long experience, is based on the following process for waste reception and storage:

- Collection vehicles entering the plant are weighed on two automatic weighbridges at inlet and outlet of the plant
- The waste trucks enter the tipping floor, which is widened to allow:
  - The tipping directly into the pit for the trucks that only contain normal sized waste
  - The tipping on a floor of the waste that contains oversized items that are collected and discharged by a mobile crane-truck into a shredder
- The waste pit has a capacity of about 15,000 m^3 (hydraulic volume) without stacking, designed to allow a future third line operation; the capacity allows 7 days of storage time with stacking with two lines in operation, and will give 4–5 days of storage time in the future with three lines in operation

Healthcare waste will be discharged into dedicated containers located in a dedicated area of the plant to avoid further human contact with such waste. Once the healthcare waste has been put into dedicated containers, these containers are lifted by a travelling crane, transported, and directly discharged into the waste hopper of either line. The empty containers are then sent to a washing area, before being returned to the reception area for healthcare waste.

Two overhead travelling cranes serve the waste pit. Provisions have been made for preventing operation of both cranes at the same time. The cranes are capable of operating in manual or semi-automatic mode.

When in operation the travelling crane is also used to mix waste in the pit, so as to ensure that the waste loaded in the hopper has a constant calorific value, insofar as this is possible. When in service, the crane is operated from the central control room.

Each hopper is surveyed by a video camera. The feed chute beyond the hopper is sufficiently high to allow for the waste to form an airtight seal with the combustion chamber. At the bottom of the feed chute, feeder rams push the waste over the feeding edge onto the front end of the grate.

6.2.1.6 The MARTIN GmbH Grate

The MARTIN GmbH reverse acting stoker itself is made up of alternate steps of fixed and moving grate bar rows that perform slow stirring or mixing stokes in an upward direction, opposite to the downward movement of the waste due to the inclination of the grate at approximately 26°.

In addition, each stroke is completed by a "relative movement" whereby each bar moves relative to the surrounding bars. This ensures cleaning of the air gaps between the bars, plus a further aeration of the waste layer.

The grate is designed for mass burning and is unique in its concept, design, and construction. It incorporates the following highly significant features:

- The moving grate bars are "reverse acting" to ensure good mixing, combustion, and flame position control
- The grate bars are made from high-grade alloy material to close tolerances
- The grate bars are shaped and have a special movement to reduce clinker formation

These features, all of which can be adjusted for control, enable the MARTIN GmbH grate to give consistent performance with a wide range of waste types, and to have a long trouble-free life. These features also provide combustion control, which, in terms of quality and flame position, is essential for consistent boiler performance.

Combustion of the waste is completed on about two-thirds of the stoker length. On the last part of the stoker, the residue (bottom ash) is progressively cooled by the under-fire (primary) air. In addition, as a result of the MARTIN GmbH system for combustion control, the amount of sifting that falls through the grate is very small, hence producing reduced loss by possible unburned material resulting in high energy recovery.

- The primary air fan suction is done above the waste pit. This ensures that odors and dusts are drawn into the combustion stream and prevented from escaping from the tipping hall into the environment.

  The primary air is blown under the stoker grate through independently controlled hydraulic dampers. This air is heated to the optimum temperature according to the waste characteristics.
- The secondary air fan draws the air from the top of the boiler house, allowing it to cool this hot area and also to ensure natural heating of the secondary combustion air.

  The secondary air is injected into the combustion chamber from carefully located nozzles to achieve a turbulent mixing of the combustion gases and complete combustion, together with a stable flame of controlled height.

The combustion grate is fitted with a submerged bottom ash ram type extractor. The bottom ash discharger is of the constant water level type and acts as a seal to the combustion chamber. A reciprocating ram, with hydraulic drive, pushes the residue toward the ash discharger's outlet.

6.2.1.7 Evacuation and Treatment of the Bottom Ash

At the outlet of each ash discharger, the bottom ash (23% of the combusted waste) falls onto a vibrating conveyor. At the outlet of the vibrating conveyors, the bottom ash falls into two belt conveyors which convey it up to the storage and maturation area.

This storage and maturation area of approx. 20,000 m^2 surface includes the following parts:

- A reception area at the bottom of about 1400 m^3 capacity, ensuring about 4–5 days of storage, where the bottom ash is automatically discharged without manual operation
- A second storage area of the untreated bottom ash, of approx. 2100 m^3 capacity, where the bottom ash is transferred manually with bulldozers.

From this storage area, the bottom ash is conveyed up to the process area, designed for a treatment (sorting of ferrous and oversize materials) capacity of 50 tons/h of ash. After treatment, the bottom ash is stored in the maturation area until it is recycled for road subbase.

6.2.1.8 CNIM Heat Recovery Boiler

The heat released from the combustion of waste is recovered in a water tube boiler that forms an integrated unit with the grate. Each boiler produces 99 tons/h of superheated steam. The boiler is of the vertical type, top-supported, and includes one steam drum and four vertical gas passes:

- First pass: Radiant combustion chamber
- Second pass: Radiant chamber with vaporizing panels
- Third pass: Evaporator bank and superheater
- Fourth pass: Superheater and economizer

The design of the boiler makes it particularly suitable for waste combustion. The boiler's main features are

- Low gas velocity
- Long residence time
- Wide spacing of tubes in the tube banks
- Boiler pressure parts with in-line cleaning well adapted to the design

The two first gas passes are empty, only composed of vaporizing radiant panels allowing the flue gas flow to cool down before it enters the superheater banks. In the third gas pass, a vaporizing bank located upstream from the superheater allows additional reduction of the gas temperature before the superheater inlet, to further decrease the risk of acid corrosion of this exchanger.

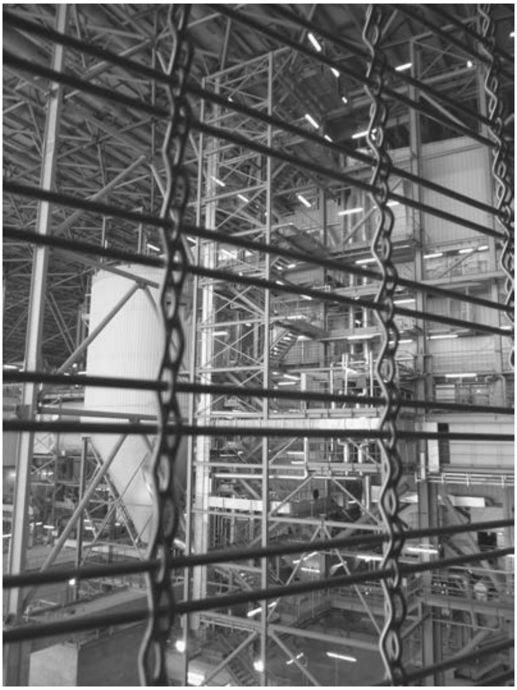

FIGURE 6.7 Entire view of the equipment of the plant.

Such a design provides very high reliability and long lifetime for the superheater, therefore minimizing maintenance operations and, consequently, reducing global operational cost. In short, with its compact and conservative design, the vertical top-supported boiler is a very efficient and reliable piece of equipment.

A full view of the equipment is shown in Figure 6.7.

6.2.1.9 Electric Power Production

The superheated steam produced by each boiler feeds a condensing type turbo generator set common to both lines. In order to achieve the maximum electrical power output, the turbine includes three steam extractions (bleeds):

- The first steam uncontrolled extraction feeds the high temperature stage of the primary air heater.
- The second steam uncontrolled extraction feeds the deaerator and the low temperature stage of the air heater.
- The third steam uncontrolled extraction feeds the possessive, condensates' low pressure heater.

The turbine exhaust steam is condensed in a vacuum air-cooled condenser.

The electrical production (37 MW) is much higher than the proper needs of the plant. The extra production (33 MW) is exported to the electric grid through a specific step-up transformer.

6.2.1.10 Flue Gas Cleaning System

The flue gas cleaning system is of the LAB (CNIM Group) semi-dry type.

The LAB semi-dry process involves the contact of the flue gases with a reagent (in this case lime slurry) in a gas reaction chamber. The acid pollutants in the flue gases are neutralized by contacting and reacting with fine alkaline particles. The reagent is sprayed by a spray turbine located at the top of the reaction chamber; this provides good contact between the flue gases and the reacting agent. The flue gases flow through the gas reaction chamber, then through the fabric filter, and are then discharged via the induced draft fan to the stack.

Figure 6.8 shows the electrostatic precipitators inside the Baku WTE plant.

6.2.1.11 Dioxins and Heavy Metals Abatement

During the contact period with the reagent as described above, heavy metals condense onto lime particles and can therefore be captured by the fabric filter. In addition, each stream is fitted with an activated carbon injection system in order to further reduce the emissions of mercury and dioxins.

NO_x reduction is obtained in two different ways:

- The "primary" treatments, allowing reduction of NO_x emission at their source by optimizing the combustion process
- The "secondary" treatments, which consist of a noncatalytic reduction process (SNCR)

This technology uses a liquid urea solution for NO_x abatement, with a "homemade" solution at 33% urea concentration obtained by dissolving solid urea in hot water.

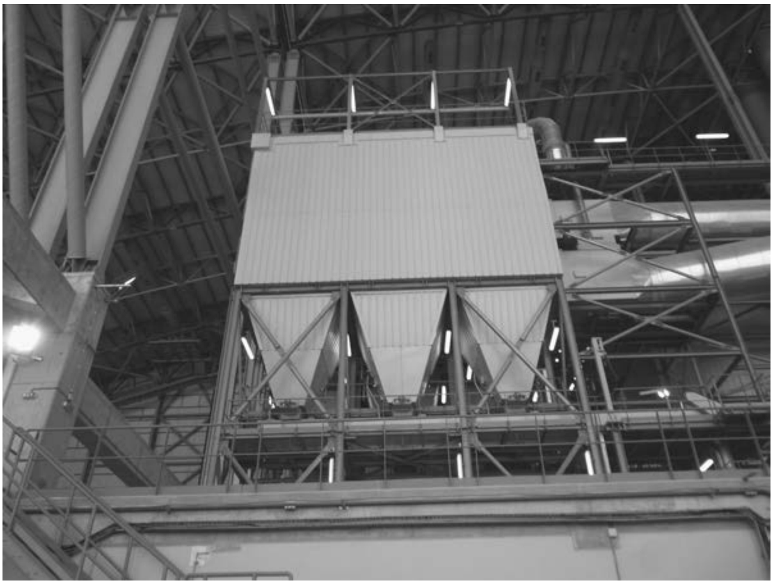

FIGURE 6.8 Electrostatic precipitators of the Baku WTE plant.

The SNCR is done with injection of the liquid urea solution in the furnace. This "liquid" SNCR allows good control of the reagent's injection, and a good mixture of the reagent and the flue gas, leading to a reduction in the reagent's consumption.

6.2.1.12 Residue Storage

Reaction products and fly ashes (4% of the combusted waste) are collected in dry form at the bottom of the baghouse filter and spray dryer reactor. These materials are transferred to two storage silos with a 7-day storage capacity and, finally, to external plants.

6.2.1.13 Emissions Monitoring

A PC-based data storage system fully equipped with the necessary software, monitor, keyboard, and printer, is dedicated to emissions monitoring and is compliant with all relevant regulations.

The following are continuously monitored and recorded for each stream:

- Total dust
- HCl (Hydrogen chloride)
- SO_2 (Sulfur dioxide)
- CO (Carbon monoxide)
- NO_x (nitrogen oxides)
- NH_3 (ammonia)
- HF (hydrogen fluoride)
- VOCs (volatile organic compounds, expressed as TOC [total organic carbon])

Associated parameters:

- O_2 and CO_2
- Water vapor content (H_2O)
- Temperature and pressure
- Volume flow

The stack and environmental aspects are subject to spot measurement for each stream by an independent body for the presence of dioxins, furans, and heavy metals.

6.2.1.14 Stack

The stack consists of an external auto-stable carbon steel windshield with two internal flues made of thermally insulated corten steel. The stack is approximately 60 m high. The chimney is fully equipped with an inner ladder (with safety hoop and interim platforms) to access the emissions monitoring tapping points, with day and night beacons as required by the relevant authority, and lightning protection.

6.2.1.15 Environmental Aspects

The location of a waste processing plant is limited by the physical landscape and the types of industry permitted in a given area. The effects associated with the project application depend on the character of the waste. The waste generated from combustion process are composed of gaseous smokes, according to their state of aggregate, and ash collected in a solid form, as well as fly ash separated during the cleaning of smoke gases.

The volume of waste in the WTE plant will be reduced over 10 times when compared to the volume of the preprocessed raw materials. Solid waste generated by the plant will not be discharged to the environment without controlling. The combustion bottom ash will be used in road construction. Fly ashes are warehoused and isolated from the environment. The composition of generated wastes will be free of any pathogenic and epidemic risks. The levels of waste discharged into the atmosphere are lower than the levels in EC Directive 2000/76.

The generation condition and quantity of wastes are controllable. Thus, the WTE plant has been programmed on a high level from the environmental point of view and impacts on the environment are negligible.

6.2.1.16 Social Aspects

The project application takes into consideration the following possible socioeconomic gains:

- *Employment opportunities*: Creation of new workplaces and training, allowing members of the population to acquire new qualifications
- *Improvement of sanitary conditions in the city*: The reduction of urban waste by processing of solid domestic waste and ensuring the sanitary and hygienic cleanliness of the city
- *Positive impacts on the health of the population*: Avoiding illegal open and uncontrolled incineration of wastes in the roads
- *Increased social efficiency*: Removal of 550,000 tons of urban waste per year from the city by the operation of the new processing plant
- *Guarantee of reduction of the existing risks*: The effective cleaning of smoke gases generated by the operation of the WTE plant is under continuous control; as a result there is a reduction in the quantity of hazardous substances discharged to the environment from uncontrolled burning in urban areas and waste dumpsites

6.2.1.17 Economic Aspects

The WTE project creates the following social and financial improvement:

- *Saving land resources*: The necessity for the creation of new waste landfills is eliminated by the construction of a WTE plant with annual production capacity of 550,000 tons in terms of combustion of solid domestic wastes; as a result, the loss of economically significant land plots will not occur.

- *Conservation of energy resources*: The concept of "energetic balance" in the processing of wastes has been offered by the Working Party of the International Energy Council: the concept is that the generated electrical energy should cover energy costs consumed by the processing of wastes.

Therefore, in general, selection of a technology is determined by the balance of generated and consumed energy. In this respect, 15% of 230 million kWh of electric energy generated in a year from combustion of wastes under the proposed project will be used to cover the plant's own needs and, as a result, economic efficiency will be achieved.

Solid domestic wastes as an alternative energy source: at present, the European legislation on alternative energy sources unanimously puts urban waste in first place. As natural resources such as oil, gas, and coal are exhausted, energy consumption is growing. Unlike the natural resources, waste is deemed to be a renewable and inexhaustible energy type. 230 million kWh of electric energy are generated from the plant constructed in Baku and economic efficiency is achieved by rendering 85% of the generated energy to the local power network.

Bottom ash as an alternative construction material: up to 23% of the preliminary weight of domestic waste is separated during the annual operation of a domestic waste processing plant. This waste (bottom ash) can be applied in road construction works. The economic efficiency is achieved not only through savings on sand and gravel, considered to be natural resources, but also saving in costs borne for their processing.

Figure 6.9 shows the interconnected equipment between the MRF and the WTE plant.

FIGURE 6.9 Interconnection equipment between the MRF and the WTE plant.

6.3 INDIA

India is the second-most populous country in the world, with nearly 1.3 billion inhabitants. Its population is growing rapidly, especially in urban areas. As of 2014, nearly one-third of the country's population lives in urban areas, and the proportion of the population living in urban areas with more than one million inhabitants has increased by 13% since 2005. India's population is becoming increasingly wealthier as well: the gross domestic product per capita in India has more than doubled since 2005 (World Bank, 2016).

As a result of these changes, per capita waste generation in India increased from 0.44 kg/day in 2001 to 0.5 kg/day in 2011; urban areas across the country now generate more than 205,000 metric tons of waste per day, and many cities' landfills are operating at or above capacity (Annepu, 2012). Population growth and increasing wealth also present physical constraints on the ability of cities to manage increasing quantities of waste. As they grow, cities must collect and transport waste across larger areas; and there is increasingly limited space for new or enhanced landfills, transfer stations, material recovery facilities, and other facilities. These constraints result in higher operating and capital costs, reduced solid waste collection efficiency and coverage, human health impacts, and public frustration.

In India, municipal solid waste is disposed of by open dumping, posing environmental threats and health hazard issues. Moreover, most of the dumping sites are saturated and, therefore, technological options that are sustainable in the long-term must be found. The WTE process can be a long-term solution for the ever-growing problem in solid waste disposal for metropolitan cities generating increasing quantities of municipal solid waste. In India, waste is processed without segregation and most of the recyclable materials go to dumping sites, adversely affecting the recyclable materials market. Therefore, these materials must be segregated at the source to enable the industry to economically process the recyclables and subsequently market the products. The new Solid Waste Management Rule of 2016 mandates segregation of waste at the source and implementation of WTE projects for all post-recycling MSW.

In a significant step toward generating power from garbage under the Swachh Bharat Mission, a Government of India mission that translates as "Clean India Movement," six WTE plants with installed capacity of about 74 MW will be commissioned this year, including two in the national capital.

A WTE plant is in development at Ghazipur to produce 12 MW of power by processing 2200 tons per day, another plant will be commissioned at Narela-Bawana in New Delhi to generate 24 MW of power from waste. There will be two WTE plants producing 11 MW each in Jabalpur and Hyderabad, in addition to a 12.6 MW plant at Nalgonda in Telangana, and a 3 MW plant in Chennai. These will be commissioned next year. There is a proposal to provide market development assistance and the government will mandate that the state electricity boards procure power from these units. In addition, the Central Electricity Regulatory Commission (CERC) is also working to determine the tariff for the power generated from WTE plants to boost their financial viability. In order to improve the scope for WTE projects, the

Power Ministry is in the process of amending the Electricity Act of 2003 to include a provision for State Electricity Discoms to mandatorily purchase all power generated from MSW disposal. CERC is also working on determining a generic tariff for solid WTE projects with main target to boost the financial viability of WTE plants in the country.

6.3.1 Jabalpur WTE Plant

The first WTE plant in India is located in Jabalpur (Central India). It became operational in May 2016 with a capacity of 660 tpd. The total investment was one of the

TABLE 6.1
Potential for WTE in Indonesia

No.	City	MSW Potential (ton/day)	Electricity Potential (MW)
1	DKI Jakarta	8733	181
2	Kota and Kab. Tegal	3519	73
3	Kota Surabaya	2562	53
4	Surakarta Klaten and Boyolali	2447	50.5
5	Kota Bandung	2114	44
6	Kota Jember	2112	44
7	Kota and Kab. Cirebon	2012	41.5
8	Kota Medan	1812	37.5
9	Kota Cianjur	1762	36.5
10	Kab. Sidoarjo	1568	32.5
11	Kab. Banyuwangi	1503	31
12	Kota and Kab. Tegal	1485	31
13	Kota Tangerang	1352	28
14	Kota Semarang	1345	28
15	Kota and Kab.Kediri	1224	25.5
16	Kota Depok	1217	25
17	Kota and Kab. Pasuruan	1215	25
18	Kota Palembang	1171	24.5
19	Kota Makasar	1029	21.5
20	Kota Malang	761	16
21	Kota Bandar Lampung	703	14.5
22	Kota Padang	682	14
23	Kota Madiun	612	12.5
24	Kota Pekanbaru	603	12.5
25	Batam	450	9.5
26	Denpasar, Bali	445	9
27	Kota Balikpapan	400	8.5
28	Kota Pontianak	340	7

smallest worldwide, due to the fact that the constructor (Hitachi Zosen Inova) integrated more than 90% of the total equipment in India.

Main technical details

- Air-cooled moving grates
- One line 660 tpd
- Energy recovery: four-pass vertical boiler
- Net calorific value: 6.9 MJ/Kg
- Thermal capacity: 1 × 48 MW
- Steam: 1 × 63 t/h (46 bar, 410°C)
- Gross Power: 11.5 MWe
- Constructor: Hitachi Zosen Innova

6.4 INDONESIA

From waste produced in Indonesia (arising from a population of 260 million people) some 5000 MW of power can be generated, making it one of the country's largest potential sources of power generation. To address both energy shortages and a growing waste problem, the Indonesian government is actively supporting the development of WTE plants. Municipalities are preparing tenders for WTE plants of up to 70 MWe and developments in this sector are expected to accelerate in future years.

In Table 6.1, data regarding Indonesia are analyzed, describing the huge potential of the country.

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7 Waste-to-Energy in Africa

Solid waste management is a growing challenge for both developed and developing countries and, according to the World Bank (2012) in Africa, waste management practices differ vastly, both among and within countries. Waste management practices between rural and urban areas tend to differ vastly. In rural areas, there tends to be no waste management infrastructure and collection service, while in urban areas, collection coverage is estimated to be 40% of the population, reaching mainly the more wealthy areas. In some African countries, such as South Africa, service delivery to urban households has reached 90%, but this has been achieved through a strong political will and an investment in waste management technologies within the municipalities.

While the municipal solid waste (MSW) generated in Africa contains relatively large quantities of recyclables (organic waste, paper, plastic, glass, and metals), typical overall recycling rates remain low, at below 10% (World Bank, 2012). However, research based on recent data for MSW in urban areas (cities) shows that recycling rates as high as 20%–30% for MSW are being achieved mainly by the informal waste sector in lower income countries. Indeed, most large African cities have an active informal waste sector, which plays a significant role in the recovery of recyclables. Waste-to-energy (WTE) is only emerging on the continent, with projects focused mainly on small-scale anaerobic digestion and landfill gas recovery. There are no data available on the total number employed in the waste sector in Africa or those earning a living through the collection and sorting of recyclables in the informal waste sector. Data from South Africa suggest that while approximately 30,000 people are employed in the formal waste sector, an estimated 2–3 times of this number earn a livelihood from the informal waste sector.

7.1 ETHIOPIA

The following subchapters present the political efforts made between the European Commission (EC) and the Ethiopian authorities in 2013 as well as the history of the development of the first waste-to-energy plant in the African continent, in Addis Ababa.

7.1.1 Joint European and African Research and Innovation Agenda: Addis Ababa Meeting

Dr. Efstratios Kalogirou was specially invited on behalf of the European Commission, Directorate General for Research and Innovation (Mrs Luisa Prista, head of the unit), to "A Joint European and African Research and Innovation Agenda on Waste Management—Waste as a Resource: Recycling and Recovery of Raw Materials," which took place in Ethiopia, on June 24 and 25, 2013 at the Hilton Hotel, Addis Ababa.

This high-level workshop brought together stakeholders from industry, research, and academia and governmental bodies from both Africa and Europe, as well as experts in the field, in order to tackle the issue of waste management from a policy, research/innovation, and business viewpoint. Around 70 participants from the entire continent of Africa participated. This one-and-a-half-day workshop was intended to stimulate project networking, to identify best/bad practices, to share experience and knowledge on existing and potential business cases, and to enhance cooperation and possible partnerships.

For both Africa and the European Union, it is mutually beneficial to cooperate and develop new initiatives on sustainable waste management. A common agenda for African and European research and innovation projects related to waste management and resource recovery is a worthy new initiative.

The main conclusions of the round tables included preparing Public-Private Partnerships (PPPs) between the European Union and African countries, with the main target being the advancement of sustainable waste management in Africa: focusing on recycling at the source, composting of preselected organic matter at the source (there are currently many African countries with fruits like bananas, mangoes, etc., which are being illegally dumped), and also developing sanitary landfills for post-recycling MSW, in order to avoid illegal dumping and illegal open area incineration in the streets.

Another main task is finding the best options for cooperation with the informal recycling sector (the scavengers), in order to officially include it in the recycling industry in Africa. Especially for highly developing countries like South Africa, Kenya, Ghana, and Nigeria waste-to-energy solutions were also taken into consideration within PPP targets.

Dr. Efstratios Kalogirou presented the successful business model of the developing country of Azerbaijan, mentioning a modern material recovery facility with a capacity of 220,000 tpa per year (Balakhani Industrial Park), in harmonic cooperation with a new, modern WTE plant in Baku, which, with a capacity of 550,000 tpa per year MSW, is the largest, newly constructed, state-of-the-art waste-to-energy plant in Eastern Europe, producing 231 GWh of energy annually as a renewable energy source. Azerbaijan is an emerging economy and an excellent example of what can be done toward sustainable waste management by developing nations like many countries in Africa (as described in detail in Chapter 6).

A second, final seminar in Brussels was held in November 2013. The outcome will be a roadmap of potential joint European-African research and innovation actions identified in the seminars.

7.1.2 Joint European and African Research and Innovation Agenda: Brussels Meeting

Dr. Efstratios Kalogirou was specially invited on behalf of the European Commission, Directorate General for Research and Innovation (Mrs Luisa Prista, head of the unit), to "A Joint European and African Research and Innovation Agenda on Waste Management—Economic opportunities on Turning Waste into a Resource," which took place in Brussels, Belgium, on November 25, 2013 at the Hotel Le Plaza.

Around 150 participants from 35 different countries in Africa and Europe participated in the second workshop in Brussels. Both workshops intended to stimulate networking projects, and possible partnerships among stakeholders (public and private sector, decision makers from governmental authorities, local industries, research institutes, universities, etc.).

Especially for highly developing countries like South Africa, Kenya, Nigeria, and Ghana, waste-to-energy solutions were also taken into consideration within PPP targets.

7.1.3 The KOSHE WTE Project at Reppi, Addis Ababa

The planned waste-to-energy facility at Reppi is located within the open dumping site and will treat roughly 1320 tons of waste a day. The facility is located in the shallowest area of the dumpsite, within a 7-hectare area out of the total 37-hectare dumpsite. The project is located within a vacant brownfield area, which was used to dump, burn, and dispose of waste without any environmental protection.

The Reppi facility started construction in January 2015 on the dumping site to eliminate the additional cost of transporting waste from the transfer station and also to decrease the environmental impact by diverting waste sent to landfills or open dumping sites. The energy needs of Ethiopia are expanding rapidly and the state must have access to a diverse range of energy sources, including new technologies like waste-to-energy (Sky Scraper City, 2016).

A photorealistic image of the Addis Ababa WTE plant is shown in Figure 7.1.

Main technical characteristics

- The total project cost is estimated to be about USD120 million, including the transmission line.
- The construction schedule is 24 months.
- The Ethiopian Electric Power Corporation (EEPCO) is the executing agency.
- The Ethiopian government is financing the estimated project cost needed to procure the necessary materials.
- Both temporary and permanent impacts are identified in the project areas. All impacts have a net positive when compared to the current system of waste disposal. Since the facility is a transition from an open dumping system to a modern waste disposal and energy recovery system, it improves the current use of the site.
- Conclusions: The WTE plant, after commission, will have a throughput of 385,000 tons per annum (tpa) and is designed to treat residual

FIGURE 7.1 Photorealistic image of the Addis Ababa WTE plant.

> municipal and commercial solid waste, and other similar waste types, using proven, high-efficiency waste combustion technology with energy recovery.

The site itself has been used as an open dumpsite and has served as the only landfill site for Addis Ababa for over 45 years. It is an area of vacant brownfield land with little ecological or visual value in its present state. The WTE facility will cover 7 hectares of the total 37-hectare open dumpsite. The proposed facility is in compliance with the intentions of the Ethiopian Government to promote sustainable methods of waste management and the WTE plant will provide essential infrastructure to help Addis Ababa meet its waste management targets.

Taking into consideration the net positive environmental impact and the benefits associated with the Reppi WTE Facility, the latter will be a major improvement for waste management services in Ethiopia, providing a state-of-the-art (and first) WTE plant in Africa.

It is also vital in reducing carbon emissions and creating a better condition for solid waste disposal in the capital. The project, which is expected to create jobs for many youths, will be one of the largest power generation sites in sub-Saharan Africa of its kind.

Some noteworthy photographs from the building period of the first WTE plant in Ethiopia follow below in Figures 7.2 through 7.13.

FIGURE 7.2 Installation of air pollution control (APC) systems of the Addis Ababa WTE plant.

FIGURE 7.3 View of the city of Reppi during the construction of the Addis Ababa WTE plant.

FIGURE 7.4 Construction phase of the Addis Ababa WTE plant.

FIGURE 7.5 Stack installation of the Addis Ababa WTE plant.

FIGURE 7.6 Installation of the combustion chamber of the Addis Ababa WTE plant.

FIGURE 7.7 Construction of the waste bunker of the Addis Ababa WTE plant.

FIGURE 7.8 Construction of the waste bunker of the Addis Ababa WTE plant.

FIGURE 7.9 Construction phase of the Addis Ababa WTE plant.

FIGURE 7.10 The local dumpsite from which waste will be diverted to the Addis Ababa WTE plant.

FIGURE 7.11 Steam turbine (generator) of the Addis Ababa WTE plant.

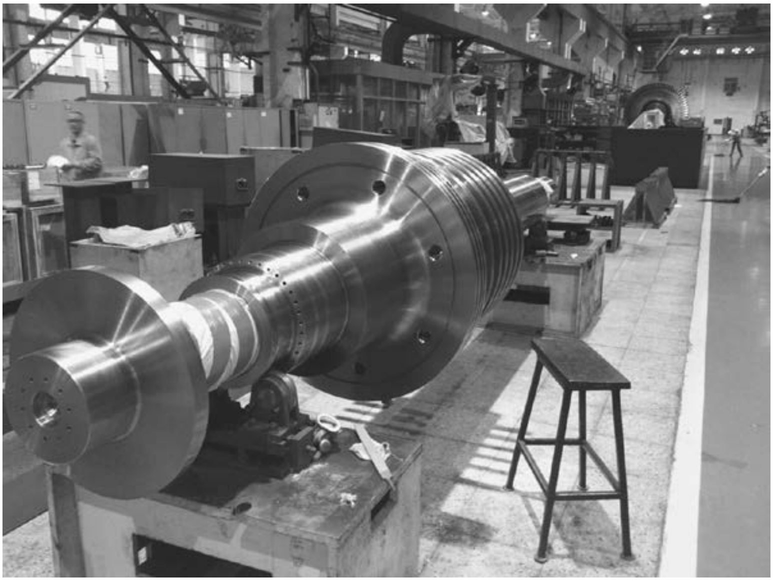

FIGURE 7.12 Installation of turbine components of the Addis Ababa WTE plant.

FIGURE 7.13 The crane that delivers waste from the bunker to the combustion unit of the Addis Ababa WTE plant.

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8 Environmental Impact of Waste-to-Energy

Carlo Vandecasteele and Chantal Block

An important aspect of MSW treatment is its environmental impact, which plays a major role in deciding on the selection of a particular waste treatment or management option. WTE installations (MSW combustors) impact the environment mainly by polluting air and generating solid residues, while water pollution is, in general, less important.

8.1 AIR POLLUTION

Around 1975, flue gas cleaning of municipal solid waste (MSW) combustors was essentially limited to thorough dust removal; little effort was made to remove toxic gases. The negative effects of air pollution in general by waste combustors were gradually recognized. By the end of the 1970s, it was clear that polychlorinated dibenzodioxins and dibenzofurans (PCDD/Fs), or dioxins, were being emitted from older incinerators. As these persistent organochlorines pose a serious risk to human health, they were a major concern for environmentalists, and later on for the general population. These concerns resulted in increasingly severe emission and immission standards, and waste combustors were thus equipped with high-performance, state-of-the-art flue gas cleaning equipment. To date, it is completely possible to construct and operate a modern waste-to-energy (WTE) plant that complies with the stringent emission limit values (ELVs) covered in Chapters 2 and 3.

8.1.1 Emissions

The major pollutants emitted by a WTE installation include HCl, SO_2, SO_3, NO, and NO_2 (which result from the oxidation of chlorine, sulfur, and nitrogen in waste), as well as CO and organic compounds (total organic carbons), including PCDD/Fs, tar, and soot (which result from incomplete combustion). Moreover, toxic metals (cadmium, mercury, antimony, arsenic, lead, chromium, cobalt, copper, manganese, nickel, vanadium, selenium) may be found in the flue gas in particulate matter (fly ash) or in the gas phase. The emissions depend on the waste composition, the design and operating conditions of the combustor, and the flue gas cleaning. To minimize emissions, suitable combustion conditions and extensive flue gas cleaning are required, as described in Chapter 3.

In state-of-the-art combustors/WTE plants, concentrations (expressed in mg/Nm^3) of the relevant pollutants in the stack gas are well below the emission limits, as shown in Table 8.1 for the Indaver grate furnace combustors, with three grate furnace lines, in Doel, Belgium (one grate furnace line is shown in Figure 8.1) (Indaver, 2017a;

TABLE 8.1
Emissions of Indaver grate furnace, Doel, Belgium for 2014 (Indaver, 2017a) and emission limit values (Directive 2000/76/EC)

Pollutant	Emission (mg/Nm³)	Limit Value (mg/Nm³)	Emission in % of Limit Value
Dust	1.0	10	10.0
CO	9.2	50	18
TOC	0.4	10	4.0
HCl	0.5	10	5.0
SO_2	1.1	50	2.2
NO_x	142	200	71
Cd, Tl	<0.0085	0.05	<17
Hg	0.0005	0.05	1.0
Metals	0.08	0.5	16
Dioxins (TEQ/Nm³)	0.0075	0.1	7.5

Van de casteele et al., 2007). For each pollutant, the table provides the emission concentration (2014), the ELV (Directive 2000/76/EC), and the emission in percent of the ELV. All emissions considered are close to or (significantly) below 20% of the ELV, except for NO_x, which is about 70% of the ELV. These values are typical for state-of-the-art WTE installations, with NO_x emissions typically much lower than depicted in the table (MVV-Energie, 2015; Vehlow, 2015). Because of lesser public perception problems with the other pollutants, this section will mainly focus on PCCD/Fs and NO_x.

Table 8.1 shows emissions from the Indaver plant in Doel, Belgium, from 2015.

Figure 8.1 shows the flowchart of the Indaver plant in Doel, Belgium.

8.1.2 PCDD/Fs, Dioxins

8.1.2.1 Properties and Toxicity

Dioxins is the collective name for (PCDD/Fs), which include a total of 210 compounds (congeners), 75 of which are PCDDs and 135 are PCDFs.

Figure 8.2 gives the structure formula of PCDDs and PCDFs. These compounds were never produced intentionally as marketable products but are formed during industrial and combustion processes.

Important physical and chemical properties of PCDD/Fs include the following:

1. They are quite resistant to (photo)chemical and biological breakdown and are therefore persistent in the environment and belong to the group of persistent organic pollutants (POPs).
2. Their solubility in water is low and decreases with the degree of chlorination which ranges from 1 to 8.
3. They accumulate in fat tissue of animals, so more elevated concentrations are found in species higher up in the food chain (biomagnification).

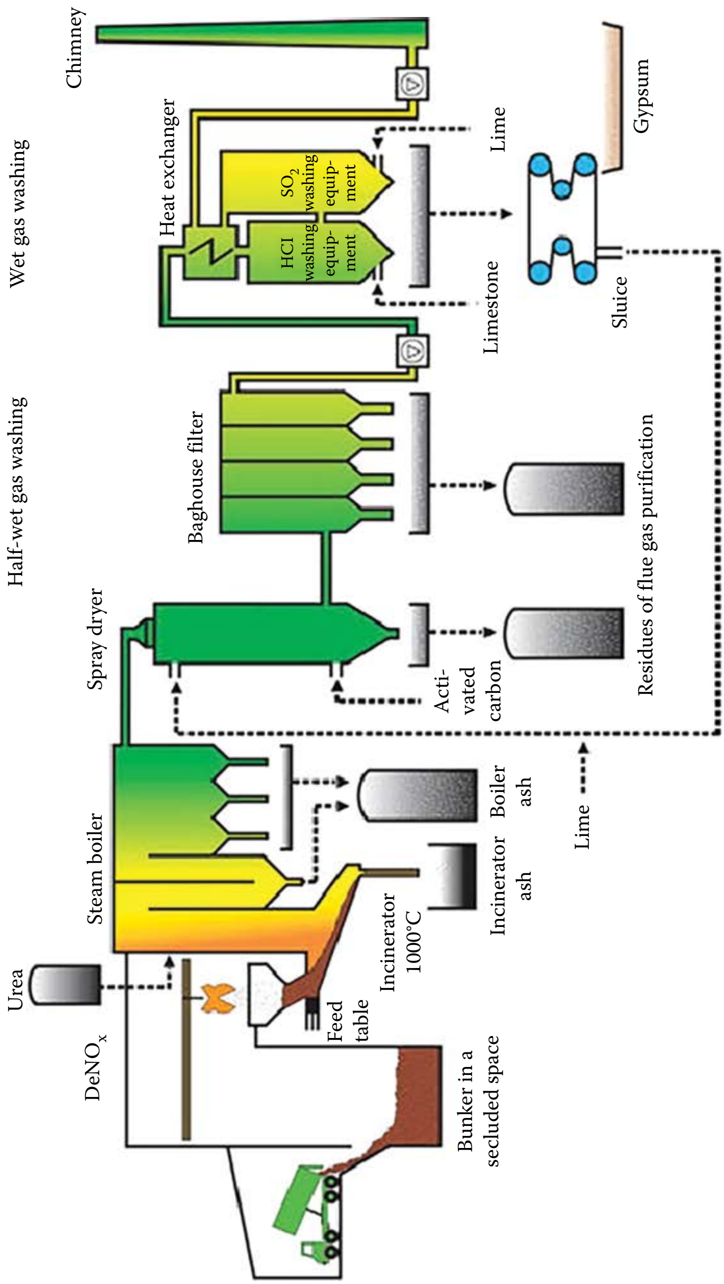
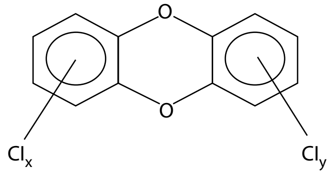


FIGURE 8.1 Grate furnace incinerator. (Indaver, 2017b, Roosteroven: Thermische verwerking met energieterugwinning, Indaver.be.)



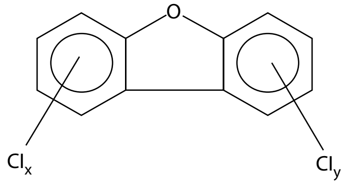


FIGURE 8.2 Polychlorinated dioxins (top) and polychlorinated furans (bottom).

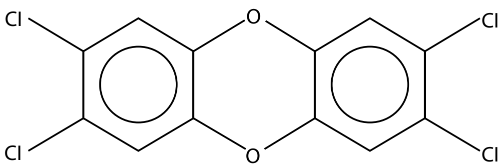


FIGURE 8.3 2,3,7,8-TCDD (2,3,7,8-tetrachlorodibenzo-p-dioxin).

4. Their volatility is low and decreases with the degree of chlorination.
5. In the environment, they occur in the air, mainly bound to (ash) particles rather than in the gas phase; in ground and surface water, they are mainly bound to suspended particles, sludge, and soil. The distribution in and between these environmental compartments is related to the physical and chemical properties mentioned.

The toxicity-weighted mass of a mixture of congeners is expressed in toxic equivalent concentration (TEQ). To this end, toxic equivalency factors (TEFs), values that express the toxicity of a given PCDD/F (congener) in terms of the most toxic congener 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD), ared used. See Figure 8.3, to which a TEF = 1.00 is given. TEF values are given for 17 PCDD/Fs (called the "dirty 17"), ranking from 0.0001 to 0.5, as shown in Table 8.2, which outlines the TEF values from the World Health Organization (WHO) (Bundesministerium fur Umwelt, 2013; Umwelt Bundesamt, 2017), and which are most frequently used but differ for some congeners. To calculate the TEQ concentration in ng/m^3, the concentration of each congener in the list is multiplied by the TEF, and the results are added.

8.1.2.2 Formation of PCDD/Fs during Waste Combustion

It is generally assumed that the PCDD/Fs in the incoming waste are destroyed during combustion and that new PCDD/Fs are formed (Everaert and Baeyens, 2002; McKay, 2002) during the cooling process of the flue gases. Over the last 20 years, much research has been devoted to unraveling the formation mechanisms of

TABLE 8.2
TEF Values from WHO and NATO

Formula	WHO-TEF[a]	NATO-TEF[b]
PCDDs		
2,3,7,8-TCDD	1	1
1,2,3,7,8-PCDD	1	0.5
1,2,3,4,7,8-HxCDD	0.1	0.1
1,2,3,6,7,8-HxCDD	0.1	0.1
1,2,3,7,8,9-HxCDD	0.1	0.1
1,2,3,4,6,7,8-HpCDD	0.01	0.01
OCCD	0.0003	0.001
PCDFs		
2,3,7,8-TCDF	0.1	0.1
1,2,3,7,8-PCDF	0.03	0.05
2,3,4,7,8-PCDF	0.3	0.5
1,2,3,4,7,8-HxCDF	0.1	0.1
1,2,3,6,7,8-HxCDF	0.1	0.1
1,2,3,7,8,9-HxCDF	0.1	0.1
2,3,4,6,7,8-HxCDF	0.1	0.1
1,2,3,4,6,7,8-HpCDF	0.01	0.01
1,2,3,4,7,8,9-HpCDF	0.01	0.01
OCDF	0.0001	0.001

Source: Umwelt Bundesamt, 2017, Dioxindatenbank. dioxindb.de (accessed January 2017).

[a] TEF-values WHO, 2005.

[b] Umwelt Bundesamt, 2017.

PCDD/Fs in the post-combustion stages of waste combustors. Most research was performed in lab-scale installations. Three PCDD/F formation mechanisms were suggested: (1) homogeneous (gas–gas phase) condensation of precursor molecules; (2) heterogeneous (gas–solid phase) condensation of precursor molecules; and (3) direct formation from carbon in ash particles, which is called de novo synthesis (Huang and Buekens, 1995, Stabnirem 2004, Altarawneh et al., 2006). PCDD/F fingerprints—that is, graphical representations of the concentration of the different PCDD/F congeners analyzed—are distinct for each mechanism. Homogeneous precursor condensation (with both precursors in the gas phase) takes place in the 400–800°C range, typically yields more PCDFs than PCDDs, and strongly favors lower chlorinated homologues (Nakahata and Mulholland, 2000; Wikstrom et al., 2004a,b; Ryu et al., 2006). In heterogeneous precursor condensation (with one precursor in the gas phase and the other adsorbed to the solid phase) and de novo synthesis, which occur typically in the 200–400°C temperature range, higher chlorinated homologues are favored (Wikstrom et al., 2004b), as the formed PCDDs and PCDFs can remain adsorbed in the solid phase for some time and may therefore undergo chlorination before release (aging). Heterogeneous precursor condensation typically yields more PCDDs than PCDFs (Huang and Buekens, 1995), whereas de novo synthesis yields more PCDFs than PCDDs (Vermeulen et al., 2014).

8.1.2.3 Prevention and Abatement

Several prevention or abatement techniques exist, which include the following:

- In principle, PCDD/F formation can be prevented by removing all waste that contains chlorine, polyvinyl chloride for example, before combustion. However, this is not very effective in general, as many sources of chlorine are present in waste.
- Residence time at a temperature of at least 850°C should be at least 2 s to assure destruction of organic compounds, including PCDD/Fs, from the waste. Subsequently, the flue gases should be rapidly cooled from 850°C to 200°C in order to avoid PCDD/Fs forming again.
- In flue gas cleaning, PCDD/Fs may be collected
  - On a filter at $T < 140°C$
  - By injection of activated carbon in the flue gases to adsorb PCDD/Fs. The activated carbon adsorbs the PCDD/Fs and is collected along with other flue gas cleaning residues on baghouse filters. This is the most frequently applied abatement technique.
- Catalytic oxidation ($TiO_2/V_2O_5/WO_3$) can be applied to destroy PCDD/Fs according to

$$\text{dioxin} + O_2 \rightarrow CO_2 + H_2O + HCl \tag{8.1}$$

  This may be combined with $deNO_x$.
- Research is being conducted on selective adsorbents with a complex pore structure, with macro (500 nm), meso (25 nm), and micro (1 nm) pores for future use as adsorbents for PCDD/Fs.

8.1.2.4 Sources and Health Effects

The Flanders Environment Agency (VMM, 2015a,b,c) annually publishes the major sources of PCDD/F emissions in Flanders. In 2015 the three major sources were (in order of decreasing importance): (1) home heating (66%), (2) industry (24%), and (3) traffic (7%). Although older incinerators were once a primary source of PCDD/F emissions, this is no longer the case as the modern WTE combustors have to comply with the emission limit of 0.1 ng TEQ/Nm^3. In 2015 the overall dioxin emission of MSW combustion in Flanders was estimated at only 0.5 g TEQ, which is only 1.9% of the total PCDD/F emissions (VMM, 2015a,b,c). Also, in other countries where the same emission limit applies, the relative contribution of WTE is comparable or even lower, as Flanders combusts a large fraction of its MSW (28% in 2015) (Ovam, 2015).

A study in the United States by Dwyer and Themelis (2015), showed that by 2012 the dioxin emissions of the U.S. WTE industry had been reduced to 0.54% of all controlled sources. The 89% of the total dioxin emissions was due to three major noncontrolled sources: landfill fires, forest fires, and backyard burning.

VMM estimated that for Flanders, Belgium, food was the primary means of exposure to PCDD/Fs (about 95%). Inhalation of air and drinking of water contributed less than 5%, and ingestion of soil and dermal contact constituted less than 2% of the PCDD/F intake.

A review of relevant literature (Block et al., 2013) considered three different approaches to estimate the health effects of PCDD/Fs by waste combustors. These include the following:

- Monitoring so-called biomarkers (PCDD/F and polychlorinated biphenyls [PCBs] concentrations in tissue, blood plasma, breast milk, and urine) in people living close to or working in the installation (Schumacher et al., 2002, 2004a,b; Mari et al., 2007; Ferre-Huguet et al., 2007)
- Calculating the incremental exposure to pollutants by means of distribution and exposure models (Karademir, 2004)
- Using models for exposure–effect relationships based on epidemiological data to estimate disease incidences from direct (air) and/or indirect (food) exposure (Roberts and Chen, 2006; Forastiere et al., 2001; Cangialosi et al., 2008)

A summary of the available information is provided as follows:

- Concentrations of biomarkers in people living close to or working in a waste combustor plants are comparable to or even lower than in nonexposed populations (Mari et al., 2007).
- The incremental PCDD/F intake for people living within 10 km of the WTE plant was estimated at 3.0×10^{-5}–0.081 pg TEQ/(kg body weight/day), where the tolerable daily intake set by the WHO is much higher, 2 pg TEQ/(kg body weight/day) (Karademir, 2004; Schumacher et al., 2004a,b).
- The maximum additional cancer risks due to PCDD/F (and cadmium) emissions in a 10×10 km^2 area surrounding the waste incineration plant was almost zero (0.0016 in 1,000,000 for exposure), much below the acceptable level used by the U.S. Environmental Protection Agency, which is 1 in 1,000,000 (Cangialosi, et al., 2008).

Van Caneghem et al. (2010) compared the amount of different persistent organic pollutants (PCDD/Fs, PCBs) in the input and output of an MSW combustor. It appeared that the amount of PCDD/Fs in the flue gas and ash granulates, the fractions that may enter the environment, were 60–400 times lower than their estimated amount in the combusted waste. The majority of the PCDD/Fs were found in boiler ash, flue gas cleaning residues, and other ash fractions that further needed solidification/stabilization, as analyzed in Chapter 3.

8.1.3 NO_x

The formation of NO_x in waste combustion originates from the nitrogen compounds present in the waste. Emission standards vary between 35 and 125 mg/Nm^3 in Japan and 200 mg/Nm^3 in most EU countries. It appears from the emissions given in Table 8.1, that NO_x has the highest percent of ELV of all regulated emissions in WTE.

As analyzed in Chapter 3, NO_x can and must be removed from the flue gas by selective catalytic reduction (SCR) or by selective noncatalytic reduction (SNCR) in order to comply with the actual ELV of 200 mg/Nm^3. In the early 1990s, 300–400°C was needed for sufficient NO_x destruction efficiency, but low-temperature catalysts reached 90% removal efficiency at only 160°C just a few years later. Lower temperatures reduce the energy losses by flue gas reheating; however, care has to be taken to ensure that no ammonia salts condense on the catalyst and clog or poison it. Replacing SNCR with SCR typically decreases NO_x values from 110 mg/Nm^3 to 44 mg/Nm^3. Improved SNCR with a lower NH_3 slip can also be reached by carefully optimizing SNCR.

Van Caneghem et al. (2016) SCR and SNCR are compared from an integrated pollution prevention and control (IPPC) perspective, estimating overall environmental impacts in different impact categories. The starting points of the study were

- The NO_x reduction efficiency of SCR, up to 90% in tail-end configuration, exceeds that of SNCR, which is typically 50% (Villani et al., 2012).
- Production, construction, and operation of the SCR unit also causes indirect (i.e., not in the combustion process, but in other phases of the life cycle) pollutant emissions and consumption of resources.

The conclusion was that replacing SNCR with tail-end SCR reduces the direct environmental impact of the combustor, that is, the environmental impact of the NO_x emitted at the stack in the impact categories acidification, eutrophication, and photo-oxidant formation, as expected from the lower NO_x emissions in the case of SCR. SCR, however, involves greater indirect impacts (i.e., impacts related to the production and operation of the catalyst unit) than SNCR in all impact categories, mainly due to the need to reheat the combustion gas.

8.1.4 Contribution of the Emissions of WTE to Air Pollution

Since the mid-1990s, the hazardous waste incineration sector has complied with the stringent ELVs from the former Waste Incineration Directive (Directive 2000/76/EC), which were later included in the Industrial Emissions Directive (2010/75/EU) on industrial emissions and integrated pollution prevention and control.

In a study for the European Union for Responsible Incineration and Treatment of Special Waste (EURITS), Block et al. (2013) estimated the share of waste combustion in the total pollutant emissions for the EU27, the United Kingdom, and Flanders (Belgium).

Table 8.3 shows the two sectors that contribute the most to total emissions of NO_x, SO_2, particulate matter, CO, heavy metals, PCDD/Fs for the EU27, along with the contribution of waste combustion. It appears that traffic, electricity and heat, industry, and agriculture are the major pollutant emitters. The share of total waste incineration to pollutant emission is very low (<1%) for NO_x, SO_2, and particulate matter, low (2%) for CO, and moderate (13% and 26%) for heavy metals and PCDD/Fs, respectively.

TABLE 8.3
Contribution of the Most Important Sectors for the Total Emissions of NO_2, SO_2, PM, CO, Heavy Metals, and PCDD/Fs for the EU27 (2011)

NO_2	%	SO_2	%	PM	%	CO	%	HM	%	PCDD/Fs	%
TR	58	E + H	47	IN	30	TR	39	TR	41	IN	37
E + H	17	IN	36	AG	24	RC	35	IN	39	RC	36
WI[a]	*0.28*	*WI*	*0.12*	*WI*	*1.0*	*WI*	*1.9*	*WI*	*13*	*WI*	*26*

[a] Italic is used to stress waste incineration (subject of this text) as opposed to other relevant polluting sectors.

TR = traffic; E + H = energy and heat; IN = industry; AG = agriculture; RC = residential combustion; *WI* = waste incineration.

Table 8.4 details the different types of waste combustion contributing to the total emissions of waste combustion for the considered pollutants for the EU27. The following subcategories of waste combustion are considered:

- Hazardous industrial waste, 2000 (Eurits, 2002)
- Other industrial waste (OIW): industrial waste other than hazardous waste + clinical waste (Eurits, 2002; CEIP, 2012)
- MSW
- Other: small-scale domestic and private waste combustion and cremation (with no state-of-the-art flue gas cleaning systems as described in Chapter 3)

It is clear from Table 8.4 that the combustion of MSW, which is very well-controlled and regulated (the modern WTE plants), is a negligible source within the category of waste incineration. The contributions to air pollution of the subcategories OIW and Other (small-scale waste combustion + cremation with no state-of-the-art flue gas cleaning systems) are significantly higher. The highest emissions appear

TABLE 8.4
EU27: Contribution of the Incineration of a Number of Waste Categories to the Total Emissions of Different Pollutants from Waste Incineration

	NO_2%	SO_2%	PM%	CO%	HM%	PCDD/Fs%
HIW	4.9	2.1	0.06	0.02	0.6	0.12
OIW	15.7	52.2	34.8	5.8	81.5	24.2
MSW	5.6	4.9	0.06	0.14	6.4	0.1
OT	73.8	40.7	65.1	94.0	11.5	75.6

HIW = hazardous industrial waste; OIW = other industrial waste; MSW = municipal solid waste; OT = other.

to originate from uncontrolled combustion (backyard burning, small-scale on-site incineration of production waste).

8.1.5 Conclusion

It can be concluded that, although WTE is a source of air pollution, the contribution of a state-of-the-art waste combustor to overall air pollution is very limited and almost negligible, even for dioxins and NO_x. While it is not possible to rule out adverse health and environmental effects from modern, well-regulated waste combustors with complete certainty, any potential damage to the health of those living close by is likely to be negligible, if detectable, according to the U.K. Health Protection Agency (2009).

8.2 RESIDUES

MSW combustion leads to significant amounts of residues: bottom ash (typically 25% of the original MSW mass or 10% of the volume) and boiler ash and flue gas cleaning residue (in total about 3%–5% of the original waste mass, depending on the waste composition and the antipollution system used, as described in Chapter 3). In principle, these residues can be landfilled, the bottom ash on a landfill for non-hazardous waste, the boiler ash and flue gas cleaning residue as hazardous waste, usually after treatment, for example, by solidification/stabilization. There are several reasons why recycling of bottom ash is more appealing than landfilling; these include the following:

- Bottom ash contains several components that are valuable and recyclable.
- Landfill costs, which generally increase with time, are avoided.
- Recycling is a higher priotrity in the waste treatment hierarchy than landfilling.

8.2.1 Bottom Ash

Municipal solid waste incineration (MSWI) bottom ash can be separated fairly easily into fractions according to composition and size for recycling. Typical fractions are ferrous and nonferrous metals, large granulates (6–50 μm), smaller granulates (2–6 μm), and a sand fraction (<2 mm) (Van de casteele et al., 2007; Verbinnen et al., 2016). In order to improve the recovery of metals, novel methods of bottom ash treatment were developed (De Vries et al., 2012; Bourtsalas, 2013). After separation, the bottom ash fractions can be recycled into roughly four types of engineering applications: (1) loose construction aggregates; (2) replacement for sand, gravel, or cement in construction material; (3) raw material in cement production; and (4) feedstock for the production of ceramic material. Some properties of the bottom ash or bottom ash fraction may limit its use in these applications: For some, leaching of heavy metals or chlorides is the major limitation (barrier); for others, the presence of metals has a negative influence on the obtained product quality. In addition to these four recycling options, bottom ash can also be used in landfills, for example, as landfill cover or construction of on-site roads. These applications, although very useful, will not be discussed further, as the disposal of waste in landfills will decrease in the future in countries where WTE plants are located, so demand for bottom ash on landfills will significantly decline.

8.2.1.1 Use of Bottom Ash in or as Construction Material

8.2.1.1.1 Loose Construction Aggregates

Some bottom ashes or bottom ash fractions can be used directly (that is, without significant further treatment) as loose construction aggregates in base layers for road construction and construction of large sound and noise barriers, embankments, artificial slopes, and so on. Many laboratory investigations have analyzed the mobility of pollutants with respect to the related environmental regulations (Hjelmar et al., 2007; De Windt et al., 2011; Dabo et al., 2009; Izquierdo et al., 2008; Birgisdottir et al., 2006; Toller et al., 2009). In general, the leaching of the heavy metals copper, lead, zinc, and nickel and of the metalloids antimony, chromium, and molybdenum is most problematic, and, in most cases, protective measures such as liners are required to prevent the leachate of these metals and metalloids present in the bottom ash from entering the surrounding soil. The performance of bottom ash (fractions), mainly leaching, as bulk/loose construction material was also evaluated by constructing large-scale test sites with bottom ash as a sublayer or base layer for roads (Hjelmar et al., 2007; De Windt et al., 2011; Dabo et al., 2009). These applications appeared to be acceptable with some restrictions, and after a long time minimum leaching values were reached, comparable to those of a reference road built with natural aggregates (De Windt et al., 2011; Dabo et al., 2009; Verbinnen et al., 2016). From an LCA assessment of the environmental impact of roads constructed with and without MSWI bottom ash replacing gravel (Birgisdottir et al., 2006) as a sub-base layer, it appeared that the environmental impact of both scenarios was comparable. Although using bottom ash can affect groundwater quality, the pollution potential of spreading de-icing salt is one order of magnitude higher. Another environmental assessment by Toller et al. (2009) also showed that MSWI bottom ash is suitable for replacing natural resources in base layers for road construction or as drainage material in landfills. The most important differences with the reference scenario were (1) reduced use of natural resources and energy and (2) increased leaching of heavy metals when using bottom ash.

The studies mentioned show that using MSWI bottom ash as loose construction aggregates is technically feasible, but leaching of heavy metals and/or chlorides and sulfates increased, leading to higher direct toxicity impact than for the reference scenario. Therefore, measures to prevent water from reaching the bottom ash layer and/or collection and treatment of the leachates are required, in addition to aftercare of the construction sites so that they would, in fact, resemble somewhat controlled landfills. In March 2012, the Dutch Waste Management Association (*Vereniging Afvalbedrijven*), representing the WTE plant operators in the Netherlands, signed the Green Deal on sustainable application of WTE bottom ash (*Green Deal Verduurzaming Nuttige Toepassing AEC-Bodemas*) with the government (Dutch Ministry, 2012), committing themselves to improving the quality of the bottom ash and extending opportunities for their application. The main parts of this agreement are:

1. By January 1, 2017, 50% of the bottom ash should be applied in applications with neither restrictions nor protective measures. By January 1, 2020, no more bottom ash can be recycled in restricted/protected applications, meaning that the current International Building Code (IBC) technology (isolate, monitor, and control), for which complicated construction, extensive aftercare, and monitoring are needed, will come to an end. This also implies that bottom ash quality should be improved mainly with respect to lower leaching. One of the other articles of the agreement states that landfilling of bottom ash should be limited to 15% of the total mass.
2. The percentage of nonferrous metals to be recovered from the bottom ash fraction with particle size greater than 6 mm should be increased to above 75% by January 1, 2017. A goal for the fraction with particle size less than 6 mm has not yet been set.

For the Netherlands, the Green Deal implies that after January 1, 2020, bottom ash can no longer be applied with IBC technology as loose construction aggregates. In many other countries (e.g., Belgium), this was never permitted. The Green Deal also sets a maximum limit for bottom ash landfilling and a minimum limit for nonferrous metal recovery. This is an important measure to encourage improvement of bottom ash quality and to find new and better technologies and applications for bottom ash recycling.

8.2.1.1.2 Use as Sand/Gravel Replacement in Structured Materials

Bottom ash can also be used in structured materials to replace natural aggregates in concrete. The two most important conditions of the final product are sufficient compressive strength, depending of the application, and leaching of heavy metals not exceeding the environmental limit values. Meyer (1986) was among the first to show the detrimental effect of the presence of metallic species (e.g., metallic aluminum or zinc) from MSWI bottom ash on the compressive strength of concrete due to the formation of popouts. These popouts occur when metallic species react with alkali salts present in the cement to form aluminum (hydr)oxides, ettringite, hydrogen gas, and hydrocalumite. The expansion caused by the formation of these compounds may rupture the concrete surface (Nielsen et al., 2009). In an attempt to solve this problem, Pera et al. (1997) suggested pretreating the bottom ash. The 4–20 mm fraction of MSWI bottom ash was used to produce two types of concrete, with 50% and 100% replacement of the natural gravel. The bottom ash was immersed in a sodium hydroxide solution for 15 days to oxidize all of the metallic aluminum present. When not pretreated (bottom ash was directly introduced into the concrete), swelling and cracking of the concrete species was observed due to the formation of hydrogen gas by oxidation of the metallic aluminium, as shown by Meyer (1986). Concrete with the pretreated bottom ash as aggregates no longer showed the same swelling and cracking. Nevertheless, regardless of this pretreatment, the 28-day compressive strength decreased with the percentage of bottom ash, and both the 50% and 100%

gravel replacement exhibited lower compressive strengths than without bottom ash, although in both cases the required 28-day compressive strength of 25 MPa was still reached. Since then, many other researchers have investigated the possibilities for using bottom ash in concrete. Keppert et al. (2012) produced concrete with 10% of the used sand replaced by the 0–4 mm fraction of MSWI bottom ash. This did not significantly affect the short-term strength development (after 28 days), but it did affect the long-term behavior (90 days), probably due to the presence of metallic aluminum causing the formation of hydrogen bubbles, although this was not visually observed. A similar negative effect on the concrete strength was observed by Müller and Rübner (2006) and also attributed to the reaction of aluminum with the cement paste to form hydrogen gas. In addition to this reaction, an alkali-silica reaction (ASR) was also observed between glass compounds in the bottom ash and the alkaline cement paste, leading to the formation of a calcium silicate hydrate (CSH) gel that swells upon contact with water and causes expansion and cracking. The damage related to ASR, however, was less severe than that due to hydrogen gas formation. Other studies also acknowledged the detrimental effect of metallic aluminum and other metals on the compressive strength of concrete. Nielsen et al. (2009) established that in order to avoid the detrimental effect on the compressive strength of the concrete, the concentration of metallic aluminum in the bottom ash fraction should not exceed 1%. When complying with that criterion, they observed no popouts, even after 2.5 years of testing. Saikia et al. (2008) tested the leaching behavior of the concrete produced with the sand fraction (0.1–2 mm) of MSWI bottom ash. The loose bottom ash sand fraction showed that leaching concentrations for cadmium, chromium, copper, molybdenum, and antimony were above the limit values for recycling waste as construction material. When the bottom ash sand fraction was incorporated into the cement mortar, leaching of most elements was reduced due to various chemical processes: formation of calcium metallates and metal hydroxides or incorporation in hydration products. Only the concentrations of copper and lead exceeded the limit values; this was attributed to the dissolution of these amphoteric elements in the high pH of the mortar, which was 12.5, compared to 10.5 for bottom ash.

These studies show that the main barrier to using MSWI bottom ash in concrete as a replacement for sand and/or gravel is the presence of a metallic species such as aluminum and zinc. These species are easily oxidized in alkaline environments, leading to the formation of hydrogen gas and expansive minerals, which causes cracks and popouts in the concrete structure, thus reducing its compressive strength. Reducing the amount of metallic aluminum and zinc in the bottom ash is therefore the main challenge to increase the amount of bottom ash that can be used as sand/gravel replacement.

8.2.1.1.3 Use as Cement Replacement in Structured Materials

Table 8.5 gives average concentrations of the main matrix elements in bottom ash (Crillesen and Skaarup, 2006).

Bottom ash is not only used as aggregate in concrete, but it can also (partially) replace cement. As a result, CO_2 and other pollutant emissions that would otherwise be generated in the cement production process are avoided. Due to the high amounts of silica and, to a lesser extent, calcium oxide, bottom ash can have pozzolanic or

TABLE 8.5
Average Concentrations of the Main Matrix Elements in Bottom Ash

Element	Concentration in Bottom Ash (%)
Si	16.8–27.4
Ca	5.12–10.3
Fe	2.11–11.5
Mg	0.19–1.18
K	0.72–1.16
Al	3.44–6.48
Na	2.02–4.80

Source: Crillesen, K., Skaarup, J., 2006, *ISWA Working Group Thermal Treatment*. Available: http://www.iswa.org/uploads/tx_iswaknowledgebase/Bottom_ash_from_WTE_2006_01.pdf

cementitious properties, but, like cement, it must be finely ground to increase the specific surface area and consequently the reactivity. Many studies were performed replacing ordinary portland cement (OPC) with bottom ash. In order to obtain a highly reactive material, the bottom ash is always milled to increase its specific surface area. Whittaker et al. (2009) produced concrete in which 10% or 40% of the OPC was replaced by MSWI bottom ash. Replacing 10% of the OPC did not influence the structural properties of the concrete, but 40% was detrimental to concrete strength. Krammart and Tangtermsirikul (2004) replaced 5% and 10% of cement in their concrete with bottom ash. Again, the compressive strength decreased with higher bottom ash percentages, which was attributed to the lower amount of $CaO/Ca(OH)_2$ in the bottom ash, resulting in the formation of less tricalcium silicate in the concrete and thus a lower compressive strength. Li et al. (2012) replaced between 10% and 50% of the OPC in blended cement with MSWI bottom ash. The mechanical properties obtained with the blended cement gradually decreased with increasing amounts of bottom ash, and it was advised to limit the bottom ash content to 30%. The leaching of heavy metals from the mortars complied with the relevant Chinese legislation, but it should be noted that the leachate concentrations would exceed European limit values. Collepardi et al. (2010) performed tests on the pozzolanic activity of ground bottom ash: They prepared concrete samples, replacing 20% of the OPC with ground bottom ash (mean particle size of 1.7, 3, or 5 μm) or other pozzolanic materials, that is, fumed silica or coal fly ash. The finest-ground bottom ash performed as well as fumed silica on the tested parameters (compressive strength, water permeability, chloride diffusion, and CO_2 penetration) and was comparable to, or better than, the OPC. The leaching of contaminants from the concrete matrix was below the European limit values.

These studies showed that untreated bottom ash acts as fine aggregates rather than cementitious material. Attempts were made to improve the compressive strengths of mortars produced with MSWI bottom ash through physical or chemical activation. Physical activation relies on intensive milling to increase the surface area available for reaction. Chemical activation is based on the addition of chemical agents capable of breaking down the structure of alumino-silicate minerals, releasing silicate and aluminate ions, which can thereafter be transformed into mechanically resistant phases. Onori et al. (2011) tried to activate bottom ash chemically by treating it with NaOH, KOH, $CaCl_2$, or $CaSO_4$. $CaCl_2$, and to some extent $CaSO_4$ showed the most positive effect on the development of the mechanical properties of the blended mortars. Mixtures with 20% of $CaCl_2$-activated bottom ash with OPC showed a higher compressive strength than the control mixture (containing no bottom ash); the compressive strength with 40% replacement was only slightly below that of the control mixture. $CaCl_2$ is known to promote the onset of pozzolanic reactions in cement mortars. The dissolved calcium can react with the amorphous, reactive silicates in the bottom ash to form the hydrated phases responsible for the compressive strength. Bertolini et al. (2004) replaced 30% of the OPC with ground bottom ash and, after comparing dry and wet ground bottom ash, observed higher compressive strengths for wet ground bottom ash than for dry ground bottom ash. This was due to hydrogen bubbles forming in the concrete made with dry ground bottom ash due to the oxidation of metallic aluminum (and other nonferrous metals) at alkaline pH. During wet grinding of bottom ash, hydrogen gas formation is already initiated, and it is completed to a large extent before the wet bottom ash is introduced to the concrete mix. Nonetheless, a large variability was observed with respect to the time required to terminate the hydrogen gas formation. When MSWI bottom ash is used as cement replacement in structured materials, the same problem arises as when it is used as sand/gravel replacement: The presence of metallic species causes the formation of hydrogen gas, which leads to popouts and cracks in the structure. Furthermore, the replacement of cement with bottom ash often leads to materials with a lower compressive strength. This is attributed to the lower reactivity of the bottom ash due to a lower specific surface area and/or the lower concentration of hydrating minerals.

The main challenges for using bottom ash as cement replacement thus include: (1) limiting the amount of metallic species and (2) activating the material for an increased formation of hydrated species. In practice, MSWI bottom ash is only sporadically used in reinforced concrete because the presence of high chloride concentrations in the bottom ash increases steel corrosion.

8.2.1.1.4 Use as Raw Material in Cement Production

The high concentrations of silicon, calcium, and aluminum minerals make bottom ash suitable for replacing raw materials in the production of Portland cement clinker. The use of CaO-bearing materials, such as MSWI bottom ash, instead of $CaCO_3$ as raw material can reduce CO_2 emissions from typical OPC production. Indeed, the heating of limestone releases CO_2 as it converts $CaCO_3$ into CaO and CO_2. The mixture used for clinker production needs to fulfil several requirements related to the ratio of silica to alumina and iron(III) oxide (silica ratio), the ratio of alumina to iron(III) oxide (alumina ratio), and lime saturation to meet the standards of the cement industry. Lam et al. (2010) mixed the components that usually make up the clinker mixture (i.e., limestone, sand, copper slag, and pulverized-fuel ash) with bottom ash. They used ash percentages between 2% and 8% and adapted the amounts of the other components accordingly to meet industry standards. Composed of up to 6% of bottom ash, the resulting clinker was comparable to OPC. The leaching behavior was also tested; all clinkers with bottom ash complied with the regulatory limits due to stabilization of the toxic elements in the clinker matrix. In similar experiments, Pan et al. (2008) produced OPC with and without bottom ash but limited the added percentage of bottom ash, which contains chlorine, to 3.5%, as the chloride concentration of the raw clinker mixture should not exceed 100 ppm on a mass base. The presence of chlorides during the high-temperature clinker-manufacturing process can also cause severe corrosion in the cement kiln. X-ray fluorescence analysis showed that the chemical composition of the clinker produced with bottom ash was identical to that of the clinker produced without bottom ash. However, the addition of bottom ash lengthened the setting time by 5%–15%. The compressive strengths of all concrete samples produced with bottom ash exceeded the standard required values for Portland cement (compressive strength higher than 281 kg/cm^2 after 28 days of curing) and did not differ significantly from the samples produced without bottom ash. The studies mentioned previously (Pan et al., 2008; Lam et al., 2010) show that bottom ash can serve as a suitable replacement for a part of the raw materials in cement production.

The main limitation for using large amounts of MSWI bottom ash in cement kilns is the presence of chlorides that can cause severe corrosion of the cement kiln and reduce the compressive strength of concrete prepared with this cement. However, using even low amounts of MSWI bottom ash (e.g., 5%) to replace raw materials in cement production can be sufficient to recycle all of the MSWI bottom ash produced.

8.2.1.1.5 Use to Produce Ceramics

MSWI bottom ash can be used to produce ceramic materials for use in building applications. Cheeseman et al. (2005) produced lightweight aggregates by the rapid sintering of MSWI bottom ash at temperatures between 1000°C and 1050°C, which gives aggregates good technical characteristics, such as density, water absorption, and compressive strength. The leaching of toxic elements from the sintered products was low, although the leaching of chromium, zinc, and cadmium was slightly higher than from the untreated bottom ash. The leaching of these elements could be further reduced by sintering at even higher temperatures (up to 1100°C), but this also changed other product properties, such as the density and water absorption of the aggregates. Bourtsalas et al. (2015) also produced ceramics from the fine (<4 mm) fraction of MSWI bottom ash by calcining it between 600°C and 1100°C; calcination at 1080°C provided the best structural properties. The pH-dependent leaching of ceramics produced at this temperature was compared with the pH-dependent leaching of untreated bottom ash. In the entire pH region tested (pH 1–11), leaching of copper, lead, and zinc was lower for the calcined samples than for the untreated samples due to the incorporation and encapsulation of the metals into newly formed glassy and crystalline phases, such as diopside, clinoenstatite, and andradite.

Other researchers have produced ceramics made of MSWI bottom ash by vitrifying the ash at temperatures between 1100°C and 1400°C. The obtained products are hard, dense, and amorphous, and the toxic elements are embedded in the amorphous matrix so that leaching of these elements is reduced. Ceramic materials like tiles and stoneware are subject to some aesthetic requirements, and it is uncertain whether these can be met by using bottom ash alone. Therefore, instead of producing ceramics from bottom ash alone, only part of the raw material (5%–10%) used to make ceramic materials (natural clays) may be replaced with bottom ash, as done by Rambaldi et al. (2010). This did not influence the technical properties of the produced ceramics and slightly lowered the required firing temperature. Attempts were also made to use vitrified bottom ash as a replacement for filler, sand, or aggregate in concrete mixtures.

The conclusions were that vitrified bottom ash ground to the appropriate size can replace up to 20% of filler material and up to 75% of gravel in concrete products. Replacement of sand did not appear to be possible, as the strength of the end product was negatively influenced. Although the use of vitrified bottom ash can save large amounts of natural materials and reduce the landfilling of MSWI bottom ash, it can be questioned whether the advantages outweigh the cost and the environmental impact of the energy-intensive vitrification process. From an economic and environmental point of view, it appears most advantageous to only use the smallest size fraction of MSWI bottom ash for this purpose (typically <2 mm or <4 mm), as this fraction usually presents most problems with regard to leaching of toxic elements. The best option seems to use the small size fraction of bottom ash to partially replace natural raw materials in the production of ceramics, as technical and aesthetical properties are more easily met than with bottom ash alone.

8.2.1.2 Overview of the Main Limitations

From this overview, it appears that each current MSWI bottom ash application has its specific requirements. For using bottom ash as loose construction aggregates, the main limitation is the leaching of heavy metals. When bottom ash is used as sand/gravel or cement replacement in structured materials, the main problem is the presence of metallic aluminum and/or zinc. These metallic species form hydrogen gas from water upon oxidation in alkaline environments, which can be detrimental to the compressive strength of the produced concrete. As a cement replacement, untreated bottom ash often shows too low hydraulic activity. MSWI bottom ash can be used to replace raw materials in cement production; the main barrier for this application is the presence of chlorides, which may cause enhanced corrosion in the cement kilns and are detrimental for cement quality. The major barrier for using bottom ash in the production of ceramic materials is the high cost of sintering or vitrifying the material, as well as the uncertainty about the aesthetic properties. Table 8.6 presents an overview of the main limitations for each engineering application of MSWI bottom ash, along with the corresponding treatment technologies.

A general, less evident challenge is that the current limit values for the recycling of MSWI bottom ash differ significantly among countries, even within the EU27. Finally, besides technical and environmental limitations, public acceptance of materials produced with bottom ash, a waste material, may constitute an additional barrier (Crillesen and Skaarup, 2006). Therefore, the implementation of European

TABLE 8.6
Overview of Main Chemical Barriers, Engineering Applications, and Treatment Technologies for MSWI Bottom Ash

Application	Main Barrier	Treatment Technologies
Loose construction aggregates	Heavy metal leaching	Dry/wet size separation Carbonation Mineral additives (Mild) heat treatment
Structured materials	Metallic Al/Zn (Cl content for reinforced concrete) (Heavy metal leaching)	Dry/wet size separation including eddy current separation
Cement production	Cl content	Dry/wet washing/extraction
Ceramics production	Heavy metal leaching	Heat treatment

Source: Verbinnen, B. et al. 2016. *Waste and Biomass Valorization.*

end-of-waste criteria for MSWI bottom ash (and other waste-derived materials) could be of key importance. Currently, in contrast to scrap metals, no end-of-waste criteria have been set for MSWI bottom ash. It may be assumed that when the end-of-waste criteria come into effect, this will boost the recycling of MSWI bottom ash.

8.2.2 Treatment Technology

Technologies to treat bottom ash for subsequent recycling were discussed in Chapter 3. Treatment technologies to overcome the aforementioned limitations were also recently reviewed by Verbinnen et al. (2016) and include

- Technologies for size separation of MSWI bottom ash and for the removal of metallic ferrous and nonferrous metals (copper, alumiun, zinc, lead, etc.): Many bottom ash applications preferably use only a limited size range of bottom ash, rather than the entire size range. The importance of removing metallic species for some applications was already previously demonstrated, and moreover, metal recovery is highly beneficial for economic reasons.
- Technologies for the removal of chlorides.
- Technologies for reducing the leaching of copper and oxyanion-forming elements, such as antimony, molybdenum, and chromium.

8.2.2.1 Boiler Ash and Flue Gas Cleaning Residues

Boiler ash and flue gas cleaning residue contain high concentrations of PCDD/Fs and heavy metals. Because of the low water solubility of PCDD/Fs and other POPs, their leaching usually does not present a problem. Leaching of heavy metals, however, typically exceeds the waste acceptance criteria for hazardous waste landfills. Therefore, treatment is needed before landfilling, which usually includes stabilization (converting hazardous waste into a more stable form [lower aqueous solubility, less toxic]) and solidification (creating a solid mass of either the original waste or waste that has been stabilized). Stabilization and solidification are often combined and called stabilization/solidification. This is usually done by adding water and cement to obtain a concrete-like material.

Figures 8.4 through 8.6 feature photographs from the island of Langøya in Norway where the stabilization of the fly ash from the WTE plant in Klemetsrud, Oslo, occurs.

According to Chen et al. (2009), stabilization mechanisms for heavy metals include

- Chemical incorporation due to formation and precipitation of species with low solubility, mainly metal hydroxides, for example, $Cu(OH)_2$, $Ca_2Cr(OH)_7$. This is the most important stabilization mechanism.
- Sorption of heavy metals on CSH gel. This is a sort of physical adsorption whereby positively charged heavy metals in pore water are attracted to the surface of negatively charged hydrated cement particles.
- Chemical adsorption, in which structural ions (e.g., Ca_2+ in crystal lattice) are replaced to form a solid solution.
- Physical encapsulation of heavy metal compounds (oxides, hydroxides, etc.) by CSH gel.

The solubility of the hydroxides of heavy metals is highly pH-dependent, but at the pH of the concrete containing the residues, the solubility of heavy metals is usually low enough to comply with the acceptance criteria of a landfill for hazardous waste.

FIGURE 8.4 Map and schematic of the island of Langøya.

FIGURE 8.5 Offshore photograph of the fly ash treatment plant in Langøya.

FIGURE 8.6 Fly ash treatment line in Langøya.

8.3 ENVIRONMENTAL COMPARISON OF WTE WITH LANDFILL AND RECYCLING

WTE has several important environmental advantages over landfilling of the MSW, which can be summarized as follows:

- Greenhouse gas emissions from WTE contribute less to climate change than those from landfills. Indeed, in WTE, carbon is largely emitted as CO_2, whereas in landfills CH_4 and CO_2 are generated and (partly) escape into the atmosphere. The global warming potential of CO_2 is indeed 21 times lower than that of CH_4, explaining its lower contribution to climate change than that of CH_4.
- It saves land, as significantly more land is needed for a landfill than for a WTE plant (only 4–7 hectares).
- It allows recycling of ferrous and nonferrous metals and granulates.
- From biomass in the MSW, (partially) renewable energy (steam or electricity) that can replace fossil fuel is produced. It is generally assumed that about 50% of the energy produced is biogenic due to biodegradable fraction and thus does not contribute to climate change.

In the waste hierarchy (Figure 8.7), WTE is situated with energy recovery, which is rather low—just above disposal (landfilling) but below recycling and reuse.

On the other hand, WTE should not be considered as a competitor to recycling. Some parts of MSW are suitable for recycling (paper, cardboard, plastics, metals, etc.) and can be collected separately. The residual waste is usually unsuitable for recycling due to high costs, low quality of the recyclates obtained. Therefore, WTE should be preferred for this part of the MSW. On the other hand, as shown in Figure 8.8, countries with almost no landfilling have a high recycling percentage for MSW, as well as a high combustion percentage. Both technologies should thus be considered as complementary and not competitive.

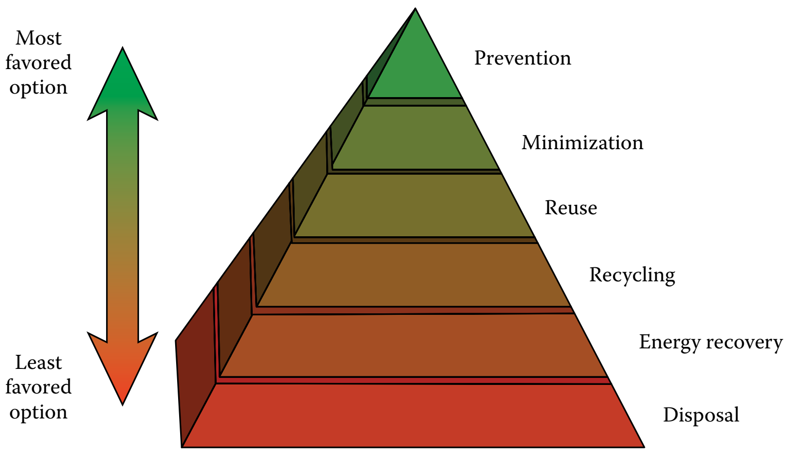


FIGURE 8.7 Waste hierarchy.

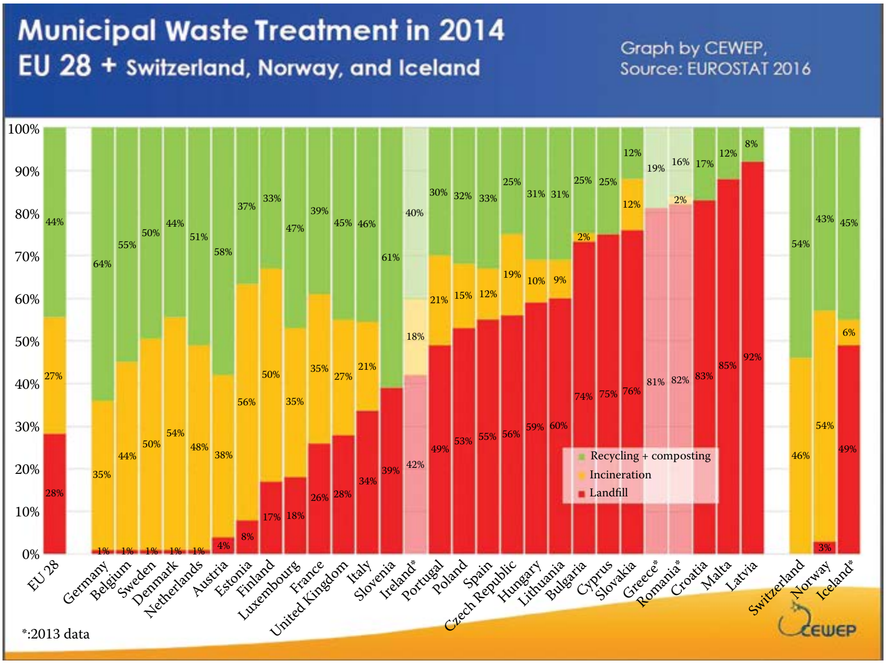


FIGURE 8.8 Recycling and composting, incineration (WTE), and landfill in European countries. (From CEWEP 2016, Municipal Waste Management in Europe in 2014, Brussels, Belgium.)

8.4 CONCLUSIONS

It has been shown that state-of-the-art MSW combustors comply with stringent EU emission limits, as well as the limits of other countries, due to thorough antipollution systems (flue gas cleaning). Although WTE is a source of air pollution, for state-of-the-art waste combustors/WTE plants, the contribution to the overall air pollution is limited, almost negligible, even for dioxins and NO_x. To date, the concerns about dioxin emissions are only of historical interest. While it is not possible to rule out adverse health and environmental effects of modern, well-regulated (municipal) waste combustors with complete certainty, any potential damage to the health of those living nearby is likely to be almost negligible, if detectable.

MSW combustion leads to several residues: bottom ash, boiler ash, and flue gas cleaning residue. After appropriate treatment, the bottom ash (largest residue fraction) can largely be reused as construction material. The other two residues (smaller residue fraction) can be solidified/stabilized.

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9 Waste-to-Energy Investment Evaluation (WTE Tool)

9.1 INTRODUCTION

Waste-to-energy (WTE) facilities, in terms of finance, are investments that require detailed design prior to implementation. Compared to mechanical biological treatment (MBT) facilities, which are labor intensive investments, WTE facilities are capital-intensive, thus fund-raising is the most important aspect to consider. As a result, any contracting authority planning to implement a WTE plant needs a solid and realistic business plan stating that such an investment would be profitable and ensures a guaranteed return.

Structuring a concrete business plan means that, first, someone should assess the initial capital expense (CAPEX) required for such a project. As a next step, expected revenues and estimated operating expenses (OPEX) should be considered, so expected profits can be calculated. Finally, having determined the expected cash flows of such an investment and considering also the funding structure of the asset, the viability and the profitability costs of the project are calculated.

Beyond a solid business model with estimated rates of return written on paper, most funding institutions and individual investors care most for other, more qualitative, elements. The most significant considerations of an investment are confidence and stability. In other words, the investor should be persuaded at least about the following facts:

- The government and the citizens wish to have a WTE plant in their territory, which means social acceptability
- There is and will be a minimum flow/capacity of waste for the years to follow that ensures the project's viability
- The client (government or a municipality) can afford the agreed-upon gate fee
- There is a market for the sale of energy (electricity and/or heating/cooling)
- There is a stable financial environment for business and the belief that it will remain so

Bear in mind that a business plan must be accompanied by supporting documents verifying a country's relevant local legislation, historical data of waste production and composition analysis, and so on. However, the most important document that will make the investor feel confident about a project's realization is a memorandum of understanding (MOU) between key stakeholders and/or a letter of intent from the contracting authority or the government/municipality about the project under discussion, stating that they are in favor of such a project. This accompanying document is called a Financing Information Memorandum (or, in brief, an Info Memo) and describes the projects, its stakeholders, and the most significant details. The typical structure of an Info Memo is

1. Executive summary, providing a short but comprehensive description of the project
2. Project scope, with details
3. The parties, describing the awarded consortium's profile and structure, and its advisors
4. Key lending considerations, presenting possible risks for the funding institutions
5. The project's technical description, stating waste historical data, previous treatment technologies, and which would be the Best Available Technology (BAT) to implement
6. Basic project financials, presenting figures of the business's financial model

In some worldwide WTE plants the architectural design plays an important role in the development of the project as it reflects public perception. A representative example is shown in Figure 9.1.

9.2 FINANCIAL MODEL

A financial model is prepared in order to evaluate the return on an investment; it is a tool that produces results depending on input values given by the user. Consequently, it is critical to understand that a tool such as a financial model produces the same quality of results as the quality of input or, as a computer scientist would say, "garbage in, garbage out." In that sense, prior to structuring of a financial model, it is crucial to retrieve solid historical data about the annual amount/tonnage and waste composition, and that information be used to calculate all required technical inputs for the model.

In most cases a financial model uses discounted cash flow analysis to predict value and return of the project, through evaluation of the expected future cash flow in relation to the amount of the initial investment. The objective is to find projects that are worth more to the sponsors than they cost—projects that have a positive net present value (NPV).

A sponsor's evaluation of a proposed project is similar to an individual's investment decision. The steps are the same:

1. Estimate the expected future cash flows from the project
2. Assess the risk and determine a required rate of return (cost of capital) for discounting the expected future cash flows (internal rate of return [IRR])
3. Compute the present value of the expected future cash flows

FIGURE 9.1 Spittelau WTE plant and the impressive design and decoration of its stack.

4. Determine the cost of the project and compare it to what the project is worth: if the project is worth more than it costs—if it has a positive NPV—it is worth undertaking

In order to reach expected future cash flows, someone has to assume realistic input of values, which are analyzed below, specifically with respect to a WTE facility.

9.2.1 Revenues

Revenues in a WTE facility mainly come from two sources. The first income source is the so-called gate fee (also known as a tipping fee). The gate fee is the amount of money paid, usually per ton of waste, in order for waste to pass through the "gate" and be processed in the WTE facility. Think of a gate fee as analogous to tolls on a highway, a ticket for a performance, or a service. A gate fee is paid by waste producers, which are primarily municipalities (providing Municipal Solid Waste [MSW]) and, secondarily, large producers (such as factories, commercial parks, airports, etc.) that are obliged to handle their own waste (industrial or commercial waste similar to MSW) at their own cost according to the polluter pays principle. Input values required for gate fee annual revenue stream calculations are:

- Gate fee in currency per quantity unit (e.g., USD/ton)
- Annual delivered tonnage in quantity unit per year (e.g., ton/yr)

Gate fee value is actually the only value that acts at the same time as input and output value. If we set gate fee as an input value (assuming that there is a maximum set by the municipality), then output values would be the investment indicators (NPV, IRR, etc.). On the other hand, if we set a minimum value of return required from the investor, then gate fees act as an output, meaning that this is the price that the investor asks for this project.

Regarding annual tonnage, there are two alternatives to be applied. The first and simpler is to choose a steady waste production per year for the project life, but keep in mind that in such a case it is more than certain that the investor would ask for guarantees of a minimum quantity, which would be considered the base case of the business model (thus stressing required returns even more). The other approach is to build an annual amount prediction based on historical and demographic data, which would be more realistic and easy to justify. In any case, it is common practice for an investor to ask for a minimum guaranteed quantity of waste, meaning that even if the "client" does not produce the predicted amount of waste, the investor will be paid for that minimum quantity as if it was delivered as input waste to the WTE facility.

The second most important revenue input is energy sales. WTE facilities, as already described in Chapter 3, produce either electricity and thermal energy (hot water or steam) or solely electricity. Few existing WTE facilities processing MSW produce only thermal power. Those two "products," even if they seem similar, are actually quite different. Selling electricity is much easier, in terms of infrastructure, than selling thermal energy, due to the fact that electricity networks with connected clients already exists. On the other hand, a thermal energy network requires a teleheating piping system that is literally a project of its own (district heating and, sometimes, district cooling).

Electricity coming from WTE facilities in many countries is considered, whole or in part, a renewable energy source (RES). This is based on the fact that MSW consists of biodegradable waste (mainly organics and paper) at a rate of 45%–60% in terms of weight, which is actually biomass. This is quite interesting business-wise, because the selling prices for electricity can grow higher than the system's marginal price, and in some countries RES producers are prioritized in supplying energy to the network. There are also cases in which a WTE facility provides steam to adjacent industrial units, which does not require significant capital investment in piping network.

Inputs required to calculate revenues from energy sales are as follows:

- Energy selling prices in currency per energy unit (e.g., USD/KWh)
- Amount of energy produced in energy units per year (e.g., kWh/yr)

Energy selling prices are different for electricity and thermal energy. Those values are country specific for electricity, although there is a typical range. Prices for thermal energy are case specific, since the product is sold to an oligopoly and not to the market. As a result, energy selling prices must be researched on a case-by-case basis.

The annual amount of energy produced is a value that must be calculated. There are rates for rough calculation, such as 550–750 kWh/ton of waste (depending on the lower calorific value and other parameters) in dedicated electricity production, however it is preferable to ask a technology provider to provide specific production values. Specifically in cases in which a combined heating and power (CHP) facility is designed, the balance of energy production between electricity and heating, needs further thorough study.

Other revenue streams which could represent less than 3% of annual turnover, come from by-product sales. In most cases metals recovered from bottom ash are 100% saleable, thus a short but steady income stream is produced. There are also less common cases in which bottom ash is sold as inert material for construction projects, but it is advisable not to take this into consideration during calculating revenues for a financing plan unless there is a contract with a buyer for this by-product.

Finally, carbon credits may add revenue due to the biodegradable fraction of waste comparing to fossil fuels, but this must be assessed on a country-by-country basis.

9.2.2 Operational Expenses (OPEX)

As mentioned before, WTE technology is a capital-intensive and not labor-intensive investment, thus operational expenses consist mainly of consumables and maintenance costs. Labor costs in a WTE facility are considerable, but not to the same extent as an MBT facility, where labor cost is the major operational expense.

Starting with the most costly expense, maintenance is of the highest importance in a WTE facility. A maintenance annual plan, as well as wear and tear and spare parts inventory management, are critical aspects of a unit's good and uninterrupted operation. The annual cost of maintenance expenses is influenced by multiple factors. The most significant ones are the unit's size in terms of annual waste capacity, the technology applied, and the quality of waste stream combusted in the plant. Annual maintenance expenses vary across a plant's lifetime, due to the fact that major maintenance work does not take place on an annual basis, but depend on hours of operation (usually 8000 hours annually). Additionally, when the unit is aging, there are parts and equipment that need replacement. Keep in mind that replacement costs should not be considered as operational expenses, since they appear on the balance sheet as capital reinvestment. All these qualitative factors are very difficult to evaluate in structuring a business plan, thus it is extremely important to have this input from the technology provider. However, a safe range to be used in case of lack of sufficient data, is from 2% to 3% of a facility's capital investment.

Another important expense category is residuals treatment and final disposal. As mentioned in Chapters 3 and 8 of this book, residuals in a WTE facility are separated into two categories, bottom and fly ash. Both of them can be treated using several methods in order to be stabilized and safely disposed of. The method to be used depends mainly on a country's legislation, but also on the site where they will be disposed of—in the sense that the characteristics of the residues should comply with the requirements for safe disposal at the residual's site. For instance, the requirements for safe disposal in a sanitary landfill in the United States differ from the requirements of a salt mine in northern Europe (Germany). Inputs required for this category are:

- Quantity of bottom and fly ash in quantity unit per year (e.g., ton/yr)
- Cost of treatment per material in currency per ton (e.g., USD/ton)
- Cost of safe disposal per material in currency per ton (e.g., USD/ton)

The first two values must be discussed and determined in consultation with the technology provider, since they depend on technology applied and the composition of waste treated. On the contrary, for disposal cost determination, the relevant disposal site should be found. There might be a standard range in the country for safe disposal of similar materials, but it is safer to find a disposal site that would accept the described residues of the WTE and ask for a price quote. Keep in mind that an investor feels safer when there are sufficient data and documents that support the plan. In general, a range of residue cost treatment and disposal is from 6 to 13 USD per ton of waste received in the unit.

The next significant cost category is flue gas cleaning expenses. Antipollution technologies in WTE plants vary significantly. Flue gas cleaning is one of the main systems for this kind of facility, representing a significant portion of the capital investment. As mentioned in Chapter 3, flue gas cleaning systems can be dry, semi-dry, or wet. Beyond differences in antipollution efficiency, these systems represent differences in operational costs. Based on a country's legislation on emissions limits and other factors, such as the presence of liquids residues, and so on, the technology provider will guide someone to the best available combination of techniques for a WTE plant (BAT). As a result, the technology provider is the one who would suggest the operational expense of the flue gas cleaning system. A typical range of this category is between 3 and 9 USD per ton of waste received in the unit.

Personnel in a WTE facility is more or less irrelevant to waste capacity, since the kind of work needed in those facilities is not entirely manual labor. The most common types of work in a WTE facility are machinery and vehicle operators, process and quality engineers, and administrative personnel. The only category of workers related to waste capacity are machinery and vehicle operators. Consequently, there are huge economies of scale in larger capacity units compared to smaller ones. Once again, the technology provider is the one who should define workers' positions and minimum experience requirements, but a typical range of personnel cost would be 4–7 USD per ton of incoming waste. However, this range may not apply to extremely small capacity units handling less than 100,000 tons of annual capacity.

Finally, the remaining operational expenses are insurance and other administrative costs. Insurance costs are dependent on initial capital investment, at a typical range of 0.3%–0.5%, depending on the country and relevant insurance market. An insurance broker could provide a clear view of the expected cost in the region of interest. Regarding other administrative costs, they could be related to total annual operational expenses or to the incoming annual waste tonnage, if data are not available. In any case, an amount for unforeseen circumstances should be kept, perhaps around 5%–7% of all other operating expenses.

9.2.3 Capital Expense (CAPEX)

Initial investment for a WTE facility is highly dependent upon the technology of choice. Technology providers guarantee different efficiencies which are closely related to capital expenses for the plant. Leading technology providers, providing state-of-the-art machinery and equipment, require, in general terms, a higher initial investment expense but, on the other hand, through their vast track record provide greater comfort to the investor regarding their experience. This qualitative factor can significantly assist with technical due diligence, thus it should be considered seriously when choosing technology providers.

Another significant factor that influences initial capital investment costs is the country of implementation. Civil works and subcontracting costs are dependent on a country's financial growth and gross domestic product (GDP), thus the infrastructure costs of a plant differ significantly among developed and developing countries. Moreover, annual capacity of waste to be treated is a driving factor of the capital expense, as a result significant economies of scale apply to large-capacity units, compared to small-capacity ones.

The construction joint venture—the technology provider and the general contractor—should be known during the structuring of the business plan for an investor or financial institution. This is because the assessment of the project's risk, during technical due diligence by the investor's technical advisor, depends vastly on the construction joint venture's participants and their track records. Additionally, the construction cost of the plant should be known and fixed, through a binding offer by the construction joint venture. This value would be the amount of capital to be provided by the financial institution or investor.

An indicative range of initial capital expense for the construction of a WTE plant is 450–900 USD per ton of annual capacity. This range correlates to unit capacity, meaning that a large unit of more than 900,000 tons per annum would cost around 450–550 USD per ton, while a smaller unit with a capacity of less than 100,000 tons per annum would cost even more than 900 USD per ton. This range applies in developed countries. Implementing a project in developing countries would mean a reduction in price by about 20%–40%, which would be further reduced in underdeveloped countries. For example, in China for the year 2016, the initial capital expense of a WTE plant can be much lower than in the United States or northern Europe (based on nearly 270 USD per ton of annual capacity).

9.2.4 Project Valuation

Having calculated annual revenues and operating expenses, the earnings before interest, taxes, depreciation, and amortization (EBITDA) are calculated. By subtracting all other financial and tax considerations (depreciation, interest payments, taxes, etc.), which are out of scope for this book, net profit is calculated. Net profit, or net income, is actually an accounting figure that does not represent real cash flow generated. Other capital expenses that are not recorded on an income statement influence available cash for the investor. Starting from net income, noncash expenses should be added up (such as depreciation), while capital expenses should be subtracted (such as change in working capital, capital expenditures, debt capital repayment, etc.), in order to reach free cash flow to equity (FCFE). FCFE is actually the amount of cash produced per year that is available to the investor. This cash flow would repay the investor's initial capital investment during the first years and, after that, the remaining cash flow in later years would represent return on investment (ROI). The most important figures for an investor are when the capital invested is to be paid back, and what the ROI will be. The main figures for investment evaluation are discussed below.

The payback period is a factor that witnesses the speed of capital repayment. For instance, a project that pays back in 7 years is more desirable for an investor than a project that returns capital invested in 10 years. Keep in mind that the payback period should be calculated using current values, in order to represent the real situation.

Another factor that investors always look for is the net present value (NPV), which is actually the cash return in present values that a project produces. Needless to say, NPV should be at least greater than zero. The rate used for discounting future cash flows in present values is, in most cases, the weighted average cost of capital (WACC). WACC depends on a project's financing scheme and combines the investor's cost of capital (also called opportunity cost), the debt's interest rate, and zero cost for subsidy, if available.

Along with NPV, many investors seek an internal rate of return (IRR). IRR is the discount rate that would make the NPV equal to zero, thus IRR should always be greater than WACC, in order for a project to be profitable. Actually IRR and NPV are like the same coin looked at from different angles. Imagine that the WACC for a project is 8% and the IRR is 10%, which means that this project has a positive NPV, and vice versa. The payback period is also, in a sense, combined with NPV and IRR, meaning that a project with small NVP and IRR is expected to have a longer payback period.

9.3 TYPES OF CONTRACTS: FINANCING

In the large construction projects industry, there are two main kinds of contracts. The first one is called an engineering procurement construction (EPC) contract, and the second one is known as a Build–Own–Operate–Transfer (BOOT) contract. The structural difference between these two is the method of financing. EPC contracts are mostly financed by public means (municipalities, governments, etc.), in contrast to BOOT projects, for which the investor, in most cases, constructs and handles the project through appropriate and specialized subcontractors.

An EPC contract includes the detailed design phase, the procurement of all equipment and materials needed for the construction, the erection phase of the facility, and, finally, the commissioning phase. By the end of a successful commissioning, the contractor has delivered the required scope of work and provides a predefined period of guarantee (ranging from 1 to 3 years). In the vast majority of cases, an

EPC contract has a fixed budget (a lump sum contract) and a fixed time schedule for project delivery by the contractor, thus the risk to the client (most probably the state) is minimized. There are other kinds of EPC contracts, such as cost-plus-fee or unit price contracts, but keep in mind that any contract other than lump sum carries increased budget overrun risks, reduces the contractor's motivation, and requires a high level of control from the client. So the reason for choosing anything other than a lump sum contract would be qualitative. For instance, cost-plus-fee contracts are chosen only in cases in which quality is the absolute concern and cost overruns are accepted by the client. There are situations in which different kinds contracts are combined, for instance, a contract type could be unit price capped with a lump sum. Finally, there are incentive contracts, which correlate a contactor's reimbursement with performance to an agreed target, such as budget, schedule, and/or quality. For example, there is an agreed-upon fee for the contractor that could be increased or decreased, depending on his performance on the agreed target.

So, there are many ways to shape an EPC contract, however, construction is only the beginning of the project's lifetime. After construction, the contracting authority must operate the plant and it is quite common for that authority to lack specialized personnel and experience. For that reason, an EPC contract is often followed by an operation and maintenance (O&M, sometimes called a facility management contract) in order for a specialized operator to run the plant so that the state can receive the required services (waste management). The duration for this kind of contract ranges, most often from 3 to 5 years, but there are cases of 10-year contracts. The exact terms and agreements are case-specific; for instance, there might be a cost-plus-fee contract or a standard annual fee plus a reimbursement per ton of waste contract, or a gate fee contract combined with a minimum annual lump sum (i.e., 50 USD/ton but at least USD1 million per year).

Given the above, someone might wonder why a contracting authority would break a project into two (EPC and O&M) or more (more than one O&M) contracts. Imagine the risk of responsibility allocation between the EPC and the O&M contractor in case of problematic operation of the plant, especially during the first years of the plant's operation, which are the most critical ones in the plant's functions.

In contrast to the above, BOOT contracts, also known in some countries as Public Private Partnership (PPP) contracts, actually transfer all available risk for the plant to the private entity (concessionaire) for the lifetime of the project. For that reason, the monthly payments to the concessionaire are called availability payments. Through availability payments the concessionaire must cover all operational expenses per month, pay for any financial costs (interest payment, capital repayment, letter of guarantees, fees, etc.) that may exist, and what remains goes to the investor's capital payback. Profit for the investor comes after the entire amount of the capital has been paid back.

Consider this from the beginning: capital expense in BOOT or PPP contracts is financed by three sources at a maximum. The first to finance is the private entity that signs the contract with the state, thus creating a public private partnership. This may be the simplest scenario, in that the private entity invests all capital expenses on its own, but this is a very rare case. Since the cost of capital of a private entity is in most cases higher than the interest rate that a bank asks for a loan, most investors prefer to ask for loans. This way of financing is called project financing and may be defined as the raising of funds on a limited-recourse or nonrecourse basis to finance an economically separable capital investment project in which the fund providers look primarily to the project's cash flow as the source of funds to service their loans and provide the return of, and a return on, equity invested in the project. In project financing the private entity is called the sponsor and the banks are called lenders. The ratio of sponsor's equity versus debt varies according to country and project risk, but a range would be from 40/60 to 20/80 respectively.

Finally, the third source of capital, if available, comes from the public partner. The only reason for the state to invest in a PPP project is to lower monthly availability payments, thus reducing gate fees paid by the populace for waste management. In most cases public funding is referred to as a subsidy and provided in milestones over the course of the construction period.

The ideal candidates for project financing are capital investment projects that (1) are capable of functioning as independent economic units; (2) can be completed without undue uncertainty; and (3) when completed, would be worth demonstrably more than they cost to complete. A WTE facility is able to satisfy all three factors, since it can act as an independent economic unit, it can be completed without uncertainty (assuming that public opposition has been addressed) and, finally, expected future cash flows discounted in present values are worth more than the capital cost required for construction.

The following diagram presents the main roles in a project finance agreement and their relationship. All start from the public partner that initiates the project. An investor comes up, probably through a tender procedure, and forms a special purpose vehicle (SPV, or special purpose company [SPC]). The asset of this SPV would exclusively be the WTE facility, thus this company is called special purpose. The shareholders of the SPV, or the sponsors, provide the required capital, along with the lenders with whom they have agreed to work. The lenders, in order to approve the loan, should exercise due diligence and recognize risks. For that reason the lenders always ask for advisors, who are part of the project's cost and paid for by the sponsors. The advisors include, at minimum, the lender's technical advisor, the lender's legal advisor, and the lender's insurance advisor. The SPV and the public partner should have their own advisors in order to be able to negotiate through contract structuring. Additionally, the SPV needs a general contractor (followed by a design team) to construct the facility, and a facility management company to operate and maintain it. Both of those should be accepted by the lenders and the public partner prior to any agreement. The SPV also needs an insurance contract during erection and operation. Finally, an independent certifier operates both during erection and operation, in order to confirm that the project is executed according to technical requirements set by the state.

Figure 9.2 shows the main roles in a project finance agreement and their relationship.

The PPP scheme assures that state services are provided in the most economical and efficient way, through fair allocation of risks and returns between the public and private sectors. Based on that, all PPP contracts have a penalty system; if services are not delivered at the required level, the SPV's availability payment is reduced

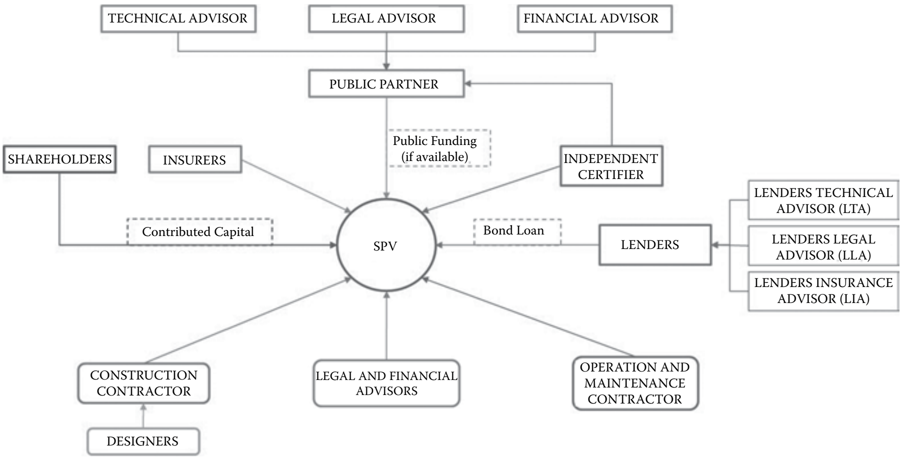

FIGURE 9.2 The main roles in a project finance agreement and their relationship.

according to the penalty system. This is part of the independent certifier's scope of work. The lifetime of a PPP contract for a WTE facility may vary from 25 to 30 years, and after that period the facility is transferred to the state for further operation. It is quite common for the state to ask for a guarantee of good operation for 3 to 5 years after a contract's termination.

Having discussed both kinds of contracts, it is easy to see that BOOT contracts are preferable for a public entity, in the sense that it receives services required with minimized risk, without needing specialized personnel or declaring numerous tenders.

9.4 WTE TOOL

Based on the above information the author of this book, Dr. Efstratios N. Kalogirou, in collaboration with Dipl. Mechanical Engineer (MBA) Mr. Manolis Klados, has developed a state-of-the-art multiparameter and multifunctional techno-economic model/tool for preliminary financial assessment of WTE projects around the globe. Easy-to-provide input values, calculate, on the spot, an indication of a project's profitability or expected gate fee, based on thoroughly selected calculation formulas derived from the abovementioned team's worldwide technical expertise. Beyond technical and financial figures, this tool also provides an indication of basic environmental parameters that are necessary in a preliminary phase for social acceptance (public perception). The WTE tool takes into consideration multiple parameters such as the composition of the MSW, lower heating value, gross domestic product (GDP), climate conditions, thermodynamic characteristics (steam parameters), the combined heat and power or electricity production, and all the abovementioned financial parameters. Figure 9.3 shows the stack of the Spittelau WTE plant adjacent to the residential area and metro line.

In the following, three representative examples are presented.

FIGURE 9.3 View of the stack of the Spittelau plant.

1. The first case study is that of a medium, typical capacity, WTE plant of 200,000 tpa (tons per annum) in a developed country, producing electricity only. The input table is presented in Table 9.1 (based on typical steam parameters of temperature 400°C and pressure 40 bar).

   Based on the inputs (Table 9.1), which are typical for a developed country, the following output table (Table 9.2) is calculated.

   The goal seek value for IRR is 11.5% (NPV of approximately USD32 million), which requires a gate fee of 75 USD/ton.

   The environmental impact results are presented in Table 9.3 (indicative numbers depending on the flue gas cleaning system used, composition of input waste, and other parameters).
2. The second case study presents a WTE plant of the same capacity plant (200,000 tpa), but now implemented in a developing country (resulting in a lower capital expense), in order to compare the requested gate fees.

   The plant would again produce electricity only (based on typical steam parameters of temperature 400°C and pressure 40 bar), but the prices might be somewhat lower, and the waste composition would have a lower heating value (LHV) due to a higher percentage of biodegradables. Finally, the funding scheme is changed to 60/40 (debt over equity), due to higher fiscal uncertainty. The input table is shown in Table 9.4 and the output table is shown in Table 9.5.

   For the same plant in a different part of the world, the gate fee is reduced to 61 USD/ton (a reduction of around 20%), in order to achieve the same return for the investor in terms of IRR. This information helps us understand

TABLE 9.1
Inputs, Case 1

1. Waste amount	200,000 tpa
2. Composition	
Categories	**% (w/w)**
Organics	48.0%
Paper	20.0%
Plastic	15.0%
Fabric	2.0%
Wood	1.0%
Glass/inerts	6.0%
Metals	3.0%
Others	5.0%
Sum	**100.0%**
3. Energy output	
Electricity only	1
CHP—Bleeding turbine type	
CHP—Backpressure turbine type	
4. Country's standard of living	
Developed country	1
Developing country	
Underdeveloped country	
5. Product selling prices	
Electricity selling price	66 $/MWh
Thermal energy selling price	11 $/MWh
Recovered metals selling price	55 $/ton
6. Financing scheme	
Debt	80%
Subsidy	0%
Equity	20%

how case-specific every WTE plant is, and how much importance must be placed on the optimal choice of input values. The environmental results would be more or less the same as those given for case 1.

3. Finally, a third case study refers to a WTE facility with a capacity of 500,000 tpa, in a developed country, producing both electricity and heating (backpressure turbine type, based on typical steam parameters of temperature 400°C and pressure 40 bar). The input values are given in Table 9.6 and the output table is given in Table 9.7.

The gate fee is reduced (compared to the 1st case) due to economies of scale for achieving the same IRR as the first example, but it is important to note that NPV is significantly increased in terms of amount, due to higher

TABLE 9.2
Technical and Financial Data, Case 1

Annual waste capacity	200,000 tpa
Lower heating value	9.02 MJ/kg
Energy production	
Electricity produced	132,247 MWh/year
Electricity produced per ton	661 kWh/ton
Electricity for sale	112,410 MWh/year
Gross electricity efficiency	26.3%
Net electricity efficiency	22.3%
Thermal energy for sale	0 MWh/year
Thermal energy per ton	0 kWh/ton
Households serviced for teleheating	0
Thermal efficiency	0.0%
Total efficiency	26.3%
R1	0.6977
Techno-economic output	
Capital expense	149,600,000 $
Capital expense per ton	748 $/ton
Loan	119,680,000 $
Subsidy	0 $
Equity	29,920,000 $
Operating expense @ constant prices	9,908,800 $/year
Operating expense @ constant prices	49.54 $/ton
Payroll	1,430,000 $/year
Residuals treatment	2,420,000 $/year
Chemicals	1,320,000 $/year
Maintenance	3,740,000 $/year
Insurance	448,800 $/year
Other administrative costs	550,000 $/year
Revenues @ constant prices	22,559,076 $/year
Revenues @ constant prices	112.8 $/ton
Income from gate fees	14,920,000 $/year
Income from electricity	7,419,076 $/year
Income from thermal energy	0 $/year
Income from metals sales	220,000 $/year
Financial evaluation based on 25 yrs of operation	
Gate fees	74.6 $/ton
Internal rate of return (IRR)	11.53%
Net present value (NPV) @ WACC	31,827,963 $
Payback period (incl. 3 yrs construction)	16.8 years

TABLE 9.3
Environmental Impacts, Case 1

Ash production	
Bottom ash	50,000 tpa
Fly and boiler ash	6000 tpa
Emissions	
Dioxins	0.140 gr/year
Particles	14,000 kg/year
HCl	14,000 kg/year
HF	1400 kg/year
SO_2	70,000 kg/year
NO_x	280,000 kg/year
Hg	70 kg/year
Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V	700 kg/year

TABLE 9.4
Inputs, Case 2

1. Waste amount	200,000 tpa
2. Composition	
Categories	**% (w/w)**
Organics	52.0%
Paper	20.0%
Plastic	13.0%
Fabric	2.0%
Wood	1.0%
Glass/inerts	5.0%
Metals	2.0%
Others	5.0%
Sum	**100.0%**
3. Energy output	
Electricity only	1
CHP—Bleeding turbine type	
CHP—Backpressure turbine type	
4. Country's standard of living	
Developed country	
Developing country	1
Underdeveloped country	
5. Product selling prices	
Electricity selling price	55 $/MWh
Thermal energy selling price	11 $/MWh
Recovered metals selling price	50 $/ton
6. Financing scheme	
Debt	60%
Subsidy	0%
Equity	40%

TABLE 9.5
Technical and Financial Data, Case 2

Annual waste capacity	200,000 tpa
Lower heating value	8.68 MJ/kg
Energy production	
Electricity produced	127,195 MWh/year
Electricity produced per ton	636 kWh/ton
Electricity for sale	108,116 MWh/year
Gross electricity efficiency	26.3%
Net electricity efficiency	22.3%
Thermal energy for sale	0 MWh/year
Thermal energy per ton	0 kWh/ton
Households serviced for teleheating	0
Thermal efficiency	0.0%
Total efficiency	26.3%
R1	0.6976
Techno-economical output	
Capital expense	112,200,000 $
Capital expense per ton	561 $/ton
Loan	67,320,000 $
Subsidy	0 $
Equity	44,880,000 $
Operating expense @ constant prices	7,404,100 $/year
Operating expense @ constant prices	37.02 $/ton
Payroll	1,072,500 $/year
Residuals treatment	1,694,000 $/year
Chemicals	1,056,000 $/year
Maintenance	2,805,000 $/year
Insurance	336,600 $/year
Other administrative costs	440,000 $/year
Revenues @ constant prices	18,366,365 $/year
Revenues @ constant prices	91.8 $/ton
Income from gate fee	12,220,000 $/year
Income from electricity	5,946,365 $/year
Income from thermal energy	0 $/year
Income from metals sales	200,000 $/year
Financial evaluation based on 25 yrs of operation	
Gate fees	61.1 $/ton
Internal rate of return (IRR)	11.52%
Net present value (NPV) @ WACC	27,636,023 $
Payback period (incl. 3 yrs construction)	16.2 years

TABLE 9.6
Inputs, Case 3

1. Waste amount	500,000 tpa
2. Composition	
Categories	**% (w/w)**
Organics	48.0%
Paper	20.0%
Plastic	15.0%
Fabric	2.0%
Wood	1.0%
Glass/inerts	6.0%
Metals	3.0%
Others	5.0%
Sum	**100.0%**
3. Energy output	
Electricity only	1
CHP—Bleeding turbine type	
CHP—Backpressure turbine type	
4. Country's standard of living	
Developed country	1
Developing country	
Underdeveloped country	
5. Product selling prices	
Electricity selling price	66 $/MWh
Thermal energy selling price	11 $/MWh
Recovered metals selling price	55 $/ton
6. Financing scheme	
Debt	70%
Subsidy	0%
Equity	30%

initial investment. In the case of electricity only, the gate fee would be further reduced due to the fact that electrity in most cases is sold in a higher rate than thermal energy, however, teleheating is a form of social compensation for a WTE plant. The environmental figures for such a unit are presented in Table 9.8 (indicative numbers depending on the flue gas cleaning system used, the composition of input waste, and other parameters).

For further detailed information on the WTE Tool presented, the reader can contact the author.

TABLE 9.7
Technical and Financial Data, Case 3

Annual waste capacity	500,000 tpa
Lower heating value	9.02 MJ/kg
Energy production	
Electricity produced	174,379 MWh/year
Electricity produced per ton	349 kWh/ton
Electricity for sale	124,379 MWh/year
Gross electricity efficiency	13.9%
Net electricity efficiency	9.9%
Thermal energy for sale	818,741 MWh/year
Thermal energy per ton	1,637 kWh/ton
Households serviced for teleheating	56,465
Thermal efficiency	65.1%
Total efficiency	78.9%
R1	1.1027
Techno-economic output	
Capital expense	346,500,000 $
Capital expense per ton	693 $/ton
Loan	242,550,000 $
Subsidy	0 $
Equity	103,950,000 $
Operating expense @ constant prices	20,927,500 $/year
Operating expense @ constant prices	41.86 $/ton
Payroll	2,475,000 $/year
Residuals treatment	6,050,000 $/year
Chemicals	2,750,000 $/year
Maintenance	7,623,000 $/year
Insurance	1,039,500 $/year
Other administrative costs	990,000 $/year
Revenues @ constant prices	52,465,162 $/year
Revenues @ constant prices	104.9 $/ton
Income from gate fee	34,700,000 $/year
Income from electricity	8,209,011 $/year
Income from thermal energy	9,006,150 $/year
Income from metals sales	550,000 $/year
Financial evaluation based on 25 yrs of operation	
Gate fee	69.4 $/ton
Internal rate of return (IRR)	11.51%
Net present value (NPV) @ WACC	81,512,259 $
Payback period (incl. 3 yrs construction)	16.2 years

TABLE 9.8
Environmental Impacts, Case 3

Ash production	
Bottom ash	125,000 tpa
Fly and boiler ash	15,000 tpa
Emissions	
Dioxins	0.350 gr/year
Particles	35,000 kg/year
HCl	35,000 kg/year
HF	3500 kg/year
SO_2	175,000 kg/year
NO_x	700,000 kg/year
Hg	175 kg/year
Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V	1750 kg/year

Source: Kalogirou, E., Klados, M., 2016, Waste To Energy Tool, available upon request.

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