Techno - economic analysis of small scale waste to energy opportunities:

A case study for Island Nations

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I declare that this dissertation is my own account of research and contains as its main content work which has not previously been submitted for a degree at any tertiary education institution.

......................................................

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Abstract

Solid waste treatment methods including reuse and source reduction, recycling, composting, waste to energy and finally landfilling have been implemented in Organisation for Economic Cooperation and Development (OECD) countries. The first being the most preferred solution. In non OECD countries especially Small Islands Developing States (SIDs), customized solid waste treatment methods must be implemented. SIDS have unique characteristics such as dependence on foreign aid for investment, their heavy reliance on imported consumer goods and resources, their vulnerability to the effects of climate change and due to the lower amount of waste being generated, conventional solid waste management processes are not appropriate. Waste to energy can play a major role in treating waste in SIDS where land is scarce and where a diversification of the energy mix is crucial.

The aim of this paper is to perform a techno - economic study to assess the smallest possible capacity of a waste to energy plant that is capable of treating municipal solid waste. An excel model was developed containing capital, operational and maintenance cost estimates. The economic performance of the model was assessed using the Net Present Value (NPV), Levelized Cost of Electricity (LCOE) and Simple Payback Period (SPP) tools.

The Maldives were used as case study for developing a small scale plant. The model consists of a small scale prototype incinerator plant for energy extraction and an Organic Rankine Cycle (ORC) unit for electricity generation. The modelling gave the following results; an NPV of AUD$846,547, a SPP of 3.8 years and a LCOE of AUD$0.11/kWh for a plant capacity of 5,274 tpa, an ORC unit capacity of 235.20kW with an incinerator having a flow rate of 752.63kg/hr, gate fees of $50/t and a sale price of electricity of $0.35/kWh. The capital costs for the incinerator and the ORC unit were AUD$194,912.09 and $776,151.84 respectively. The biggest contributor to the capital expenditure was the flue gas treatment system with a total of AUD$ 814,156.04. Sensitivity analysis showed that the NPV was more sensitive to the price of electricity than to the gate fees.
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1. Introduction

1.1 Background Information

With the development of the industrialized world, mankind has experienced a wide range of benefits such as a noted increase in the standard of living. From access to health care, decrease in poverty rate, increase in literacy and electrification rate, developing countries have benefited alongside the Organisation for Economic Co-operation and Development (OECD) countries in this worldwide revolution (OurWordInData 2015). Figure 1 is a summary of some of the works done by (Bourguignon 2003) and demonstrates that there has been a constant decline in absolute poverty over time. The absolute poverty line is considered to be earning less than US$1.25 per day.

![Figure 1: Share of the world population living in absolute poverty over time (Bourguignon 2003)](image)

This increase in standard of living is not without consequences. The race towards more resources, the increases in energy needs and products available to consumers have brought about other challenges that the world needs to face. One such challenge is the unprecedented
levels of pollution that is being experienced in our present era. Air pollution, with the uncontrolled release of greenhouse gases has increased over the last decade and is linked to our way of living as shown in Figure 2.

![Figure 2 Global CO2 emissions per capita over the years (Bourguignon 2003)](image)

One of the consequences of the unprecedented economic development is a substantial increase in the amount of solid waste. As the generation of Municipal Solid Waste (MSW) being closely related to economic development, industrialization and consumption pattern has grown alongside the Gross Domestic Product (GDP) (World Bank 2012).

Figure 3 clearly shows that in OECD countries where there has been increases in GDP, the generation of MSW has also increased (European Environment Agency (EEA) 2015). Developing nations are also following this trend. The latter has witnessed a steady rise from 415kg per capita in 1980 to 560 kg per capita in 2006 (Stehlik 2009). To successfully tackle this challenge, measures had to be devised and applied to manage the growing amount of solid waste.
OECD countries have established proper Solid Waste Management (SWM) schemes that encompass the whole spectrum of the waste following the hierarchy of waste. According to Foolmaun et al, it can be classified as being:

- Source Reduction
- Reuse
- Recycle
- Resource Recovery
- Incineration – Waste to Energy
- And finally Landfilling

Source Reduction being the most preferred solution and the landfilling the least preferred one.
Figure 4 shows the integrated approach to promote the best practices for SWM. When all the preferred solutions have been implemented, the waste is sent to Waste to Energy (WtE) treatment plants and/or to the landfills. WtE plants will recover the energy of the waste in the form of heat to either generate electricity or process and district heating or both in some cases (Chen 2003). Landfilling should be the least preferred and the last mode of treatment for solid waste management.

Even if it lies low on the solid waste hierarchy, Waste to Energy plants are now playing a decisive role in an integrated SWM process and they are becoming more and more common due to the resources they can provide (United Nations 2015). Due to economies of scale, WtE plants are generally built as large as possible in OECD countries. They are based on similar feedstock characteristics of the MSW and the large quantities of MSW collected (World Bank 2012). In addition, WtE plants have become more modernized with state of the art technologies for meeting stringent emissions (Ricaud 2011). On the other hand, non–OECD countries like Small...
Island Developing States (SIDS) are now facing the challenge of sustainably disposing their solid waste.

SIDS have been identified to be 52 islands in total that have totally different characteristics that define them. They are located in the Indian Ocean, Caribbean, the Pacific, the Atlantic, Mediterranean and South China Sea. Being small islands they have distinctive features like:

- Dependence on foreign aid for investment
- Geographically isolated thus they depend on air and sea transport
- Extremely vulnerable to the effects of climate change (coastal erosion, rise in sea level)
- Heavily reliant on imports for consumer goods and resources

(Agamuthu and Herat 2014)

Given these inherent characteristics, SIDS cannot follow the traditional SWM guidelines that are performed in OECD countries as their low population and amount of waste generated does not encourage the adoption of certain SWM practices. There is an evident problem of economies of scale for example. Furthermore, land scarcity is yet another challenge and this worsens the ‘Not In My Back Yard syndrome’ (NIMBY) (Agamuthu and Herat 2014). Despite these challenges, a customized SWM program has a place for the sustainable development of SIDS.

Landfilling can be considered to be the easiest way to dispose of MSW in SIDS (Brunner and Fellner 2007). Some countries like Mauritius have been able to implement other practices like composting and part recycling (Mohee, Surroop, and Jeetah 2012). But there is still a major part of the MSW generated that goes directly to the landfills. Thus on smaller scales, the viability of the other SWM practices are in question. One way to change this trend is to implement WtE plants.
WtE plants could be a viable option for SIDS as it would help to decrease the volume of the waste sent to landfills and thus increase their lifetime. Land being a precious resource in SIDS, it is imperative that they make the most out of the landfill sites before choosing the next. Furthermore, WtE plants when providing electricity could be a way to diversify the energy mix and thus strengthen the economy. They would be less dependent on fossil fuel imports for generating electricity. That being said, WtE plants in SIDS would face unique challenges.

The characteristics of MSW collected in SIDS is different from OECD countries. Apart from the smaller quantity of waste collected, a high moisture content and a lower calorific value are additional differences that are present (Agamuthu and Herat 2014). Despite these challenges, investigating the implementation of smaller scale WtE plant could prove to be beneficial to an integrated SWM program in SIDS.
1.2 Scope and aim of the project

The aim of this work will be to perform a techno–economic analysis of the smallest scale of Waste to Energy plant that could be applied to SIDS.

To achieve this, the following steps will be done;

- The scale – the total amount of MSW to be treated per year - will be obtained. This will depend on the locality or the waste generators. This could be a small town, a community or an agglomeration of hotels.
- Several technologies available for waste to energy plants will be evaluated and the best one for treating the waste will be chosen.
- The investment costs will be estimated together with their operating and maintenance costs.
- The revenues obtained from the electricity sale and the gate fees – the amount paid for removing one tonne of MSW – will be calculated
- All the data collected will be put into an excel model
- The financial viability of the project will then be assessed from the above data.

The paper will mostly focus on the financial viability of the endeavour. Wherever no up to date costs would be available, data from literature would be obtained and brought back to present day dollars. Other worldwide factors such as changes in commodities that could also affect the financial model won’t be taken into account as it would add too much scope and complexity to the model. Obtaining proper up to date prices from firms would be a future work project. Concerning the engineering portion of the paper, the technologies chosen will be regarded as “black boxes” with set efficiencies. The detailed engineering design of the plant is also the subject of future work.
1.3 Thesis overview

**Step 1**

In order to have a proper grasp of an integrated SWM system, the other treatment processes such as recycling, composting and landfilling will be discussed briefly in the first chapters. The core of the literature review will look at different WtE options that are available, their advantages and disadvantages.

**Step 2**

An excel model will be set up. Two scales will be used to test it, a large scale of 100,000 tons per annum (tpa) and a medium scale of 10,000 tpa. This part will be also used to explain how the model works.

**Step 3**

This would be the core of the paper where the small scale system will be evaluated. The Maldives will be used as a case study. The excel model will be asses the viability of a small plant having a scale of around 5000 tpa.

**Step 4**

The last part will contain the results and discussion and the sensitivity analysis portion.
2. Literature Review

2.1. Solid Waste Management Practices

This part of the paper will look at the different options available for managing solid waste. They include source reduction, reuse, recycling, resource recovery, incineration and landfilling. Foolmaun, Chamilall, and Munhurrun (2011) illustrate this hierarchy in Figure 4 with the least preferred to the most preferred route.
2.1.1. Reuse and Source Reduction

As its name suggests, source reduction is a way to eliminate the waste before it is created. This can be done in several ways ranging from careful design and manufacture of products to choice of biodegradable material (The Maryland Department of the Environment 2015).

Examples of Source Reduction include reduction in packaging, using products that can last longer and the reuse of materials and products. Ultimately these strategies reduce the pressure on landfills as there is less waste being disposed in the end (United States Environmental Protection Agency 2002).

Reuse and source reduction should, therefore, be used to a maximum wherever possible. Due to its greatest impact on a solid waste management system, it remains the most desired option to treat solid waste.

2.1.2. Recycling

Recycling is the process by which specific waste streams are segregated and used to produce new products. Generally recycled products require less material for their manufacture than when using raw materials (Clean up 2009).

Recycling has several advantages as listed below:

- It reduces the amount of waste being sent to landfills thus increasing their lifetime.
- There is less stress on resources such as water, fiber and minerals
- It helps promote the recycling industry that provides jobs
- It helps to protect the environment

(United States Environmental Protection Agency 2015)
2.1.3. Composting

The composting process degrades the organic content of the waste to obtain a ‘stable end product’ that can be used as a fertilizer or soil improvement. Yard trimmings and food wastes are generally used as feed from Municipal Solid Waste (MSW) and this further helps in reducing the volume sent to the landfills. In addition, a useful product is also obtained which can be used a substitute for chemical fertilizers (Stebbins 2014).
2.1.4. Landfilling

Landfilling is the only solid waste treatment that can deal with all the material of the solid waste spectrum. The other options discussed above generally handles only certain specific streams of the MSW generated.

Other options will still need their residues to be landfilled. Thus landfilling will always form part of a solid waste management system. It is considered to be the cheapest and simplest form of solid waste treatment (McDougall et al. 2001). Figure 5 shows a cross section area of a typical landfill.

![Modern Sanitary Landfill Cross Section](image)

Figure 5 Cross section area of a typical landfill (Eco Landfill Solutions 2010)

Modern landfills consist of the following:

- a liner system to provide a boundary to the environment. This will also prevent the leachate from seeping into the ground
- a system for the collection of the leachate and the gas generated
- and progressive addition of cover layers when waste deposition is finished
After care management of landfills is a very important part of the site management. Thirty years is a common basis time-lapse and this needs to be accounted in the financial feasibility of the landfill (Laner et al. 2012).

Despite this, landfilling still remains a very common means of disposal of waste in developing countries (Brunner and Fellner 2007). The apparent low short term costs and the relatively minimum resources required for this type of waste treatment makes it a very attractive solution.

One last alternative that remains for solid waste management is the incineration route or the Waste to Energy (WtE) route when taken more broadly. In the next section of the literature review, a detailed examination of the WtE option will be undertaken. Its importance will be discussed together with examples from around the globe.
2.2. Waste to Energy (WtE)

2.2.1. Definition

Using waste as a resource for harnessing energy is not a recent process. Incinerators burning garbage to produce heat have been used in the past in OECD countries. The first incinerator called the destructor was commissioned in the UK in 1874. Destructors became widespread before World War I and some also were used to generate electricity (Herbert 2007).

As previously mentioned WtE sits on the lower end of the Solid Waste Management (SWM) spectrum and should be used when all the other options have been utilized. Nevertheless a general trend towards WtE practices is now being witnessed. Several largely populated countries like China and India have seen a growth in the share market for WtE (World Energy Council 2013). The trend can be further illustrated around the globe as shown in Figure 6 and Figure 7 respectively.
Figure 6 Production of energy from waste (United Nations 2015)
Figure 7 Energy production from industrial waste in Waste to Energy plants (United Nations 2015)
WtE has the advantage to regard waste as a resource where useful energy could be extracted. Furthermore, whenever possible, additional benefits include hazard and volume reduction and recovery of mineral and chemical content (Integrated Pollution Prevention and Control (IPPC) Bureau 2006).
2.2.2. Public perception of Waste to Energy Plants

Adoption of new WtE projects need the approval of the local community and the public in general. Incinerators have often faced strong public opposition. According to (Yassin et al. 2009), public perception plays a major role in the adoption of WtE technologies in Solid Waste Management (SWM). They have identified three major observations that reinforce this point:

- the NIMBY (Not In My Back Yard) effect
- emission concerns and
- the waste that could potentially be recycled/minimized

Most of the time, proper dialogue between the relevant authorities, the promoters of the project and the public can dissipate these doubts. Taking the United Kingdom as an example, the pertinent authorities such as the UK Health Protection Agency has shown evidence of emissions that were treated to comply with stringent health standards such as the Waste Incineration Directive. Now it is imperative that stringent limits are met by the WtE plants in regards to their solid, liquid and air waste (Pavlas et al. 2011).

Moreover, several other countries such as Austria, Denmark, Germany and the Netherlands, which have more complex recycling policies in place, show that WtE rates can be viable with high rates of recycling (Yassin et al. 2009).
2.2.3. Waste to Energy trends in the world

Incineration is not a new phenomenon. Several countries have already incorporated WtE as a means of heat and electricity recovery and at the same time reducing the amount of waste sent to landfills (Stein and Tobiasen 2004). This is shown in Figure 8.

Europe is the leader in WtE where incinerating waste has been a long standing practice yet it is only recently that the heat released has been used for useful purposes (Ricaud 2011).

Europe is not the only actor in the Wte field. The United States are also actively developing that route as illustrated in Table 1 below. A summary of the different technologies in use and their status is also shown. The variety of technologies will be looked upon into more details later in the literature review.
Table 1 Summary of the different technologies and their status in the United States. (Funk, Milford, and Simpkins 2013) pg 6

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
<th>Mode of Operation</th>
<th>Commercially Available for WTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion</td>
<td>Thermal conversion of a feedstock utilizing excess air or oxygen as oxidant to generate heat.</td>
<td>-Grate</td>
<td>87 installations in the United States</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Bubbling fluidized bed</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Circulating fluidized bed</td>
<td></td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>Thermal conversion of a feedstock in the absence of air or oxygen as oxidant to generate a synthesis gas or fuel and pyrolysis oil. (Plasma arch capabilities of operating in excess of 20,000°F.)</td>
<td>-Horizontal</td>
<td>Two installations in the United States</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Vertical (updraft/downdraft)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Plasma arch</td>
<td></td>
</tr>
<tr>
<td>Gasification</td>
<td>Thermal conversion of feedstock in a limited atmosphere of air or oxygen as oxidant to generate a synthesis gas or fuel.</td>
<td>-Horizontal stationary</td>
<td>0 installations in the United States</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Horizontal rotating</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Vertical (updraft/downdraft)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Stationary grate</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Bubbling fluidized bed</td>
<td></td>
</tr>
<tr>
<td>Anaerobic Digestion</td>
<td>Biochemical conversion of a feedstock in the absence of oxygen to generate biogas.</td>
<td>-Mesophilic (77°F–100°F)</td>
<td>Multiple installations in the United States (total quantity unknown)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Thermophilic (122°F–135°F)</td>
<td></td>
</tr>
</tbody>
</table>

Wte help in other sectors as well. The flexibility of the technologies now available could help in alleviating the transportation industry and as well as increasing the potential for electrical efficiency (Münster and Lund 2010). Moreover a more diversified electricity mix could also be a result when incorporating Wte facilities.

Energy security and protection from the changing prices of fossil fuels is a crucial imperative for Small Island Developing States (SIDS). Most SIDS are reliant on petroleum and coal imports for their energy production. A diversification of their energy mix would prove beneficial to their economy and stability (Elahee 2011).
2.3. Waste to Energy Technologies

2.3.1. Energy Recovery Technologies

Energy Recovery technologies refer to the means available to extract the maximum energy from the MSW resource for later use. As the waste resource is non-homogenous in nature, this recovery process can be challenging. Thus a multitude of techniques are now available to recover the energy depending on its nature. Figure 9 below, summarizes the different WtE pathways that can be used. Some technologies are better suited than others for certain specific composition of wastes as it will be explained in the later sections.

Figure 9 Different waste to energy pathways (Funk, Milford, and Simpkins 2013)
The characteristic of the waste being fed to the WtE plant has a huge impact on the efficiency of the plant. MSW by their very nature have varied features. Their calorific value, the amount of energy that is obtained when they are completely burnt, is around 10.4 MJ/Kg. Furthermore, if careful sorting is done, i.e. metals and glass components are removed, it can go as high as 18.5 – 18.7 MJ/kg (Ricaud 2011).

For example the removal of:

- glass and metal would reduce the ash content, thus increase in Lower Calorific Value (LCV),
- paper would reduce the LCV
- Light packaging would reduce the LCV
- Clinical wastes would increase the LCV

(European Commission 2006)
2.3.2. Combustion

In a conventional combustion WtE system, heat liberated from the incineration of waste is present in the flue gas going out of the furnace. The flue gas is then passed through a series of heat recovery equipment that captures this heat to increase the energy content of steam. The steam can later be used for generating electricity by a steam turbine or heat or both in Combine Heat and Power systems (Ricaud 2011).

Mass burn technology is the most common form of thermal treatment processes of MSW (Funk, Milford, and Simpkins 2013). Mass burn incinerators occupy most of the WtE landscape. In Europe 90% of WtE plants are incinerators. They tend to be built on a large scale as they offer inherent economies of scale advantages (Ricaud 2011). Combustion or Incineration is a fully developed technology but it encounters several challenges such as the high capital, operational and maintenance costs (of facilities) (about 3X higher than a coal power plant of same nominal capacity), low electric conversion efficiencies (around 20%) and public opposition (Arena 2011).

On the other hand, mass burn offers a number of interesting advantages over the other types of thermal treatment. It can reduce significantly the volume of the waste sent to landfills and it can eliminate dangerous waste successfully making it the most preferred solution for handling hazardous wastes. Besides the heat recovery aspect is even more interesting as it can lead to the production of thermal or electrical energy (Chen 2003).

The Moving grate, Rotary Kiln and the Fluidized bed technology are the three types of combustion methods that are most common (Stein and Tobiasen 2004). Each will be briefly reviewed in the next sections.
Moving Grate

Moving grate incinerators are the most common form of incineration plants. They consist of a moving grate where the waste is burned. Figure 10 gives a graphical display of a typical moving grate incinerator. The air from below will cool down the grate and acts as primary air of combustion. Secondary air is also added to further aid the combustion process (Stein and Tobiasen 2004).

![Figure 10 Moving grate incinerator (Stein and Tobiasen 2004)](image)

Electrical efficiencies of 20–25% for Combined Heat and Power plant (CHP) and 25–35% are typical of incineration plants (Stein and Tobiasen 2004). The biggest WtE incineration plant is the Afval Energie Bedrijf CHP plant in Amsterdam. It started its operations in 2007. It can process 1.5 million tonnes of MSW per year with a capacity of 114.2MW and efficiency of 30% (World Energy Council 2013).
The rotary kiln is made up of an inclined rotating drum. The waste is added at the top and it tumbles down the axis. The rotary kiln is popular for smaller incineration systems (Stein and Tobiasen 2004).

The thermal efficiencies are quite low, 70% due to the large amount of excess air added. On the other hand they can be of modular installation and can process small flow rates. Successful rotary kiln combustion processes have been used for burning clinical wastes (Ricaud 2011).
**Fluidized bed**

They generally consist of a bed of sand where the air is passed through. The air apart from being used up in the combustion helps in making the bed of sand behave like a fluid. Fluidized beds have the advantage of efficient thermal heat transfer. The waste that can be treated by this technology needs to be processed to obtain certain characteristics (Stein and Tobiasen 2004).
2.3.3. Gasification

Gasification can be considered to be an indirect combustion stage where oxygen is added partially (sub stoichiometric amounts). The results are a syngas having a relatively high calorific value that can be stored and used at a later stage or at different sites/stages. The components of the gas are carbon monoxide, hydrogen gas and low amounts of methane. The syngas can also contain contaminants such as PM, alkali, sulphide or chloride compounds (Arena 2011).

**Figure 12** gives the schematic of a conventional gasification process.

![Figure 12 Schematic of a conventional gasification process (Young 2010)](image)

With the right combination of starting feedstock, operating conditions and equipment, such as moving grate incinerator, rotary kilns or even fluidized bed, the syngas can be used for different applications such as in reciprocating engines, gas turbines or as a chemical feedstock (Arena...
Gasification technologies include several arrangements such as updraught, downdraft, bubbling fluidized bed, circulating fluidized bed and rotary kiln reactors (Stein and Tobiasen 2004).

The process parameters are typically high pressures (around 40 Bars) and high temperatures from 500–1400°C. Ash is produced, having more or less the same characteristics of the ash present in WtE mass burn incinerators (Ricaud 2011). Figure 13 shows a schematic of the process according to the Energos Technology.

According to Arena, Gasification has several advantages over normal incineration. Formation of pollutants namely dioxins, nitrous, and sulphur oxides is reduced as compared to conventional incineration. Secondary wastes are less environmentally harmful, for example a vitrified slag is
obtained as bottom ash. Moreover as there is a reduction in the amount of flue gas that is
obtained, this decreases its treatment costs. In general a 30 % decrease in the volume of flue
gas can be observed. The possibility of cleaning the syngas prior to firing help to remove
problematic corrosion intensive materials such as HCl and this further helps in reducing costs.

Another noticeable advantage is the higher efficiencies that can be obtained. Higher steam
temperatures can be achieved and this has a direct positive impact on the process (Arena 2011).

The modularity, that is the scaling down of the system is an important feature (Yassin et al.
2009). Current data during the last few years shows that gasification plants smaller than
100,000t/year are manageable but the financial feasibility of each plants need to be carefully
assessed. Japan is the leader in gasification plants till now.

The feedstock having specific characteristics is essential for a successful gasification plant. This
can be quite problematic due to the nature of untreated MSW can have varying properties.
2.3.4. Pyrolysis

In contrast to gasification, in pyrolysis no oxygen is used other than what is already present in the fuel itself. It is actually the first step of the gasification process. A gasification stage can be followed or the process can be stopped (Ricaud 2011). The simplified schematic of the pyrolysis process can be shown in Figure 14.

![Figure 14 Schematic of the pyrolysis process (Young 2010)](image)

A liquid product, a portion of non-condensable gases and a solid residue (char) is produced (Stein and Tobiasen 2004). Thus pyrolysis is an endothermic process whereby heat is used to degrade the waste (400–800°C) in the absence of oxygen. The products are

- A gas having a high energy content 10–20 MJ/Nm³ (Ricaud 2011)
- Waxes and oils
- Solid fractions

The economic feasibility of ‘standalone’ facilities is still in question. Yet pyrolysis is most of the times combined with incineration or gasification sections (Arena 2011).
2.3.5. Plasma Gasification

In Plasma Gasification, the waste is degraded by very high temperatures by an electrical arc. Temperatures can reach between 5000 and 15,000°C (Ricaud 2011). It consists of two graphite electrodes in the plasma furnace. An electrical arc is produced between the electrodes when an electric current is passed. The arc is generated at the tip of the electrodes and the conducting receiver. Air is used as the plasma between the electrodes due to its low cost. (Mountouris, Voutsas, and Tassios 2006).

![Figure 15 Schematic of plasma gasification process (Mountouris, Voutsas, and Tassios 2006)](image)

The feedstock generally needs to be treated to meet the requirements of the furnace, proper moisture content is required, for example, and this is achieved by drying the feed if necessary. Size reduction is performed by shredders.

Before entering the energy recovery part, the gas needs to be cleaned. Acidic compounds (HCl, SOx), particulate matter, heavy metal and moisture have to be removed (Mountouris, Voutsas, and Tassios 2006).
2.4. Energy / Electricity generation side

Now that the energy has been extracted from the waste resource, it has to be used in another part of the plant to convert it into useful high quality electrical energy or to lesser quality thermal energy. This can be done on the recovery side.

Electrical generation has been considered to be a way of increasing the quality of the energy present in the waste (Pavlas et al. 2011). Recovering thermal energy from the waste has also helped in increasing the value of the waste as a resource.

The next sections will explain the options that can be used from the traditional steam turbines to the waste heat recovery type such as the Organic Rankine Cycle (ORC).

2.4.1. Steam Turbines

The Steam turbine layout is generally used in large scale WtE plants for the generation of electricity. They are based on the Rankine Cycle and the outputs that can be obtained vary from electrical power, steam, hot water or a combination of the three. Figure 16 shows a simple Rankine cycle on the right with the corresponding processes involved at the left. The latter shows whether energy is fed to the system or not.
Steam is generated from the boiler. The energy from the steam is extracted in the turbine whereby the mechanical energy is converted to electrical energy. Low pressure steam can also be obtained and transformed to hot water in dedicated heat exchangers such as condensers. Figure 17 shows a typical Steam Rankine cycle (World Bank 1999).
2.4.2. Organic Rankine Cycles (ORC)

In essence, the ORC is analogous to the Steam Rankine Cycle. There is still vaporization of a fluid at high temperature, which produces mechanical work when it expands at a lower pressure. Thus the same components in a conventional Steam Rankine Cycle are present, such as a boiler, a turbine, a condenser and a pump as shown in Figure 18. But in this case an organic fluid is used which has a lower boiling point. Efficiencies can range from 24% to 30% with more complex design point (Quoilin et al. 2013).

The Organic Rankine Cycle (ORC)

Figure 18 Organic Rankine Cycle layout from Pratt& Whitney (Pratt & Whitney 2015)
According to (Quoilin et al. 2013) ORC turbines are now used extensively for waste heat recovery. They are considered a pivotal way of reusing the waste heat to generate electricity. They are considered to be a CHP generation through a bottoming cycle.

As an organic fluid is used instead of water as the working fluid, the adequate choice of the working fluid is of utmost importance as it will have implications on the system efficiency and the operation of the turbine and its impact on the environment (Liu, Chien, and Wang 2004).

Figure 19 Schematic diagram of ORC systems with (right) and without recuperator (left) (Quoilin et al. 2013) fig 1

Figure 19 shows a typical ORC systems with and without recuperators. The latter helps to reheat the working fluid before entering the boiler (Quoilin et al. 2013).
ORC are especially interesting in small scale biomass applications as shown in Figure 20.

Opposite to large scale steam turbine units, ORC units are generally designed to be of smaller scale. They can range from a few hundred watts to several megawatts. Several companies are already using ORC for waste heat recovery. This is shown in Table 2.
Table 2 Non exhaustive list of ORC Manufacturers (Quoilin et al. 2013)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Applications</th>
<th>Power range [kWe]</th>
<th>Heat source temperature [°C]</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORMAT, US</td>
<td>Geo., WHR, solar</td>
<td>200–70,000</td>
<td>150–300</td>
<td>Fluid: $\nu$-pentane and others, two-stage axial turbine, synchronous generator</td>
</tr>
<tr>
<td>Turboden, Italy</td>
<td>Biomass-CHP, WHR, Geo.</td>
<td>200–2000</td>
<td>100–300</td>
<td>Fluids: OMITS, Solkatherm, Two-stage axial turbines</td>
</tr>
<tr>
<td>Adorotec/Maxxtec, Germany</td>
<td>Biomass-CHP</td>
<td>315–1600</td>
<td>300</td>
<td>Fluid: OMITS</td>
</tr>
<tr>
<td>Opcon, Sweden</td>
<td>WHR</td>
<td>350–800</td>
<td>&lt;120</td>
<td>Fluid: Ammonia, Lysholm Turbine</td>
</tr>
<tr>
<td>GMK, Germany</td>
<td>WHR, Geo., Biomass-CHP</td>
<td>50–5000</td>
<td>120–350</td>
<td>3000 rpm Multi-stage axial turbines (K9K)</td>
</tr>
<tr>
<td>Bosch KWK, Germany</td>
<td>WHR</td>
<td>65–325</td>
<td>120–150</td>
<td>Fluid: R245fa</td>
</tr>
<tr>
<td>Turboden PureCycle, US</td>
<td>WHR, Geo.</td>
<td>280</td>
<td>91–149</td>
<td>Radial inflow turbine, Fluid: R245fa</td>
</tr>
<tr>
<td>GE CleanCycle</td>
<td>WHR</td>
<td>125</td>
<td>&gt;121</td>
<td>Single-state radial inflow turbine, 30,000 rpm, Fluid: R245fa</td>
</tr>
<tr>
<td>Cryostar, France</td>
<td>WHR, Geo.</td>
<td>n/a</td>
<td>100–400</td>
<td>Radial inflow turbine, Fluids: R245fa, R134a</td>
</tr>
<tr>
<td>Tri-o-gen, Netherlands</td>
<td>WHR</td>
<td>160</td>
<td>&gt;350</td>
<td>Radial turbo-expander, Fluid: Toluene</td>
</tr>
<tr>
<td>Electratherm, US</td>
<td>WHR, Solar</td>
<td>50</td>
<td>&gt;93</td>
<td>Twin screw expander, Fluid: R245fa</td>
</tr>
</tbody>
</table>

The main differences between an ORC and a conventional steam turbine according to (Quoilin et al. 2013) have been summarized in Table 3 below.

Table 3 Advantages and drawback of ORC against steam turbines cycle (Quoilin et al. 2013) table 3

<table>
<thead>
<tr>
<th>Advantages of the ORC</th>
<th>Advantages of the steam cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>No superheating</td>
<td>Higher efficiency</td>
</tr>
<tr>
<td>Lower turbine inlet temperature</td>
<td>Low-cost working fluid</td>
</tr>
<tr>
<td>Compaciness (higher fluid density)</td>
<td>Environmental-friendly working fluid</td>
</tr>
<tr>
<td>Lower evaporating pressure</td>
<td>Non-flammable, non-toxic working fluid</td>
</tr>
<tr>
<td>Higher condensing pressure</td>
<td>Low pump consumption</td>
</tr>
<tr>
<td>No water-treatment system and deaerator</td>
<td>High chemical-stability working fluid</td>
</tr>
<tr>
<td>Turbine design</td>
<td></td>
</tr>
<tr>
<td>Low temperature heat recovery, once-through boiler</td>
<td></td>
</tr>
</tbody>
</table>
• Organic fluids remain in the superheated state after the expansion. Furthermore, there is no condensation which reduces corrosion on the blades of the turbine. This greatly increases the life time of the system to 30 years compared to 15–20 years for steam turbines.

• As the organic working fluid has a much lower boiling point, low temperature heat streams can be recovered.

• Smaller components sizes are required. For the steam cycle, as there is an increase to the square of the fluid velocity with increases of pressure drop, a lower volumetric flow rate is required. Thus bigger components are needed for ORC installations.

• With small density difference between the liquid and vapor state for organic fluids, steam drums and recirculation is avoided when considering the ORC cycle. This accounts for a simpler boiler design.

• In conventional steam cycles, high pressures of 60 to 70 bars are required and this adds to the overall costs of the system. The system is less complex for an ORC set up because pressures does not exceed 30 bars. In addition the working fluid uses a heat transfer loop. It is not heated directly by the heat source meaning that the heating oil can be at ambient pressure. Another benefit is that this set up would not require additional man power in terms of power operators for the plant.

• Water is the working fluid for the Rankine cycle. Due to the complexity of a steam turbine set up, there is always risks of water losses due to boiler blowdown, leaks and drainage. It is crucial, therefore, to attach a water treatment plant together with a state of the art deaerator in most cases to provide high quality feed water boiler to make up for these losses. This further accounts for additional costs.

• As the enthalpy drop with the organic fluid is much lower between stages, single or two stage turbines can be used for ORC cycles. On the other hand, steam cycles would require much more complex equipment and this would, undeniably, add to the cost.
• With lower enthalpy drop in ORC cycles, lower tip and rotating speeds are obtained. This allows direct drive arrangement without the use of a reduction gear in some cases. The design is simplified and this reduces the costs further.
• Lower inlet turbine temperatures for ORC are obtained. This leads to less thermal stresses on the turbine blades and the boiler.
2.5. Typical composition of flue gas from Municipal Solid Waste incinerators

The composition of the flue gas greatly varies from facility to facility. Incomplete combustion, the waste stream components and their proportions and their segregation are the main factors that affect the composition of the flue gas. Table 4 shows some typical flue gas composition with 11% of oxygen content from municipal solid waste, clinical waste and industrial waste respectively without treatment processes.

Table 4. Typical flue gas composition at various plants with 11% O2 reference (European Commission 2006)

<table>
<thead>
<tr>
<th>Components</th>
<th>Units</th>
<th>Municipal waste</th>
<th>Incineration plants for Hazardous waste</th>
<th>Industrial sewage sludge (fluidised bed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust</td>
<td>mg/Nm³</td>
<td>1000 – 5000</td>
<td>1000 – 10000</td>
<td>30000 – 200000</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>mg/Nm³</td>
<td>5 – 50</td>
<td>&lt;30</td>
<td>5 – 50</td>
</tr>
<tr>
<td>TOC</td>
<td>mg/Nm³</td>
<td>1 – 10</td>
<td>1 – 10</td>
<td>1 – 10</td>
</tr>
<tr>
<td>PCDD/PCDF</td>
<td>ng TEQ/ Nm³</td>
<td>0.5 – 10</td>
<td>0.5 – 10</td>
<td>0.1 – 10</td>
</tr>
<tr>
<td>Mercury</td>
<td>mg/Nm³</td>
<td>0.05 – 0.5</td>
<td>0.05 – 3</td>
<td>0.2</td>
</tr>
<tr>
<td>Cadmium + thallium</td>
<td>mg/Nm³</td>
<td>&lt;3</td>
<td>&lt;5</td>
<td>2.5</td>
</tr>
<tr>
<td>Other heavy metals (Pb, Sh, As, Cr, Co, Cu, Mn, Ni, V, Sn)</td>
<td>mg/Nm³</td>
<td>&lt;50</td>
<td>&lt;100</td>
<td>800</td>
</tr>
<tr>
<td>Inorganic chlorine compounds (as HCl)</td>
<td>mg/Nm³</td>
<td>500 – 2000</td>
<td>3000 – 10000</td>
<td></td>
</tr>
<tr>
<td>Inorganic fluorine compounds (as HF)</td>
<td>mg/Nm³</td>
<td>5 – 20</td>
<td>50 – 550</td>
<td></td>
</tr>
<tr>
<td>Sulphur compounds, total of SO₂/SO₃, counted as SO₂</td>
<td>mg/Nm³</td>
<td>200 – 1000</td>
<td>1500 – 50000</td>
<td></td>
</tr>
<tr>
<td>Nitrogen oxides, counted as NO₂</td>
<td>mg/Nm³</td>
<td>250 – 500</td>
<td>100 – 1500</td>
<td></td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>mg/Nm³</td>
<td>&lt;40</td>
<td>&lt;20</td>
<td>10 – 150</td>
</tr>
<tr>
<td>CO₂</td>
<td>%</td>
<td>5 – 10</td>
<td>5 – 8</td>
<td></td>
</tr>
<tr>
<td>Water steam (H₂O)</td>
<td>%</td>
<td>10 – 20</td>
<td>6 – 20</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Sewage sludge plants are those for the incineration of industrial sewage sludge
2. The information in this table refers to German plants. The values seen at older plants can be considerably higher, especially in the case of emissions influenced by furnace-technical parameters e.g. CO, TOC, etc.
3. Hazardous waste values refer to mixed HW merchant plants rather than dedicated stream plants.

According to the (World Bank 1999) there exists two broad types of measures for the control of pollutants from the flue gas. These include primary measures, which consist of efficient combustion techniques with the adequate amount of oxygen and allowing for intimate mixing which will help in reducing the effect of incomplete combustion, and Secondary measures that precipitate, adsorb, or transform the pollutants. Special care has to be taken with hydrochloric acid, hydrogen fluoride, sulphur dioxide, dioxins, oxides of nitrogen and mercury. They would require advanced and more costly chemical treatment equipment.
Table 5 below shows the composition of the flue gas after treatment compared to the European Union limits. It can be observed that proper selection of technologies and adequate operational habits during the combustion process, as mentioned above, will be able to treat the flue gas to the suitable standards.

Table 5 Comparison of emission limits set by EU legislative and performance of flue gas cleaning system in up-to-date incinerators (Pavlas et al. 2011)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Emission limit—daily average (mg/m³)</th>
<th>Raw gas concentration (boiler exit) (mg/m³)</th>
<th>Cleaned gas concentration (stack) (mg/m³)</th>
<th>Emission control system efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>10</td>
<td>10,000</td>
<td>0.03</td>
<td>&gt;99.9</td>
</tr>
<tr>
<td>HCl</td>
<td>10</td>
<td>150</td>
<td>6</td>
<td>96</td>
</tr>
<tr>
<td>SO₂</td>
<td>50</td>
<td>100</td>
<td>3</td>
<td>97</td>
</tr>
<tr>
<td>NOₓ</td>
<td>200</td>
<td>600</td>
<td>120</td>
<td>80</td>
</tr>
<tr>
<td>CO</td>
<td>50</td>
<td>10</td>
<td>10</td>
<td>N/A</td>
</tr>
<tr>
<td>Dioxins/furans (PCDD/F)*</td>
<td>0.1 (ng TEQ/m³)</td>
<td>2.5 (ng TEQ/m³)</td>
<td>0.05 (ng TEQ/m³)</td>
<td>98</td>
</tr>
</tbody>
</table>

* Toxicity of a mixture of dioxins and dioxin-like compounds is expressed by the toxic equivalent, TEQ
2.5.1. Emissions and their context in the SIDS paradigm

For the purpose of this thesis, an important point will have to be defined; it is the relativity of the different emissions that a proposed WtE plant could bring. In fact it is important to put SIDS into context. Some countries have only laws that govern certain aspects of pollution control such as transportation (Government of the Maldives 2013).

Taking the Maldives as an example, open burning is already taking place in landfills such as the one of Thilafushi (Peterson 2013). These uncontrolled practices are even worse for the environment. Harmful emissions are released without control, together with leachates and toxic ashes. In this regard, the implementation of a WtE plant will be able to tackle many challenges that small islands face. By implementing such projects, the practice of open burning will be stopped. The waste would be treated in a WtE plant having the necessary control measures to ensure safe emissions. This would definitively be a better alternative to business as usual.

Nevertheless one major hurdle for the development of such projects would be the capital costs and among it the costs relating to the treatment of flue gas. To help the financial model and also to help kick start the project, a new paradigm needs to be developed. This entails looking at certain high investment portions of the plant in a modular form. For example, the whole range of flue gas treatment could be added over time. This would help alleviate the financial model for starting the project. It could be argued that the emissions levels would not be comparable to emissions levels in Europe. But the truth is that it will still be better than business as usual that is open burning. (The business as usual scenario would be the uncontrolled emissions of toxic waste due to open burning in the landfills.) Over the course of the project, other waste treatment portion will be added so that emissions levels as compared to the stringent ones obtained in OECD countries are met.
Of course, this would also mean that there would be the release of a certain portion of toxic waste into the atmosphere. Looking at the in depth toxicity and the effects of the bioaccumulation of these compounds would be out of scope for this paper. One future work could be to look at the different portions of flue gas treatment that can be added over time and how the release of certain compounds bio accumulate into the fauna and flora.
2.6. Flue gas treatment technologies

This section will look into more details in the different types of technologies available for the treatment of flue gases. At this present time, there exists a variety of options to allow the gases released to be treated up to the standards.

The flue gas is considered to have two parts present that need to be treated. The physical part that contains solids which can be handled by bag filters, cyclones and other apparatus that make use of the weight of the particle and its size and the gaseous part. The latter contain harmful gases such as acid gases, oxides of nitrogen (NOx), dioxins and furans. They can be removed by a number of mechanisms such as adsorption, condensation or bio-filtration among others.

2.6.1. Particulate emission treatment

Particulate matter (PM) is made up of a complex mix of particularly small particles and liquid drops. It contains metals, organic compounds, dust particles and soil. It can also contain acids. The smaller particles having 10 micrometers or smaller in diameter have the most detrimental effect on the health as they are not trapped by the nose and the throat and get deposited directly into the lungs.

In general, there are five methods used for controlling particulate emissions:

1. Gravity separators
2. Inertial separators
3. Electrostatic precipitators
4. Fabric filters
5. Wet scrubbers
Each of them will be looked at briefly.

Gravity and inertial separators, including so-called “cyclones,” are dry, “no-moving parts” devices. They take advantage of the relatively high specific gravity of certain types of particulate matter, including fly ash, dust, cement particles, and organic solids. **Figure 21** shows a schematic of a gravity separator and an inertial separator.

![Figure 21 Gravity Separator](image)

**Figure 21 Gravity Separator (Flemish Region 2015) to the left and an Inertial Separator to the right (CFFET - Chemical, Forensic, Food & Environmental Technology 2009)**

Electrostatic precipitators like in **Figure 22** take advantage of the electrostatic charge on the surface of particles, either present from natural phenomena or induced.
Figure 22 Electrostatic precipitator (United States Environmental Protection Agency 2011)
Fabric filters as shown in Figure 23 make use of physical blocking and adsorption. Wet scrubbers make use of a liquid to entrap particulates, thus removing them from a gas stream.

Figure 23 Fabric filter (Flemish Region 2015) and Wet Scrubbers (University of Guelph 2015)
2.6.2. Gaseous Pollutant treatment processes

There are five methods in general use for removing gaseous pollutants from gas streams.

1. Adsorption

It is considered to be the most efficient technology for the removal of volatile organic compounds. Adsorption is the process whereby gaseous compounds get deposited on the surface of a solid. There is a shift of pollutants from the gas phase to the solid phase. Some solids offer a high surface area and have adsorptive capacity such as activated carbon.

The use of activated carbon is the most common product used with the highest porous capacity 1,000 to 1,500 m$^2$/gram. There are now other products and resins, silica gel, etc. available on the market. The used carbon can be reheated for re use but the ‘adsorptive capacity’ (Woodard & Curran 2005) decreases with use. The adsorbed pollutants will be burnt, resulting into CO$_2$, ash and water vapor. The ash will need to be disposed of.

A set up generally consists of cylindrical columns filled with carbon, and most of the times several are connected in series where the flue gas is directed through. This layout helps in maintenance by removing ‘used cylinders’.

2. Absorption

Dissolution summarizes fundamentally the process of absorption. A liquid is put into contact with the flue gas in a cylindrical tower where both the flows are opposite – liquid flows from the top and the gas inlet from the bottom and is forced to go up.

Absorption is a shift from air pollution control to liquid pollution control, thus it is not a final step in effluent treatment. Time of contact plays a major role for efficient reaction. Figure 24 shows a typical packed tower absorber.
3. Condensation

A decrease in temperature or an increase in pressure or a combination of both is necessary to condense a gas. This is the principle of the condensation step. Decrease in temperature is most commonly used in industry.

Condensers are often used as useful units for removing easily condensable gases like vapors of sulphuric acid. They are a useful step for protecting the equipment down the line. **Figure 25** shows some types of condensers for pollution control.
4. Incineration

As its name suggests, a high temperature is required for this type of flue gas treatment. It consists of a combustion chamber whereby the organic pollutants are converted to CO$_2$, water and ash. Heavy metals could be added to the ash and this can prove to be problematic.

The incineration step is mainly used for odor control, hydrocarbon reduction and destruction of volatile organic compounds VOCs. Catalytic oxidizers as compared to thermal oxidizers use catalysts, lower temperatures required and accelerate the rate of reaction.

5. Bio-filtration

Living materials such as plants and microorganisms are used to capture and destroy the pollutants. The contaminated air is mixed with a dilute concentration of biodegradable organic gases with a normal concentration of oxygen. Water addition for dissolution is supplied. The microorganisms then biodegrade the contaminants.
3. Methodology

3.1. Large scale - 100 ktpa

The model was used to assess the viability of a large scale plant namely one having a capacity of 100,000 t per annum.

The different components of the model would be:

- Waste composition and energy content as shown in Figure 26.
- **Part 1** - An incinerator with the corresponding efficiency
- **Part 2** - A conventional steam turbine installation
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price per t</td>
<td>$750.00</td>
</tr>
<tr>
<td>Capital cost of incinerator</td>
<td>$75,000,000.00</td>
</tr>
<tr>
<td>Boiler Operating cost</td>
<td>$0.028/kWh</td>
</tr>
<tr>
<td>Total Boiler operating cost</td>
<td>$2,357,165.07</td>
</tr>
<tr>
<td>Total Cost of labor</td>
<td>$1,767,873.80</td>
</tr>
<tr>
<td>Hours of operation/hr</td>
<td>7008</td>
</tr>
<tr>
<td>Total operating cost</td>
<td>$4,125,038.87</td>
</tr>
<tr>
<td>Operating costs $/kWh</td>
<td>$0.014/kWh</td>
</tr>
<tr>
<td>Total Energy out of incinerator / kWh</td>
<td>255,104,444.44</td>
</tr>
<tr>
<td>Energy input / kWh</td>
<td>318,880,555.56</td>
</tr>
<tr>
<td>Total Energy out of ORC / kWh</td>
<td>84,184,466.67</td>
</tr>
<tr>
<td>Scale of plant tpa</td>
<td>100,000.00</td>
</tr>
<tr>
<td>Capacity of steam turbine unit kW</td>
<td>12,012.62</td>
</tr>
<tr>
<td>Hourly rate kg/hr</td>
<td>14,269.41</td>
</tr>
<tr>
<td>Eff</td>
<td>80%</td>
</tr>
<tr>
<td>Revenues from gate fee pa</td>
<td>$10,000,000.00</td>
</tr>
<tr>
<td>Revenues per year</td>
<td>$21,214,485.60</td>
</tr>
<tr>
<td>Discounted revenues over lifetime of project</td>
<td>$119,390,189.11</td>
</tr>
<tr>
<td>Excess air required</td>
<td>1.5</td>
</tr>
<tr>
<td>Air required kg/kg of Waste</td>
<td>6.030434937</td>
</tr>
<tr>
<td>Hourly rate kg/hr</td>
<td>86,050.727</td>
</tr>
<tr>
<td>Flue gas out Nm3/kg</td>
<td>5.271396161</td>
</tr>
<tr>
<td>Volumetric flow rate m3/hr</td>
<td>70,245.49</td>
</tr>
<tr>
<td>Hourly rate Nm3/hr</td>
<td>75,219.69</td>
</tr>
</tbody>
</table>

The image contains a flowchart showing the energy extraction and steam generation systems. Part 1 – Energy Extraction is shown in Figure 26, and Part 2 – Energy Conversion unit – Steam is shown in Figure 27.
For this scale, data for costs and efficiencies were readily available from (World Bank 1999).

**Step 1 Composition and quantity of waste**

**Waste elemental composition**

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>Amount</th>
<th>Mass content g/kg of waste</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>300</td>
</tr>
<tr>
<td>H</td>
<td>4.3</td>
<td>43</td>
</tr>
<tr>
<td>S</td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>N</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>O</td>
<td>24</td>
<td>240</td>
</tr>
<tr>
<td>Cl</td>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td>H2O</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>Ash</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>total %</td>
<td>100</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 6 Elemental composition of the MSW waste resource - 100 ktpa scale

The equation for the lower calorific value of the waste can be obtained from the works of Hulgaard and Vehlow 2010.

\[
H_{low} (kJ/kg) = 348 \text{ C\%} + 939 \text{ H\%} + 105 \text{ S\%} + 63 \text{ N\%} - 108 \text{ O\%} - 24.5 \text{ H2O\%}
\]

<table>
<thead>
<tr>
<th>Hlow</th>
<th>kJ/kg</th>
<th>Total /tpa</th>
<th>kWh/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>11479.7</td>
<td></td>
<td>100,000.00</td>
<td></td>
</tr>
<tr>
<td>11.4797</td>
<td>MJ/kg</td>
<td>318,880,555.56</td>
<td></td>
</tr>
<tr>
<td>3188.8</td>
<td>KWh/t</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7 Lower calorific value of the waste resource - 100 Ktpa
According to Hulgaard and Vehlow 2010, this is the typical municipal solid waste elemental composition that can be obtained in OECD countries. From this composition and the empirical equation above the lower calorific value of the waste can be calculated. Furthermore the mass content (g/kg of waste) is also calculated. Using the total amount of waste obtained per year, the total theoretical amount of energy that can be extracted is obtained.
Step 2 Incinerator calculations

This is the part that concerns the incinerator. With the efficiency set at 80 % - this is the standard efficiency for larger incinerators (Ricaud 2011) – the total energy output can be obtained.

Total Energy output = 80% * 318,880,555.56 kWh/year = 255,104,444.44 kWh/ year
Several other components are calculated here namely

- the hourly rate,

Hourly rate = Capacity Factor * 365 * 24hrs

Capacity factor is defined as percentage value of the year during which the plant would be operational. We have chosen a capacity factor of 80% for the model, thus allowing also a time for shut down and maintenance.

- the gate fee revenues

Gate fee revenues = Gate fees * Total amount of waste per year = $100 / t * 100,000 tpa = $10,000,000.00

- the flue gas flow rate

The flue gas flow rate calculations are shown in the appendix.

- the amount of air required for combustion when in excess of 50%

Costs are also calculated.

- The total cost of the incinerator is taken as a whole. Here an indicative price of $750 per tonnes of waste for both the incinerator and the steam turbine unit is used (World Bank 1999)

- The total operating cost of the boiler is obtained by adding the total cost of labour and the maintenance cost.

The boiler operating cost and the cost of labor $/kWh have been obtained from (Darrow et al. 2015)
Using the efficiency of the steam turbine unit, the theoretical amount of energy extracted from the waste resource per year can be calculated. The revenue stream from the sale of electricity can be obtained.

- **Energy generated by the steam turbine** = 33% * 255,104,444.44 kWh/yr = 84,184,466.67 kWh/yr
- Revenues from electricity sale = 84,184,466.67 kWh/yr * Price of electricity * (100 \% - Parasitic loads)
- Parasitic loads are considered to be the loads that are required just for running the plant. A 10 \% estimate was used.
- A price of electricity of 0.35$\$/kWh was used. This is the electricity price prevailing in the Maldives.

The capacity of the unit is obtained by dividing the total amount of energy per year by the total hours of operation per year.

Capacity of turbine = \frac{84,184,466.67 \text{ kWh}}{7008 \text{ hrs of operation per year}} = 12,012.62 \text{ kW}
**Summary of the plant – Financial parameters**

<table>
<thead>
<tr>
<th>Capacity factor</th>
<th>Gate fee $/t</th>
<th>Price of electricity $/kWh</th>
<th>Parasitic loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>80%</td>
<td>$50.00</td>
<td>0.35</td>
<td>10%</td>
</tr>
</tbody>
</table>

**Figure 29 Financial summary of the plant - 100ktpa scale**

Figure 29 gives the financial summary of the plant. The yellow cells are the ones that can be modified. Therefore the capacity factor, the gate fees, the price of electricity, the parasitic loads, the different interest rates and the lifetime of the project can be changed. The PWF stands for the Present Worth Factor.

Important parameters that the model calculates is the simple payback period, the levelized cost of electricity and the net present value of the project. The equations for obtaining these values are found on section 4.5, Performance of the model.
This financial summary of course can only give a partial result for the overall viability of a large scale WtE plant. Besides the purpose of this paper was to look into details into smaller scales. This has been done in the next sections.

From the results screen, it can be shown that a large scale plant would be financially viable. This is due to the high electricity prices prevailing in the Maldives. Furthermore this shows us that large scale plants are more financially viable that smaller ones. Providing this amount of waste for handling the power system would not be feasible in many SIDS, due to the lower amount of waste being generated.
3.2. Medium scale – 10k tpa

The energy content of the waste and the total amount of energy that could be extracted is calculated as in section 3.1 Large scale - 100 ktpa

The costs data for this plant were obtained from a supplier specializing in small scale gasifiers called Sierra Energy. Their gasifier together with their electrical plant costs approximately AUS $10.8 million. Unfortunately the treatment costs were not obtained and an indicative price of $1 million was used (Regenerate Industries 2015).

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>Amount</th>
<th>Mass content g/kg of waste</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>300</td>
</tr>
<tr>
<td>H</td>
<td>4.3</td>
<td>43</td>
</tr>
<tr>
<td>S</td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>N</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>O</td>
<td>24</td>
<td>240</td>
</tr>
<tr>
<td>Cl</td>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td>H2O</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>Ash</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>total %</td>
<td>100</td>
<td>1000</td>
</tr>
</tbody>
</table>

From $H_{low} (kJ/kg) = 348 C% + 939 H% + 105 S% + 63 N% - 108 O% - 24.5 H2O%$

| Hiow | 11479.7 | Total /tpa 10,000.00 |
|      | 11.4797 Mj/kg | Total energy available kWh/year 31,888,055.56 |
|      | 3188.8 Kwh/t | |

Figure 30 Energy content from the waste - 10,000 tpa scale
3.3. Components of the model for smaller scales

The literature review above has provided useful information on the choices that were available for conventional WtE plants.

Concerning the energy recovery part, we have found that some technologies favor smaller scales such as gasification. However this would not be practical in this case. Even if higher efficiencies could be reached, higher operation and maintenance costs would be required (Quoilin et al. 2013). In addition gasification would require a fuel with specific conditions such as moisture and...
composition. As the waste will be mainly unsorted and manually fed, this would add to the complexity of the overall project.

On the other hand, a conventional small incinerator would be able to burn the waste collected without too much problems. The smaller scale would prove to be challenging but this has been done in the past. There are already small scale incinerators available nowadays. For the purpose of the thesis the prototype built by Practical In Action will be used as basis as it can handle lower flow rates.

On the energy generation side, the conventional steam Rankine cycle would not be possible. The smaller scale and the high investment costs and operating costs required for these installations would be the main challenges. In addition, further auxiliary equipment and plant requirement for water treatment would also be mandatory. The Organic Rankine Cycle on the other hand would provide a solution to this problem. The latter can be used for lower capacities and now they come fully automated. This would reduce the need for specialized personnel on site.

Treatment of flue gases plays a major part in the dynamics of a WtE plant. Thus a dry flue gas treatment system will be investigated with the following

- injection of sodium bicarbonate for the neutralization of acid gases,
- the use of activated carbon filters (or injection of activated carbon) for removal of heavy metals, dioxins and furans, VOCs etc (SO2 to some extent)
- and the use of bag filters for the removal of particulate matter.

Furthermore solid residue resulting from the incineration process and the flue gas treatment will be incorporated so as to have a cost estimated as well. The following Case Study of the Maldives will illustrate the different parts of the model.
In summary, the small scale model will have the following component;

- Small scale incinerator
- ORC unit for energy generation
- Dry flue gas system
4. Case Study

4.1. The Maldives

4.1.1. Geographical location

The Maldives are a set of islands found south of India in the Indian Ocean having a land area of 298 km$^2$ and a coast line of 644 km. It was a British protectorate in 1887 and became a republic in 1968. The Maldives enjoy a hot humid tropical climate, with a dry monsoon season from November to March and a rainy season from June to August. The estimated population in 2014 was around 393,595.

Tourism is the main economic activity of the island and it contributes to 30% of the GDP and 60% of foreign exchange receipts. The Maldives are facing the long term challenge of soil
erosion as 80% of its land area is found 1 m above sea level. It relies heavily on fossil fuels for
the generation of its electricity (CIA - Central Intelligence Agency 2013).
4.1.2. Energy Sector

The Maldives does not have any conventional sources of energy like oil and gas for supplying its energy needs. Petroleum fuels such as diesel fuel oil are used for generating electricity by the state owned power utility STELCO and some 1000 electrical generators disseminated in the other islands.

Water desalination for the production of potable water is practiced and together with steam generation take a toll on the overall energy consumption of the country. Biomass has been used as fuel for cooking and domestic purposes in the outer islands but recently this trend has shifted to kerosene or liquefied petroleum gas (LPG). Besides the imported petroleum products also provide for the whole transportation system of the country (SARI/EI - South Asia Regional Initiative for Energy Intergration 2008). Table 8 extracted from the South Asia Regional Initiative for Energy Intergration website gives a summary of energy usage in the Maldives.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Uses</th>
<th>Energy, Mtoe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene</td>
<td>Lighting and cooking</td>
<td>5,070</td>
</tr>
<tr>
<td>LPG</td>
<td>Cooking, Industrial metal works</td>
<td>630</td>
</tr>
<tr>
<td>Diesel</td>
<td>Land and water (domestic and international) transport, industrial operations, and electricity generation</td>
<td>117,998</td>
</tr>
<tr>
<td>Gasoline</td>
<td>Land and water transport</td>
<td>8,979</td>
</tr>
<tr>
<td>Aviation Fuel</td>
<td>Air transport (domestic &amp; international)</td>
<td>5,353</td>
</tr>
</tbody>
</table>

Table 8 Energy use in the Maldives - extracted from SARI/EI (2008)
4.1.3. Municipal solid waste in the Maldives

The topography of the Maldives makes it a unique challenge for developing proper SWM practices. The islands are separated by lagoons or the sea, some can be near or others km apart. Burying waste into the ground, free dumping into the sea, or open burning are frequently practiced. This has cause major degradation of land and water resources. The lack of proper waste management strategies has been a major factor in the degradation of the land in the Maldives (Government of the Maldives 2013).

SWM is also closely linked to the coastal degradation and the destruction of the fragile marine ecosystem that exists in this pristine environment. In addition some islands are densely populated and here lies the other challenge of the protection of human health and safety (Government of the Maldives 2013).

Studies have been performed to estimate the characteristics of the MSW obtained in the Maldives. (Peterson 2013) summarised the following information on MSW;

- 860 tonnes are generated per day with an annual average of 312,075 tonnes per year
- The tourism sector contributes to 21% of the total amount of waste
- The Safari vessels –which consist of 157 boats providing transport and tourist activities around the atolls generate 8 tonnes of MSW on average per day. 67% of their waste is of food origin.

Table 9 gives a summary of the amount of wastes generated from the different portions that populate the islands.
A direct correlation among income and population area was observed, the higher the income level the higher the generation of wastes. Furthermore, the waste generated is expected to rise to 513 t/day in 2025 with an increase in population from 70,816 in 2012 to 411,000 in 2025 (World Bank 2012).

Waste generation per day figures obtained from other sources like the Ministry of Environment - Government of Japan (2015) correlates with the figures of Peterson (2013). They will be used for the purpose of the model:

- In Male’ average 2.8 kg per capita per day –
- In the atolls around 0.66 kg per capita per day –
- Tourism Industry stands at 7.2 kg per guest per day

Seasonal variations have also been observed. From October to April the amount of waste generated per day can increase to 205 t and drop to 160 t per day for non-peak seasons. This is explained by the increase in tourists’ arrivals. This will not be accounted for in the model.
4.1.4. Estimating the average composition of the waste in the Maldives

The composition of the waste is very important as it provides the basis for the design of the small scale WtE plant. (Peterson 2013) has already started characterizing the components present in the waste streams as shown in Table 10.

<table>
<thead>
<tr>
<th>Component</th>
<th>Island Communities</th>
<th>Resorts</th>
<th>Safari Vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food, Garden/Yard Wastes, and Paper Products</td>
<td>70%</td>
<td>80%</td>
<td>67%</td>
</tr>
<tr>
<td>Recyclables - Metals / Plastics</td>
<td>3%</td>
<td>5%</td>
<td>9%</td>
</tr>
<tr>
<td>Residuals</td>
<td>27%</td>
<td>15%</td>
<td>24%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

It can be observed that a high organic fraction as from around 70%, a high residual composition from 15% to 27% and a low percentage of recyclables are the main characteristics of the MSW present in the Maldives. We refer to residuals as construction debris, concrete, glass and miscellaneous components such as batteries and leather.

Obtaining precise data was more difficult. Fortunately, more detailed compositions extracted from a Waste Audit that was carried out in Gili Lankanfushi Maldives Resort was found. The results are shown in Table 11.
Having chosen the composition, the viability of the waste as a combustible material had to be verified. The Tanner diagram is a useful chart that can help identify potential combustible material. Thus according to Figure 33 it can be deduced that the waste could still be used in an incinerator. Even if its calorific value would be low due to the high moisture content.

<table>
<thead>
<tr>
<th>Total weight per year/ kg</th>
<th>Percentage , %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Food waste</strong></td>
<td>191,433.96 72.73</td>
</tr>
<tr>
<td><strong>Plastic / Polyethylene waste</strong></td>
<td>6120.8 2.32</td>
</tr>
<tr>
<td><strong>Paper and Cardboard</strong></td>
<td>10329.07 3.92</td>
</tr>
<tr>
<td><strong>Glass</strong></td>
<td>18743.05 7.12</td>
</tr>
<tr>
<td><strong>Aluminium</strong></td>
<td>4582.16 1.74</td>
</tr>
<tr>
<td><strong>Hazardous wastes</strong></td>
<td>106.1 0.04</td>
</tr>
<tr>
<td><strong>Unsorted wastes</strong></td>
<td>31886.4 12.11</td>
</tr>
</tbody>
</table>

A target of at least 7 MJ/wet kg is required to enable incineration viable (Komilis, Kissas, and Symeonidis 2014). Thus for the purpose of the model, the worst case scenario in terms of the composition of waste would be one having a very low calorific value with high moisture content.

It is worth noting that even though the composition of the waste was obtained, the chemical composition (on which the model bases itself) of the MSW in the Maldives could not be
assessed. One future work would be to have precise chemical analyses be made on the MSW to determine its chemical composition. In the meantime, the chemical composition available in textbooks has been used. This corresponds to MSW that can be obtained in OECD countries.
4.1.5. Current practices for the treatment of solid waste in the Maldives

There are at present three landfill sites, north at Kulhudhufushi, central at Thilafushi and south at Hithadhoo (Government of the Maldives 2013). The facility of Kulhudhufushi in the north is not working properly as it has been implemented on a populated island as the inhabitants do not accept the waste from the other islands to their landfills, arguing that “your garbage is not in my backyard”.

For disposing the increasing amount of waste generated from Male, the capital and the surrounding islands, Thilafushi the central landfill is used. It is a reclaimed island and was created around 2 decades ago. Point to be noted though, the landfill at Thilafushi is not an engineered landfill and has a life expectancy of 80 years (Government of the Maldives 2013). Open fires are common practice to reduce the waste collected. This leads to the creation of toxic wastes released directly into the atmosphere (Siraj 2013). Figure 34 shows a schematic of the current practices of SWM in the Maldives.
There is a transport system in place for moving the waste from Male to Thilafushi. It is made up of three barges making two crossings per day. Each can carry tipping trucks having a capacity of 15 tonnes. No fee is charged to the customer for this transport. The waste producers voluntarily transport the waste from the point of generation to the transfer station (Government of the Maldives 2013).

There are no proper solid waste management framework for the other inhabited islands. The island forests are used as dumping grounds and the open burning practices are common. This allows leachates to penetrate into the lagoon system, greatly disrupting the ecosystem (Government of the Maldives 2013).

The infrastructure is non-existent for the collection of the waste in many islands. The Indian Ocean Tsunami in 2004 further confirmed this fact. This was a wakeup call for the government to act and a clean-up programme was set up. Islands Waste Management Centres were also built on the islands that were most severely impacted by the tsunami (Government of the Maldives 2013).
Waste disposal is more regulated for the tourists’ resorts. There is a regulation “Regulation on Disposal of Garbage” already in place. The latter requires that all resorts burn their combustible waste and plastic bags with on incinerators. Cans and bottles have to be crushed. Ideally only processed recyclable waste and non-combustible waste can be removed from the waste stream to be disposed elsewhere. In reality the mixed solid waste are most of the time transported on resort dhonis that travel between Male and Thilafushi. There is a cost of unloading the waste that has to be accounted for, obtained by the amount of time it has to wait at the unloading platform (Government of the Maldives 2013).

Moreover the current arrangements for the collection of the waste are inadequate. In many cases plastics are just dumped near the beach and there have been cases where unconsolidated wastes were entering the lagoon systems. Some islands still practice open burning (Ministry of Environment - Government of Japan 2015).
4.1.6. Location on the atolls of the project

The case study was selected to be near an agglomeration of several hotels. This could mean that one of the hotels could be used for installing the plant. Thus the supply of electricity and
the transport fees would be secured. Furthermore, it would encourage the resorts to send their waste to the WtE plant instead of the landfill.

The following hotels together with their rooms’ space availability have been chosen as shown in Table 12. From (Peterson 2013) we have chosen a fixed generation of solid waste per day of 7.2 kg per person. In addition to this we have also assumed that the hotels would be full for the whole year. These are parameters that could be changed afterwards in the excel model.

Table 12 Room availability and scale of plant

<table>
<thead>
<tr>
<th>Resort</th>
<th># of rooms</th>
<th># persons per room</th>
<th>Solid waste generated per person kg/day</th>
<th>% usable days per year</th>
<th>days per year</th>
<th>Total amount of waste, kg/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baros</td>
<td>75</td>
<td>3</td>
<td>7.2</td>
<td>100%</td>
<td>365</td>
<td>591,300.00</td>
</tr>
<tr>
<td>Four Seasons Resort at Kuda Huraa</td>
<td>96</td>
<td>3</td>
<td>7.2</td>
<td>100%</td>
<td>365</td>
<td>756,864.00</td>
</tr>
<tr>
<td>Taj Exotica Resort &amp; Spa</td>
<td>64</td>
<td>3</td>
<td>7.2</td>
<td>100%</td>
<td>365</td>
<td>504,576.00</td>
</tr>
<tr>
<td>Velassaru Maldives</td>
<td>129</td>
<td>3</td>
<td>7.2</td>
<td>100%</td>
<td>365</td>
<td>1,017,036.00</td>
</tr>
<tr>
<td>Centara Grand Island Resort &amp; Spa Maldives</td>
<td>112</td>
<td>3</td>
<td>7.2</td>
<td>100%</td>
<td>365</td>
<td>883,008.00</td>
</tr>
<tr>
<td>LUX Maldives</td>
<td>193</td>
<td>3</td>
<td>7.2</td>
<td>100%</td>
<td>365</td>
<td>1,521,612.00</td>
</tr>
</tbody>
</table>

Total 5,274,396.00

Three persons per rooms were chosen, being an average between couples and a family of 4.

The total amount of solid waste generated per person has been obtained from the works of (Peterson 2013). Consequently for the basis of the model, a capacity of 5274 t per year would be investigated.
4.2. Design – WtE plant in the Maldives

The following sections will provide design details of the individual components of the model used for the case study.

4.2.1. Incinerator

As seen in the sections above, the data for small scale incinerators is quite scarce. Large scale counterparts are more frequent. Fortunately, works have been carried out in this sector. One particular project was performed by a Non-Governmental Organization based in the United Kingdom called Practical in Action.

They worked on a small scale prototype incinerator for MSW. A minimum of sorting of the waste would be required so as to remove glass, metal and batteries that could further complicate the flue gas treatment process. The incinerator would be manually fed and this would remove the complexity of having moving grates that would increase the capital costs.

Some parameters of the incinerator plant are found below;

- Throughput of 400kg/hr of MSW
- Construction materials required;
  - Refractory brick and refractory cement and iron for making the necessary structure – iron bars, steel sheets
- Removal of the ash has to be done manually. Care must be taken to prevent excessive air ingress.

Starting up the incinerator has to be performed by biomass available locally. This could also be a means of controlling the combustion of the MSW which has a high humidity content. Furthermore the incinerator could work with waste having a calorific value of 7000 – 9000 kJ/kg
(Intermediate Technology Consultants 2015). The detailed plans of the incinerator can be found in the appendix.

In general large scale incinerators have high thermal efficiencies which can easily reach 85% (Ricaud 2011). Being conservative, we have chosen a thermal efficiency of 70% as a smaller scale incinerator would be less efficient.

4.2.2. Organic Rankine Cycle for energy recovery

Due to the complexity and costs required for installing a steam turbine unit, the ORC system will be chosen. It works best at smaller scales and can come in packages fully automated. This would help in reducing the complexity of the project. Too much detail has not been used into this section. We would assume that the ORC will be connected to the flue gas conducts for generating electricity. The unit will be treated as a ‘black box’ with a set efficiency of 14%.

4.2.3. Flue gas treatment

A dry flue gas treatment system will be used. It will consist of the following components;

- Addition of Sodium Bicarbonate pellets for neutralization of acid gases
- Activated carbon for removal of
  - Heavy metal
  - Dioxins and furans
  - SO2 and HCL
- Bag filter for removal of particulate matter
4.2.4. Refuse Derived fuel (RDF) plant

The high calorific portion of processed MSW is defined to be Refuse Derived Fuel (RDF) (Gendebien et al. 2003). RDF is basically processing the MSW to improve its characteristics as a fuel. The processes that can be applied to MSW are listed below;

- Mechanical Biological pre - treatment (MBT) is the least expensive and most common technologies used to produce RDF.
  - Metals and inerts are removed
  - Organic fractions are selected for composting – with or without a digestion phase
  - Selects high calorific values for RDF
  - A ‘dry stabilization process’ where separated waste is dried out (by composting processes) to give a product of higher calorific value

RDF is successful in Europe with source separation and recycling already in place like Germany, Austria and the Netherlands. The non-recyclable high calorific waste obtained is suitable for RDF. In 2003 total amount of RDF used in the EU was 3 million tons. It has mainly been used for co combustion in EU such as in cement plants.

As a rule of thumb according to Gendebien et al. (2003), with low incineration costs, implementing MBT will depend greatly whether the RDF it produces can be used at low costs. But even with a well-established source separation and high incineration costs, MBT is still viable.

Furthermore even if costs of making RDF are high, when burnt more efficiently in incinerators (dedicated) the higher calorific value can ‘pay for’ (Gendebien et al. 2003) the prior processes.

Thus an RDF facility can provide fuel with more constant characteristics and also enable other energy recovery options such as gasification and pyrolysis. On the other hand, it will also reduce
higher recycling rates as most of the streams present in the waste will be used as fuel. For the purpose of the work, the detailed design of an RDF plant would be out of scope. Instead, a cost approximation could be added to reflect the processing done to the waste resource to increase its calorific value.

4.3. Economics – Wte plant in the Maldives

The next sections will illustrate the methods used for estimating the costs of the different components of the model. As data was not readily available, in most cases, costs from the past had to be used and discounted to today’s dollars. Furthermore in some cases like for the incinerator, simple costs functions were obtained.

4.3.1. Incinerator

There are several factors that influence the costs of an incinerator such as plant design, the capacity of the plant, the policies already in place, the boundaries for the disposal of the waste and the uses of the energy generated (Stubenvoll, Bohmer, and Szednyj 2002).

The incinerator that will be used would follow the plans from a prototype that was built in the Non-Governmental Organization, Practical in Action. Some of the plans used are found in the appendix.

They have built a low cost incinerator for 20,000 pounds sterling, around $44,056.96. The plans are shown below. This cost was for a rate of 400 kg/hr of MSW fed. A simple extrapolation was obtained for estimating the capital costs of a small scale incinerator. This is shown in Figure 36.
From Figure 36 we have estimated the price of the incinerator to be $87,912.09 by taking a MSW flow rate of 800 kg/hr.

4.3.2. Auxiliary equipment

In large boilers, auxiliary equipment are used to control the different flows of air and water. The air circuit would consist of fans, dampers and equipment to collect dust. On the other hand the steam circuit would contain the necessary feed and water recirculation pumps, the numerous valves and the soot blowers (Rayaprolu 2009). For this model we will be focusing on forced draft, the secondary and the induced draft fan.
Loh, Lyons, and White III (2002) have tried to put costs onto different equipment. The summary of the fan sizing is found in Table 13 below.

<table>
<thead>
<tr>
<th>GPM</th>
<th>Purchased costs US$</th>
<th>Installed cost US$</th>
<th>Flow rate m3/hr</th>
<th>Purchased costs $</th>
<th>Installed cost $</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>$1,100.00</td>
<td>$7,000.00</td>
<td>0.16</td>
<td>$1,907.40</td>
<td>$12,138.00</td>
</tr>
<tr>
<td>1500</td>
<td>$1,100.00</td>
<td>$7,400.00</td>
<td>345.00</td>
<td>$1,907.40</td>
<td>$12,831.60</td>
</tr>
<tr>
<td>5000</td>
<td>$1,800.00</td>
<td>$9,800.00</td>
<td>1,150.00</td>
<td>$3,121.20</td>
<td>$16,993.20</td>
</tr>
<tr>
<td>10000</td>
<td>$2,500.00</td>
<td>$13,100.00</td>
<td>2,300.00</td>
<td>$4,335.00</td>
<td>$22,715.40</td>
</tr>
<tr>
<td>25000</td>
<td>$6,700.00</td>
<td>$27,900.00</td>
<td>5,750.00</td>
<td>$11,617.80</td>
<td>$48,378.60</td>
</tr>
<tr>
<td>50000</td>
<td>$13,300.00</td>
<td>$49,900.00</td>
<td>11,500.00</td>
<td>$23,062.20</td>
<td>$86,526.60</td>
</tr>
<tr>
<td>75000</td>
<td>$19,900.00</td>
<td>$64,900.00</td>
<td>17,250.00</td>
<td>$34,506.60</td>
<td>$112,536.60</td>
</tr>
<tr>
<td>100000</td>
<td>$31,400.00</td>
<td>$93,400.00</td>
<td>23,000.00</td>
<td>$54,447.60</td>
<td>$161,955.60</td>
</tr>
<tr>
<td>150000</td>
<td>$44,600.00</td>
<td>$126,500.00</td>
<td>34,500.00</td>
<td>$77,336.40</td>
<td>$219,351.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conversion rate</th>
<th>1.734 US$/AUS$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A correlation for the costs of the secondary, and forced draft and the induced draft fan was obtained. GPM stands for gallons per minute</td>
<td></td>
</tr>
</tbody>
</table>
| As the mass balances of the flue gases were already calculated in the previous section, the cost of the different fans could be estimated.
Thus the estimated costs for the secondary and forced draft fan were $24,684.73 respectively and $26,432.70 for the induced draft fan.

Using the consumer price index from the Australian Bureau of Statistics, the 2002 prices were brought to the present day. The secondary and forced draft fan amounted to $34,642.40 and the induced draft fan to $37,095.49. For simplicity the costs were rounded to the nearest thousand.
4.3.3. Organic Rankine Cycle

According to Rettig et al. (2011) the following curve shown in Figure 38 has been developed to estimate the cost of ORC turbines.

![Figure 38 Estimated costs of ORC turbines with capacity (Rettig et al. 2011)](image)

Actual prices for ORC turbines were not easily obtained. According to Ocean Ethanol (2010), a company that offers services for the installation of ORC turbines among others, the cost of a typical 225kW turbine with flow rate of 300 gallons per minute (68.1 m³/hr) was US $600,000. This equals to AU $3700 per kW. Another company, gTET which specializes in the design and operation of ORC units for increased energy efficiency, a price of AU $2900 / kW (gTET 2014). A price of AU $3,300 /kW (the average of the two) will be used.
4.3.4. Flue gas treatment

The following section deals with the costs of the different portion of the dry flue gas set up. For the model, some compounds responsible for the formation of acid gases such as HCl and HF were assumed to be present in the ash content. Furthermore, their concentrations in the final flue gas was estimated from literature.

**Capital and maintenance costs of the sodium bicarbonate injection system and the activated carbon beds.**

Several of the costs estimates were obtained from (Stubenvoll, Bohmer, and Szednyj 2002). From their report they were able to summarize the costs involved for the setting up of a dry flue gas treatment system consisting of calcium oxide injection and activated carbon treatment. The summary is shown in Table 14.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Throughput per line</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>75,000 t yr⁻¹</td>
</tr>
<tr>
<td><strong>Consumption of electricity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific consumption</td>
<td>kWh t⁻¹</td>
<td>13</td>
</tr>
<tr>
<td>Specific costs of energy consumption</td>
<td>€ t⁻¹</td>
<td>0.33</td>
</tr>
<tr>
<td><strong>CaO-consumption incl. waste disposal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific consumption</td>
<td>kg t⁻¹</td>
<td>14.44</td>
</tr>
<tr>
<td>Stoichiometric factor</td>
<td></td>
<td>1.50</td>
</tr>
<tr>
<td>Specific costs for adsorption</td>
<td>€ t⁻¹</td>
<td>4.50</td>
</tr>
<tr>
<td><strong>Activated coke consumption</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific consumption</td>
<td>kg t⁻¹</td>
<td>1.00</td>
</tr>
<tr>
<td>Specific costs of activated coke</td>
<td>€ t⁻¹</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Disposal costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific amount of accumulated waste</td>
<td>kg t⁻¹</td>
<td>28.50</td>
</tr>
<tr>
<td>Specific costs for waste disposal</td>
<td>€ t⁻¹</td>
<td>4.28</td>
</tr>
<tr>
<td><strong>Maintenance and wear</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Share of investment costs</td>
<td>%</td>
<td>1</td>
</tr>
<tr>
<td>Specific costs of maintenance</td>
<td>€ t⁻¹</td>
<td>0.23</td>
</tr>
<tr>
<td>Specific costs of filter wear</td>
<td>€ t⁻¹</td>
<td>0.78</td>
</tr>
<tr>
<td><strong>Investment costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific investment costs</td>
<td>€ t⁻¹</td>
<td>1,725,000</td>
</tr>
<tr>
<td>Rated specific overall costs</td>
<td>€ t⁻¹</td>
<td>12.78</td>
</tr>
</tbody>
</table>

Table 14 Costs involved for the installation and operation of dry flue gas system (Stubenvoll, Bohmer, and Szednyj 2002)
Thus for the basis of the model, the capital costs for sodium bicarbonate injection and the activated carbon bed will be taken together.

The prices in euros corresponds to the prices in 2002. To overcome this problem, the conversion rates between the euro and the Australian dollar was obtained during this period.

<table>
<thead>
<tr>
<th>Capital investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale / tpa</td>
</tr>
<tr>
<td>75000</td>
</tr>
<tr>
<td>100000</td>
</tr>
<tr>
<td>150000</td>
</tr>
</tbody>
</table>

The equivalent in Aus $ was obtained dated back in 2002. From (Australian Bureau of Statistics 2015), the equivalent dollar value date in June 2015 was obtained. Finally the specific investment costs were plotted against the scale of the plant to obtain an equation relating the two as shown in Figure 39.
The equation was used to calculate the specific investment of the endeavour. This amounted to $8.70 / t of waste to be treated. Therefore $8.70 / t \times 5274 t = $ 45,911.51

The same principle was followed to evaluate the operating and maintenance costs. The following results were obtained;

- The activated carbon consumption was estimated to be $0.73 /t of waste
- The operation and maintenance costs were evaluated to be $0.82 /t of waste

The detailed calculations can be obtained in the appendix section.

**Cost of the reagents for the removal of acid gases**

The amount of sodium bicarbonate required for neutralizing the acid gases has already been calculated above.

From the equations 52,727.71 kg per year would be required. Taking the costs of 1 ton of sodium bicarbonate to be $343, the cost of the reagent will be $18,454.70 per year.
Capital costs for the Non-catalytic flue gas cleaning (SNCR) system

Here again costs from (Stubenvoll, Bohmer, and Szednyj 2002) have been used for estimating the cost of Non-catalytic flue gas cleaning (SNCR).

Table 16 Costs involved for the installation and maintenance of a SNCR (Stubenvoll, Bohmer, and Szednyj 2002)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>75,000 t yr⁻¹</th>
<th>100,000 t yr⁻¹</th>
<th>150,000 t yr⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumption of electricity</td>
<td>kWh t⁻¹</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Specific costs of energy</td>
<td>€ t⁻¹</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>NH₃/OH consumption (as NH₃ solution 25 %)</td>
<td>kg t⁻¹</td>
<td>4.88</td>
<td>4.88</td>
<td>4.88</td>
</tr>
<tr>
<td>Specific costs</td>
<td>€ t⁻¹</td>
<td>0.73</td>
<td>0.73</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Maintenance and wear

- Share of investment costs % 2 2 2
- Investment costs € 700,000 800,000 1,000,000
- Specific investment costs € t⁻¹ 0.96 0.82 0.69
- Rated specific overall costs € t⁻¹ 1.92 1.76 1.59

Following the same principle, the specific investment costs were extracted from the table, plotted and brought to today’s dollar value.

Table 17 Specific investment costs for SNCR

<table>
<thead>
<tr>
<th>Scale / tpa</th>
<th>Capital investment</th>
<th>AUD / t in 2002</th>
<th>$ / t in 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>75000</td>
<td>0.96</td>
<td>1.665366081</td>
<td>2.3</td>
</tr>
<tr>
<td>100000</td>
<td>0.82</td>
<td>1.422500194</td>
<td>1.97</td>
</tr>
<tr>
<td>150000</td>
<td>0.69</td>
<td>1.19681871</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Changes in Specific investment costs of Non catalytic flue gas cleaning SNCR component with scale
Using the graph and substituting the scale of the plant in the equation, we obtain a specific investment cost of $4.74/ t.

Thus for a scale for a scale of 5,274.40 tpa, we would need an investment cost of $25,003.09.

The same principle is followed for the NH4OH consumption (as NH3 solutions 25%),

<table>
<thead>
<tr>
<th>Scale / tpa</th>
<th>eur/ t</th>
<th>AUD /t in 2002</th>
<th>$ /t in 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>75000</td>
<td>0.73</td>
<td>1.266372124</td>
<td>1.75</td>
</tr>
</tbody>
</table>

Thus the consumption costs = $ 1.75 /t

For the wear and tear,

<table>
<thead>
<tr>
<th>Scale / tpa</th>
<th>eur/ t</th>
<th>AUD /t in 2002</th>
<th>$ /t in 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>75000</td>
<td>0.19</td>
<td>0.329603704</td>
<td>0.45</td>
</tr>
<tr>
<td>100000</td>
<td>0.16</td>
<td>0.277561014</td>
<td>0.38</td>
</tr>
<tr>
<td>150000</td>
<td>0.13</td>
<td>0.225518324</td>
<td>0.31</td>
</tr>
</tbody>
</table>

The graph is plotted to give Figure 40.

From the graph, the specific maintenance costs of the SNCR is $0.97/ t. The total operation and maintenance costs = ($0.97/ t + $1.75/ t) * 5,274.40 tpa = $14,382.62

Capital cost for the bag filter component
Much of the information used for estimating the capital cost for the bag filter was taken from a company called Neundorfer, specializing in treatment of flue gas. They provided a template for the estimated costs of a reverse air baghouse but this was dated in 1986. The necessary conversions have been made to estimate the costs in present day Australian dollars.

We assumed an Air to cloth ratio of $2.5 : 1 \text{(ft}^3\text{/min}) / \text{ft}^2$.

Using a flow rate of flue gas of 3967.3 Nm$^3$/hr calculated from the simulation;

$$V_f = \frac{Q}{A_{nc}}$$

Where $V_f$ is the filtration velocity, ft/min, Q is process exhaust rate, acfm and $A_{nc}$ is net cloth area, ft$^2$

Solving for $A_{nc}$, $V_f = 2.5 \text{ ft/min and } Q = 3967.3 \times 0.589 = 2336.7 \text{ acfm (actual cubic feet per minute)}$

Total net area of cloth required = 934.7 Ft²

Using Table 20 below, we can convert the net area of cloth to obtain the gross area required.

<table>
<thead>
<tr>
<th>Net Cloth Area, $A_{nc}$ (ft$^2$)</th>
<th>Factor to Obtain Gross Cloth Area, $A_c$ (ft$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 4,000</td>
<td>Multiply by 2</td>
</tr>
<tr>
<td>4,001 - 12,000</td>
<td>Multiply by 1.5</td>
</tr>
<tr>
<td>12,001 - 24,000</td>
<td>Multiply by 1.25</td>
</tr>
<tr>
<td>24,001 - 36,000</td>
<td>Multiply by 1.17</td>
</tr>
<tr>
<td>36,001 - 48,000</td>
<td>Multiply by 1.125</td>
</tr>
<tr>
<td>48,001 - 60,000</td>
<td>Multiply by 1.11</td>
</tr>
<tr>
<td>60,001 - 72,000</td>
<td>Multiply by 1.10</td>
</tr>
<tr>
<td>72,001 - 84,000</td>
<td>Multiply by 1.05</td>
</tr>
<tr>
<td>84,001 - 96,000</td>
<td>Multiply by 1.06</td>
</tr>
<tr>
<td>96,001 - 108,000</td>
<td>Multiply by 1.07</td>
</tr>
<tr>
<td>108,001 - 132,000</td>
<td>Multiply by 1.06</td>
</tr>
<tr>
<td>132,001 - 160,000</td>
<td>Multiply by 1.05</td>
</tr>
</tbody>
</table>

Total gross area = 934.7 ft$^2 \times 2 = 1869.4$ ft$^2$
Figure 41 above gives the cost functions of the different components of the baghouse filter as a function of the cloth area. Substituting a cloth area of 1869.4 ft$^2$, we have the following results in Table 21.

![Figure 41](image)

<table>
<thead>
<tr>
<th>Insulation costs</th>
<th>Stainless steel add on</th>
<th>Base cost</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2,625.55</td>
<td>$23,482.90</td>
<td>$42,363.32</td>
<td>$68,471.77</td>
</tr>
</tbody>
</table>

Fiberglass bags for the reverse air baghouse with rings will be used. The cost is $0.99/ft$^2$.

Total bag costs = 0.99 * 1,869.43 = $1,850.74

According to (Neundorfer 1995), a template has been used for calculating the other component which will make up the total capital costs. All the details have been summarized in Table 22 below.
The total capital costs of the baghouse have been estimated to be US $205,673.82 for the year 1986.

Taking the exchange rate to be 1 US $ = 1.49 AUS $ in 1986 from (Reserve Bank of Australia 2015), this will correspond to AUS $306,976.03 in 1986.

Finally using the consumer price index calculator as above, $306,976.03 is equivalent to $743,241.44 in today’s dollars.
4.3.5. Solid Residues

The amount of solid residues from the combustion process can vary from 20% – 30% by mass of the original waste (Department for Environmental Food and Rural Affairs 2013). For the model, 25% by mass will be chosen.

The total amount of solid residues produced per year $25\% \times \text{Scale of the plant}$.

The cost associated to this will be $= \text{Mass of solid residue per year} \times \text{Gate fee}$
4.4. Revenues of the project

The major difference between WtE plants and conventional combustion energy generation units is how the fuel is regarded. Waste ‘has a negative price’ (World Energy Council 2013) which is correlated with gate fees. The latter together with the other by-products of the plants such as electricity and process heat are considered to be the main source of income for a WtE plant. As a rule of thumb the electricity generated can be considered as base load supply and it is given priority over other generation units (World Energy Council 2013).

Revenues from electricity sale is simply obtained by multiplying the total amount of energy that could be obtained within one year with the electricity sale price. An efficiency factor as a parasitic load is applied here. It is regarded as the total amount of energy that would be used by the plant itself. So if there is a parasitic load of 10%, 90% of the energy would be available for producing electricity.

From Figure 42 we will use an electricity tariff of 3.925 MRP/ kWh for simplicity, the average domestic tariffs from 2.20 MRP to 3.85 MRP with the surcharge of 0.9 MRP/kWh. This is equivalent to $ 0.35/ kWh.
Gate fees or tipping fees are basically fees that are applied to customers for the disposal of their waste (Waste Management 2015). They will make up for the other revenue stream of the plant. The gate fee used for the model is $50/ton of waste transported.
4.5. Performance of the model

The financial viability of the model will be assessed using the three tools below, the Levelized cost of electricity, the Simple Payback Period and the Net Present value of the project.

4.5.1. Levelized cost of electricity

Levelized cost of electricity (LCOE) is a way to measure the cost of the electricity generated. It takes into account all the costs of the system such as the capital costs, the operation and maintenance costs, insurance and incentives. This total is divided by the total amount of energy that would be generated within its lifetime. Adjustments for inflation and the necessary discounting is also performed to reflect the time value of money (RENEWABLE ENERGY ADVISORS 2015).

For the model,

\[
\text{LCOE} = \frac{\text{Capital costs of all the equipment} + \text{Discounted operational and maintenance costs}}{\text{total amount of energy generated over the lifetime of the project}}
\]

4.5.2. Simple payback period

It is defined as being the number of years that would be required to recover the initial investment of the project. It does not account for the time value of money (Jewell 2007).

\[
\text{Simple payback period} = \frac{\text{Total capital investment}}{\text{Net revenues per year}}
\]

4.5.3. Net Present Value

The Net Present Value (NPV) is a method in which all discounted inflows and outflows of cash are added together and subtracted from the cost of the initial investment. A positive NPV
indicates that the return on investment will be greater and thus it should be a project to be
looked upon further. A negative NPV indicates that the overall costs outweigh the revenues of
the project and it is not viable financially (Law 2014).

For the model

\[
NPV = \text{Total discounted revenues} - (\text{total discounted costs} + \text{initial investment})
\]

The total discounted revenues will include the total sales of electricity discounted over the
lifetime of the project and the gate fees also discounted. The total discounted costs will be
made up of the total operating and maintenance costs and costs of reagents discounted over
the lifetime of the project.
4.6. Results and Sensitivity Analysis

The different costs obtained from the previous sections were put into the model. The model is made up of three distinct parts. Recalling the three parts;

Part 1 - the **Energy Extraction** part which consists of the incinerator and the costs associated with it. The energy content previously calculated, the scale of the plant and the corresponding efficiency will give the total amount of energy that can be recovered per year. The efficiency of the incinerator can be altered to change its throughput.

Part 2 – the **Energy generation** part, which uses the energy left from the incineration process to generate electricity and the revenues from its sale. By specifying the cost per KW of the ORC capacity the investment costs can be changed.

Part 3 – the **Flue gas treatment and Solid Residue Disposal** which uses the total amount of flue gas generated by the incinerator to size the different flue gas treatment components. These have already been explained in the previous section.

Figure 44, Figure 45 and Figure 46 above give a better detailed view of the components.
Part 1 – Energy Extraction shown in Figure 44

Part 2 – Energy generation shown in Figure 45

Part 3 – Flue gas treatment and solid residue disposal shown in Figure 46
Figure 44: Energy Extraction - Incinerator

- Total
- Hour of Operation
- Cost of Labor $/hr

- Energy Input kWh
- Scale of Plan Mpa
- Hourly Heat Loss

- Total Cost of Labor
- Total Operating Cost

- Boiler Operating Cost
- Boiler Cost

- Heat Content of Waste
- Emission
- Energy

- Cycle Unit
- Organic Rankine - Generation
- Energy

- To Flue Gas Treatment
- To Solid Residues

- Energy Extraction - Incinerator

- First Cost Direct $35,000,000
- Second Cost Direct $35,000,000

- Volume of Low-Rank Ash
- Hourly Heat Loss
- All Required Kehg of Waste

- Excess All Required

- Revenue from Gate Fee $863,198.00
Figure 45: Energy generation - ORC unit

Energy Generation - Organic Rankine Cycle Unit

- Energy from extraction
- ORC unit
- Capital cost: $3,000.00
- Fuel: $2.30
- Efficiency: 30%
- Total energy out of ORC: 24.3 MW
- Fuel cost: $0.04
- Total energy in: 24.075 MW
- Operating costs: $2.30
- Revenue per year: $243,264.20
- Capacity of steam turbine: 20 MW
- Discounted revenue over lifetime: $544,262.5
Figure 46: Flue gas treatment and solid residue disposal.
Table: Plant Summary

<table>
<thead>
<tr>
<th>Plant Summary</th>
<th>Capacity tpa</th>
<th>Turbine capacity kW</th>
<th>Total number of years</th>
<th>PWF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5,274.40</td>
<td>235.20</td>
<td></td>
<td>5.63</td>
</tr>
</tbody>
</table>

Table: Operational and Maintenance costs

<table>
<thead>
<tr>
<th>Operational and Maintenance costs</th>
<th>Incinerator Op&amp;M costs</th>
<th>ORC Op&amp;M costs</th>
<th>Cost of NaHCO3</th>
<th>Cost of Activated carbon + maintenance cost</th>
<th>Cost of Baghouse filters</th>
<th>Selective Cat</th>
<th>Solid residue transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>per year</td>
<td>$ 80,764.95</td>
<td>$ 23,075.70</td>
<td>$ 18,454.70</td>
<td>$ 82,062.61</td>
<td>$ 20,064.00</td>
<td>$ 14,382.62</td>
<td>$ 76,478.74</td>
</tr>
<tr>
<td>Total</td>
<td>$ 103,840.65</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$ 211,442.67</td>
</tr>
<tr>
<td>Discounted costs over lifetime of project</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1,889,950.17</td>
</tr>
<tr>
<td>Total discounted costs over lifetime of project</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1,774,341.19</td>
</tr>
</tbody>
</table>

Table: Revenues

<table>
<thead>
<tr>
<th>Revenues</th>
<th>Gate fee</th>
<th>Electricity sale</th>
<th>Simple payback period /years</th>
<th>Levelized cost of electricity $/kWh</th>
<th>Net present value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ 263,719.80</td>
<td>$ 519,203.25</td>
<td>3.81751139</td>
<td>0.11</td>
<td>$ 846,547.59</td>
<td></td>
</tr>
</tbody>
</table>

Figure 47 Results Summary

Figure 47 gives a summary of all the costs of the project and the associated revenues. Finally, the three performance criteria of the model, the Simple payback period, the LCOE and the NPV are shown.
Contribution to Capital Cost

Table 23 is summarized in Figure 48. The ORC unit is the greatest contributor to the overall capital costs. Followed by the incinerator. On the flue gas treatment part, it can be observed that the Baghouse system is the greatest expense. This is probably due to the amount of data that was obtained. The information available for estimating the baghouse filter part was extensive as compared to the other flue gas treatment components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incinerator</td>
<td>$194,912.09</td>
</tr>
<tr>
<td>Orc Unit</td>
<td>$776,151.84</td>
</tr>
<tr>
<td>Activated carbon system + NaHCO3 system</td>
<td>$45,911.51</td>
</tr>
<tr>
<td>Baghouse system</td>
<td>$743,241.44</td>
</tr>
<tr>
<td>Selective cat removal</td>
<td>$25,003.09</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$1,785,219.98</strong></td>
</tr>
</tbody>
</table>

**CAPITAL COST CONTRIBUTION**

- Incinerator: 11%
- Orc Unit: 43%
- Activated carbon system + NaHCO3 system: 3%
- Baghouse system: 42%
- Selective cat removal: 1%

Figure 48 Capital Cost contribution chart
Sensitivity Analysis

A Sensitivity Analysis was performed on various inputs of the model. The main idea behind the Sensitivity Analysis is to see how sensitive the output of the model would be by changing certain parameters. This is especially important as some of the costs used were estimates.

Net Present Value Analysis

Changing Electricitiy prices and Gate Fees

Table 24 Sensitivity Analysis - Effect on NPV when changing electricity price and gate fees

<table>
<thead>
<tr>
<th>Electricity Price</th>
<th>NPV (in $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-75%  0.09</td>
<td>562,255.76</td>
</tr>
<tr>
<td>50%  0.18</td>
<td>786,724.53</td>
</tr>
<tr>
<td>25%  0.26</td>
<td>1,517,213.30</td>
</tr>
<tr>
<td>0%  0.35</td>
<td>2,247,702.07</td>
</tr>
<tr>
<td>25%  0.44</td>
<td>929,375.01</td>
</tr>
<tr>
<td>50%  0.53</td>
<td>2,149,548.78</td>
</tr>
<tr>
<td>75%  0.61</td>
<td>2,978,190.84</td>
</tr>
<tr>
<td>100%  0.70</td>
<td>3,807,833.90</td>
</tr>
</tbody>
</table>

Gate fees

<table>
<thead>
<tr>
<th>Gate fees</th>
<th>NPV (in $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-75%  12.50</td>
<td>2,135,210.55</td>
</tr>
<tr>
<td>50%  25.00</td>
<td>1,871,793.27</td>
</tr>
<tr>
<td>25%  37.50</td>
<td>1,608,356.00</td>
</tr>
<tr>
<td>0%  50.00</td>
<td>1,344,918.72</td>
</tr>
<tr>
<td>25%  62.50</td>
<td>1,081,481.44</td>
</tr>
<tr>
<td>50%  75.00</td>
<td>818,044.16</td>
</tr>
<tr>
<td>75%  87.50</td>
<td>554,606.89</td>
</tr>
<tr>
<td>100%  100.00</td>
<td>291,169.61</td>
</tr>
</tbody>
</table>

From Table 24, we can see that the project is already financially viable at a gate fee of $50. This is due to the high electricity prices prevailing in the Maldives. The model is more responsive to changes in electricity prices.
Simple Payback period Analysis

Changing Electricity prices and Gate fees.

Table 25: Sensitivity Analysis - Effect on Payback Period when changing electricity price and gate fees

<table>
<thead>
<tr>
<th>Gate fees</th>
<th>-75%</th>
<th>-50%</th>
<th>-25%</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>3.82</td>
<td>0.088</td>
<td>0.175</td>
<td>0.263</td>
<td>0.350</td>
<td>0.438</td>
<td>0.525</td>
<td>0.613</td>
</tr>
<tr>
<td>-75%</td>
<td>12.50</td>
<td>28.7</td>
<td>6.4</td>
<td>9.0</td>
<td>5.5</td>
<td>3.9</td>
<td>3.0</td>
<td>2.5</td>
</tr>
<tr>
<td>-50%</td>
<td>25.00</td>
<td>16.0</td>
<td>15.6</td>
<td>7.3</td>
<td>4.8</td>
<td>3.5</td>
<td>2.8</td>
<td>2.3</td>
</tr>
<tr>
<td>-25%</td>
<td>37.50</td>
<td>56.8</td>
<td>11.1</td>
<td>6.1</td>
<td>4.2</td>
<td>3.2</td>
<td>2.6</td>
<td>2.2</td>
</tr>
<tr>
<td>0%</td>
<td>50.00</td>
<td>22.8</td>
<td>8.6</td>
<td>5.3</td>
<td>3.8</td>
<td>3.0</td>
<td>2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>25%</td>
<td>62.50</td>
<td>14.3</td>
<td>7.0</td>
<td>6.6</td>
<td>3.5</td>
<td>2.8</td>
<td>2.3</td>
<td>2.0</td>
</tr>
<tr>
<td>50%</td>
<td>75.00</td>
<td>10.4</td>
<td>5.9</td>
<td>4.1</td>
<td>3.2</td>
<td>2.6</td>
<td>2.2</td>
<td>1.9</td>
</tr>
<tr>
<td>75%</td>
<td>87.50</td>
<td>8.2</td>
<td>5.1</td>
<td>3.7</td>
<td>2.9</td>
<td>2.4</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>100%</td>
<td>100.00</td>
<td>6.7</td>
<td>4.5</td>
<td>3.4</td>
<td>2.7</td>
<td>2.3</td>
<td>2.0</td>
<td>1.7</td>
</tr>
</tbody>
</table>

For the model, a target year of 5 years was chosen. At the electricity and gate fees prices the target Simple Payback Period (SPP) can be achieved. Of course, the SPP will even more decrease with increases with electricity price of gate fees. It can also be seen that the model is more sensitive to changes in electricity price than to changes in gate fees.
4.7. Additional Revenues

Additional revenues can be obtained through different organisations that fight against climate change. One of these organisms is the Clean Development Mechanism (CDM) under the United Nations Framework Convention on Climate Change-UNFCC.

Basically the CDM is a way for a project in developing countries to receive funding and earn certified emission reduction credits (CER). One CER is equivalent to one tonne of CO₂. Developed countries then trade these CERs to meet their emissions reduction objectives following the Kyoto Protocol. Thus sustainable projects are encouraged and increased flexibility for reducing emissions in developed countries is also available (United Nations Framework Convention on Climate Change-UNFCC 2015).

The CDM has been one of the major driving forces in developing MSW WtE plants. Current projects that have already been funded range from 260 k tpa to 400k tpa. The process of getting funds from the CDM is long and passes through several steps from the design of the project, the benchmarking - what would be the emissions levels without the implementation of the project and after its implementations among others. This is can be done by companies specializing in this endeavour. Other forms of revenues such as the one from the CDM can be obtained and can help in the financial viability of the project.
5. Conclusions

The main aim of this work was to perform a techno – economic study on the smallest Waste to Energy plant that could be financially viable in land scarce countries. The Maldives were used as case study to put this model into practice. First of all an agglomeration of hotels was chosen to estimate the total amount of waste that could be produced, collected and processed for generating electricity. Thus a scale of 5274 tpa was obtained. A small scale incinerator and an ORC unit with dry flue gas treatment components have been used in the simulation model. The capital costs and the operation and maintenance costs of the plant were estimated using interpolation and data from literature.

The incinerator was modelled using a prototype that was built by an NGO called Practical Action. The capital cost of the prototype was $44,056.96 and using the interpolation, the capital costs of the small scale incinerator of the model was estimated to be $87,912.09. The ORC unit was estimated to be $776,151.84 which is equivalent to $3,300.00 / kW for an ORC capacity of 235 kW. For the flue gas treatment the investment costs for the activated carbon unit, the baghouse unit and the selective catalytic removal were estimated to be $45,911.51, $743,241.44 and $25,003.09 respectively. The total operating costs and the revenues from the sale of electricity and gate fees were calculated and discounted over the lifetime of the project. With gate fees of $50/t of waste and electricity prices of 0.35 $/kWh, the model gave SPP of 3.8 years, LCOE of 11 cents and a NPV of $846,547.59.

From the initial calculations of the model, it can be deduced that the project is financially viable. Apart from the financial aspect though, small scale waste to energy plants can provide a solution for the growing amount of solid waste in the Maldives. The electricity generated by the plant would help in reducing the petroleum imports for the diesel generators. Furthermore, a small
scale WtE plant could also help in addressing the SWM practices in the atolls. As the practice now is to throw the waste into the ocean and to dump it into local landfills, the implementation of a WtE plant would be a better option as compared to ‘business as usual’. There are other benefits that would be created in terms of jobs, through the collection and transportation of the waste for example.

Moreover sensitivity analyses were also performed to assess the most sensitive inputs in the model. It was found that the price of electricity plays a major role for the success of the project, more than the gate fees. High electricity prices prevailing in the Maldives due to a high reliance on diesel imports for generating electricity are favourable for the implementation of the project. It should be noted however that this model has limitations which will be discussed in the next section of the paper and the results obtained can only be used as a guide for further study.
6. Limitations of the study

As the scope of the study was large there were limitations that were inherently present. These limitations are discussed below with suggestions for future study provided.

The boundaries of the project

As the setting up of an incineration plant is complex even at small scales, it was not feasible to delve into all the components that would be present in practice. These were left out of the project. One major example was the waste water generated at the plant, its treatment costs and how it would be treated. One way of reducing this factor was to use a dry flue gas treatment. Waste water will still be generated by the plant and this has not been accounted for.

Incinerator technology

The detailed fluid and combustion technology of an incinerator could not be used. This would be a project by itself due to its complexity. For the purpose of this paper, the incinerator has been treated as a black box with a certain low efficiency, taking energy in, flue gas with emissions and energy out with ash.

Toxicity limits

A detailed study need to be done for assessing the short term and long term effects of the different compounds that could be emitted by the plant. Only a comparison can be made between the status quo and the emission after the project.

Refused Derived Fuel Plant

The design of a RDF plant is in itself a whole project. In this work, we could only assess the relative merits of implementing one RDF plant in terms of increase LCV and decrease emissions due to sorting.

Treatment of solid residues
The plant would also create solid residues from the combustion and from the treatment of flue gas. We would go out of scope if we went into too much detail. For the paper, a certain mass of ash is collected and sent directly to the main landfill for treatment.

**Electricity Sale**

The plant would produce electricity continuously as a base load power generation. Thus we are assuming that there is a demand for the consumption and hence sale of the electricity.

**Costs estimates**

Most of the costs were obtained from previous books and sources which were not recent. When these costs were brought back to today’s dollars, we have assumed that there were no other changes that would occur to alter their respective costs other than the inflationary costs and the exchange rate at the time. There are additional factors that are present that can alter the costs of the different components, they have not been taken into consideration.

**Waste composition**

Even if the composition of the waste was obtained, the chemical composition was not available. This could be matter for future work. In the meantime, a typical waste composition OECD countries from textbooks has been used.
7. Further work

Below would be some further work that could be undertaken on the basis of this initial investigation into small scale power in SID:

- The chemical composition of the waste needs to be characterized and recorded. This would help in identifying the best place for setting up the plant.
- A detailed techno–economic study of setting up an RDF plant needs to be done.
- Proper engineering works need to be performed to look at the different challenges that this kind of plant would have.
- It is imperative to have up to date costs values to update and refine the model accordingly.
8. References


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http://www.worldenergy.org/.


9. Appendices

9.1. Heat content of the waste

Lower calorific value (kJ/kg) = 348 C%+939 H%+105 S% + 63 N% - 108 O% - 24.5 H2O%

(Hulgaard and Vehlow 2010)

Table 26 MSW elemental composition - example

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>25</td>
</tr>
<tr>
<td>H</td>
<td>4</td>
</tr>
<tr>
<td>S</td>
<td>2</td>
</tr>
<tr>
<td>N</td>
<td>0.5</td>
</tr>
<tr>
<td>O</td>
<td>22</td>
</tr>
<tr>
<td>Cl</td>
<td>1</td>
</tr>
<tr>
<td>H2O</td>
<td>25</td>
</tr>
<tr>
<td>Ash</td>
<td>20.5</td>
</tr>
</tbody>
</table>

Municipal solid waste having the characteristics as shown in Table 26 will have a heat content of 9709 kJ/kg or 2696.9 kWh/t.

2696.9 kWh/t is obtained by dividing 9709kJ/kg per (1000*3.6)

As 1kWh = 3.6 MJ

9.2. Air requirements for combustion process

The procedure for calculating the amount of air required for the combustion process has been according to (Hulgaard and Vehlow 2010).

Using Carbon (C), Hydrogen (H), and Oxygen (O), Sulphur (S) and Nitrogen (N) for the basis of the calculation. As an example consider the composition shown in Table 27 below.
9.3. Carbon and Hydrogen

Mass of C = 300 g /kg of waste

1 mol of C = 12 g

Number of moles of C = 300/12 = 25 moles

Mass of H = 43 g/kg of waste

1 mol of H = 1 g

Number of moles of H = 43/1 = 43 moles

Using stoichiometric equations,

\[ C + O_2 = CO_2 \]

\[ H + \frac{1}{2} O_2 = \frac{1}{2} H_2O \]
Moles of O$_2$ required for the combustion of C = 25 moles – (1 mole of C requires 1 mole of O$_2$)

Moles of O$_2$ required for the combustion of H = 10.75 – (1 mole of H required $\frac{3}{4}$ moles of O$_2$)

Total number of moles required = 25 + 10.75 = 35.75 moles

Amount of O$_2$ already present in the waste = 240 g/kg of waste = 7.5 moles - (240/32)

1 mole of O$_2$ = 32 g

Thus net amount of O$_2$ required = 35.75 – 7.5 = 28.25 moles

We assume that 1 mol of ideal gas = 22.41 lts @ std conditions

Volume of O$_2$ = 28.25 mol / (22.41 /1000) = 0.633083 Nm$^3$

We assume that O$_2$ makes up 21% of dry air, thus total stoichiometric amount of dry air required for combustion = 0.633083 / 0.21 = 3.014678571 Nm$^3$

The density of air = 1.293 kg/Nm$^3$

Taking excess air to be 150% or 1.5, total dry volume of air = 3.014678571 Nm$^3$ * 1.5 = 4.522018 Nm$^3$

Following the rule of thumb that there is an increase of 1% in volume at 60% humidity,

Total volume of air = 4.522018 Nm$^3$ * (1 + 1/100) = 4.567238 Nm$^3$

9.4. Sulphur

S + O$_2$ = SO$_2$
1 mol of S requires 1 mol of O₂

32 g of S requires 32 g of O₂

2 g of S requires \((\frac{32}{32}) \times 2 = 2\) g of O₂ /kg of waste

### 9.5. Oxides of Nitrogen

Assume that 50% becomes NO and the other 50% becomes NO₂

\[ \text{N} + \frac{1}{2} \text{O}_2 = \text{NO} \]

1 mol of N requires \(\frac{1}{2}\) moles of O₂

5 g of N (we have assumed that 50% of the N is converted to NO) requires \(\frac{16}{14} \times 5 = 5.714286\) g of O₂/Kg of waste

\[ \text{N} + \text{O}_2 = \text{NO}_2 \]

1 mol of N requires 1 mol of O₂

5 g of N (the rest is converted to NO₂) requires \(\frac{32}{14} \times 5 = 11.42857\) g of O₂/ kg of waste

Total amount of O₂ required for the combustion of S and N = 19.14286 g / kg of waste = 0.598214 mol / kg of waste = 0.0134 Nm³

Total amount of dry air required = 0.0134 Nm³ / 0.21 = 0.06381 Nm³

Adding humidity and excess air for complete combustion = 0.096671 Nm³

Total amount of air for the combustion process = 4.567238 + 0.096671 = 4.663909 Nm³ / kg of waste

Mass of air required = 6.030435 kg / kg of waste
9.6. Amount of flue gas produced

Moisture content in the waste = 200 g/ kg of waste

1 mol of H₂O = 18 g

Number of moles = 200/18 = 11.1111 moles

Recalling, total stoichiometric air volume required for combustion = 4.663909 Nm³ / kg of waste

Volume of water evaporated = 11.1111 * (22.41 lts/mol /1000) = 0.249 Nm³ / kg of waste

Volume of CO₂ formed = 25 moles * (22.41 lts/mol / 1000) = 0.53525 Nm³ / kg of waste

Volume of H₂O produced from H = (43 mol of H /2 ) * (22.41 lts /mol /1000) = 0.460315 Nm³ / kg of waste

The same principle is followed for calculating the volume of SO₂, NO and NO₂ formed.

<table>
<thead>
<tr>
<th>Tota humid air</th>
<th>Water evaporated</th>
<th>CO2 formed</th>
<th>H₂O from H</th>
<th>SO₂ produced</th>
<th>NO produced</th>
<th>NO₂ produced</th>
<th>O₂ used in</th>
</tr>
</thead>
<tbody>
<tr>
<td>required</td>
<td>from waste itself</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>combustion</td>
</tr>
<tr>
<td>4.663909464</td>
<td>0.249</td>
<td>0.53525</td>
<td>0.460315</td>
<td>0.001401</td>
<td>0.008004</td>
<td>0.008004</td>
<td>0.646483</td>
</tr>
</tbody>
</table>

Thus the total theoretical flue gas flow rate = 5.271396161 Nm³ / kg of waste

9.7. Chemical reactions

We have considered only the removal of Hydrogen fluoride (HF), Sulphur dioxide (SO₂) and Hydrochloric acid (HCl).

HCL removal

NaHCO₃ + HCl = NaCl + CO₂ + H₂O

1 mole of HCL gas requires 1mole of NaHCO₃

36 kg of HCl requires 83 kg of NaHCO₃

By proportion, we can obtain the stoichiometric amount required for the neutralization reaction.
For example if there is 170,000 kg per annum of HCl to be expected from the flue gas,

Amount of NaHCO₃ = (83/36) * 170,000 = 391,944.44 kg per year.

The same principle is applied to SO₂ and HF removal.

SO₂ removal

2NaHCO₃ + SO₂ + 1/2 O₂ = Na₂SO₄ + 2 CO₂ + H₂O
1 mole of SO₂ requires 2 moles of NaHCO₃
62 kg of SO₂ requires 83 kg of NaHCO₃
For 400,000.00 kg of SO₂ per year, amount of NaHCO₃ = 535,483.87 kg

HF Removal

NaHCO₃ + HF = NaF + CO₂ + H₂O
1 mole of HF requires 1 mole of NaHCO₃
19 kg of HF requires 83 kg of NaHCO₃
For 5,100.00 kg of HF per year, amount of NaHCO₃ = 22,278.95 kg

This gives us 949,707.26 kg of NaHCO₃ per year

Taking an efficiency of reaction to be 95 %,

= 999,691.86 kg would be required per year.

9.8. Activated carbon consumption

Using the exchange rate of 1 Euro to AUS $1.734, 0.3 EUROS * AUS $1.734 = AUS $0.5204. Using the converted supplied by (Australian Bureau of Statistics 2015), $0.73 in dollar terms for 2015.

<table>
<thead>
<tr>
<th>Scale / tpa</th>
<th>eur/ t</th>
<th>AUD /t in 2002</th>
<th>$/t in 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>75000</td>
<td>0.3</td>
<td>0.5204269</td>
<td>0.73</td>
</tr>
</tbody>
</table>
9.9. Operation and maintenance costs for activated carbon unit

The same principle as applied above is performed.

<table>
<thead>
<tr>
<th>Scale / tpa</th>
<th>eur / t</th>
<th>AUD /t in 2002</th>
<th>$ /t in 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>75000</td>
<td>0.23</td>
<td>0.399993957</td>
<td>0.56</td>
</tr>
<tr>
<td>100000</td>
<td>0.22</td>
<td>0.381646394</td>
<td>0.53</td>
</tr>
<tr>
<td>150000</td>
<td>0.2</td>
<td>0.346951267</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Specific maintenance costs of Activated Carbon component with scale

\[ y = -0.101 \ln(x) + 1.6915 \]
The scale is entered into the equation obtained to give $0.82586744 / t$ of waste processed.

9.10. Incinerator plans

Figure 49 Combustion Chamber – Internal Details - Small Scale Incinerator from the NGO Practical In Action (Intermediate Technology Consultants 2015)
Figure 50 Combustion Chamber Small Scale Incinerator from the NGO Practical In Action (Intermediate Technology Consultants 2015)
Figure 51 General ducting Small Scale Incinerator from the NGO Practical In Action (Intermediate Technology Consultants 2015)
9.11. Typical set up of flue gas treatment in large scale incinerators

Schematics extracted from (World Bank 1999) for the wet and the dry system are shown in Figure 52 and Figure 53. The level of emission control is shown on the right with the percentage amount of pollutant emitted to the atmosphere.

The pollutants are as follows:

- Dust
- Hydrochloric acid - HCL
- Sulphur dioxide - SO2
- Oxides of nitrogen - NOx
- Heavy metals
- Hydrogen fluoride - HF
- Mercury - Hg
- Dioxins
Figure 52 Wet air pollution control system with dioxin control (World Bank 1999) pg 75
Figure 53 Dry air pollution control of incinerators (World Bank 1999) pg 76
These guidelines from the (World Bank 1999) demonstrate that there is a wide variety of options available for the treatment of the flue gases, depending on the standards to which the flue gases are released. Both the dry and wet system can attain the same objectives in terms of standards.

In general, when talking about typical WtE plants, we would be referring to incinerators or mass burn facilities. They are the most common types of set up available as previously mentioned. The incineration pathway will follow the schematic in Figure 54 below.

![Figure 54 Schematic of a typical Waste to energy plant using the incineration route (Young 2010)](image)

According to (Funk, Milford, and Simpkins 2013), there are 4 activities involved in the WtE processing MSW:

- Collecting the waste and receiving a tipping fee for it
- Processing the waste
- Conversion of the waste to thermal or electrical energy
- Distribution on the energy
The different sections, namely, Pre-treatment, Incineration, Energy Recovery and Energy Production are summarized in Figure 55 together with several options that could be implemented in each section.

Figure 55 only concentrates on the combustion technology pathways with the corresponding efficiencies specifically the mass burn moving grate technology.

The technical report from the (World Bank 1999) gives some guidelines on the waste resource that needs to be supplied to the plant. The waste, therefore, has to have a Lower Calorific Value (LCV) of waste at least 6 MJ/kg in all the seasons and an annual lower calorific value having an average of not less than 7 MJ/kg.

Furthermore, a scale of not less than 50,000 tons of waste per annum was set as the minimum.

This, of course, is the whole purpose of this paper and need not be taken into account.
(Pavlas et al. 2011) has illustrated a modern state of the art waste to energy plant on the mass burn, moving grate technology, which is the most common form of WtE plants worldwide. Figure 56 gives the different sections of a simplified WtE plant. Thus four main parts can be identified namely:

- Energy recovery - the incinerator
- Energy generation - Steam turbine unit
- Flue gas treatment
- Stack

The incineration process involves a lot of steps that have been explained by (Pavlas et al. 2011).

- Moving grate where waste is burnt
- Flue gas is led to secondary combustion chamber and allowed sufficient residence time for further decomposition of more stable components
- A temperature of 900–950°C has to be maintained
- Steam produced sent to condensing turbine
- Possibility of extracting the condensing steam for heat purposes
- Low grade heat is removed and cooled by an air cooler
- Flue gas goes to flue gas treatment
- Dust removed in ESP
- Dioxin removal
- PM removal and destruction of Dioxins and Furans (catalytic fabric filtration system – DeDIOX (Pavlas et al. 2011))
- Acid compounds SO2, HCl, HF + heavy metals removed with NaOH in wet scrubber.
- NOX (selective non-catalytic reduction method ) removed by applying urea in secondary combustion chamber in proper temperature range of 900–1000°C
9.13. Incineration residues

It is imperative that the residues produced during the combustion process and the flue gas treatment are carefully disposed of. This section of an incineration plant cannot be looked upon in detail in this paper due to its complexity. Nonetheless, it can be useful to address this part briefly. (World Bank 1999) gives some guidelines on this matter:

- A well operated and controlled landfill should be made available for the final residues of the combustion process. Being dedicated to the operation of the WtE plant, it should be designed in such a way as to be able to receive all the residues from the plant during its lifetime.
- Careful leachate management is of crucial importance to prevent water pollution.
- Additional facilities could be added such as the recovery of scrap metals for recycling.
- Portion of the non-toxic slag could be recovered and machined for further utilization as gravel.
- Dry residues should not be allowed to escape easily to the ambient air so as to prevent excessive dust formation.

Conventional grate fired mass burn systems for MSW are generally built as large as possible to take advantage of economies of scale. But this model is not the best solution in every case. Lower waste tonnage and higher transportation costs have tipped the balance when considering big incinerators. This is specially the case in rural locations. Thus smaller scale units are preferred with lower waste input such as 50,000 tons per year (Stein and Tobiasen 2004). One challenge of small scale is to be able to meet all the strict emission standards and at the same time be able to overcome capital costs.

Europe has witnessed a variety of scales due to the availability of the MSW as shown in Figure 57.

As a result of her works on smaller scales, (Ricaud 2011) has classified three scales namely:

- Small with a through put of less than or equal to 100,000 tpa
- Medium with through put with range of 100,000 – 250,000 tpa
- Large with through put of more than 250,000 tpa

Figure 57 Plant capacity in Europe (Ricaud 2011) adapted from (International Solid Waste Association - ISWA 2012)
The novelty of this work is that it will consider smaller scales and a redefinition of the scales will need to be addressed. In this context we will define the new scales as shown below:

- Small with 5,000 tpa
- Medium with 10,000 tpa
- Large with 100,000 tpa

The crux of the problem will be to investigate the viability of the small scale set up as the bigger ones have commonly been investigated.

Following this idea, some technologies are best for certain ranges as illustrated in Table 28.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Typical application range (tonnes/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moving grate (mass burn)</td>
<td>120 - 720</td>
</tr>
<tr>
<td>Fluidised bed</td>
<td>36 - 200</td>
</tr>
<tr>
<td>Rotary kiln</td>
<td>10 - 350</td>
</tr>
<tr>
<td>Modular (starved air)</td>
<td>1 - 75</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>10 – 100</td>
</tr>
<tr>
<td>Gasification</td>
<td>250 - 500</td>
</tr>
</tbody>
</table>

*Note: values are for typical applied ranges – each is also applied outside the range shown*

The advanced treatment technologies offer a clear advantage over general combustion of similar scale. That being said, the experience in these technologies is not well developed or is starting to pick up in the market now. Furthermore, the more advanced treatment technologies have difficulties in treating unsorted MSW. In any case, the choice of technology is much less crucial than the point of scale and site location in coming to a decision for a WtE plant (Longden et al. 2007).

On the other hand, smaller scale plants according to (Longden et al. 2007) have the advantage of
• Lowest transportation costs – they can be located close to the waste generating ‘places’

• They are more easily accepted by local communities

• They have improved environmental performance in some areas

• Being modular
  
  o they can be build step by step and this helps in securing funds – capital expenditure

  o they can be customized more easily to react to other policies treating solid waste like recycling, composting and re use.
9.15. Efficiency and economics of scale

Studies conducted on the scale of plants and their efficiencies tend to show that the bigger the scale the more efficient are the plants. An electrical efficiency of 20.9% for small WtE plants have been reached as compared to 30% for larger capacities (Ricaud 2011).

Economics is the major contributor to this change in efficiency. It makes sense to invest into more advanced technologies if there is a greater amount of waste to be treated and thus more revenues to be obtained (Ricaud 2011).

Lower cost per tonne of waste can be achieved with large scale and superior CO₂ emissions reduction when the generation of electricity is only taken into account (Longden et al. 2007).