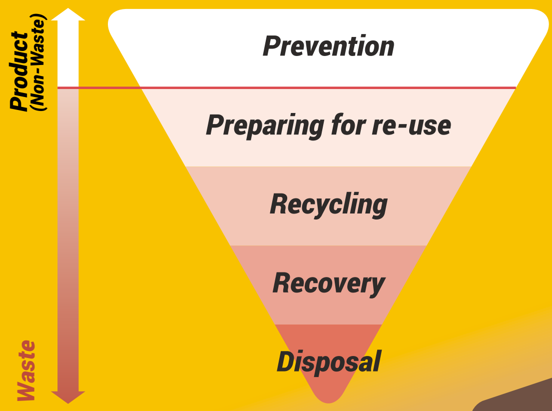
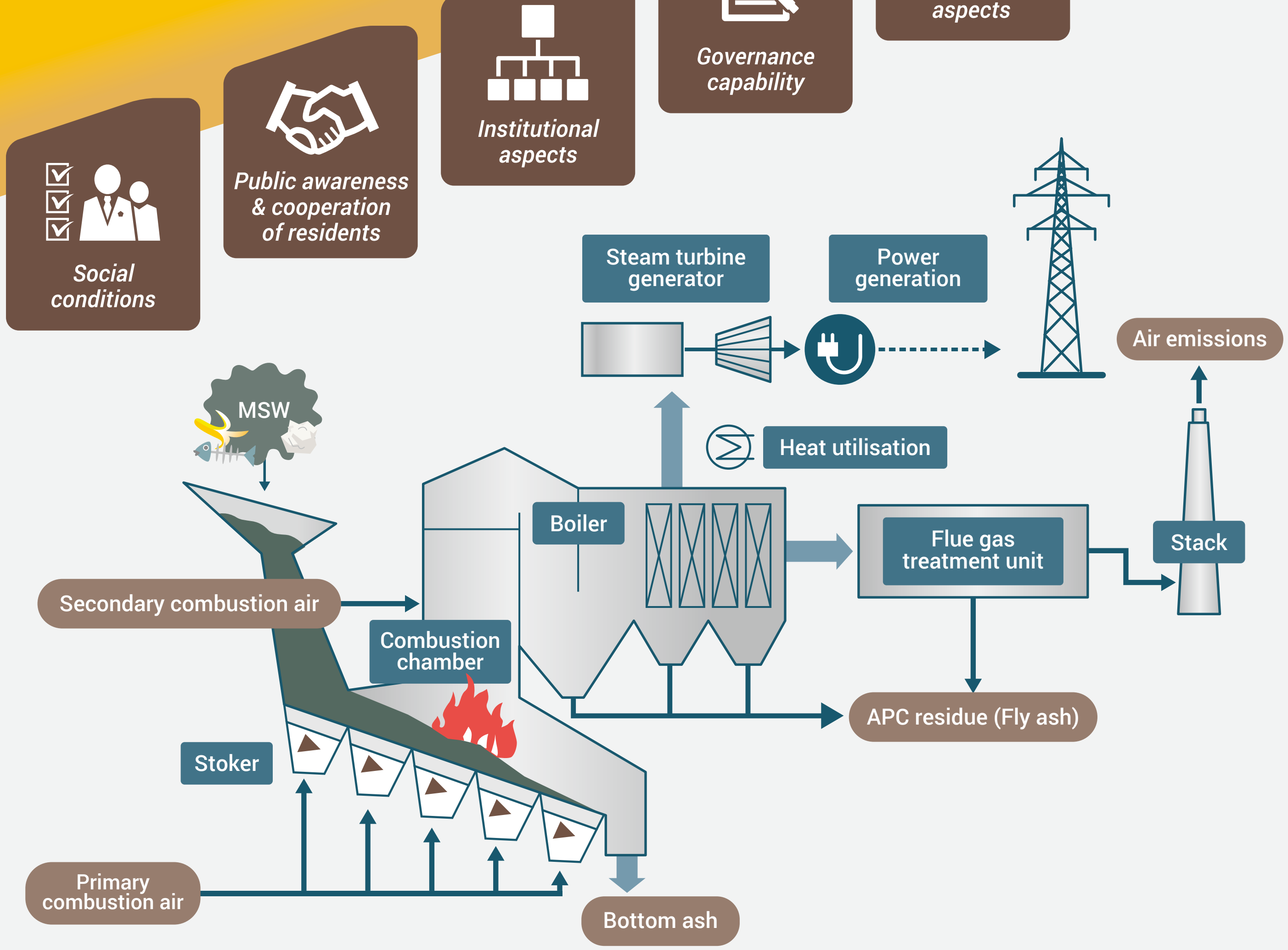
CCET guideline series on intermediate municipal solid waste treatment technologies

Waste-to-Energy Incineration





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CCET guideline series on intermediate municipal solid waste treatment technologies:
Waste-to-Energy Incineration

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The International Environmental Technology Centre works with developing countries to implement sustainable solutions to environmental challenges, with focus on holistic waste management.

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List of Abbreviations

APC	Air Pollution Control
FIT	Feed-in Tariff
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GHGs	Greenhouse Gases
IPCC	Intergovernmental Panel on Climate Change
JICA	Japan International Cooperation Agency
LCV	Lower Calorific Value
MSW	Municipal Solid Waste
PPP	Public-private Partnership
SDGs	Sustainable Development Goals
WtE	Waste-to-Energy

About this Waste-to-Energy Incineration Guideline

The issue of MSW management is considered to be one of the key drivers for countries worldwide to achieve the goals of both the Paris Agreement and the 2030 Agenda for Sustainable Development. Under the Paris Agreement, countries' nationally determined contributions (NDCs) can include action on waste management as part of efforts to reduce greenhouse gas (GHG) emissions, using waste as a source of energy, recycling and reuse; and recovering methane from landfills. Goal 11 (sustainable cities and communities) of the Sustainable Development Goals (SDGs) includes target 11.6, which focuses on reducing the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management issues. SDG 12 (responsible consumption and production) includes targets focused on environmentally sound management of all waste through prevention, reduction, recycling and reuse (targets 12.4 and 12.5) and reduction of food waste (target 12.3). However, according to the World Bank (2018), global annual waste generation is expected to jump from 2.01 billion tonnes in 2016 to 3.40 billion tonnes over the next 30 years, and this trend is especially true in developing countries in Asia and Africa. This suggests that there has been very little success in reversing the trend of the increased generation of MSW, meaning that the world has continued on its course to becoming one "throwaway society". While WtE incineration is one the best options for waste volume reduction and energy recovery, **only a circular economy will ensure the decline of per capita waste generation and offer a long-term solution to the global waste problem.**

Position of WtE incineration in the waste hierarchy

The introduction of WtE incineration technology should follow the waste hierarchy (Fig. 1). In this scenario, priority is placed on prevention to reduce waste generation, followed by re-use and recycling. Evaluating the waste stream and identifying additional potential for reducing, reusing and recycling waste is also a critical part of the MSW decision-making process. WtE incineration projects can be categorised as a type of complementary technology for the recovery of energy from any remaining non-recyclable MSW, and should therefore not compete with waste reduction, reuse and material recycling measures.

Furthermore, **WtE incineration is just one potential element out of many in a functioning MSW system.** WtE incineration plants alone cannot solve existing waste problems, and decisions on selecting WtE incineration as an appropriate technology should be made on the basis of an integrated MSW management plan in the respective city or country.

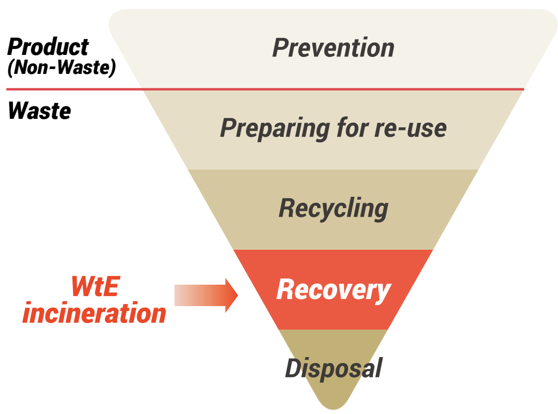


Fig. 1 Waste hierarchy for sustainable waste management (Source: EU Waste Framework Directive[1])

1 EU Waste Framework Directive (Directive 2008/98/EC on waste): https://ec.europa.eu/environment/waste/framework/

Target audience & purpose of this guideline

This guideline focuses on WtE incineration technology for MSW, mainly household waste and commercial waste, in urban areas of Asian developing countries.[2] The guideline aims to assist decision-makers and policymakers at the national and city levels, residents and other stakeholders who are in search of additional knowledge and information that will help them to form a clear picture of what WtE incineration entails, when considering the potential for introducing WtE incineration technology as an appropriate option for improving waste management. This guideline will:

(1) provide **a holistic understanding** about WtE incineration technology including both **advantages and disadvantages**, as well as information about the **technical and non-technical** aspects of planning a sustainable WtE incineration plant

(2) propose **key evaluation criteria** and a **pre-check flow** in the MSW decision-making process to objectively determine and evaluate criteria when considering the potential of introducing WtE incineration technology, and

(3) provide **technical knowledge** for discussion with plant manufacturers.

Approach and structure of this guideline

This guideline is primarily based on the expertise and practical experiences of plant operators and private companies in the MSW management sector in Japan and other countries, as well as available literature. It consists of four main parts: Chapter 1, "Introduction", provides basic information about the concept of WtE incineration technologies and its history, advantages and challenges. Chapter 2, "Pre-conditions for Sustainable WtE Incineration Facilities", describes the key evaluation criteria needed when planning a WtE incineration plant and provides a pre-check framework for sustainable WtE incineration facilities. The key evaluation criteria include technical, as well as non-technical facets, i.e. social conditions, public awareness and cooperation of residents, institutional aspects, governance capability and financial aspects. Chapter 3, "Main Technology and Discussion Points with Plant Manufacturers", explains techniques used in the WtE incineration process, emissions and important points to consider when coordinating with WtE incineration plant manufacturers. Chapter 4, "Case Studies", features actual examples from both developed and developing countries.

Planning to establish a WtE incineration facility is a complex process and should be accompanied by a professional and thorough feasibility assessment. This guideline should be used **at the beginning of the planning stage to help decision-makers accurately assess the present situation in cities and determine the probability of introducing a WtE incineration facility that will complement their overall MSW system.** Only after confirming its probability for success should a project move on to the next step, which is a more detailed feasibility study and implementation plan before the actual construction of a WtE incineration plant.

Message for the busy reader

Busy readers can look over Chapter 1 to quickly gain a general overview of WtE incineration. For readers considering the potential of introducing WtE incineration, please use Fig. 4 on page 6 as a guide to check conditions that must be in place at the beginning of the planning stage. Details on the technology involved in WtE incineration can be found in Chapter 3.

2 The terms "developed and developing countries" in the CCET Guidelines are used to define economies as classified by the World Bank in its World Development Indicators report published in 2016. The term "developed countries" refers to high-income countries and regions, while the term "developing countries" encompasses low-income, lower middle income, and upper middle income countries and regions.

1 Introduction

1.1 Definition of MSW Waste-to-Energy (WtE) incineration

WtE incineration is the process of direct controlled burning of waste in the presence of oxygen at temperatures of 850°C and above, coupled with basic mechanisms to recover heat and energy and more sophisticated mechanisms to clean flue gas, utilise wastewater, and assimilate diverse streams of waste (Fig. 2). MSW incineration is a reliable form of thermal treatment technology that has evolved substantially over the years together with countermeasures for air pollution and dioxins (Makarichi et al., 2018). **The main benefits of MSW incineration are volume reduction and disease control**, and it is a practical way to treat MSW in large or populated cities as it can be localised in an urbanised zone. **WtE incineration** also offers the **added benefit of using waste as a resource to produce energy**. This form of incineration also decreases carbon emissions by offsetting the need for energy from fossil fuel sources and reduces methane generated from landfills if used as an alternative to landfilling (IPCC, 2007). However, the introduction of MSW incineration has its own barriers (Karim and Corazzini, 2019; GAIA, 2019), such as (1) high costs to construct and operate incinerators, (2) insufficient income from waste disposal and energy sales to cover all costs, (3) the minimum amount of feedstock required for operations, which could potentially divert waste away from the 3Rs, and (4) risks to human health.

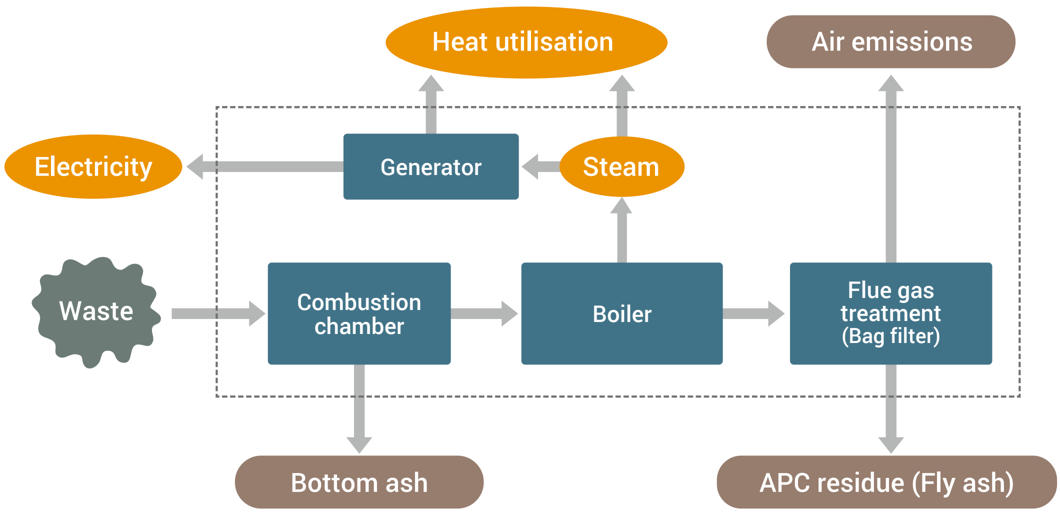


Fig. 2 Typical flow chart of WtE incineration plant (Source: author)

1.2 Historical background and main features of WtE incineration

Waste incineration began because of the need to control outbreaks of disease and reduce the rising volume of waste that resulted from continuous population growth in towns and cities in the late 19th century. From a sanitary point of view, incineration is the most effective method of treating both raw waste that can rot and waste that may cause infection and disease. Meanwhile, more waste, such as paper and plastic, is being generated as a result of economic development, which is putting pressure on final disposal sites.

Incineration has been developed as the most effective method of reducing the volume of waste sent to final landfills.

WtE incineration has been developed to make effective use of energy during incineration. The latest plants constructed for WtE incineration by manufacturers in Japan can **typically convert 20% to 25% of energy, and sometimes more, into electricity**. After a set amount of energy is removed for self-consumption from the total amount produced, the remaining energy can be transmitted to other facilities and customers. In areas such as Northern Europe where there is a high demand for heating, hot water can also be supplied for district heating. Today, when the world is concerned about the impacts of climate change and energy system transitions, it is necessary to consider the option of using as much energy generated by WtE incineration as possible. In recent years, WtE incineration offers even more benefits as a result of the introduction of national subsidy systems such as FIT schemes in Japan, China and Thailand, by which energy generated from the WtE incineration process can be sold to outside customers. However, in general, profits alone cannot adequately cover the operating costs of incinerators.

The incineration of waste is a concern for residents and other stakeholders because air pollution issues, such as dust and dioxins, can result when inadequate environmental measures are taken in those facilities. Today, the use of the latest environmental technologies and facilities, such as those for dioxins, **make it possible to meet strict environmental standards**. However, due to the poor reputation of older incinerators, residents often oppose construction, and there is now a greater need to work towards dispelling negative public perceptions and change the reputation of incineration to one of an effective and acceptable technology.

In addition, the WtE incineration facility can **act as an alternative way to back-up power**, especially in the event of a power failure during a disaster. This has been considered to be an important additional benefit in Japan in recent years.

An overview of the advantages, disadvantages and requirements of WtE incineration based on a literature review (Kumar and Samadder, 2017; Karim and Corazzini, 2019; Psomopoulos et al., 2009; GAIA, 2019; GIZ, 2017; UNEP, 2019) is shown in Table 1.

1.3 Opportunities and challenges for cities in developing Asian countries

In recent years, the amount of waste in urban areas in particular has increased dramatically due to population growth, urbanisation and lifestyle changes in Southeast Asia and other developing countries around the region. As a result, the importance of intermediate treatment facilities to reduce the volume of waste, such as incineration plants, has emerged as pressure increases on the remaining capacity of final disposal sites. Coupled with increasing energy demand and global support, expectations are rising that WtE incineration will be a more stable source of energy than even solar and wind power, resulting in increased demand for WtE incineration systems in the future. Typically, WtE incineration poses opportunities for:

(1) Cities with rising waste quantities and limited space for landfill as they become more urbanised that are seeking ways to quickly reduce the volume of waste.

(2) Cities that are seeking additional benefits from waste treatment, such as reducing greenhouse gas emissions by eliminating landfills, as well as recovering energy from waste and increasing economic incentives through waste management and energy recovery.

(3) Cities that are seeking effective technology for sterilisation and waste-related infections, as the high-temperature conditions in WtE incineration systems are effective in controlling infections from viruses or microbes in waste and residue after recycling.

Table 1 Main advantages, disadvantages and requirements of WtE incineration

	Advantage	Disadvantage	Requirement
Technology	1. WtE incineration is useful in reducing the volume of waste for landfilling, controlling disease and recovering energy (heat and electricity).	1. Technologies used in the facility are complicated (construction and operation).	1. WtE incineration requires waste with sufficiently LCV. 2. Waste composition should be investigated carefully.
Environment	1. Incineration is an efficient way to reduce waste volume destined for landfills, which allows landfills to be effectively used.	1. APC residue (fly ash) and solid residue (bottom ash) must be properly treated because of the risks they pose to human health.	1. Environmental standards, including air pollution, ash disposal, and water pollution regulations, must be in place. 2. Bottom and fly ash must be safely disposed at a secure landfill site.
GHG emissions	1. WtE incineration helps reduce greenhouse gas (GHG) emissions in two ways: (1) by eliminating methane gas emissions from landfills when used as an alternative option and (2) by using energy from waste as a substitute for fossil fuel.	1. Compared with source reduction and reuse, WtE incineration facilities release higher levels of GHG emissions.	1. Although not a requirement, life cycle assessments and emission control measures are recommended.
Economic implications	1. Generated energy can be used or sold through regulatory incentives such as FIT schemes. 2. Carbon credit under the Clean Development Mechanism (CDM) may be used where possible.	1. Construction and operation costs are expensive. Revenue from selling electricity and other recyclables does not sufficiently cover the operating costs of incinerators.	1. Local authorities should consider how to cover all construction and operation costs with tipping fees, revenue from various schemes and other subsidies.
Resource perspective	1. Electricity, steam and heat can be recovered. 2. Valuable materials like metals may also be recovered from bottom ash.	1. WtE incineration requires a guaranteed stream of waste for stable operation, which is a major disincentive for preventing the generation of waste. 2. Power generation efficiency is limited because of acid flue gas. 3. There are fewer ways to use steam and heat compared to electricity.	1. Efforts should be made to minimise the generation of waste and to promote recycling and reuse as much as possible. The option of WtE incineration should also be examined in line with waste management hierarchy and 3R policies. 2. The use of energy as steam and heat should be expanded, which is a more efficient source of energy than electricity.
Social aspects, other	1. WtE incineration is effective in preventing infections from viruses and microbes and controls the spread of waste-related infections. 2. WtE incineration facilities can act as an alternative way to back-up power, especially in the event of a power failure because of a disaster. 3. WtE incineration facilities play a role in the circular economy.	1. Local residents often object to the construction of incinerator facilities because of feelings of anxiety due to adverse effects on health, environmental pollution, odours, and falling land prices, as well as feelings of discontent stemming from psychological issues as a result of inadequate explanations, unclear reasoning behind the selection of sites or other reasons.	1. Consensus on construction must be obtained from surrounding residents and the facility should be open to them for observation. 2. The cooperation of residents in separating waste at source is a prerequisite for WtE incineration.

(Source: author)

However, it is worth noting that there are a number of barriers to the introduction of WtE incineration in developing countries. WtE incineration alone cannot solve problems; reducing waste at source followed by reuse and recycling is an integral part of waste management and should be considered prior to designing a WtE incineration plant. WtE incineration should also be embedded in an integrated solid waste management system that is tailored to specific local conditions, such as waste composition, collection and recycling, financing, and other aspects. There have been numerous examples where "proven" technologies in developed countries have failed in developing countries because sufficient attention was not paid to "soft" strategic aspects, namely, political, institutional, social, financial, economic and technical elements (UNEP, 2019; GIZ, 2017; IEA Bioenergy, 2013; World Bank, 2000). For example, in developing countries,

- the high moisture content, low combustibility, and seasonal variations of waste make it unsuitable for direct incineration. Waste quantity may also vary by collection and transportation system, governance ability, season or as a result of natural disasters. The lack of careful monitoring and assessment may also raise risks and result in operational failure;

- a lack of investment and high operation costs has given rise to WtE incineration plants in low-income countries that meet only basic technical standards and may exclude backup systems such as pumps, piping, electronic control systems, additional furnaces or appropriate flue gas filter systems. Breakdown risks associated with these low-cost plants are higher due to the lack of backup systems. Furthermore, unstable long-term funding leading to operational failure due to high operational costs may cause the municipality to take on substantial financial risks;

- Public-private partnerships (PPPs) have emerged as a promising alternative to improve the performance of MSW management. However, in many cases, the private sector has been left at the helm, or local authorities failed to properly manage the facility constructed and operated by the private sector;

- the weak enforcement of environmental laws, especially the absence of continuous emission monitoring, and a lack of due diligence by investors and the public sector may lead to a higher level of negative human health impacts and irreversible environmental damage; and

- insufficient numbers of skilled staff to operate installed systems in an efficient and effective manner may already put a city on the path to failure.

To prevent the risk of failing at a cost to the municipality and local environment and ensure success when introducing WtE incineration plants, **it is important to carefully check that local waste management conditions are appropriate before introducing** a high-cost, complicated, and technologically advanced WtE incineration plant. This point is explained in Chapter 2.

In some cases, other intermediate treatment technologies, such as composting, Mechanical-Biological Treatment or Anaerobic Digestion, may be preferable depending on the composition of waste, segregation/collection rate and other related factors (see Fig. 3). Detailed information about other intermediate treatment technologies can be found in other CCET guidelines in this series, i.e., CCET guideline series on intermediate municipal solid waste treatment technologies: Composting, CCET guideline series on intermediate municipal solid waste treatment technologies: Mechanical-Biological Treatment, and CCET guideline series on intermediate municipal solid waste treatment technologies: Anaerobic Digestion.

2 Pre-conditions for Sustainable WtE Incineration Facilities

Various conditions must be in place in order to successfully introduce a WtE incineration facility. Based on a decision-maker's guide published by the World Bank (Rand et al., 2000), ISWA's guideline on WtE incineration in low and medium income countries (ISWA, 2013), GIZ's Waste-to-Energy Options in Municipal Solid Waste Management (GIZ, 2017), and JICA's guideline on WtE incineration,[3] **key evaluation criteria can be verified from six perspectives (Fig. 3)—social conditions, public awareness and cooperation of residents, institutional aspects, governance capability, financial aspects and technological aspects.** Following the six perspectives together with relative key evaluation criteria for each, **a modified pre-check flow (Fig. 4) can be used as a guide at the beginning of the planning stage.** The key evaluation criteria and pre-check flow are presented to assist decision-makers and policymakers in taking a closer look at whether local conditions are suitable for WtE incineration and developing a transparent assessment of what technology best fits with these conditions. This does not, however, replace the need for a professional assessment on feasibility when planning a WtE incineration project. Only after confirming its probability for success should a project move on to the next step, which is a more detailed feasibility study and implementation plan for introducing appropriate technology before the actual construction of a WtE incineration plant, as shown in Fig. 3.

Key evaluation criteria are divided into three groups: **(1) mandatory key criteria (in pink), (2) strongly advisable key criteria (in yellow) and (3) advisable key criteria (in green).** Arrows should be followed to proceed to the next step in cases where evaluation criteria are met. If criteria have not been met, the following actions are recommended:

(1) **in cases where mandatory key criteria are not met, WtE incineration is not yet suitable.** It is strongly recommended that the evaluation be suspended or that the situation be re-evaluated after improvements are made;

(2) **in cases where strongly advisable key criteria are not met, support measures should be introduced, or alternative proposals considered;**

(3) **in cases where advisable key criteria are not met, caution should be exercised as WtE incineration can be risky to implement.**

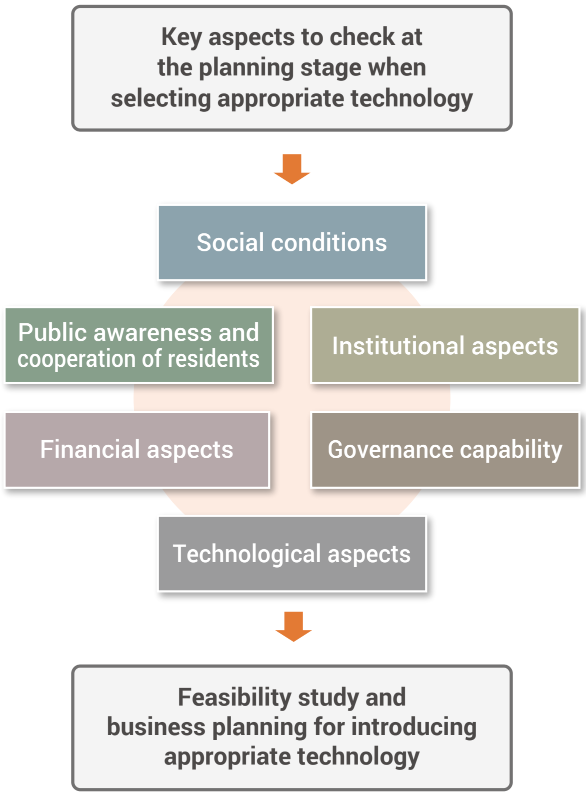


Fig. 3 Key aspects to check at the planning stage when selecting appropriate technology

(Source: author)

3 JICA WtE incineration guideline (in Japanese), a document from the explanatory meeting on the WtE incineration guideline held on 9 November 2018.

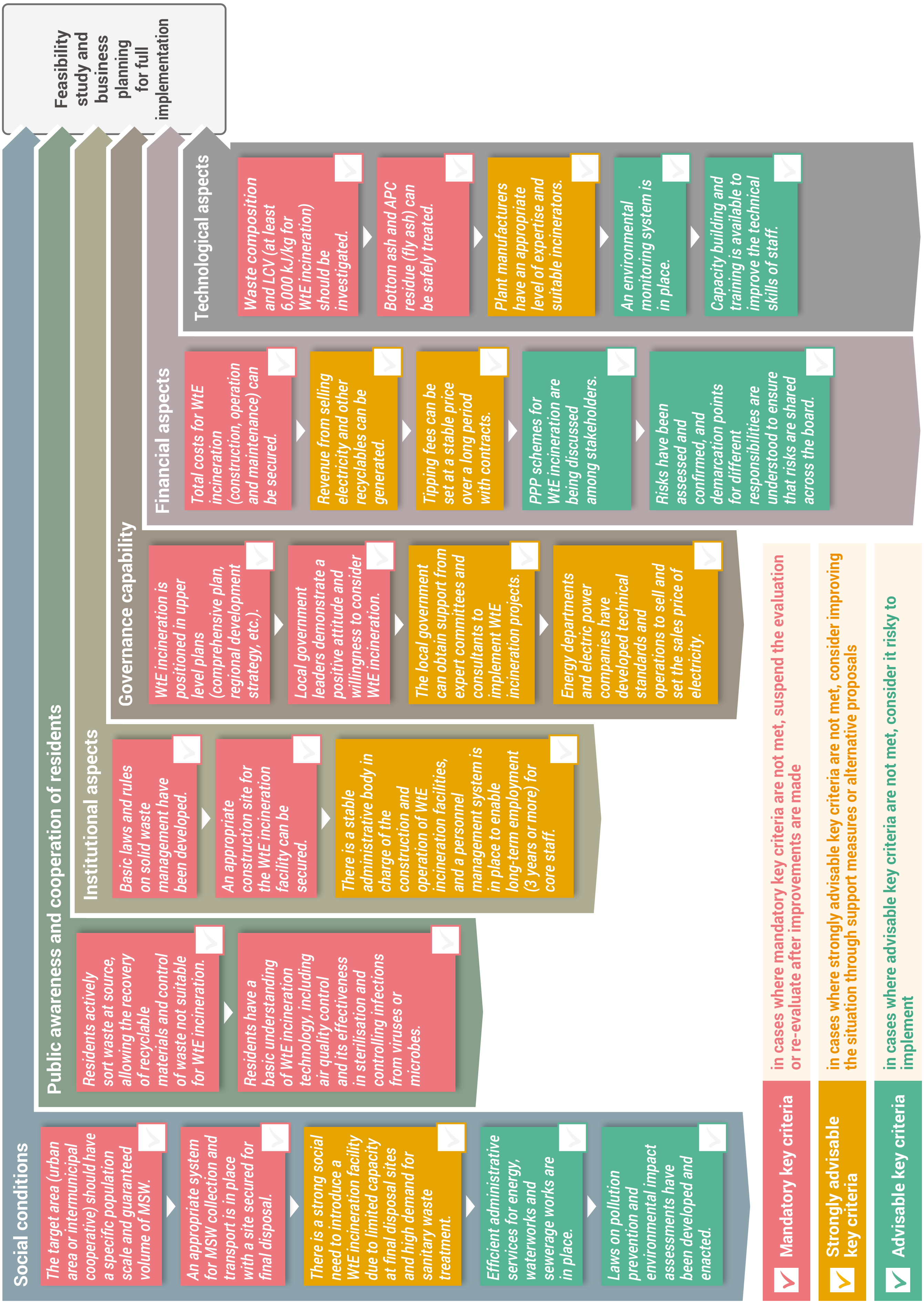


Fig. 4 Pre-check flow to be conducted at the beginning of the planning stage when developing WtE incineration project (Source: author)

2.1 Social conditions

Mandatory key criteria

The target area (urban area or intermunicipal cooperative) should have a specific population scale and guaranteed volume of MSW.

At the very beginning, **the boundary of coverage, target population and available MSW volume** need to be estimated to determine the size of a WtE incineration plant as this is a key factor that must be considered when planning a WtE incineration plant.

The amount of MSW generated, expressed as the amount of waste generated per person per day, is generally accepted to be around 1 kg per capita but varies from city to city. In addition, the amount can also differ depending on whether a municipality classifies and collects commercial waste as MSW. In developed countries, the amount of MSW often exceeds 1 kg/person/day; in the United States, this figure is over 2 kg/person day, and in Japan, it is slightly below 1 kg/person/day. In many developing countries, this figure stands at 0.5 to 1 kg/person/day, but the amount tends to be higher in larger cities where it can exceed 1 kg/person/day (Table 2) and is expected to increase even more in the future.

Table 2 MSW generation in Southeast Asian countries

Country	Generation of MSW (thousand tonne per year)	Generation per capita (kg/d)	Data source year
Cambodia	6,818	0.49	2005
Indonesia	68,389	0.76	2006
Malaysia	10,845	0.99	2012
Myanmar	5,616	0.44	2012
Philippines	35,580	0.70	2012
Thailand	27,820	1.15	2018
Viet Nam	15,618	0.47	2015

(Source: Liu et al., 2018)

If WtE incineration is planned as an alternative to direct landfill because the remaining capacity of the landfill cannot adequately handle the increasing volume of MSW, the target capacity of a WtE incineration plant can also be estimated from the current volume of MSW.

Furthermore, the efficiency of generating electricity generally increases along with the scale of the facility, while construction costs and operation per unit of waste throughput decrease. **In order to achieve an optimal performance level for generating electricity, it is generally recommended that the supply of combustible MSW should amount to at least 100,000 tonnes per year (a yearly average of 274 tonnes/day, or 300-330 tonnes/day if considering the operating rate)** (GIZ, 2017; ISWA, 2013). The most common WtE incineration plants constructed in Japan—a country with the largest number of incineration facilities in the world and where MSW generation is around 1 kg per capita per day—are those with capacities of 100, 150, 200 and 300 tonnes/day/unit.[4] Most plants have multiple incinerator units to guarantee the safe and continuous operation of the plant, and the operation rate of each unit is assumed to be around 80%.[5] Depending on local conditions, even larger units of 500 or 600 tonnes/day/unit or those smaller than 100 tonnes/day/unit, for example, are also available.

Mandatory key criteria

An appropriate system for MSW collection and transport is in place with a site secured for final disposal.

A basic requirement for the successful implementation of WtE incineration is the existence of an efficient MSW management system since WtE incineration requires a guaranteed stream of waste for stable operation throughout the year. Furthermore, WtE incineration does not remove the need for a dedicated landfill for the disposal of final residue, including bottom ash and APC residue (fly ash).

Strongly advisable key criteria

There is a strong social need to introduce a WtE incineration facility due to limited capacity at final disposal sites and high demand for sanitary waste treatment.

Strong social needs must be identified, such as landfill capacity, high demand for sanitary disposal of waste, and strong awareness of environmental protection and global warming issues. In areas where these social considerations do not exist, introducing a WtE incineration facility is likely to be a cause of contention.

Advisable key criteria

Efficient administrative services for energy, waterworks and sewerage works are in place.

A sufficient level of social infrastructure, such as electricity and water supply and sewerage, must be in place near the planned construction site of a facility to secure the utilities required for the operation of a WtE incineration facility. Moreover, local capacity and experience with well-managed urban infrastructure indicate that complex systems can be handled locally.

4 Summary of data from the Ministry of the Environment of Japan database (in Japanese)

5 For example, Tokyo Metropolitan Government plans for each unit to operate 293 days per year. https://www.union.tokyo23-seisou.lg.jp/kihonkeikaku/documents/27_ippaikihonnkeikaku_zenpenn.pdf

Advisable key criteria

Laws on pollution prevention and environmental impact assessments have been developed and enacted.

If environmental laws and regulations are not in place, there is a risk that discussions and decisions on environmental measures for WtE incineration facilities will be made without certainty of the results. Laws and regulations related to environmental assessments, emission standards for flue gas and other standards differ in the method of implementation and status by country or region, and therefore, must be clarified before facilities are constructed.

2.2 Public awareness and cooperation of residents

Mandatory key criteria

Residents actively sort waste at source, allowing the recovery of recyclable materials and control of waste not suitable for WtE incineration.

In developing countries, the composition of MSW is mostly organic with a high moisture content, reducing LCV and lowering incineration efficiency. Therefore, **waste separation is a prerequisite for WtE incineration to ensure that recyclable materials are recovered and to increase the calorific value of waste.** Residents are an integral part of the waste separation process as they separate waste at source to remove inappropriate waste for incineration, such as hazardous materials and incombustible waste (bulky mineral waste, metals, etc.). Vast amounts of MSW are generated by residents, making their cooperation in sorting waste and controlling emissions essential. The ability to check the level of cooperation of residents also demonstrates the capabilities of local governments and their level of performance in waste management.

Mandatory key criteria

Residents have a basic understanding of WtE incineration technology, including air quality control and its effectiveness in sterilisation and controlling infections from viruses or microbes.

Focus should be directed on the distrust residents have towards WtE incineration facilities. In the past, concerns about air pollution stemmed mainly from the release of untreated flue gas including dioxins from incineration plants. The administration must take a proactive stance in dealing with such concerns. Time will be needed to help residents around construction sites understand that **modern incinerators comply with standards because of extensive measures being taken in facilities to protect air quality.** Furthermore, it has been recognised that high-temperature combustion is an effective process for sterilisation and controlling infections from viruses or microbes. High-temperature conditions have also been noted as effective in the decomposition of infectious wastes, as well as waste containing manure.

2.3 Institutional aspects

Mandatory key criteria

Basic laws and rules on solid waste management have been developed.

There must be a legal basis in place to promote proper waste disposal by installing waste disposal and WtE incineration facilities. Waste disposal systems and competent authorities must first be identified and a legal foundation for the construction of treatment facilities should be developed.

Mandatory key criteria

An appropriate construction site for the WtE incineration facility can be secured.

Securing a construction site is a fundamental part of satisfying requirements and achieving the goals of WtE incineration plans. Sites are also subject to various laws and restrictions, such as urban planning and building standard laws, so it is important to promote plans from a comprehensive perspective. The stability and reliability of the local government are also an important part of this criteria. As mentioned in the previous section, **the most important, but difficult, point in constructing a WtE incineration facility is the ability to secure a site where consent from residents in surrounding areas can be obtained.** Appropriate sites may be located in urban or rural areas; there are cases in Japan and Europe where WtE incineration plants are located in the middle of the urban centres. It is also possible to consider locating it at an industrial park, where demand for steam is anticipated, if the location is close enough to the city (waste source).

Strongly advisable key criteria

There is a stable administrative body in charge of the construction and operation of WtE incineration facilities, and a personnel management system is in place to enable long-term employment (3 years or more) for core staff.

Since waste management is a public service and the construction of the WtE incineration facility should be based on a city's long-term plan for waste management and urban development, **the stability of the administrative body should be the primary focus from an institutional perspective.**

2.4 Governance capability

Mandatory key criteria

WtE incineration is positioned in upper level plans (comprehensive plan, regional development strategy, etc.).

WtE incineration technology should be formally/legally recognised in upper level plans such as comprehensive plans, regional development strategies, and other relevant plans, including national and local waste management plans and strategies. Positioning a WtE incineration plant in such plans ensures that planning, construction and operation will be integrated and smoothly implemented.

Mandatory key criteria

Local government leaders demonstrate a positive attitude and willingness to consider WtE incineration.

The introduction of a WtE incineration facility is also influenced by political trends and strongly impacted by the will of those in power in local governments. Local government leaders must demonstrate a positive attitude towards the introduction of the WtE incineration facility.

Strongly advisable key criteria

The local government can obtain support from expert committees and consultants to implement WtE incineration projects.

A variety of expertise is needed in the planning and construction of a WtE incineration facility, including technical skill. Therefore, the project should be conducted with support from external experts and consultants. That said, the most important point to consider is the capability of the administrative body to execute the project, including the capacity to consult with power companies in advance on the practical issues of selling electric power. For these reasons, **the administrative body must have a certain ability to plan, execute and maintain the WtE incineration system.**

Strongly advisable key criteria

Energy departments and electric power companies have developed technical standards and operations to sell and set the sales price of electricity.

If a WtE incineration plant is connected to the power system of an electric power company to transmit electricity, the electricity generated at that plant can be sold to the electric power company. Therefore, in order to maintain the quality of electricity (voltage, frequency, etc.) and to prevent malfunctions or failures in one power generation facility from affecting others, **the administration must be able to consult with the electric power company on technical standards specified by competent ministries or divisions, as well as the technical requirements issued by the electric power company.** Also, it is recommended to confirm the existence of technical standards for electricity sales and the adjusted unit price for electricity sales from WtE incineration plants.

2.5 Financial aspects

Mandatory key criteria

Total costs for WtE incineration (construction, operation and maintenance) can be secured.

It is necessary to secure financial resources for the entire project cycle, including costs for construction, operation and maintenance. Examples of ways to generate income include **direct waste fees from residents, gate fees when waste is delivered to a plant site, revenue from the sale of recycled energy and recovered materials such as electricity, heat and steam, waste tariffs, local or national subsidies, cross financing of MSW services through other local fees or taxes, national or international revenue such as carbon funds, tax refunds and the application of special FIT for electricity.** Among them, income from both tipping fees and electricity sales are normally important sources of financial income for WtE incineration.

Strongly advisable key criteria

Revenue from selling electricity and other recyclables can be generated.

Income from the sale of electric power generated by WtE incineration and other recyclables is also a major financial source. In referring to similar situations in recent years, it is desirable for FIT or other regulatory incentives to be established to ensure that sales revenue remains sustainable over the long term. Therefore, it is necessary to examine how these systems are implemented in different countries. Factors affecting the volume of electric power sales include the incinerated amount of MSW, LCV of waste, electricity generation efficiency, and operating time of electricity generation equipment, for example.

Strongly advisable key criteria

Tipping fees can be set at a stable price over a long period with contracts.

Tipping fees (or gate fees) are expenses paid by the local government to the business operator of an incineration facility based on the amount of waste incinerated. Tipping fees are a major source of income for incineration, and it is crucial to secure such financial resources for long-term stable operation. **In Asian developing countries, tipping fees for landfilling and incineration are set at a level of ten to several tens of US dollars per tonne of MSW, which do not sufficiently cover the operating costs of WtE incinerators.**

Advisable key criteria

PPP schemes for WtE incineration are being discussed among stakeholders.

PPPs, which recognise the relative strengths and advantages of government, private and civil society organisations, have emerged as a promising complementary approach to improve the provision of MSW management services in many countries. PPPs involve collaboration between a government agency and a private company to finance, build and operate projects.

There are several different types of PPP for WtE incineration as shown in Table 3. In recent years, Design-Build and Operate (DBO) has been the type of PPP most often selected in Japan for WtE incineration projects. However, in developing countries, facilities are mainly constructed with funding from international and private sources due to large upfront capital investment and high operating costs. Build-Operate-Transfer (BOT) or Build-Own-Operate (BOO), where the public sector assumes a lower risk, is the preferred type of PPP in Asian countries. In these types of PPP for WtE incineration, **the administrative body plays an important role in conducting technical reviews and drawing up contracts, requiring both the public and private sectors to have a common understanding of WtE incineration projects and their expected roles and responsibilities.** If the two key issues of (1) the uncertainty of the WtE incinerator supply chain, including the quality or heat value of the waste collected, and (2) the form of capital for recovering WtE incineration and operational costs are carefully addressed, the project would have a better chance of success.

Advisable key criteria

Risks have been assessed and confirmed, and demarcation points for different responsibilities are understood to ensure that risks are shared across the board.

Finally, parties involved in the WtE incineration project should understand and clarify the many risks associated with the project (Table 4) and discuss how to share risks.

Table 3 Types and characteristics of WtE incineration projects

Type		Details	Financing	Design and construction	Management administration	Ownership
DB (Design-Build)		The public sector raises funds and the private business operator designs and builds a facility with sufficient capacity. The public sector also operates and manages the facility.	Public	Private	Public	Public
DBO (Design-Build-Operate)		The public sector raises funds. The private operator designs, constructs, manages and operates the facility under a long-term comprehensive contract.	Public	Private	Private	Public
PFI (Private Finance Initiative)	BTO (Build-Transfer-Operate)	The private business operator raises funds to build a facility. After building this facility, the investor transfers it to the public sector. The private operator manages and operates the facility under a long-term comprehensive contract.	Private	Private	Private	Public
	BOT (Build-Operate-Transfer)	The private business operator raises funds and performs a public service using the constructed facility. The public sector compensates the private business operator for services. When the contract term expires, the private operator transfers the facility to the public sector.	Private	Private	Private	Private Public
	BOO (Build-Own-Operate)	The private business operator raises funds and performs a public service using the constructed facility. When the contract term expires, the private operator takes possession of the facility and continues operations.	Private	Private	Private	Private

(Source: revised by author based on JICA WtE incineration guideline)

Table 4 Main risks to be considered

Stage	Risk	Content
General issues	Changes in legal systems	Changes in laws, regulations, etc.
	Changes in tax systems	Changes in corporate and consumption taxes
	Licensing delays	Delays in licensing for business operators, subsidies, etc.
	Third-party compensation risk	If there is a claim for compensation due to noise, vibration, offensive odours, or other environmental pollution
	Dealing with residents	Matters related to opposition, lawsuits, etc.
	Land acquisition	Matters related to securing construction sites
	Accidents	In the event of an accident
	Environmental protection	If the project has an effect on the environment
	Postponement and cancellation	Government disapproval, project cancellation, failure, etc.
	Price fluctuations	Inflation and deflation
	Interest rate change	When changes in interest rates affect borrowings, etc.
	Other unpredictable risks	Natural disasters, riots, etc.
Planning and design	Financing	Measures for securing necessary funds
	Survey	Risk of changes to plans due to deficiencies in field surveys of landforms, geology, etc.
	Design	Matters related to design
Construction	Construction delays	Risks of delayed service due to construction delays, suspension of construction, etc.
	Increased construction costs	Risks associated with increased construction costs
	Performance	Risk of failure to meet requirements
Operation	Plan changes	Changes in business need and content
	Uncertainty and changes in waste	Risks related to securing the quantity of planned waste and changes in waste quality
	Damage to facilities	Risk of damage to facilities due to accidents, excluding force majeure
	Performance	In the event that the required performance level cannot be met
	Increased operating costs	Increased costs resulting from inadequate management

(Source: revised by author based on JICA WtE incineration guideline)

2.6 Technological aspects

Mandatory key criteria

Waste composition and LCV (at least 6,000 kJ/kg for WtE incineration) should be investigated.

It is important to have accurate data on the quantity and quality of waste at the planning stage. The quantity of waste has been discussed in 2.1. To understand waste quality, data on waste composition and LCV[6] should be obtained through actual investigations (World Bank, 2000). **WtE incineration differs from power generation using fossil fuels in that the amount of power generated depends on the properties of waste (especially LCV).** If the waste does not satisfy specific properties, the facility may not be able to generate the expected amount of electricity or the facility itself may be inoperative. Furthermore, **the composition and LCV of the waste change over time due to seasonal variations in waste content.** For example, waste may contain more moisture in the rainy season. Such aspects must be addressed in the design of the furnace and the overall process of loading waste. Various studies suggest that the **LCV must be, on average, at least 7,000 kJ/kg and never fall below 6,000 kJ/kg** for WtE incineration to recover energy (ISWA, 2013; GIZ, 2017).

Waste composition has a close relationship with LCV. Kawai et al. (2016) proposed the use of **a triangle diagram to confirm whether the current proximate composition (moisture, ash, and volatile) of municipal solid waste would be suitable for incineration,** composting and RDF production. The triangle diagram shows that the applicable range of techniques can be roughly identified by waste composition. For example, incineration technology can be applied to waste with a moisture content of 75% or less and a volatile content of 20% or more, which corresponds to a LCV of 3,352 kJ/kg or more. Furthermore, in cases where energy recovery is a part of the incineration process, these technologies are generally applicable for waste with a moisture content of 65% or less and a volatile content of 30% or more, with a LCV of 6,285 kJ/kg or more.

Based on the above study and the composition of waste in countries in each of the different income groups presented in the World Bank Group report (World Bank, 2018; Fig. 5), **the applicable range of MSW incineration and WtE incineration can be determined together with the proximate composition of different country groups** (Fig. 6). The composition of waste in low-income countries indicates that this waste can be incinerated, but it does not fall within the scope of energy recovery from incineration. The composition of waste in middle-income countries (upper middle and lower middle are plotted at approximately the same position) is just about applicable for energy recovery through incineration. Waste in high-income countries falls within the scope of energy recovery through incineration.

Considering the overall composition of waste, the greatest impact can be found in the proportion of food and kitchen waste with high moisture levels. If the amount of organic waste is about 50% to 60%, incineration becomes an option. However, it is not suitable for energy recovery, which is only possible when the ratio of plastic and paper increases and food and kitchen waste falls to approximately 50% or less.

6 LCV is determined by subtracting the heat of vaporisation of the water from the higher heating value. This treats any H_2O formed as a vapor. Please see: https://all-water.org/

Box 1 Waste classification and composition

Waste is broadly classified into **organic waste** that is biodegradable and comes from either plants or animals, namely food and kitchen waste, as well as green waste such as pruned branches, and **inorganic waste** such as plastics, paper, glass, and metals. However, in terms of WtE incineration, MSW can be categorised into "**combustible**" or "**non-combustible**" wastes. Combustible waste consists of **organic waste** and **other burnable waste** such as paper, plastic, and textiles that were not separated at source as recyclable resources. **Non-combustible waste** includes ceramic ware (teacups, plates, flowerpots, etc.), metals, glass (bottles, flower vases, mirrors, etc.), ash, and other items. Such non-combustible wastes should be removed at source from waste to be incinerated.

Waste composition is influenced by many factors, such as the level of economic development, cultural norms, geographical location, energy sources, and climate. In general, as a country urbanises and populations become wealthier, the consumption of inorganic materials increases, while the relative organic fraction decreases. As shown in Fig. 5, the ratio of organic waste (food and green) tends to be highest (56%) in low-income countries and lowest (32%) in high-income countries (World Bank, 2018; wet weight based). However, food and kitchen waste generally contain large quantities of moisture, whereas plastic, paper and textiles have a lower moisture content. Higher moisture content reduces the LCV and combustion efficiency.

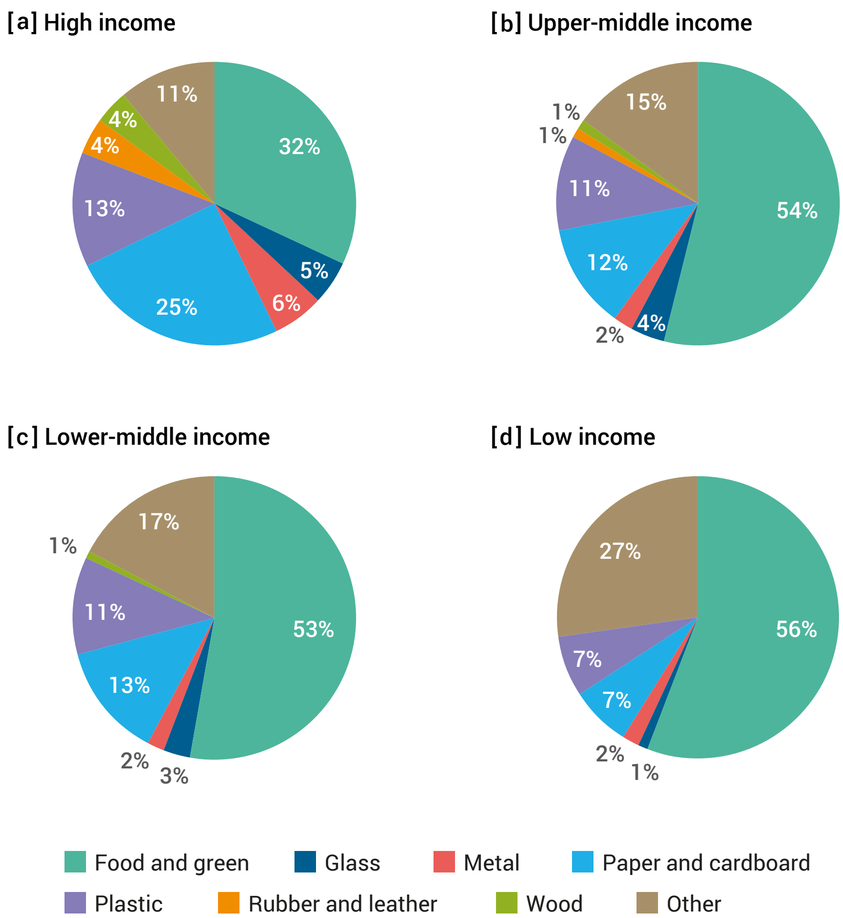


Fig. 5 Country income levels and waste composition

(Source: revised by author based on World Bank (2018))

Box 2 LCV for WtE incineration

If the LCV falls below 6,000 kJ/kg, for example 4,500 kJ/kg, or even lower with auxiliary fuel, incineration would be still possible, however, it would not be efficient for WtE incineration. **In general, waste in developing countries contains a high percentage of food and kitchen waste and a LCV than that in developed countries.** To reduce moisture content in combustible waste, developing countries should focus on source separation and reducing the moisture content of food and kitchen waste. Also, waste should be collected taking care to prevent rainwater from seeping into the waste collected at curbside especially during the rainy season. It is also useful to request cooperation from the public to reduce moisture before disposing of kitchen waste.

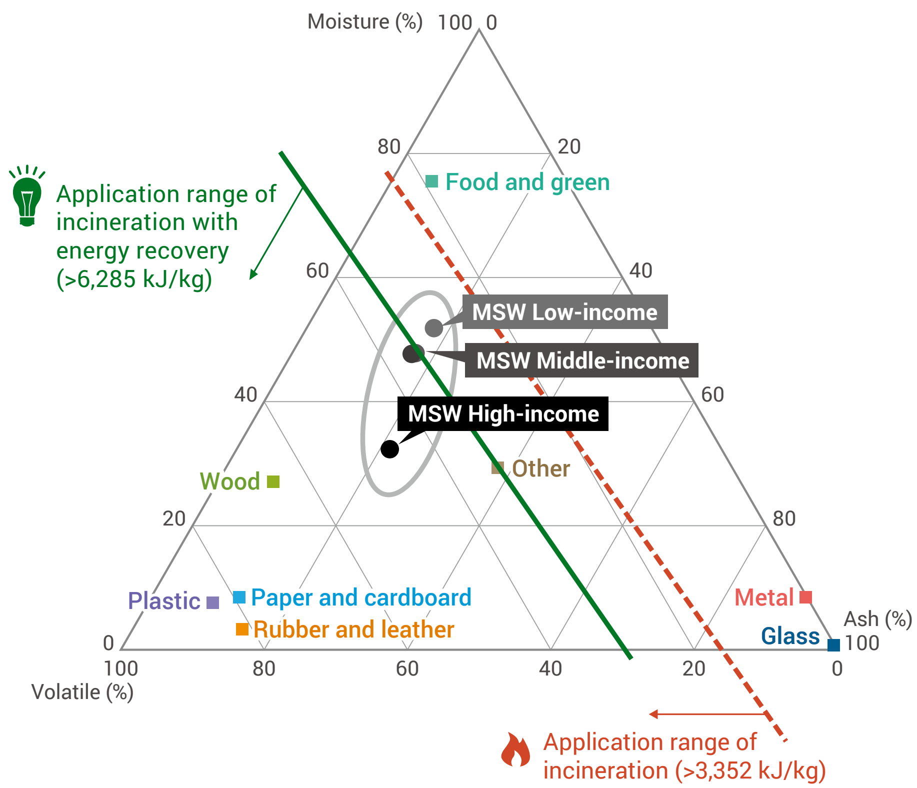


Fig. 6 Proximate composition of different country groups and application range of incineration and WtE incineration
(Source: prepared by author based on Kawai (2016) and World Bank (2018))

Mandatory key criteria

Bottom ash and APC residue (fly ash) can be safely treated.

Bottom ash and APC residue (fly ash) are always discharged during the WtE incineration process. This residue should be properly treated for reclamation in a controlled landfill or for recycling. Although various recycling methods have been developed for bottom ash and APC residue (fly ash), limitations still exist and the total volume cannot always be accepted. In all cases, a controlled landfill should be secured for reclamation. (See 3.5)

Strongly advisable key criteria

Plant manufacturers have an appropriate level of expertise and suitable incinerators.

Stoker-type incinerators are the most popular type of WtE incineration system for MSW. Other types include fluid bed-type incinerators and gasification melting furnaces (explained in more detail in Chapter 3). One of the keys to success is to call on experienced plant manufacturers to submit appropriate proposals. Plant manufacturers should be evaluated from the perspective of their achievements in construction and operation. An outline of WtE incineration technology and points to discuss with plant manufacturers are described in the following section.

Advisable key criteria

An environmental monitoring system is in place.

Flue gas, wastewater, noise, vibration, and odour generated by the operation of WtE incineration facilities must be appropriately monitored both by specialised analytical organisations and continuous measurement systems. It is important not only to prevent environmental pollution but to also gain the understanding and trust of local residents.

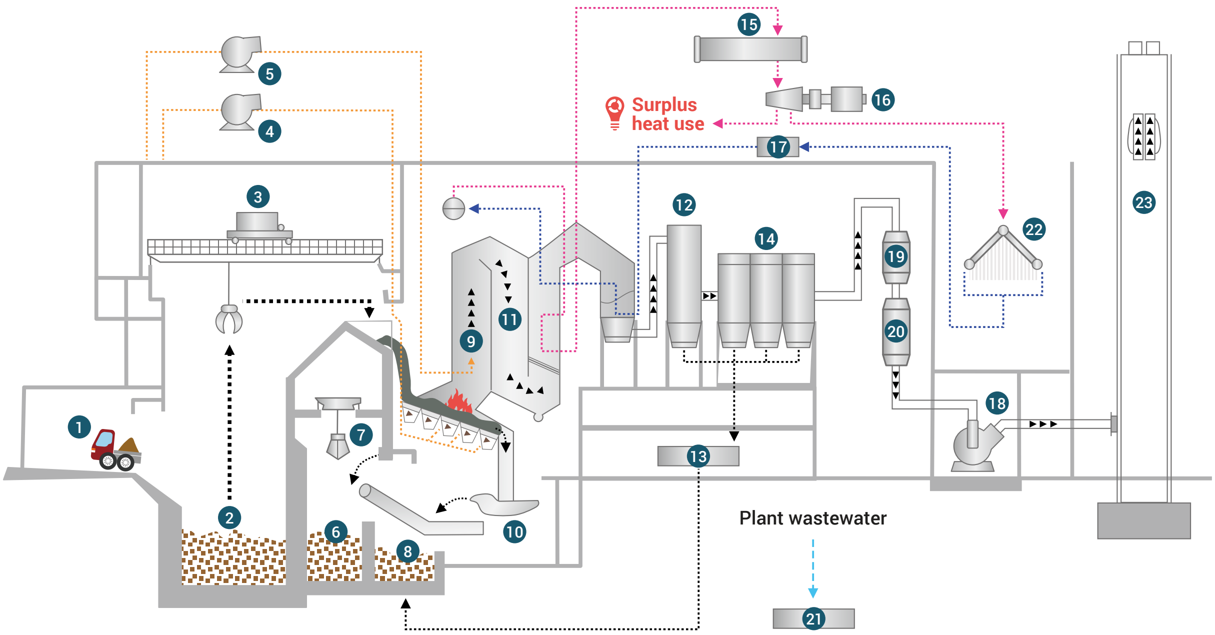
Advisable key criteria

Capacity building and training is available to improve the technical skills of staff.

A WtE incineration plant is not simply a black box for generating electricity, heat or steam, but includes sophisticated technologies that require experienced management and well-trained technical staff. In order to train and develop engineers that can operate WtE incineration plants, expert knowledge must be made available to build capacity. It is important to have an organised human resource development system that incorporates a long-term perspective.

3 Main Technology and Discussion Points with Plant Manufacturers

An example of a conventional incineration facility is illustrated in Fig. 7. This configuration can be typically seen in facilities in urban areas in Japan, where there are strict APC requirements for dust, acidic gases, NOx, mercury and dioxin removal. There are five main processes: 1) waste pit for the storage of waste before it is fed into the furnace, 2) incineration furnace operated at a temperature over 850°C, 3) heat recovery and gas cooling to under 200°C, 4) flue gas cleaning system typically including a bag filter and 5) ash discharge and treatment. In addition, the NOx reduction system is often equipped to meet stricter requirements for reducing NOx emissions in urban areas.



Symbols: Waste flow; Gas flow; Steam flow; Wastewater flow; Ash flow; Air flow; Condensate flow

1. Platform
2. Waste pit
3. Waste crane
4. Primary forced draft fan
5. Secondary forced draft fan
6. Ash pit
7. Ash crane
8. Treated ash pit
9. Combustion chamber
10. Ash pusher
11. Boiler
12. Cooling tower
13. APC residue (fly ash) treatment equipment
14. Bag filter
15. Steam reservoir
16. Turbine generator
17. Condensate tank
18. Induced draft fan
19. Steam-type gas re-heater
20. Catalytic reactor
21. Wastewater treatment equipment
22. ACC (Air-Cooled Condenser)
23. Stack

Fig. 7 Example of a conventional incineration plant configuration – Stoker type furnace

(Source: revised by author based on facility pamphlets)

3.1 Incinerator classifications

Discussion point with plant manufacturer

Stoker-type incinerators are the most popular type of WtE incineration system for MSW. Other types include fluid bed-type incinerators and gasification melting furnaces.

Specific incineration technologies vary among individual plant manufacturers. An example can be seen in stoker-type incinerators. The mechanical structure of fire grating equipment differs according to waste quality, such as moisture content and LCV, as well as in the proportion of organic, paper and plastics content. Often, MSW in Asian countries has a high moisture content. If grating equipment is not designed with specifications that take this into consideration, for example, waste may burn too slowly and be discharged before complete combustion, or may burn too quickly and form large lumps on the grating equipment. For this reason, **it is necessary to order a WtE incinerator from a plant manufacturer with extensive experience and strong technical skills in all areas of the entire incineration system.**

> *In the past, batch-type incinerators (each batch cycle includes input, ignition, combustion, cooling and discharge) and semi-continuous type incinerators (that start in the morning and stop at night in a 1-day cycle) were frequently installed around Japan. However, it has become clear that unstable combustion generates dioxins, resulting in the adoption of continuous incineration (24-hour incineration) systems in most incinerators.*

Typical continuous incinerators include stoker-type incinerators, fluidised bed-type incinerators, and gasification melting furnaces. Stoker-type and fluidised bed-type incinerators aim to completely combust waste in a furnace with the addition of a sufficient supply of oxygen. On the other hand, the gasification melting furnace differs in terms of air supply, treating bottom ash through a high temperature melting process. Today, stoker-type incinerators are most common. The following offers a brief description of these incinerators.

(1) Stoker-type incinerators

The word “stoker” means “set of grates”. The input waste is combusted as it gradually progresses downstream through the movement of moveable grates. The combustion chamber is divided into three stages: “dry zone”, “combustion zone” and “burn-out zone” (Fig. 8). Even waste with high moisture content can be efficiently combusted

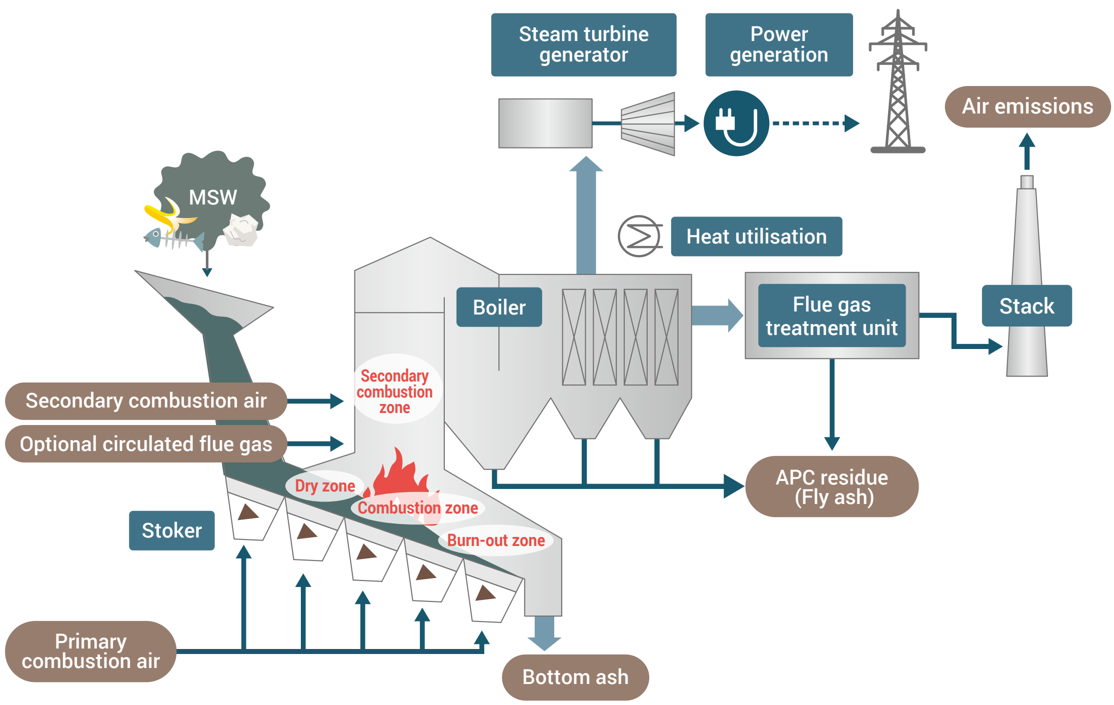


Fig. 8 Example of a stoker-type incinerator (Source: revised by author based on facility pamphlets)

with an appropriate retention time in the dry zone, which is one of the reasons why stoker-type incinerators are usually adopted for MSW. In the combustion zone, a sufficient amount of air is supplied to burn combustibles. Unburned but combustible residue is completely combusted in the burn-out zone. The design and operating conditions of this three-stage combustion chamber must be adjusted appropriately according to the amount and quality of waste.

(2) Fluidised bed-type incinerators

A fluidised bed-type incinerator (Fig. 9) has a layer of sand at the bottom of the combustion chamber, and air is blown into the sand layer from the bottom to turn the sand into fluid. Once the sand layer is heated, the waste continues to combust on its own on the fluidised bed. Sand layers can dry and burn MSW instantly even when waste with a high moisture content is added because of the sand's high heating capacity. In addition, fluidised bed-type incinerators can be restarted in a short period of time after operation stops. However, due to high combustion speed, incomplete combustion may generate high levels of CO gas if the incinerator is not properly designed and operated. This type of incinerator is more suitable for combusting homogeneous materials such as sludge, rather than heterogeneous MSW.

(3) Gasification melting furnace

The gasification melting furnace is a system that melts bottom ash directly in the furnace to produce molten slag (Fig. 10). Molten slag has higher density than bottom ash and more potential to be utilised as construction material.

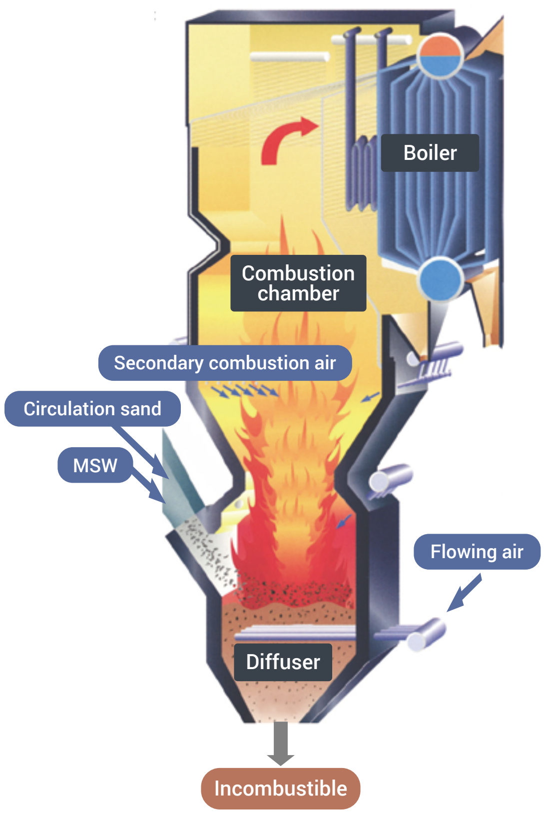


Fig. 9 Example of a fluidised bed-type incinerator
(Source: revised by author based on material[7] from the Ministry of the Environment, Japan)

7 https://www.env.go.jp/recycle/circul/venous_industry/ja/skill_pdf/t003.

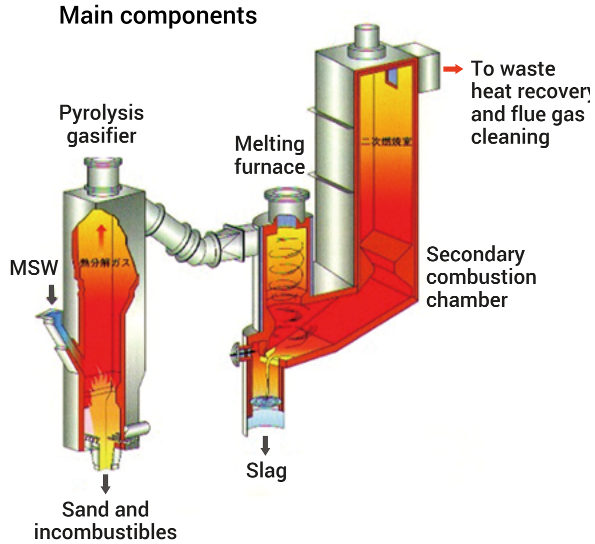
The gasification melting process includes two types of furnaces: a pyrolysis and gasification melting furnace using a fluidised bed (Fig. 10 [a]) or a kiln, and a direct melting furnace that utilises a vertical shaft furnace (Fig. 10 [b]).

Pyrolysis and gasification melting is a process in which waste is thermally decomposed with a lower amount of oxygen or heated indirectly to induce pyrolysis (partial combustion) within a temperature range that is lower than the combustion temperature to generate pyrolysis gas. In fluidised bed and kiln-type furnaces, this process occurs in each furnace, which is separated from the melting furnace. In the second stage, combustion air is added into the melting furnace to completely burn out the pyrolysis gas at high temperatures, and solids are melted using the heat generated by combustion at temperatures that can reach between 1,200 and 1,300°C. In recent years, it is rare to see kiln-type furnaces.

Vertical shaft furnace melting is a process in which waste travels down gradually in a vertical shaft furnace from the upper drying layer to the middle pyrolysis layer and lower melting layer.

Compared to conventional incineration methods, the option of gasification melting has not been adopted as quickly as other methods because of high costs and the difficulties it poses in terms of operation.

[a] Fluidised bed-type gasification melting furnace: Main components



[b] Shaft furnace-type gasification melting furnace system

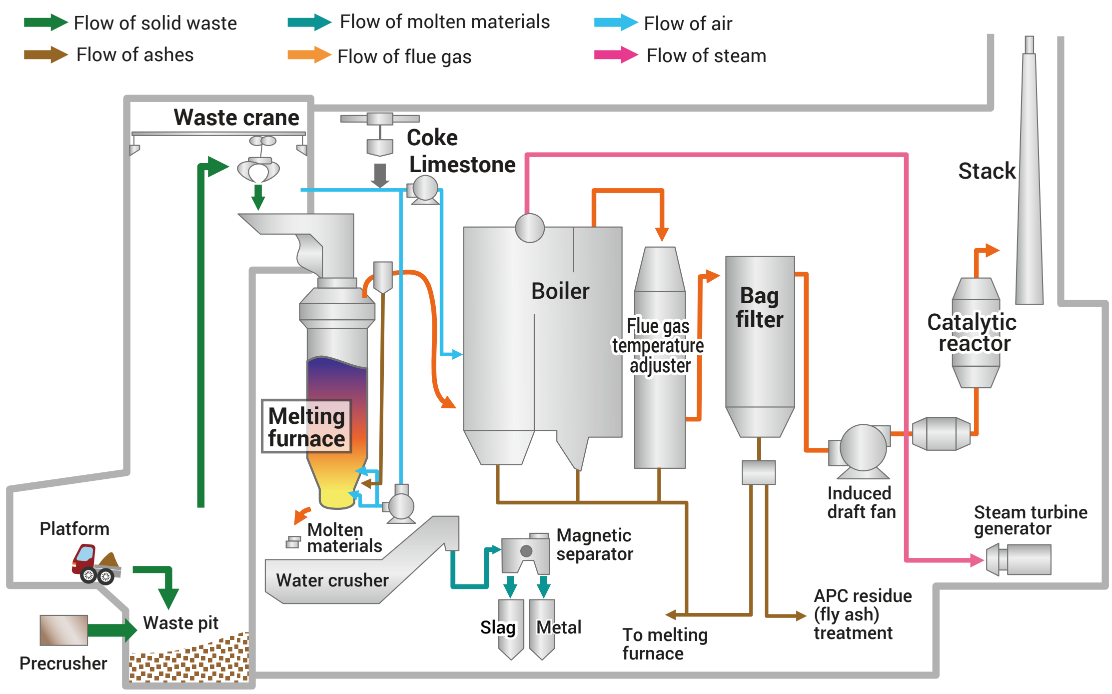


Fig. 10 Examples of gasification melting furnaces (Source: revised by author based on facility pamphlets)

3.2 Operation parameters for combustion

Discussion point with plant manufacturer

Key parameters for combustion include air ratio for input and CO concentration for output. To prevent the generation of dioxins, the "3Ts" (Temperature, (retention) Time, and Turbulence) are critical.

An incinerator must be designed for complete combustion of both solid residue and flue gas (Takuma Environmental Technology Research Group, 2017). A sufficient temperature and retention time with an appropriate air ratio are required for complete combustion. The air ratio is the ratio of the actual amount of air supplied to a theoretical amount of air for combustion. The typical air ratio of primary air supplied to a solid combustion chamber is 1.2 to 1.4. In order to prevent incomplete combustion of flue gas, a temperature of 850°C or more and a retention time of two seconds or longer with enough turbulence are required in the secondary combustion zone, which also prevents dioxins from forming. The secondary air added to the secondary combustion zone brings this ratio to 1.7 to 1.9. Recently, a lower air ratio design has been developed to improve energy recovery efficiency. (See case study 4.1)

In order to monitor combustion conditions, the oxygen (O_2), carbon dioxide (CO_2), and carbon monoxide (CO) concentrations should be measured continuously. According to guidelines in Japan to prevent dioxins, CO concentrations should be 30ppm (37.5 mg/m^{3}N) or less (O_2 as 12%; 4-hour average value).

3.3 Heat recovery and power generation

Discussion point with plant manufacturer

The steam conditions of boilers significantly affect the output of power generators. It is desirable to design systems that incorporate high-temperature and high-pressure steam boilers.

One of the objectives of WtE incineration is to recover energy from waste combustion heat by generating steam. Since the high-temperature flue gas that has been generated from waste combustion must be cooled for flue gas treatment, a WtE incineration plant is equipped with a boiler system that recovers thermal energy during the cooling process. Thermal energy is recovered as steam in the boiler while flue gas is cooled by heating water indirectly in water pipes. Most steam is sent to a steam turbine and then used to generate electricity. Steam and heated water discharged through the steam turbine can also be used as another heat source option.

As illustrated in Fig. 11, steam is generated in a waste heat boiler. **The most influential factor in the boiler is the steam condition, which is mainly defined by temperature and pressure, and the water-steam cycle.** As the steam temperature and pressure edge up higher, energy recovery efficiency also rises. Values have greatly increased from the past; up until around 1990, the standard value was 300°C and 3MPa or less. But today, **the typical standard value in Japan is around 400°C and 4 MPa, which can increase power generation efficiency up to about 20%.**

As reference, steam from coal or natural gas fired power plants has a temperature of 500°C or higher and pressure between 15 and 25 MPa or higher, with a power generation efficiency of 40% or more. WtE incineration systems cannot be designed with high-temperature and high-pressure systems like power *plants because the flue gas contains corrosive gases, such as hydrogen chloride.*

As a result of recent technological developments, steam temperature and pressure can be higher, which also raises power generation efficiency to 25% or 30%. Several additional types of equipment are required to recover heat more efficiently. A superheater heats the steam from the boiler, and an economiser heats water fed to the boiler using the residual heat of combustion flue gas.

In addition, if the steam can be transported to and utilised at a nearby factory, energy savings will double in comparison to cases in which steam is used for power generation (Fujii et al., 2019). Steam sent from incinerators to nearby factories is an approach that has already been taken in such locations as Ulsan Industrial Park in South Korea. This approach has been proven to be both environmentally and economically beneficial, even for short payback periods (Behera et al., 2012).

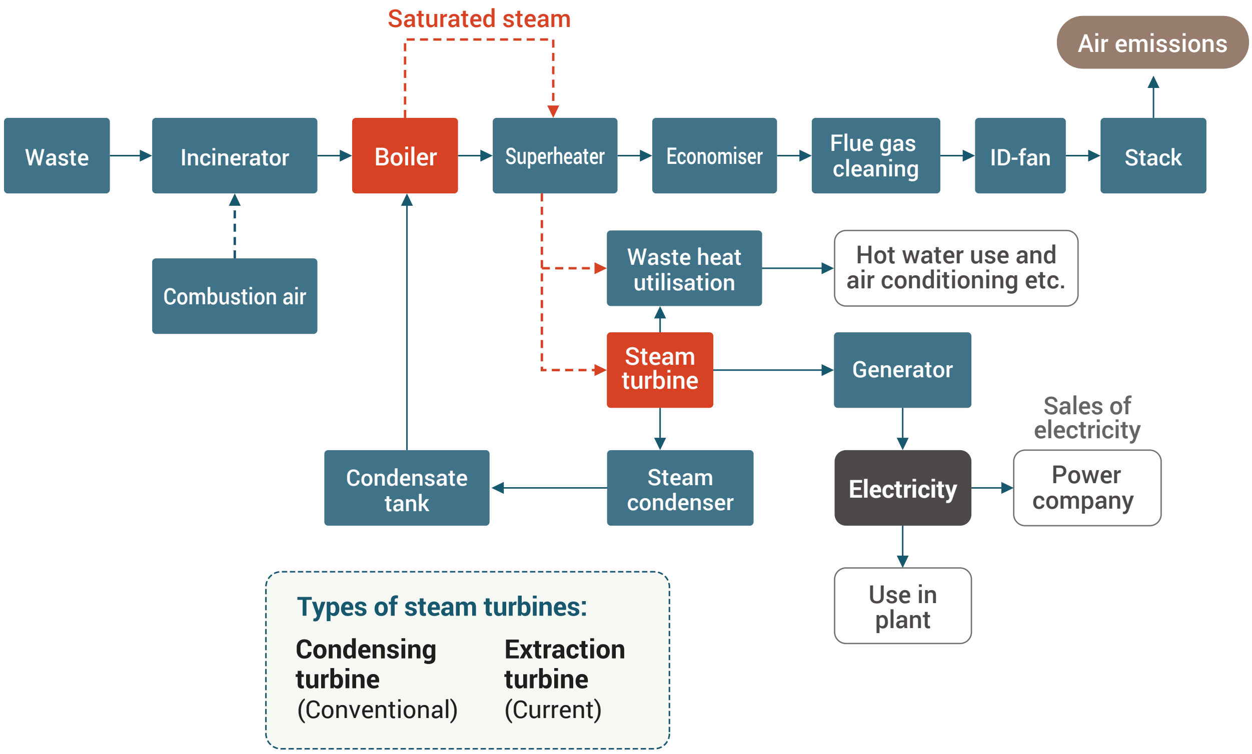


Fig. 11 Plant configuration of boiler and peripheral equipment (Source: author)

3.4 Air pollution and wastewater control process to reduce environmental impact

Discussion point with plant manufacturer

Air pollution can be prevented with the use of an integrated control process. To prevent the generation and emission of dioxins, combustion must be controlled and flue gas must be treated properly.

To construct a WtE incineration plant, it is important to consider environmental impacts caused by the emission of various pollutants to the atmosphere, especially from the perspectives of public awareness and acceptance. Advanced technologies for APC that have been developed in recent years can effectively eliminate the emission of various pollutants. In general, air pollutants that should be controlled include dust, acidic gases, NOx, dioxins and mercury (Takuma Environmental Technology Research Group, 2017).

As for wastewater, many plants use closed systems that do not generate wastewater. In such systems, wastewater generated during the treatment process is sprayed as coolant in furnaces, which then evaporates and is treated by flue gas treatment systems. If the moisture content in MSW is high, seeped water may collect in the waste pit and must be treated.

Bag filters are used to remove air pollutants from flue gas through filtering. An alkali agent such as lime powder and powdered activated carbon are injected into flue gas before it passes through the bag filter. Air pollutants, except NOx, can be removed through the following mechanisms.

- Dust is removed by filtering.
- Acidic gases such as hydrochloric acid (HCl) and sulfur dioxide (SO_2) are reacted with an alkali agent and removed.
- Dioxins and mercury are adsorbed into powdered activated carbon and removed.

To monitor flue gas, dust, HCl, SO_2, and NOx must be measured continuously. Continuous measurements of mercury using equipment that has been developed in recent years should also be considered as there has been more focus on mercury emissions since the Minamata Convention (2013). Periodical measurement of these items by specialised analytical organisations is also required. Dioxins should be measured periodically because they cannot be measured continuously.

> *In the past, electrostatic precipitators were often used to remove dust from flue gas. However, it has been discovered that waste incinerators generated dioxins because of De Novo synthesis in electrostatic precipitators with operating conditions around 300ºC. Around the 1990s, electrostatic precipitators were rapidly replaced with bag filters, which are suitable for operation at temperatures of 200ºC or lower to prevent the generation of dioxins. In addition, since mercury is a volatile metal, it can be collected more efficiently in the bag filter's lower temperature range.*

Removed pollutants are discharged from bag filters together with the injected alkali agent and activated carbon as "Air Pollution Control (APC) residue", often called "fly ash". **APC residue (fly ash) must be disposed of properly as hazardous waste.**

Box 3 Dioxins control

Dioxins are substances that can be relatively easily broken down when incinerated at high temperatures. However, the formation of dioxins, called the *De Novo* synthesis process, can occur in incineration systems at around 300°C. **Modern incineration plants can reduce the emission of dioxins to less than the emission standard by appropriate incineration and flue gas treatment.** Countermeasures for dioxins in incinerators are summarised below.

- **Complete combustion in incinerator**
  Maintain low CO values as a standard indicator. Since operation at unstable temperatures may generate CO, temperatures must be stabilised through continuous operation. The "3Ts" (Temperature, (retention) Time, and Turbulence) in the combustion chamber are important, as mentioned.
- **Prevent *De Novo* synthesis**
  To avoid generating dioxins due to *De Novo* synthesis, the use of electrostatic precipitators that retain flue gas at temperatures of around 300°C should be avoided.
- **Collection of dust using bag filters**
  Trace amounts of dioxins can be adsorbed using activated carbon and removed by bag filters. A denitrification catalyst, described below, also has the function of decomposing dioxins.

(Source: author)

All these advanced APC technologies should be incorporated in a systematic manner as shown in Fig. 12. In order to minimise environmental impacts and maximise energy recovery, it is necessary to design and construct the most rational process.

Box 4 NOx reduction

Unlike other acidic gases, NOx cannot be removed with bag filters and requires a different system. There are three main ways to reduce NOx. These three methods can be used alone or in combination depending on the required level of reduction (see Fig. 12).

(1) Combustion control: In this method, flue gas inside the combustion furnace is kept in a low-oxygen atmosphere. However, controlling NOx emissions is a trade-off with an increase in CO. **To reduce both at the same time, the temperature and air ratio in the combustion furnace must be finely controlled.** One option is to recirculate some of the combusted flue gas to the furnace to form a low-oxygen atmosphere.

(2) Non-catalytic denitrification: In this method, an ammonia or urea solution is sprayed into the combustion furnace to reduce and decompose nitrogen oxides. The temperature in the combustion chamber to be sprayed should be above 800°C. Though this method is rather simple, the amount of solution sprayed and the temperature of the flue gas must be precisely controlled, and it is not as efficient as catalytic denitrification.

(3) Catalytic denitrification: In this method, NOx in flue gas reacts with ammonia and oxygen through the action of a catalyst such as Vanadium (V) oxide/Titanium dioxide (V_2O_5/TiO_2) and decomposes into nitrogen and water. Since this catalyst requires clean flue gas that does not contain dust at a temperature of 200°C or higher, the flue gas is reheated after passing through the bag filter and is then sent to a catalyst denitrification device. **Removal efficiency is expected to be about 95%.** However, this type of reheating process reduces the amount of power generated because it uses steam. Although this method is more efficient than combustion control or non-catalytic denitrification, it poses a disadvantage in terms of cost. Therefore, this method tends not to be used as long as standards can be met with a combination of combustion control and non-catalytic denitrification. Recently, a low-temperature catalyst of around 180°C has been developed, which does not require flue gas to be reheated.

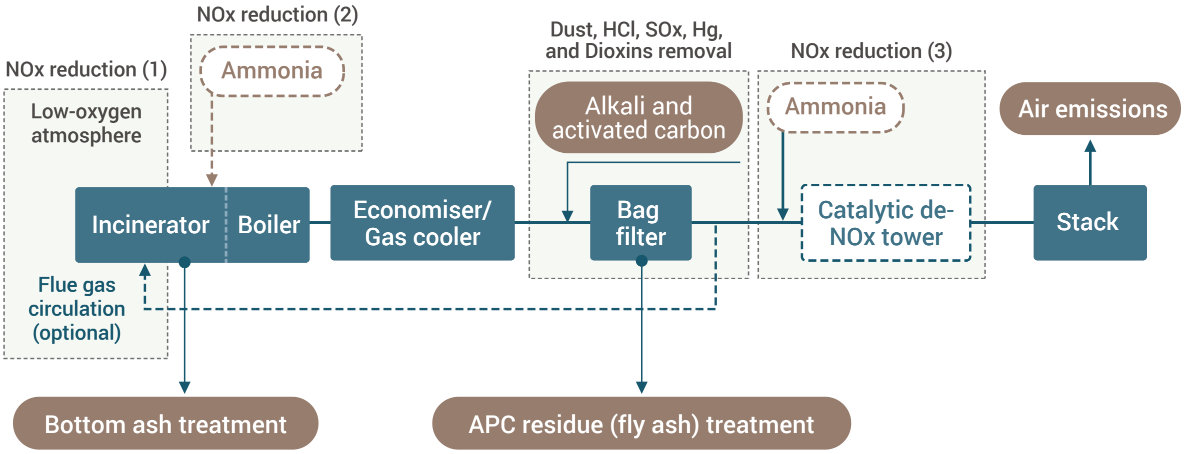


Fig. 12 Configuration of the latest flue gas treatment process with peripheral processes

3.5 Bottom ash and APC residue (fly ash)

Discussion point with plant manufacturer	**Quality of bottom ash and APC residue (fly ash) should be checked for loss on ignition (LOI) and harmful substances before reclamation or other treatment.**

Incinerators always generate bottom ash and APC residue (fly ash). **The most common method of treatment is reclamation in a controlled landfill site.** The characteristics of bottom ash and APC residue (fly ash) differ according to the type of incinerator. The following description is mainly based on a stoker-type incinerator (Takuma Environmental Technology Research Group, 2017).

When bottom ash is discharged from an incinerator, "Loss on Ignition (LOI)", which indicates unburned content in bottom ash, should be measured to ensure the quality of combustion. In Japan, LOI of bottom ash is regulated at 5% or less. It is also necessary to check that harmful substances such as heavy metals and dioxins do not exceed regulation values.

Bottom ash often contains pieces of steel, which are derived from the waste and can be recovered using a magnetic separator.

For bottom ash, there are several treatment methods available other than reclamation in waste landfills. However, these recycling methods remain limited and not all bottom ash can be accepted for treatment. In all cases, controlled landfills should be secured for reclamation.

- **Use of bottom ash as raw material for cement.** Bottom ash can be fed as a substitute for cement raw material between 0.5% to 1% of the total input. The limited amount is due to the content of repellent elements such as chlorine.

- **Use as construction material after treatment such as sintering, solidification and/or stabilisation (S/S) with chemicals, and aging.** This is needed to meet the safety criteria of harmful substances in the treated bottom ash.

- **Melting under high temperature generates slag aggregate.** Bottom ash is melted under high temperatures (1,250°C or more) in a coke-bed, fuel or electric furnace. After discharging and cool down, a high-density, glass-like material called "slag" is generated that can be used as construction material. Although the quality of this slag is high, the construction and operation costs of melting facilities also run high. In the melting process, secondary fly ash and metal ingots are generated as by-products, both of which can potentially be accepted as feed for the smelting process. **In gasification melting systems, the ash composition in the original MSW is directly melted in melting furnaces and then discharged as slag.**

APC residue (fly ash) is normally collected using bag filters and then discharged. It consists mainly of an injected alkaline agent and salt compound with an acidic gas, such as sulfur dioxide and hydrogen chloride, as well as dust containing harmful components such as heavy metals and dioxins. **In order to prevent toxic substances from leaching, APC residue (fly ash) is generally reclaimed in a controlled disposal site after treatment with cement or chemicals.** APC residue (fly ash) is also stored underground in some countries. Since it contains salt and other heavy metals, it is more difficult to treat than bottom ash and there are few examples of its adoption for recycling worldwide.

4 Case Studies

4.1 Clean Plaza (Yokote City, Japan)

Japan is home to a large number of MSW incinerators. Smaller plants make up a large percentage of MSW incinerators but these face difficulties in reaching levels that are high enough to efficiently recover energy. However, the number of relatively efficient MSW incinerators has been increasing in recent years, even though their plant sizes are comparatively small. This is largely due to technological advances in the field of thermal treatment of various waste materials.

Among such MSW incinerators, Clean Plaza in Yokote City (population: 90,000) constructed in March 2016 is an ideal example because the facility size is relatively small (47.5 x 2 = 95 tonnes/day), although the power generation efficiency of the plant was designed to be close to 20%. The plant configuration is illustrated in Fig. 13. The plant's high efficiency is realised with the application of high-temperature and high-pressure boiler conditions of 400ºC and 4 MPa.

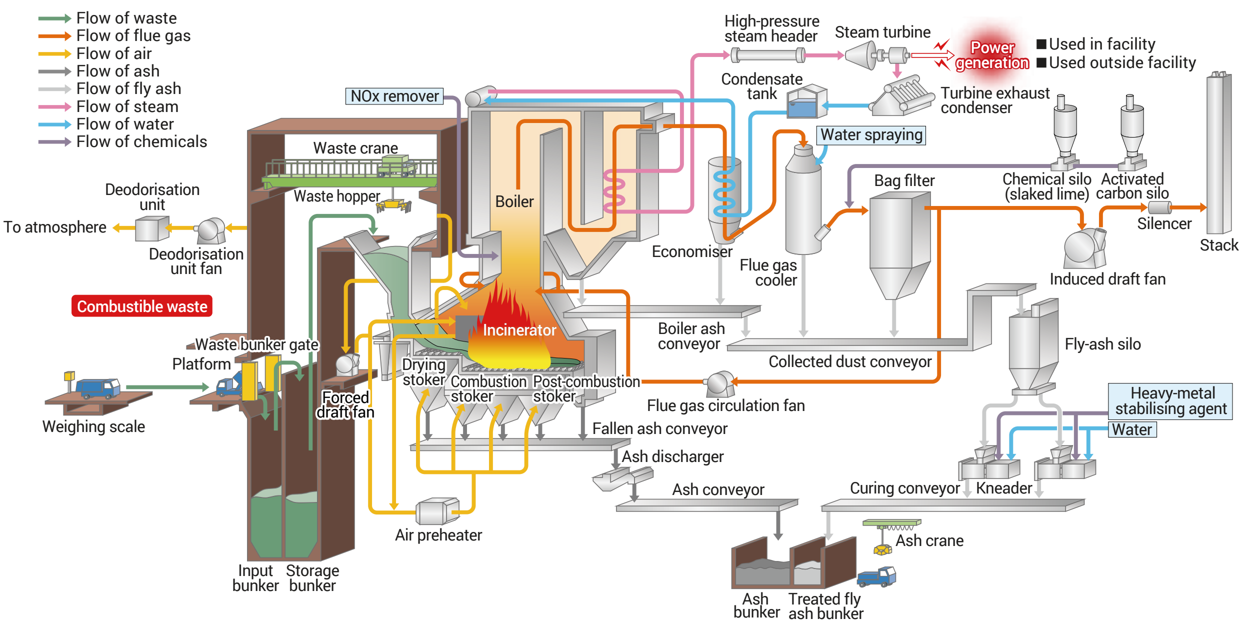


Fig. 13 Incineration process at plant in Yokote City

(Source: Yokote City)

This incineration plant was designed to recover maximum energy even though incinerator capacity was relatively small. To enable highly-efficient recovery, the plant must 1) operate a stoker-type incinerator with an air ratio around 1.2 or 1.3 throughout the entire plant, which is rather low compared to conventional incinerators, and 2) apply high-pressure and high-temperature conditions (400ºC and 4 MPa) in the power generation system. Furthermore, in order to increase boiler efficiency, the vacuum degree of condensers must be increased. The development of materials for equipment and piping also helps improve efficiency. As a result, the designed value for gross power generation efficiency of 19.6% was reached several years ago. Load test results before the start of operation are shown in Table 5 (Tsukamoto et al., 2016).

Table 5 Load test results before the start of operation

Measured item		Unit	Result
Boiler main-steam flow rate	Z_1 Z_2	t/h	6.15 (No.1 furnace) / 6.13 (No.2 furnace)
Boiler main-steam temperature	–	ºC	400 (No.1 furnace) / 401 (No.2 furnace)
Boiler main-steam pressure	–	MPa	3.94 (No.1 furnace) / 3.95 (No.2 furnace)
Main steam flow rate at turbine inlet	–	t/h	9.82
Turbine bypass steam amount	Z_b	t/h	2.10
Generator output	P_g	kW	1,670
Amount of waste treated (No.1 furnace)	B_1	t/h	2.01
Amount of waste treated (No.2 furnace)	B_2	t/h	2.04
Waste LCV (calculated)	H	kJ/kg	8,940
Gross power generation efficiency [a)]	η	%	16.6
Gross power generation efficiency with turbine bypass factored in [b)]	η'	%	20.0

a) $\eta = (P_g \cdot 3600)/\{(B_1 + B_2) \cdot 1000 \cdot H\}$
b) $\eta' = (P_g \cdot 3600)/\{(B_1+B_2) \cdot [1- Z_b /(Z_1+Z_2)] \cdot 1000 \cdot H\}$

Based on actual plant data collected three years after the start of operation, the relationship between the amount of waste incinerated and power generated can be illustrated in Fig. 14. Although the data, which covers about three fiscal years from April 2016 to December 2018, are apparent values because they include possible fuel injection other than MSW, the unit power generation value is estimated at 400 kWh per tonne of MSW incinerated. These values have become significantly higher than values investigated in the first half of the 2000s. This is a clear indication that advances in technology can achieve remarkable results.

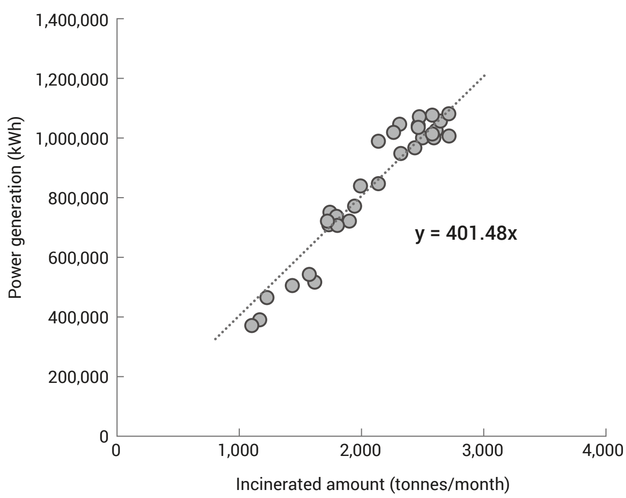


Fig. 14 Relationship between waste incineration volume and power generation results in the past three years

(Source: author)

Water injection is used to cool flue gas after the boiler process; however, cooling methods using economisers have increased in the past few years to lower energy consumption. NOx is reduced by the injection of urea into the furnace, a non-catalytic reduction technique that can also save energy. Dioxins and mercury are removed with the injection of activated carbon. Recent data on dioxins in effluent gas were 0.0073, 0.00025 and 0.00087 ng-TEQ/m^3N in April, July and October 2018, respectively,[8] and these values are significantly lower than flue gas criteria in Japan. The concentrations of dioxins in the same period were below detection limits for bottom ash and between 0.20 and 0.58 ng-TEQ/g for APC residue (fly ash), respectively.

The energy recovered from waste incineration is also used as heat to melt snow on roads in winter because Yokote City is located in an area with heavy snowfall in the northern part of Japan.

4.2 Joetsu Clean Center (Joetsu City, Japan)

The characteristics of MSW are dependent on people's lifestyles and the collection methods for MSW employed in a particular area. The average LCV of MSW in Japan is around 8,000 kJ/kg-MSW (slightly less than 2,000 kcal/kg-MSW), with a moisture content of around 40% (W/W). However, if kitchen waste containing higher percentages of moisture could be avoided when waste is collected, the LCV of collected waste would be higher than average waste.

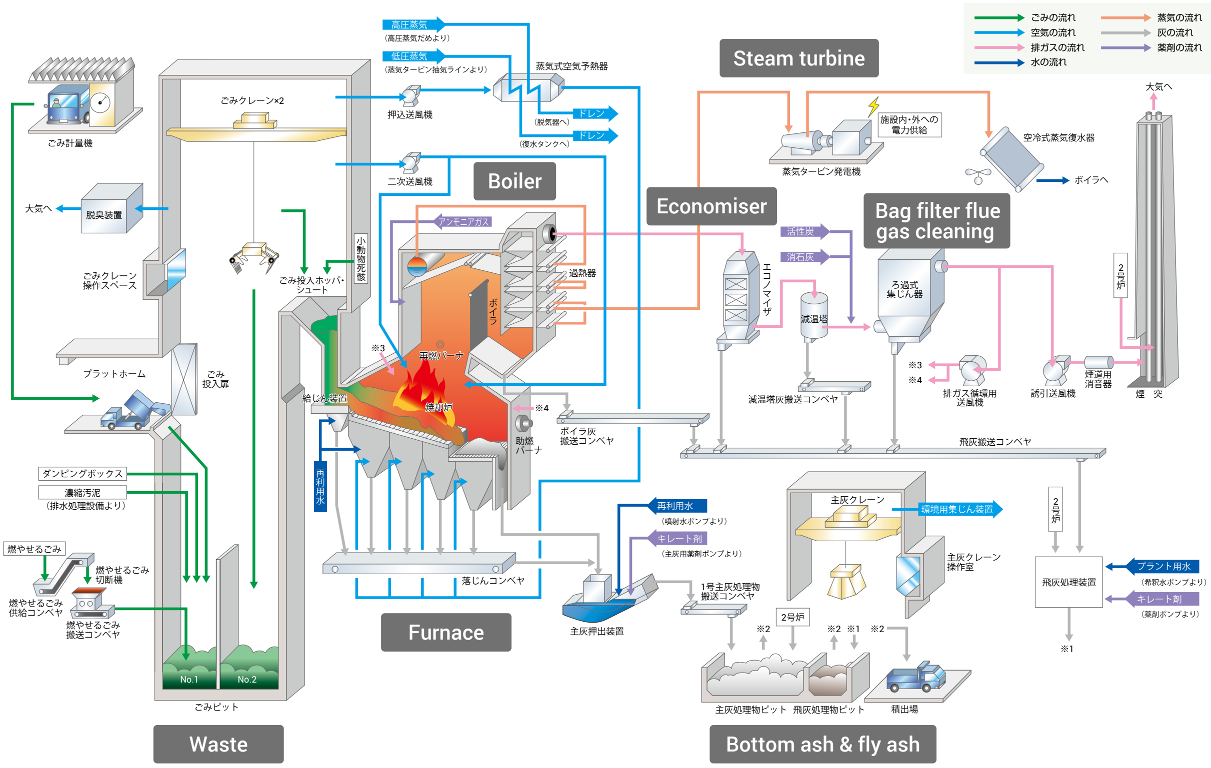
MSW to be incinerated at the incineration facility in Joetsu City (population: 190,000) has a higher LCV (8,100 to 15,900 kJ/kg) than the typical MSW in other parts of Japan. This value is derived from the fact that kitchen waste in this city is collected separately. Table 6 shows data on this facility, and Fig. 15 shows the processes used in this facility. A distinct feature of this facility is that at 5.0 MPa and 420°C, steam conditions are better than at other plants. Generators enable the output of 6,290 kW of power and results in a generation efficiency of over 20%. Furthermore, in order to increase the efficiency of energy recovery, the facility uses NOx reduction technology without a catalyst. Fig. 15 (a) and (b) show the boiler (a) and turbine generator (b) in this plant.

Table 6 Facility information and data on MSW incineration treatment

Furnace	Stoker furnace (Continuous operation)
Treatment capacity of MSW	85 tonne/day x 2 furnaces (Total 170 tonne/day)
LCV of waste	8,100 – 15,900 kJ/kg
Combustion air cooling and heat recovery equipment	Natural circulation water piping boiler: Maximum evaporation amount: 19.44 tonne/hour x 2 units Steam condition: 5.0 MPa and 420 °C
Flue gas cleaning process	De-NOx without catalyst (by injecting ammonia gas into the furnace), cooling tower, bag filtration
Residual heat use equipment	Bleed condensate turbine (6,290 kW)
Effluent water treatment process	Closed system for all types of wastewater, including processed wastewater and rainwater, with its reuse in on-site facilities after treatment and injection into gas cooling towers

(Source: Moriyama et al., 2018)

8 Yokote City web site: https://www.city.yokote.lg.jp/kankyo/page0000318.html



(a) Boiler

(b) Turbine generator

Fig. 15 Incineration process at Joestu Clean Center (Source: Joestu city)

Final residue (bottom ash and fly ash) are safely treated before final disposal. Bottom ash is landfilled without any treatment, while fly ash is landfilled after appropriate treatment by reagents to reduce leaching of heavy metals. Bottom ash can also be used as raw material for cement.

There are a number of similar examples of modern incineration plants with high power generation performances in Japan. What can be learned in this section is that:

- WtE incineration can be fully realised even if the scale of an incineration plant is relatively small (100 to 200 tonnes/day). There are many examples of small-scale yet successful plants with high power generation efficiency around 20%.

- To achieve high efficiency in WtE incineration facilities, high-performance equipment must be installed in the incineration plant.

Furthermore, solid waste should have an appropriate composition for incineration. Stable MSW generation and collection are also important.

4.3 Lengthy track record in incinerator operation (Phuket, Thailand)

There are two incinerators in Phuket. Construction started on the first incinerator in 1996 by the Department of Public Works in the Ministry of Interior which had been in operation since 1999 with a capacity of treating 250 tonnes of MSW per day. However, the **operation of this incinerator has been suspended due to facility maintenance since 2012**. A second incinerator **built in 2009 with a total capacity of 700 tonnes of MSW per day has been operated since 2012 by a private company (PJT Technology Co., Ltd.)** (Fig. 16 and 17).

Stoker Incinerator Plant [No. 1]
Capacity: 250 tonnes/day, stoker type
Initial cost: THB 780 million
Annual operation: 7,000 hours

Stoker Incinerator Plant [No. 2]
Capacity: 350 tonnes/day x2, stoker type
Initial cost: THB 940 million
Annual operation: 7,000 to 8,000 hours

Fig. 16 Overview of incinerators in Phuket
(Source: Tavorn (2019))

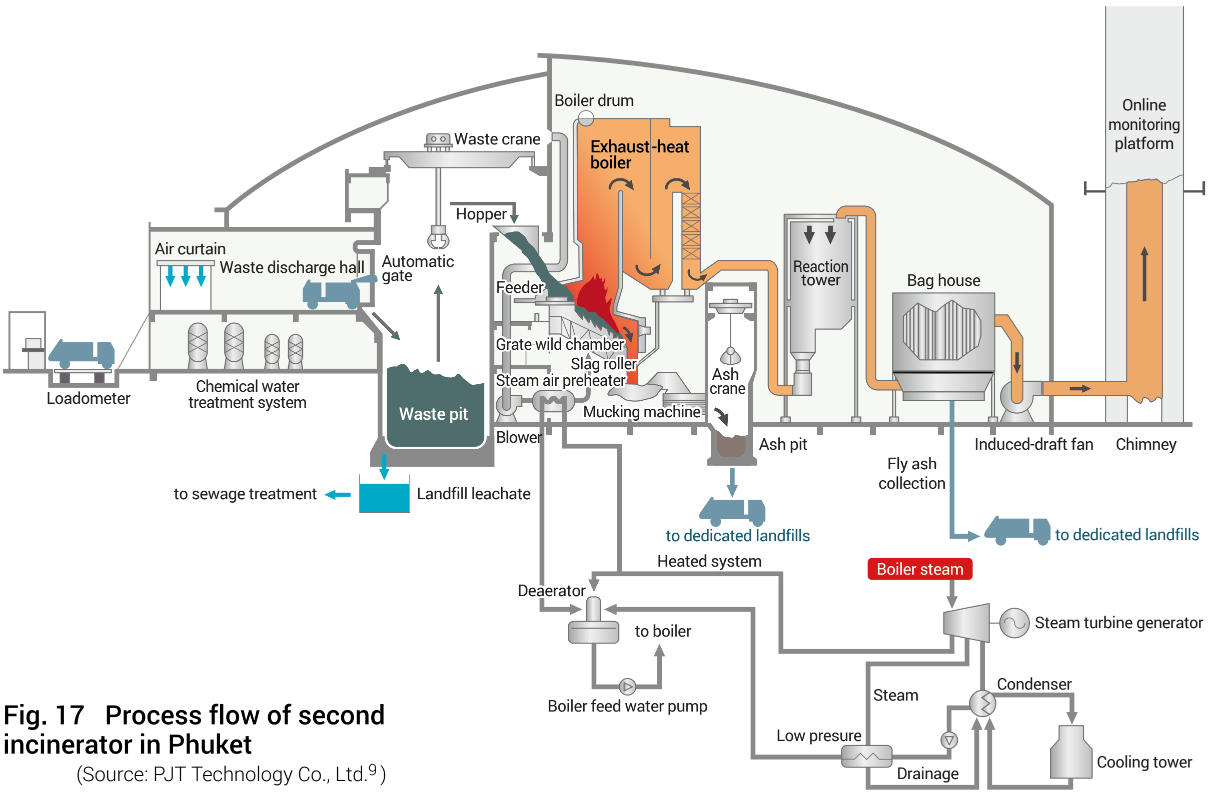


Fig. 17 Process flow of second incinerator in Phuket
(Source: PJT Technology Co., Ltd.[9])

9 http://pjt.co.th/index.php/products/

Phuket Province is the largest island in the Andaman Sea in southern Thailand with an area of 543 km^2. In 2017, the population stood at 410,211, with the number of tourists and visitors reaching over 14 million. **Phuket City Municipality (CM) is responsible for the management of a waste disposal complex, which treated 928 tonnes of MSW per day in 2018** with an area of about 500,000 m^2 (including a landfill area of 214,400 m^2, incinerator plant area of 73,600 m^2, waste water treatment area of 52,800 m^2, and buffer zone of 124,800 m^2).

In 2017, PJT Technology Co., Ltd. reported THB 545 million in total revenue and THB 275 million in total expenses to the Department of Business Development under the Ministry of Commerce. Considering an incineration capacity of 700 tonnes/day, operation 320 days/year, and treatment capacity of 224,000 tonnes/year, revenue per tonne can be estimated at THB 2,433 **(tipping fees were estimated at THB 520 per tonne, electricity sales**[10] **at THB 1,913 per tonne, and expenses at THB 1,226 per tonne**). Over its **historical background and phase-by-phase development,** Phuket CM held public hearings on the construction of a stoker-type incinerator power plant in 1994. Construction started in 1996 on the first incinerator with a capacity of 250 tonnes/day funded by the Ministry of Interior and an executive committee on waste management in Phuket Province was established. **The first stoker incinerator started operating in 1999, generating around 2.5 MW in electricity,** but the total volume of waste (about 350 tonnes/day) exceeded the capacity of the incinerator, resulting in excess waste being dumped in a landfill site since 2003.

Phuket CM formulated a Solid Waste Management (SWM) master plan in 2007, holding public hearings for the second stoker incinerator power plant and offering an investment contract to PJT Technology Co. Ltd. in 2009. **Phuket CM's decision to award a concessionaire was a major turning point.** The new 700 tonne/day WtE incineration plant started operation in 2012, generating 12MW in electricity and the first incinerator was shut down in 2012 for maintenance. Phuket CM submitted an application to the central government to subsidise maintenance costs which was not granted, resulting in the suspension of operations at the first incineration plant.

It is necessary to collect a specific amount of waste in order for WtE incineration facilities to operate efficiently. Thailand's Pollution Control Department (PCD), the competent authority for municipal waste policies and technologies, recommends that clusters be formed among multiple municipalities (PCD 2017). **It is noteworthy that the Phuket Governor and Phuket CM formed an executive committee on waste management in Phuket Province** with around 18 municipalities, local communities and environmental NGOs (non-governmental organisations) in 1996.

According to Pattaraporn (2015), **SWM in Phuket has evolved continuously since the formation of the executive committee.** The executive committee proposed the development of a SWM master plan for the area in 2007. **A memorandum of understanding on SWM signed in 2008 stated that municipalities should collect and transport waste to the disposal centre run by Phuket CM and pay disposal (incineration and landfill) fees of THB 520 per tonne,** but the success of such collaboration was dependent on the capacity and policies of each municipality. However, the implementation of the plan was limited in scope. A public official explained that **since no staff was responsible for operation, the plan was not implemented.** The 2014 Phuket SWM Master Plan, clearly under the responsibility of the Phuket Office of Natural Resources and Environment, is perceived differently. The executive committee has also seen an increase in its authority and role. This allows the problems of SWM to be managed concurrently. Nevertheless, **the effectiveness of**

10 This affordable pricing has mostly been made possible through Thailand's national subsidy programme, Adder, and FIT selling rates, which are estimated to be about THB 5/kWh or more.

these institutions and policies depends on the level of awareness of relevant authorities and the public about the severity of the problems, their level of commitment and cooperation in implementing changes.

Understandably the composition of waste in Phuket is mostly organic with high moisture content, resulting in LCVs and inefficient incineration. In the early days, food waste was collected and traditionally used as livestock feed especially for swine. However, due to a boom in tourism and urbanisation, piggeries were forced to close, and owners sold their land or moved to neighbouring provinces where land was much cheaper. Because of such social changes, **surplus food waste was shifted into the main waste stream and** organic components sent to incinerators almost doubled from 34% in 1993 to 64% in 2004. **As a result, the quantity of dioxins and furan gas was found** to be 2.13 ngTEQ/Nm^3 in contrast to the allowable concentration of 0.5 ngTEQ/Nm^3 as per the 2005 national emission control standard for solid waste incinerators. Subsequent to the formulation of the Phuket SWM master plan in 2007, the Department of Environment Quality Promotion collaborated with local governments and NGOs launched public participation campaigns to promote waste reduction and separation at source. The **initiation of an organic waste separation model producing fertiliser using aerobic composting and its successful implementation in pilot communities** found that if 15% to 20% of organic waste could be removed from the main waste stream, it would raise the LCV of mixed waste to the designed range, and maintain efficiency in combustion, reduce incomplete combustion emissions and increase electricity generation yield (Pireeyutma, 2011). Both environmental and energy problems can be improved through waste separation by communities.

A number of lessons can be learned from the case study of Phuket.

1. **Social aspects:** As a major tourist destination, Phuket CM has been authorised to take responsibility for the management and operation of a waste disposal complex.

2. **Technological aspects:** Stoker incinerators are a robust technology with an appropriate design for WtE incineration, but landfills are still needed for dumping ash and excess waste that cannot be incinerated (about 23% of total weight).

3. **Institutional aspects:** The memorandum of understanding on SWM signed in 2008 stated that municipalities are responsible for collecting and transporting waste to the disposal centre run by Phuket CM and paying disposal fees.

4. **Governance aspects:** The Phuket Governor and Phuket CM formed an executive committee on waste management in Phuket Province.

5. **Financial aspects:** Private investment for the second incinerator helped the local government move past their financial barriers, while national subsidy programmes, such as "Adder" (Thailand's policy measures that have been in place since 2007 motivating the private sector to invest in projects to produce electricity using renewable energy) or FIT selling rates for electricity are being used to make the project feasible with affordable tipping fees.

6. **Cooperation and understanding of residents:** Public participation in waste reduction and waste separation are keys to making SWM more efficient.

Today, Phuket is facing another crisis as the volume of total waste approaches 1,000 tonnes/day. The Phuket CM plans to call for investment in WtE incineration shortly, beginning a new phase in its challenge for sustainable SWM.

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About the CCET Guideline series

CCET in partnership with the United Nations Environment Programme (UNEP) - International Environmental Technology Centre (IETC) and the Ministry of Environment, Japan (MOEJ) provides technical assistance to national, sub-national and local governments in developing countries on the development and implementation of waste management strategies. During the implementation of CCET activities, it was found that the issue of waste management is more complex in developing countries, characterised by dramatic urbanisation that has led to an increase in volume and types of waste (including dangerous chemicals and metals, such as mercury, lead, etc.), but with a lack of capacity to sustainably perform proper waste management, including legislation and policies for realistic long-term planning, limited collection and a lack of proper disposal, scavenging issues, poor funding, low public awareness, and other issues. Furthermore, a significant number of inappropriate technologies and equipment has been introduced due to insufficient knowledge on sustainable waste management practices. There is an urgent need to provide accurate information to assist policymakers and practitioners so that they have a clear and holistic view of all waste management technologies.

The CCET guideline is a series consisting of key technology options that act as pieces of a puzzle to identify an optimal technology mix for addressing the unique challenges faced by governments. It is commonly accepted that there are no universally right or wrong answers to what technology is appropriate for any one region. Rather, solutions need to be developed locally and tailored specifically to local needs and conditions. Citizens and stakeholders need to be involved in designing a diverse set of services which, in turn, needs to be delivered at affordable costs. As with the pieces of a puzzle that form a clear picture when connected, the CCET guideline series offers knowledge-based support for the development of strategies and action plans.

The main purpose of this guideline series is to assist policymakers and practitioners at the national and municipal levels in selecting appropriate waste management technologies and executing related policies to improve waste management. CCET is focusing on fundamental intermediate treatment technologies, including composting, Mechanical-Biological Treatment (MBT), Anaerobic Digestion (AD), and Waste-to-Energy (Incineration).

This guideline series:

(1) is a user-friendly, knowledge-oriented product that provides clear, concise and comprehensive points, which makes it easy to identify optimal options at a glance;

(2) has been developed from a "resource perspective" rather than a "waste treatment perspective" based on the concepts of the 3Rs, waste hierarchy and circular economy;

(3) addresses both the physical (technical) elements of collection, disposal and recycling as well as the "soft" aspects of governance, public awareness and participation, and institutional and financial aspects to encourage social engagement; and

(4) is supported by good practices.

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