Guidelines for Low-Cost Incineration Systems

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GUIDELINES FOR LOW-COST INCINERATION SYSTEMS

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Abstract

In low-income countries, effective waste management remains a critical challenge, with incineration emerging as a practical solution to reduce waste volumes and mitigate environmental health risks. This report examines the feasibility and performance of three incineration technologies - De Montfort incinerators, barrel incinerators, and open pits - in the context of low-income settings. The study evaluates each technology based on parameters such as construction cost, operational efficiency, emissions, and ease of maintenance. Additionally, it explores strategies for managing bottom ash, focusing on its safe disposal and potential for resource recovery. The potential for harnessing energy from incineration processes is also analyzed, assessing the viability of energy recovery systems adapted to local conditions. Our findings indicate that while De Montfort and barrel incinerators offer more controlled combustion and lower emissions compared to open pits, the latter remains prevalent due to its minimal cost and simplicity. For proper low-cost incineration, the most effective and safest solution is to build a de Montfort incinerator. Proper bottom ash management is also critical to minimize environmental contamination, with options including stabilization, landfilling, and recycling for construction materials. Energy recovery presents a promising avenue, yet its implementation is still hampered by technical and financial barriers, though harnessing incineration heat may still be possible in a low- and middle-income setting. The report concludes with recommendations for optimizing incineration practices in low-income countries, emphasizing the need for context-specific solutions that balance environmental protection, public health, and economic constraints.

1 Introduction

Effective waste management is a critical component of public health and environmental sustainability, yet it poses significant challenges, particularly in low-income countries. According to United Nations: Office on Drugs and Crime (2022), "The waste sector contributes 10% of greenhouse gas (GHG) emissions globally. Open dumping accounts for 31% of this figure, with some lower-income countries relying on it for up to 93% of their waste disposal. Waste transported illegally ends up in public ecosystems, illegal landfills, or is burned in the open." These regions often face a myriad of obstacles including limited financial resources, inadequate infrastructure, and lack of technical expertise, all of which hinder the establishment of efficient waste management systems. Consequently, improper waste disposal practices prevail, leading to adverse impacts on the environment, human health, and overall quality of life.

This report aims to provide comprehensive guidelines for enhancing waste management practices in low- and middle-income countries. It will explore the current state of waste management in these regions, identify key challenges, and propose strategic interventions tailored to low-income settings.

With rapid urbanization and population growth, the volume of waste generated globally is increasing rapidly. The United Nations Environment Programme (2024) predicts a global solid waste growth from 2.1 billion tonnes in 2023 to 3.8 billion tonnes in 2050. Without effective management, this burgeoning waste poses severe risks to public health through the proliferation of disease vectors and contamination of water sources, especially in countries that currently lack appropriate waste disposal infrastructure. Additionally, the environmental consequences are profound, contributing to land degradation, water pollution, and greenhouse gas emissions. By developing and implementing robust waste management strategies, low-income countries can mitigate these risks, improve public health outcomes, and move towards sustainable development.

1.1 Solid Waste Management

Solid waste encompasses a wide range of discarded materials, including household refuse, industrial by-products, construction debris, and hazardous substances. Effective waste management strategies aim to minimize waste generation, maximize resource recovery through recycling and composting, and ensure safe disposal of residual waste. Traditional waste management practices, such as landfilling and open burning, are increasingly recognized as unsustainable due to their contribution to land degradation, greenhouse gas emissions, and public health risks.

The complexity of solid waste management necessitates an integrated approach that combines technical, economic, and social dimensions. Advances in waste processing technologies, policy frameworks, and community engagement are pivotal in transitioning towards a circular economy where waste is re-envisioned as a resource. This integration requires collaborative efforts among governments, industries, and citizens to implement effective policies, enhance infrastructure, and foster behavioral changes toward waste reduction and sustainable consumption.

To properly grasp the scale of solid waste management in high-income countries, here is the example of the Hagenholz waste-to-energy plant in Zürich, Switzerland which was visited on 24th May 2024. It is comprised of two main channels, each with an incineration capacity of 120'000 tonnes per year. This means each channel is capable of incinerating over 300 tonnes of waste per day. The channels are divided into five main parts: the waste bunker, the incinerator, the bottom ash recovery, the flue gas cleaner, and the chimney. Air filtration is by far the largest part of the plant, outlining the importance of filtering the flue gas for public health (ERZ Entsorgung + Recycling Zürich, 2014). The control room is almost entirely computerized, with screens and sensors to monitor every critical aspect of the plant (see Figure 1.1). The waste bunker is entirely controlled through digital systems, to make sure nobody has to go inside the vast waste bunker, where waste is picked up and moved by a giant claw (see Figure 1.2).

At the end of the incineration, the hot bottom ash is cleaned of its soluble contents and cooled in water, before being sorted and finally sent to an engineered landfill site. Out of the 52'000 tons of bottom ash the plant produces per year, 4'000 tons of metal are recovered, most of which is sold to be recycled. The flue gas on the other hand is sent to a series of filters to remove most toxins and pollutants it contains. The flue gas heat is recovered and used to heat and power the city of Zürich. In 2013, the plant generated 97 GWh of electricity and 404 GWh of heat for the city. According to Swiss Federal Office of Energy (2023), a Swiss resident consumes on average 6.45 MWh of electricity per year (including electricity for heating), therefore this plant covers the electricity demand of over 75'000 people.

Figure 1.1. ERZ Hagenholz control room Zürich, Switzerland, 24.05.2024.

(a) Waste bunker (b) Waste claw

Figure 1.2. ERZ Hagenholz waste bunker and claw Zürich, Switzerland, 24.05.2024.

1.2 Solid Waste Management in Africa

Solid waste management in Africa presents a unique set of challenges and opportunities due to the continent's rapid urbanization, economic growth, and diverse socio-economic conditions. Africa is the continent with the largest urban population growth (UN-Habitat, 2024). As African cities expand and populations grow, the volume of solid waste generated has also increased significantly, putting pressure on existing waste management systems. Inefficient waste handling practices, inadequate infrastructure, and limited financial resources worsen the environmental and health risks associated with improper waste disposal.

In many African countries, traditional waste management methods, such as open dumping and uncontrolled burning, remain prevalent even for medical waste, as was observed by Mbongwe, Mmereki, and Magashula (2008) in Botswana. These practices contribute to environmental degradation, including soil and water contamination, air pollution, and greenhouse gas emissions (Amfo-Otu *et al.*, 2015), (Bakare, Alimba, and Alabi, 2013). This was even observed specifically near hospitals, where many health-related studies are performed, like Auta and Morenikeji (2013) in western Nigeria. Furthermore, they pose serious public health risks, including the spread of infectious diseases and respiratory problems. According to N'Guessan *et al.* (2021), a big part of HIV-AIDS and hepatitis infections observed at Daloa Regional Hospital (Ivory Coast) can be attributed to poor hospital waste management.

Despite these challenges, there are significant opportunities for improving solid waste management in Africa. Innovations in waste processing technologies, such as waste-to-energy conversion, composting, and advanced recycling methods, offer potential pathways for sustainable waste management. The implementation of integrated waste management systems that prioritize waste reduction, resource recovery, and environmentally sound disposal is essential. Philippe Thonart *et al.* (2005) have created an extensive study on waste management in southern countries. They mention examples of people sorting waste in landfills to find valuable materials. Reuse of materials and objects is a crucial aspect of daily life in low-income countries, as was observed by Kalina *et al.* (2022).

Many different solutions have been proposed for low-cost waste management where the current infrastructure is lacking. Today, there are three main low-cost options to incinerate waste: open pit burning, barrel incinerators, or de Montfort incinerators. Open pit burning, although very convenient and virtually free, is not ideal because it is dangerous and there is no control of temperature and fumes. Barrel incinerators are a good option for the disposal of waste in emergencies because they are easy to build with basic equipment, but unfortunately, they have a very limited lifespan. The last option, de Montfort incinerators, was specifically designed by Prof. D.J. Picken for use in low- and middle-income countries. To understand the consequences of poor incineration, it is necessary to study what incineration and its effects on the environment and health are.

1.3 Incineration emissions

Incineration, the process of burning waste materials to reduce their volume and mass, and sometimes to generate energy, is associated with several types of emissions. These can all be addressed with different mitigation strategies. Emissions resulting from incineration processes are typically classified into three primary categories: greenhouse gases, air pollutants, and toxic emissions. Greenhouse gases, such as carbon dioxide (CO2) and nitrous oxide (N2O), contribute to global warming and climate change. Air pollutants, including oxides of nitrogen (NOx) and sulfur dioxide (SO2), can have detrimental effects on air quality and human health. Toxic emissions, which may contain heavy metals and dioxins, pose significant risks to both the environment and public health. More information about the causes and effects of the different types of emissions from incineration processes can be found from National Research Council (US) Committee on Health Effects of Waste Incineration (2000). The legal framework for incineration in Europe is the *Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (Recast) (Text with EEA relevance)* (2011).

Greenhouse Gases (GHGs)

- **Carbon Dioxide (CO_2)**: Incineration releases CO_2, a major greenhouse gas, contributing to global warming. This is the most important greenhouse gas emission linked to incineration and is inevitable. The only effective way to reduce these CO_2 emissions is to avoid incineration altogether when possible, by recycling, reusing, or composting.
- **N_2O, NO_x, NH_3, CH_4**: other potent greenhouse gases, present in much smaller quantities according to Bernt Johnke (2001), but due to their high CO_2-equivalent emissions they must still be taken into account.

Air Pollutants

- **Particulate Matter (PM)**: These particles come in many sizes and shapes and can be made up of different chemical components. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye, while others are so small they can only be detected using an electron microscope. Exposure to PM can affect both the lungs and heart. Fine particles (PM2.5 or smaller) are considered particularly harmful because they can be inhaled deeply into the lungs and may even enter the bloodstream. Health effects can include respiratory issues and cardiovascular problems. Improving the combustion process to ensure the complete burning of waste can reduce the formation of PM.

Otherwise, installing high-efficiency filters like fabric filters or electrostatic precipitators can capture fine particles before they are released into the atmosphere.

- **Nitrogen Oxides (NOx)**: Contribute to smog formation and respiratory problems. It is possible to minimize the formation of NOx by controlling the amount of oxygen and maintaining optimal temperatures. Otherwise, we can use selective non-catalytic reduction (SCNR) (injecting ammonia or urea in the combustion chamber) to react with NO_x to convert it into nitrogen and water vapor.

- **Sulfur Oxides (SOx)**: Can cause acid rain and respiratory issues. To reduce SO_x emissions, pre-treatment of waste to remove sulfur-containing materials before incineration is possible. Otherwise, one can use scrubbers in the gas cleaning process or selective catalytic reduction (SCR) systems.

- **Volatile Organic Compounds (VOCs)**: Contribute to ground-level ozone formation and can have various health effects. They can be avoided through complete combustion and gas cleaning with systems like activated carbon filters.

- **Carbon Monoxide (CO)**: Can interfere with the body's ability to transport oxygen. It is caused by incomplete combustion of organic compounds and, therefore can be reduced through efficient combustion by using a good incinerator design or auxiliary burners.

Toxic Emissions

- **Dioxins and Furans**: These compounds are highly toxic and can cause reproductive and developmental problems, damage the immune system, interfere with hormones, and also cause cancer. Due to their high lipid solubility, they accumulate in the food chain, leading to higher exposure and health risks for humans and wildlife. To minimize the formation of dioxins and furans, incineration processes must achieve complete combustion of waste materials at temperatures of over 850°C for over 1 second (WHO, 2023). Fabric filters, electrostatic precipitators, or activated carbon filter systems can capture them from the exhaust gases.

- **Heavy Metals**: Mercury, lead, cadmium, and others can be released, posing severe health risks. The best ways to remove heavy metals from incineration processes are pre-treatment of waste, flue gas cooling (making them less volatile and easy to collect), or activated carbon filters.

Bottom ash

Bottom ash is mostly incombustible residue. This is an inevitable part of incineration and, therefore cannot be avoided altogether, but the best way to reduce the amount of bottom ash is to ensure complete combustion and to sort non-combustible materials before incineration. It also contains inert materials such as glass or ceramics and metals. Some heavy metals are present and should be removed before the bottom ash is landfilled. This can be done through washing and leaching (dissolving them), or they can be stabilized using cement or lime.

1.4 Research questions

Incineration is a great way to treat and reduce the volume of municipal solid waste. It is also seen as one of the most effective practices to manage the spread of disease from medical waste. It is however very expensive, and its high cost is even a source of discussion in high-income countries (Federal Department of Economic Affairs, Education and Reasearch, 2018). It is therefore necessary to prioritize different aspects of incineration to ensure incineration is always performed in the best way possible, even when financial resources are limited. The three following questions mainly guided this study:

1. What incineration technology can minimize dioxin and particulate matter emissions in low- and middle-income settings?
2. How should the incineration ashes be managed to minimize contamination through the ground, the air, and animal presence?
3. Which is the most efficient and useful way to harness energy from incineration in low- and middle-income settings?

2 Results and discussion

2.1 Emissions mitigation strategies

Many filtration systems are expensive and require a lot of maintenance. However, some processes can be very low-cost. The most valuable emissions mitigation strategy is waste sorting and reduction. Sorting and recycling metals before they are incinerated is a great way to avoid having extra bottom ash to dispose of and increases the proportion of combustible waste in the incinerator, thus increasing temperature and combustion efficiency. The same can be applied to glass and ceramics, many of which can be reused directly. Sorting recyclable plastics is also a great way to reduce different types of emissions. As mentioned in 1.3, most emissions can be reduced through more efficient combustion, therefore higher temperatures and longer residence types are best. This aspect will be further studied in 2.2. Sorting organic waste for composting and methane production can also be highly beneficial. It allows for the transformation of waste into compost and the generation of methane as a resource. Simple low-cost methane digesters can either be purchased from companies such as Flexi BioGas or HomeBiogas or they can be homemade (see Instructables: Biogas Digester).

To remove soluble heavy metals from bottom ash, washing, and leaching is probably the most appropriate solution, but the metal-rich water must then be properly disposed of. To remove heavy metals from flue gas there are two possible solutions: activated carbon or flue gas cooling. The waste-to-energy plant in Zürich uses activated carbon and water to remove a large part of the emissions present in the flue gas, which are relatively inexpensive solutions. These could probably only be implemented in middle-income countries, as they must be frequently replaced, thus increasing the long-term running costs. Flue gas cooling however can be a great way to recover some of the heavy metals and particulate matter present in the flue gas. To perform flue gas cooling, there are two main options: using a shell-and-tube heat exchanger or using a Cyclone Heat Recovery System, such as mentioned by W.-H. Chen and J.-C. Chen (2001). More on how flue gas cooling can work is studied in section 2.4.

Finally, an option to filter some particulate matter is using a dry scrubber, such as a cyclone separator. They are devices used to remove particulates from an air, gas, or liquid stream without the use of filters, through vortex separation. In our case, this stream would be the flue gas. The separated particles are collected in a hopper or other collection container located at the base of the cyclone. Since they have no moving parts (thus requiring little maintenance) and are made with a simple, low-cost design, they can be a great alternative to be adapted in low-cost incinerators. A test run was performed by Mosè Peduzzi (2024).

2.2 Incinerator technologies

This section is a study of the three different incinerator technologies: De Montfort incinerators, barrel incinerators, and open pit burning. To compare these incinerators, the following characteristics will be analyzed: technology, emissions control, efficiency, cost, environmental impact, and safety. The technology consists of how precisely engineered and designed these incinerators are. Emissions control covers the ability to filter and monitor the emissions coming out of the incinerator. Efficiency comprises the combustion efficiency and whether or not extra fuel is needed for proper combustion. Cost includes both investment and operational costs, and environmental impact includes both air pollution and soil contamination. Finally, safety is how safe the incinerator is to use, including fire hazards and protection of the incinerator operator. The comparison will be done by establishing a score on a scale of 1 to 10 for each category. A score of 10/10 does not mean it is the best score possible, but the best out of the three solutions presented. As a general rule, the final recommendation is to use a properly engineered incinerator whenever possible, therefore open-pit burning is to be avoided.

Table 2.1. General incinerator recommendations

Incinerator type	**Recommendation**
De Montfort	First choice, but the highest cost (USD 1000$)
Barrel	To be used in emergencies and when portability is required
Open Pit	To be avoided except in case of a big emergency

2.2.1 De Montfort incinerators

Prof. D.J. Picken designed De Montfort incinerators as cheap medical waste incinerators that can be built almost anywhere. If built, maintained, and used properly, it should be able to reach 800°C with a residence time of 1 second, although in practice this is often not the case. The most up-to-date designs today are the Mark 7, Mark 8A, and Mark 9, and these are the only incinerators that are included on the De Montfort Medical Waste incinerator website. They suggest using the Mark 7 in emergency situations only, the Mark 9 for large-scale applications, and the Mark 8a in most other situations. Therefore, we will focus on the Mark 8A. The Mark 8A incinerator is comprised of 8 main parts (see Figure 2.1):

1. Loading door, where waste is inserted into the incinerator
2. Primary combustion chamber, where the waste is first heated and combustion starts
3. Air inlets
4. Fire grate, where the ashes accumulate
5. Ash door, used to take the ashes out of the incinerator
6. Gas transfer tunnel, through which the first combustion gases go
7. Secondary combustion chamber, where the second combustion takes place.
8. Chimney

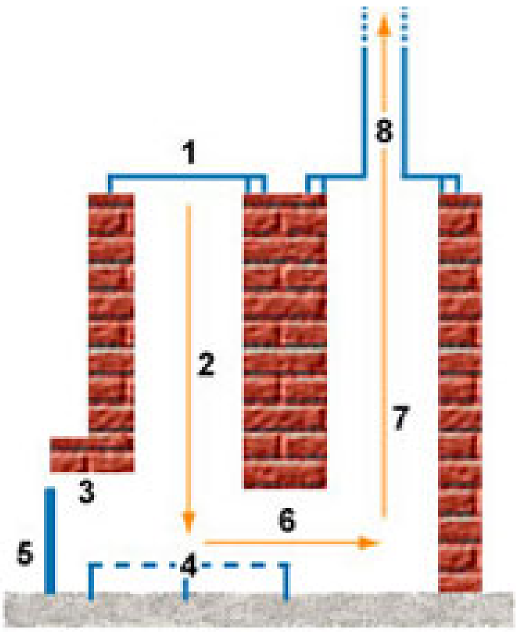

Figure 2.1. De Montfort incinerator cross-section. Image taken from De Montfort Medical Waste Incinerator Website.

One of the key advantages of the De Montfort Medical Waste Incinerator Mark 8A is its ability to handle a variety of medical waste types, including sharps, contaminated dressings, and pathological waste. Its design ensures that combustion gases pass through the secondary chamber, promoting thorough burning and reducing the release of pollutants. The incinerator is designed to be manually operated, with waste loaded into the primary chamber and ashes removed regularly. The high-temperature operation minimizes the production of smoke and odorous emissions, contributing to a safer environment for both healthcare workers and the surrounding community.

The construction process involves using bricks and mortar to build the combustion chambers and the chimney. They can be built according to Joos Van Den Noortgate, Dawn Taylor, and Yannick Garbusinski, 2012, and should cost anywhere between 250 to 1000 USD to construct (see De Montfort Medical Waste Incinerator Website, 2024). Recently, Mosè Peduzzi (2024) from the global health engineering lab at ETH Zürich built two de Montfort incinerators in Cape Maclear, Malawi. The total cost for the normal incinerator was around 700 USD and 800 USD for a Mark 8A with an added cyclone separator in the secondary chamber. It is, therefore, possible to adapt these incinerators to add technology to such incinerators such as particulate filters and sensors (see Figure 2.2). Due to their simple construction, they can also be built for specific situations, for example during national immunization campaigns (Guévart E *et al.*, 2009).

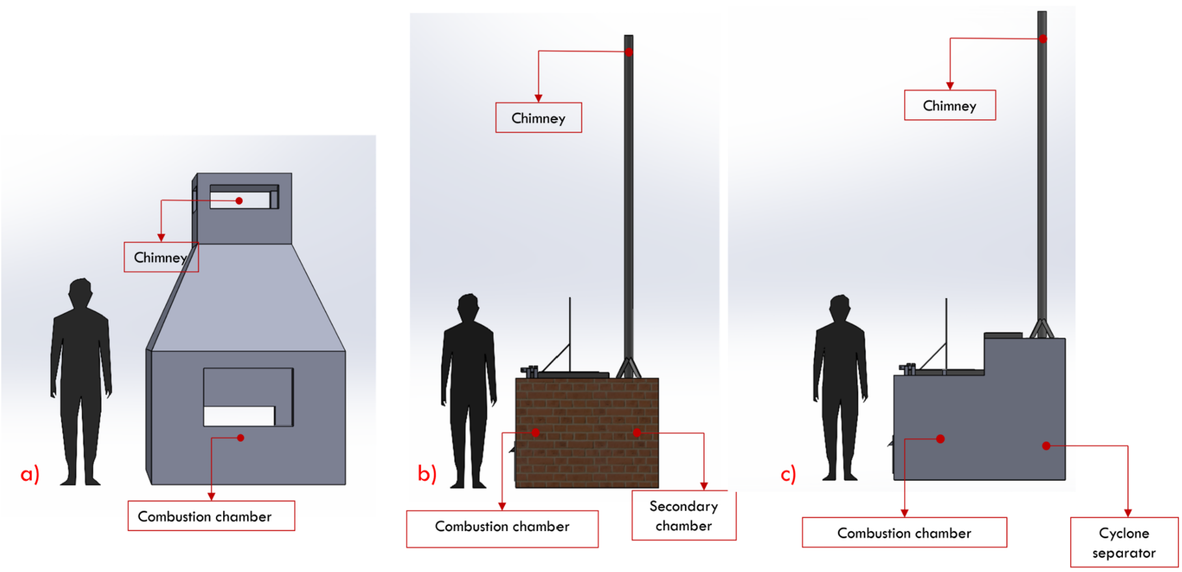

Figure 2.2. View of three different incinerators with placement of temperature sensors: a) Old incinerator b) De Montfort incinerator c) De Montfort incinerator with cyclone separator, image courtesy of Mosè Peduzzi (2024).

However, like all incineration processes, the De Montfort Medical Waste Incinerator Mark 8A has some limitations. Proper operation and maintenance are crucial to ensure its effectiveness and longevity. Operators need to be trained in its use and safety procedures to prevent accidents and ensure optimal performance. Additionally, while the incinerator significantly reduces the volume of waste, it still produces ash that needs to be disposed of safely.

To maximize the benefits of the De Montfort Medical Waste Incinerator Mark 8A, it is important to follow best practices for medical waste segregation and incineration. Only appropriate waste types should be incinerated, and hazardous materials such as chemical waste and heavy metals should be excluded. Regular maintenance, including cleaning the combustion chambers and chimney, is essential to maintain efficient operation and extend the incinerator's lifespan.

The De Montfort Medical Waste Incinerator Mark 8A provides a practical and effective solution for managing medical waste in low-resource settings. By ensuring proper use and maintenance, healthcare facilities can safely and efficiently dispose of hazardous waste, reducing the risk of infection and environmental contamination. All these things considered, we can start establishing a score for each category. This score will be based on a best-case scenario, meaning that the incinerator is built and operated according to the official de Montfort website guidelines:

- **Technology:** The technology of the De Montfort incinerator initially seems very basic, however, it is better than one might think. It includes two combustion chambers to increase the temperature and residence time of the incineration. It is a well-designed incinerator that can be adapted to suit the needs of specific situations. Perhaps the design can be improved upon, for example with a cyclone separator, but more research must be done to confirm their use. For a low-cost incinerator, it is a great design. Technology score: 10/10

- **Emissions control:** including a chimney out of which all the flue gas comes, as well as two combustion chambers, the emissions control for a low-cost, low-tech incinerator is very good. The only improvement that can be made is to add an external burner with fuel linked with a temperature sensor to increase the temperature of combustion when the desired temperature isn't reached, but this is unreasonable to suggest in a low-income setting. Emissions control score: 10/10

- **Efficiency:** With the two combustion chambers and the thick brick walls, the efficiency of the de Montfort incinerator is highest out of all three solutions. Peak efficiency depends on the nature of the waste, it is therefore sometimes necessary to add an external fuel to improve it, but it is still better than the other incinerators presented. Efficiency score: 10/10

- **Cost:** The de Montfort incinerator is the most expensive of the three solutions. Cost score: 5/10

- **Environmental impact:** The environmental impact of the de Montfort incinerator is the lowest out of the three solutions. Since it has a higher temperature and residence time than the others, it generates less air pollution. The controlled and protected location of the ashes also means there is no leaching of the ashes into the ground if the incinerator is used while it rains. Environmental impact score: 10/10

- **Safety:** Safety is another one of the areas where this incinerator trumps the other ones. It is considerably safer, with the loading door on top and the entirely closed design. It protects the operator from any explosions inside, as well as permits the operator to dump waste inside it without touching the waste beforehand. This means that as long as the operator uses personal protective equipment, they should stay safe. Safety score: 10/10

Table 2.2. De Montfort Incinerator scoring

	Technology	Emissions control	Efficiency	Cost	Environmental	Safety
SCORE	10	10	10	5	10	10

To conclude this section on de Montfort incinerators, we can see that in general, they are a good alternative to the other technologies. The whole discussion around de Montfort incinerators can be summarized with the following quote: "When new and appropriately operated and maintained, these high thermal capacity incinerators can achieve relatively high operating temperatures (700 to 800°C), largely destroying the waste and helping to reduce production and emissions of dioxins and furans in stack gases and ash. These incinerators are far preferable to waste burning in open pits or steel drums, and user acceptance appears generally high. As discussed below, however, these incinerators are not performing optimally due to significant operation, maintenance, and management issues." (Batterman, 2004)

2.2.2 Barrel incinerators

Barrel incinerators are simple, often homemade, devices used for burning waste materials. They typically consist of a metal drum, usually a 55 gallon steel barrel, modified to facilitate the burning process. There are many different ways to create barrel incinerators, some are extremely simple (see Kathrin Kellogg (2024)) and others are slightly more complex and technical (see Joe Andolina (2024)).

A standard 55-gallon steel drum is commonly used due to its availability and durability. Holes are drilled into the sides and bottom of the barrel to improve airflow, which helps achieve a more efficient burn by ensuring adequate oxygen supply to the fire. Some barrel incinerators include a grate inside to elevate the waste above the bottom, allowing air to circulate underneath. A mesh lid or cover may also be used to contain ash and embers while allowing smoke to


Figure 2.3. Commercial engineered barrel incinerator. Sourced from: Mavi Deniz.

escape. The barrel is often placed on cinder blocks or a metal stand to further improve airflow and ensure stability.

Barrel incinerators are commonly used for burning leaves, branches, and other yard waste, particularly in rural or suburban areas. There are several advantages to using barrel incinerators. They are relatively inexpensive to set up, especially if using a recycled barrel. They are easy to build with basic tools and materials and are portable, allowing them to be moved to different locations as needed. However, there are also disadvantages. Barrel incinerators can produce significant amounts of smoke and harmful pollutants if not used properly. There is a risk of uncontrolled fires if not monitored carefully. Additionally, many areas have regulations or bans on the use of barrel incinerators, due to environmental and safety concerns (see Minnesota Pollution Control Agency, 2024) Finally, they have a limited lifetime because the steel drum will rust and deteriorate over time. The scoring for barrel incinerators is the following:

- **Technology:** These are rudimentary incinerators, but extra complexity can be added to increase temperature and residence time (see Joe Andolina, 2024). They aren't quite as good as de Montfort incinerators since they aren't considered permanent solutions, though many different variations exist and they are often portable. There even are engineered commercial solutions (see Mavi Deniz, 2023 and Figure 2.3). Technology score: 6/10

- **Emissions control:** Similarly to the de Montfort incinerator, external burners, filters, or particle separators can be added. They usually don't have a chimney, therefore flue gas is released very close to the ground, thus polluting the air people breathe. Emissions control score: 6/10

- **Efficiency:** With poor insulation and a single combustion chamber, incineration efficiency is lower than the de Montfort incinerator. It also highly depends on the nature of the waste (see Paul M. Lemieux, 1997). Efficiency score: 7/10

- **Cost:** These incinerators require some manufacturing and building to be done, therefore they aren't free. However, they use mostly readily available and cheap materials. Unfortunately, due to their full metal construction, they will rust over time and deteriorate quickly, thus needing to be replaced and increasing total cost. Cost score: 7/10
- **Environmental impact:** The air pollution generated is poorly contained and contains more particulate matter than de Montfort incinerators, but there is little leaching into the ground if the barrel incinerator is maintained properly. Taking the ashes out without dropping them on the ground is usually a challenge. Environmental impact score: 6/10
- **Safety:** Safety concerns are high with the barrel incinerator since it is less robust and controlled than a de Montfort incinerator. To be safely used, one must wait for it to fully cool down before emptying the ashes and reloading it. When it starts presenting rust or structural damage, it becomes considerably more dangerous. Safety score: 5/10

Table 2.3. Barrel Incinerator scoring

	Technology	Emissions control	Efficiency	Cost	Environmental	Safety
SCORE	6	6	7	7	6	5

Barrel incinerators offer a practical solution for waste disposal in certain contexts, but they must be used responsibly to minimize environmental impact and ensure safety. The best recommendation for barrel incinerators is to limit their use to the incineration of organic waste, or emergencies because of their low-cost and portable nature. Long-term use is not recommended because a lot of maintenance will be required, therefore using a De Montfort incinerator simply makes more sense.

2.2.3 Open pit burning

Open pit burning is a method of waste disposal where waste materials are burned in an open pit or trench dug into the ground. This practice is commonly used in areas without access to formal waste management systems. The pit provides a contained space for the fire, helping to control the spread of flames and containing the ash produced.

The process involves digging a pit of appropriate size, depending on the volume of waste to be burned. The pit is typically shallow and wide, allowing for sufficient oxygen flow to sustain the fire. Waste materials are placed in the pit and ignited, with the fire consuming the waste over time. Regular monitoring and management of the fire are essential to ensure complete

Figure 2.4. Burn pit in Balad, Iraq. Picture taken by Senior Airman Julianne Showalter, 332d Air Expeditionary Wing. Sourced from: Defense Visual Information Distribution Service.

combustion and to prevent the fire from spreading beyond the pit. It is often used for the disposal of agricultural waste, such as crop residues and brush, as well as household waste in areas lacking formal waste disposal services. It can be a quick and effective way to reduce waste volume and manage organic materials.

However, open pit burning has several disadvantages. It can produce large amounts of smoke and harmful pollutants, including particulate matter, carbon monoxide, and volatile organic compounds, which can negatively impact air quality and human health. Evidence of the impact on human health can be found in the United States military, which often used burn pits in areas where incineration was unavailable. The consequences of inhaling fumes from open pits can be so bad that the Department of Veteran Affairs gives specific disability benefits to veterans who were exposed (see U.S. Department of Veteran Affairs, 2024). The risk of uncontrolled fires is also significant, particularly in dry or windy conditions, posing a threat to surrounding areas. This is why the practice is often subject to legal restrictions due to environmental and safety concerns. According to U.S. Department of Defense, 2019, open pits are still used by the U.S. Military (see Figure 2.4) because of the "short-term nature of contingency locations", "infrastructure gaps and limited contract disposal capabilities in contested environments" and "resource investments required to fund, install, operate and maintain" other solutions.

The use of open waste burning is still common in many areas, according to Beat Stauffer and Dorothee Spuhler, 2024. It is used either to reduce the volume of waste or to "reclaim the valuable metals" from electronics (see Figure 2.5)

To minimize the risks associated with open pit burning, it is important to follow safety guidelines. Always choose a location for the pit that is far from structures, vegetation, and flammable

Figure 2.5. Open waste burning in Ghana to recover metals from electronics, 2008. Photograph by Kate Davison, sourced from: GREENPEACE.

materials. Only burn materials that are safe to incinerate, avoiding hazardous substances like plastics and chemicals. Monitor the fire continuously and have firefighting equipment, such as water or fire extinguishers, readily available. Be aware of local regulations and obtain any necessary permits before conducting an open burn.

- **Technology:** there is little-to-no technology in open pit burning. Technology score: 1/10
- **Emissions control:** There are no emissions control systems with open pit burning. Without even a chimney, one can't even control where the fumes are going. Also, it is very hard to add any filters or sensors to monitor the emissions. Emissions control score: 6/10
- **Efficiency:** The incineration efficiency is the lowest of all technologies. Sometimes, incineration may be effective, but it depends on the type and amount of waste, as well as weather conditions (wind and rain). There is no design to guarantee efficiency. Efficiency score: 1/10
- **Cost:** Open pit burning is free since one only has to dig a hole to burn waste inside. Cost score: 10/10
- **Environmental impact:** without any proper control on emissions, as well as leaching into the ground in case of rain, the environmental impact is the worst in the case of open pit burning (Gwenzi *et al.*, 2016). Environmental impact score: 1/10
- **Safety:** Open pits lack any type of protection against fire or explosions. It is very dangerous to burn general waste in an open pit, since sometimes bottles or containers may

explode. In case of wind or dry conditions, the fire may spread if not properly cared for. Getting rid of the ashes is also very difficult to do safely, even with protective equipment. Safety score: 1/10

Table 2.4. Open pit burning scoring

	Technology	Emissions control	Efficiency	Cost	Environmental	Safety
SCORE	1	1	1	10	1	1

The general recommendation for open-pit burning is to avoid it altogether. If however, it is mandatory due to a complete lack of finances or emergency situations, the best practice is to dig the pit as far from human activities as possible and make sure the operator uses personal protective equipment (gloves, masks, protective clothing) and use fuel to increase the temperature of the fire for higher efficiency.

2.3 Bottom ash management

For bottom ash management, we will focus on a best-practice strategy. This is because bottom ash composition depends on the nature of the incinerated waste, the incinerator used, and how the incinerator was used. The challenge for ash management lies on both the technical and social side because if unused, bottom ash must be disposed of in a socially and environmentally friendly way.

Bottom ash management is an integral part of incineration. Incineration reduces the volume of waste and gets rid of most diseases, but the ash produced can still contain hazardous substances, including heavy metals and polycyclic aromatic hydrocarbons, which necessitates careful management (see Gwenzi *et al.*, 2016, Zhao *et al.*, 2010, Auta and Morenikeji, 2013).

First, the ash is allowed to cool after incineration. This cooling process can take place in designated ash pits or containment areas that are lined to prevent leachate from contaminating the soil and groundwater. Once cooled, the ash is typically collected and subjected to further treatment or disposal processes.

One common method of managing incinerator bottom ash is stabilization and solidification. This involves mixing the ash with binding agents, such as cement or lime, to reduce the leachability of hazardous components. The stabilized ash can then be safely disposed of in controlled landfill sites designed to contain and isolate the waste from the environment. The implementation of engineered landfills is, however, a challenge due to cost and space.

Figure 2.6. Large metal chunks recovered from bottom ash. Zürich, Switzerland 24.05.2024

In addition to stabilization, other methods such as ash washing or vitrification may be employed, depending on available resources and infrastructure (Luo *et al.*, 2019). Ash washing involves rinsing the ash with water to remove soluble contaminants, while vitrification uses high temperatures to convert the ash into a stable, glass-like material. In developed countries, valuable metals such as aluminum, brass, and gold are sorted, filtered out, and sold to be reused (see Figure 2.7). There are large chunks of metal in the bottom ash that can be easy to locate and remove by hand (see Figure 2.6), but also smaller pieces that are harder to see. This is done automatically with highly complex systems, but part of it could be done manually (such as sieving using a home-made trommel screen or magnetic separation with a simple magnet, Holm and Simon, 2017, Prof. Dr. Rainer Bunge, 2016). Recovering metals from electronics is already done in low-income countries (see Figure 2.5), therefore it is a great opportunity to do it safely and sustainably.

Education and training are critical components of effective ash management. Workers handling incinerator bottom ash must be trained in proper safety procedures to prevent exposure to hazardous substances. This includes wearing personal protective equipment (PPE), such as gloves and masks, and following protocols for safe handling and transport of the ash. Furthermore, community awareness programs can help to educate the public about the importance of proper waste disposal and the role of incineration in waste management. These programs can encourage community participation in waste segregation, reducing the amount of hazardous

Figure 2.7. Sorted aluminum recovered from bottom ash. Zürich, Switzerland 24.05.2024

materials that end up in incinerators. Encouraging the sorting of bottom ash to recover and reuse valuable metals or glass can also be an extra incentive to have a sustainable waste disposal infrastructure. Many high-income countries use the remaining bottom ash for building materials for infrastructure, and it can be very promising if done properly (Pihl, 1997), (Mu'azu, 2009). However, Rübner, Haamkens, and Linde (2008) has observed that the bottom ash must be well-treated beforehand to avoid adverse, and sometimes dangerous, effects from poor concrete composition. This is why even some high-income countries, such as Switzerland, do not use their bottom ash for construction.

Once filtering and recycling of bottom ash is done, it must be disposed of. The key for the disposal is that the bottom ash must be isolated in such a way that it cannot leach into the ground, it cannot fly away and animals or people cannot walk on it. To prevent leaching into the soil, the disposal site must be lined properly. Macrosheet (2023) mentions the use of either natural or synthetic liners for ash storage ponds, with synthetic liners usually made of HDPE or PVC. The ash must be covered, either with water, sand or a solid cover to prevent it from flying away with the wind. The location must also be protected to avoid animal or human contact, which can be dangerous for health and safety reasons.

In conclusion, incinerator bottom ash management in low-income countries like Malawi involves a combination of technical solutions and community engagement. By implementing best practices for ash stabilization, disposal, and worker safety, and by creating community awareness, these countries can mitigate the environmental and health risks associated with incineration. Continued support and collaboration are essential to improving waste management practices and protecting public health and the environment.

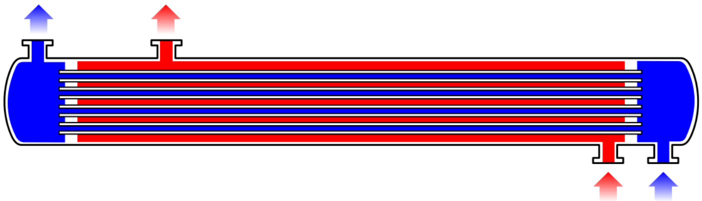

Figure 2.8. Shell & tube heat exchanger, sourced from: Wikimedia Commons, CC BY-SA 3.0

2.4 Energy harnessing

Energy harnessing is one of the biggest discussions today in municipal waste management in high-income countries. With many privately owned incineration plants, as well as new sustainability laws, waste has become a valuable resource for electricity and heat production. While it is unreasonable to suggest a full waste-to-energy plant in countries with a GDP per capita under $3000 USD (Brunner and Rechberger, 2015), harnessing incinerator heat could be possible. This can be used to heat water, for cooking for example. Water can pass into tubes that pass near the secondary chamber of the incinerator, to be then sent to heat cooking stoves such as the changu changu moto, often used in Malawi (Ripple Africa, 2023). A simple shell and tube heat exchanger (see Figure 2.8) can be used to cool down the flue gas, thus reducing emissions of some polluting substances as mentioned in 2.1, and to heat the water. If the water cannot be heated enough for cooking or cleaning, it can be heated to help heat composters, to increase their efficiency with higher temperatures. To verify if this would be feasible/useful, basic heat exchanger calculations should be made. These calculations are based on the calculations from Primo, 2020. Disclaimer: these are only for scale and feasibility purposes, and are by no means final. A full study is required to estimate the cost and real dimensions, considering specific efficiencies and a full analysis of the system. First, we have the basic formula for a classical heat exchanger:

$$\dot{Q} = \dot{m}C_p(T_{out} - T_{in}) = UAT_{lm} \tag{2.1}$$

where $\dot{Q}$ is the heat transfer rate in J/s, $\dot{m}$ is the mass flow rate in kg/s, C_p is the specific heat capacity in J/kg·K, T_{out} and T_{in} are the outlet and inlet temperatures in K, U is the overall heat transfer coefficient in J/s·m^2·K, A is the total heat transfer surface in m^2, and T_{lm} is the logarithmic mean temperature difference in K (see equation 2.2).

$$T_{lm} = \frac{(T_{flue,in} - T_{water,out}) - (T_{flue,out} - T_{water,in})}{ln(\frac{T_{flue,in} - T_{water,out}}{T_{flue,out} - T_{water,in}})} \tag{2.2}$$

Where $T_{flue,in}$ is the temperature of the flue gas at the entrance of the heat exchanger, $T_{water,out}$ is the temperature of the water going out of the heat exchanger, $T_{flue,out}$ is the temperature of the flue gas going out of the heat exchanger, $T_{water,out}$ is the temperature of the water going out of the heat exchanger.

In our case, we want to estimate the heat transfer area required to heat our water (with a specific heat C_p = 4180 J/kg·K) from 25°C to 60°C at a flow rate of 0.03 kg/s, with a flue gas flow rate of 0.03 m^3/s (based on Picken and Bennett, 2004). We will have to make assumptions for heat transfer coefficient, flue gas specific heat, and flue gas temperature. The first assumption to be made will be the flue gas input temperature, or $T_{flue,in}$. Using the data from Mosè Peduzzi, it is safe to assume a temperature of 200°C for the flue gas inside the chimney, which is the temperature we will use. For the heat transfer coefficient, we will base our assumption on typical values, sourced from The Engineering Toolbox. Our chosen value for U is a conservative 200 W/m^{2}K. We will assume a 100% heat conservation between the water and the gas, therefore $\dot{Q}$ is both the gas heat loss and the water heat gain. In reality, this number is impossible, since there are always losses in the system due to heat dissipation in the air. The flue gas-specific heat will be assumed as 1,256 kJ/m^3·K. The results can now be calculated:

$$\dot{Q} = m_{\dot{water}} C_{p,water}(T_{water,out} - T_{water,in}) = 0.03 \cdot 4180 \cdot (60 - 25) = 4389\ W \tag{2.3}$$

$$\dot{Q} = m_{\dot{gas}} C_{p,gas}(T_{gas,out} - T_{gas,in}) = 0.03 \cdot 1256 \cdot (200 - T_{gas,out}) = 4389\ W \tag{2.4}$$

Therefore, $T_{gas,out}$ = 83.52°C. We can now calculate the mean logarithmic temperature T_{lm} and finally the area, A:

$$T_{lm} = \frac{(T_{flue,in} - T_{water,out}) - (T_{flue,out} - T_{water,in})}{ln(\frac{T_{flue,in} - T_{water,out}}{T_{flue,out} - T_{water,in}})} = \frac{140 - 108.52}{ln(\frac{140}{108.52})} = 123.56°C \tag{2.5}$$

$$A = \frac{\dot{Q}}{UT_{lm}} = \frac{4389}{200 \cdot 123.56} = 0.178\ m^2 \tag{2.6}$$

These calculations indicate that the heat exchanger would require an area of a minimum of 0.178 m^2 to deliver the requested performance. This is a reasonable size for a small heat exchanger. Even with 50% efficiency, this size would be doubled but the system would still be realistic to create. More studies must be performed to design such a system, by defining more precisely the specifications (such as water and flue gas temperatures and flow rates).

Another option to harness the heat from the flue gas was studied by W.-H. Chen and J.-C. Chen (2001). They used a cyclone heat recovery system. They did not adapt it to a de Montfort incinerator, they used it on an incinerator with an incineration capacity of 150 kg/hr (reminder: the de Montfort Mark 8A has a capacity of 12kg/hr). Their general results were more favorable from an air-pollution control standpoint than from an energy recovery standpoint, but it must still be considered.

To conclude this part on energy harnessing, the only real suggestion for low- and middle-income countries is to use the heat from incineration directly as a heat source. Using a simple heat exchanger would be possible, but a cost calculation is still necessary.

3 Final recommendations

3.1 Waste recovery

Waste recovery is a whole challenge in itself, yet it is vital for incineration processes. The aim should be to incinerate only what is necessary, making waste segregation at the source a top priority. The most effective way to enhance incineration efficiency and reduce the volume of waste burned is to remove metals and organic materials. Metals can be recycled or repurposed, while organic waste is best composted, with anaerobic digesters being ideal for recovering valuable methane. Reusing and recycling some plastics is an option, but it demands additional infrastructure that may not be present in low- and middle-income areas, thus incineration might be the only solution. Engaging and educating the community is essential. Medical waste must be consistently separated to avoid disease transmission, and waste handlers should always use personal protective equipment, including masks and gloves.

3.2 Incineration system

Taking into account the scoring system from section 2.2, the overall recommendation is to give precedence to an engineered incinerator like the de Montfort mark 8A, or a similar improved or adapted model. It stands out as the most secure, cleanest, and efficient option among the three incinerators. Should a portable incinerator be necessary, barrel incinerators present a fast and economical option, though safety concerns dictate that incineration occurs well away from residential areas. The justification for open waste burning is challenging due to its adverse effects on human health and the environment. It should only be considered acceptable in the context of emergency medical waste incineration to limit the spread of infectious diseases.

3.3 Bottom ash management

After the incineration process is complete, the resulting bottom ash should be managed in a secure and regulated area. It is recommended that this area be lined to avert the leaching of contaminants into the soil, and covered to inhibit the dispersion of ash by wind. Access to the landfill site by animals and people must be restricted to minimize health and safety risks.

3.4 Energy harnessing

Energy harnessing can be a great way to reduce the total long-term cost of the incineration system. For low- and middle-income countries, the only realistic options are to use the heat directly to heat water. This can either be done with a cyclone heat recovery system or a basic shell-and-tube heat exchanger.

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