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Energy from municipal solid waste in Chennai, India
– a feasibility study

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Abstract

Solid waste management is one of the most essential functions in a country to achieve a sustainable development. In India, it has been one of the least prioritized functions during the last decades. The most common ways to treat waste in India today are open dumping and uncontrolled burning. These methods are causing severe environmental pollution and health problems. India is one of the world's largest emitter of methane gas from waste disposal. Since methane is a strong greenhouse gas, even small emissions have large impact on the climate. Improper treatment of waste will also affect peoples' health, first of all by the spreading of toxic compounds from uncontrolled burning and secondly by leakage of sewage from the dumping grounds into the groundwater.

When waste is incinerated in an incineration plant there are many environmental benefits. First of all, the possibility of using flue gas treatment prevents emissions of toxic compounds to emit to the air compared to if waste is burnt uncontrolled. Secondly, the amount of waste going to the dumpsite will decrease, resulting in a reduction of methane formation and less leakage of sewage from the dumpsite to the groundwater.

Chennai is the fourth largest city in India with a population of 4.3 million (2001 census). It is the Corporation of Chennai, CoC, which has the overall responsibility for solid waste management in the city. With street sweepers, tricycles and compactors they collect and transport the waste to one of the two dumpsites in the city; Perungudi in the north or Kodungaiyur in the south. Like most municipalities in India, CoC has experienced difficulties keeping in pace with last decades' industrialization, resulting in insufficient collection of municipal solid waste and over burdened dumpsites. Another consequence of the rapid industrialization is the increased demand for electricity. Today there is not enough installed capacity of power stations in Chennai to meet this demand, leading to daily power cuts.

If the waste on the two dumpsites will be left untreated, the dumpsites are only expected to be useful until the year 2015. To prolong the lifespan of the dumpsites CoC has signed a contract with the company Hydroair Tectonics, who shall minimize the waste on Perungudi. There is a chance that there will be a similar contract on Kodungaiyur as well. This company will build a processing plant that will segregate the waste into recyclable, inert, organic and burnable material. The inert and organic waste will be processed further into bricks and compost, which will be sold on the open market. The burnable material will be processed into a fluffy fraction called RDF-fluff. In the initial stage the RDF-fluff will be sold to coal-fired industries as "green coal". In the future Hydroair Tectonics plans to build a combustion unit for burning RDF and generate electricity, which will be sold to the grid.

This report will give an overview of the current waste and electricity situation in Chennai and analyze whether Hydroair Tectonics should build this combustion unit or if they should sell the generated RDF to industries. The result will be presented in a case study.

Populärvetenskaplig sammanfattning

Ett fungerande avfallshanteringssystem i världens länder är väsentligt för att åstadkomma en global hållbar utveckling. Indien har, liksom många andra utvecklingsländer, stora brister i sitt avfallshanteringssystem. De vanligaste metoderna att hantera avfallet i landet idag är okontrollerad deponering och öppen förbränning, vilka är de värsta metoderna när det gäller miljö- och hälsoeffekter. Indien är en av världens största utsläppare av metan från avfallsdeponering. Eftersom metan är en stark växthusgas ger även mindre utsläpp betydande påverkan på klimatet. Ett fungerande avfallshanteringssystem är dessutom viktigt för att förhindra sjukdomsspridning. Varje år dör tusentals människor i Indien av sjukdomar orsakade av bristfällig renhållning.

Den senaste tidens urbanisering och ekonomiska utveckling som har präglat landet har resulterat i en lavinartad ökning av mängden hushållsavfall. Samtidigt har behovet av elektricitet ökat som en ytterligare konsekvens av detta. Idag har Indien stora problem med att tillgodose behovet av el i landet, vilket leder till dagliga elavbrott. Regeringen i Indien har under de senaste åren insett vilket omfattande problem de står inför och har mer aktivt börjat arbeta för att förbättra el- och avfallssituationen. Genom att införa striktare regler för avfallshantering och samtidigt förbättra investeringsklimatet för elproduktion från förnyelsebara energikällor hoppas de komma tillrätta med de båda problemen. Vad många politiker förespråkar är energiproduktion från avfall; en lösning som både minskar mängden sopor till dumparna och samtidigt genererar elektricitet .

Borlänge Energi har under lång tid varit engagerad i avfallsprojekt i utvecklingsländer. Deras engagemang i Indien började med ett samarbete med organisationen Hand in Hand som är en Non-governmental Organization, NGO, i Chennai. Detta examensarbete är skrivet på uppdrag av Borlänge Energi och har finansierats genom ett Minor Field Study, MFS, - stipendium från Sida. Syftet med arbetet är att göra en förstudie om möjligheten att bygga en avfallsförbränningsanläggning med energiutvinning i Chennai.

Situationen i Chennai idag

Chennai är Indiens fjärde största stad med 4,3 miljoner invånare (2001 census). Idag är det kommunen i Chennai, CoC, som har det övergripande ansvaret för stadens avfallshantering. Staden är uppdelad i 10 administrativa zoner. För att effektivisera avfallshanteringen har CoC outsourcat avfallshanteringen i 4 av de 10 zonerna till det privatägda företaget Neel Metal Fanalca. Metoden för uppsamling och transport av avfallet är dock densamma. Med hjälp av gatusopare, trehjulingar och tyngre lastbilar samlas avfallet ihop och transporteras sedan till en av stadens två dumpar, Kadungaiyur i norr eller Perungudi i söder. Dessa dumpar är okontrollerade, vilket innebär att de varken har någon uppsamling av lakvatten eller utvinning av deponigas. Varje dag transporteras cirka 1 500 ton avfall till vardera av dumparna. Om denna avfallsmängd inte minskar de närmsta åren beräknas dumparnas livslängd sträcka sig till år 2015. Uppsamlingen av avfall i Chennai sker med en effektivitet av 73 procent. Det avfall som inte samlas upp förbränns under okontrollerade former längs vägar och i gränder. Hushållsavfallet i Chennai består till största delen av organiskt avfall och inert material, som grus och sand. Det lägre värmevärdet ligger på 1,6 MWh/ton.

Vardagen i Chennai präglas av strömavbrott som ibland varar i flera timmar. I januari år 2009 kunde 7,5 procent av elbehovet i staden inte tillgodoses. Idag sker ingen utvinning av energi från avfall i Chennai.

Situationen i Chennai i framtiden

I takt med att dumparna i Chennai börjar bli överfyllda med sopor har kommunen i Chennai arbetat för att hitta en lösning som minimerar mängden sopor på dumparna och därmed förlänger deras livstid. Nyligen skrev de kontrakt med ett företag från Mumbai, Hydroair Tectonics, för att de ska ta hand om allt avfall som dumpas på Perungudi. Det kan tänkas bli ett liknande kontrakt på Kadungaiyur i framtiden. Till en början kommer företaget att bygga en sorteringsanläggning på dumpen som mekaniskt och manuellt separerar olika fraktioner av avfallet. De olika fraktionerna bearbetas sedan vidare till användbara produkter. Av den organiska och inerta fraktionen tillverkas kompost respektive tegelsten, som säljs på den öppna marknaden. Återvinningsbart material separeras och säljs till återvinningsföretag. Den brännbara fraktionen hackas sönder till en fluffig massa kallad RDF-fluff, som kan användas som bränsle för energiproduktion. Till att börja med kommer Hydroair Tectonics att sälja RDF-fluffet till koleldande industrier som ett substitut till kol. I ett senare skede funderar företaget på att investera i en förbränningsanläggning för energiproduktion.

Fallstudie

I detta examensarbete beskrivs de ekonomiska och tekniska förutsättningarna för att bygga en anläggning för energiproduktion från förbränning av RDF-fluff. Resultatet presenteras i en fallstudie som kommer kunna användas av Hydroair Tectonics för att bedöma om de ska bygga en anläggning eller inte.

I fallstudien beskrivs en typanläggning för energiproduktion för förbränning av RDF. Två scenarier för energiproduktion undersöks. I det ena fallet förbränns RDF för att generera el, som säljs till nätet. I detta fall blir anläggningens elektriska effekt 10,5 MW. I det andra fallet förbränns RDF-fluff tillsammans med industriavfall, för att generera el som säljs till nätet och processånga som säljs till en närbelägen industri. I detta fall blir den elektriska effekten 12,2 MW och den termiska effekten 12,5 MW. Det senare fallet innebär högre lönsamhet, för det första genom att fler produkter tas tillvara och för det andra för att inblandningen av industriavfall ger bränslemixen ett högre energiinnehåll.

Beroende på vilken återbetalningstid Hydroair Tectonics accepterar, varierar den totala anläggningskostnaden för att det ska vara mer lönsamt att bygga anläggningen än att sälja RDF-fluffet till industrier. Resultatet blev följande:

Vid antagandet att Hydroair Tectonics väljer en återbetalningstid på 15 år bör företaget:

- förbränna RDF i en anläggning för generering av el, om de totala anläggningskostnaderna på 15 år inte överstiger 540 miljoner kr
- förbränna RDF tillsammans med industriavfall i en anläggning för generering av el och processånga, om de totala anläggningskostnaderna inte överstiger 910 miljoner kr
- sälja RDF till industrier för 150 kr per ton om ovanstående fall inte gäller.

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Uppsala, May 2009.

Camilla Axelsson & Theres Kvarnström

Nomenclature

BFB	Bubbling Fluidized Bed
BOOM	Build, Own, Operate and Maintenance
CDM	Clean Development Mechanism
CEA	Central Electricity Authority
CER	Certified Emission Reduction
CFB	Circulating Fluidized Bed
CH_4	Methane
CMDA	Chennai Metropolitan Development Agency
CoC	Corporation of Chennai
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2 eq	Carbon dioxide equivalent
CPCB	Central Pollution Control Board
DNA	Designated National Authority
DOE	Designated Operational Entity
DST	Department of Science and Technologies
EB	Executive Board
ENTEC	Environment Technology
EU	European Union
HCl	Hydrogen chloride
HF	Hydrogen fluoride
HgCl	Mercury chloride
HHV	Higher Heating Value
H_2O	Water
IET	International Emission Trading
IPCC	International Panel on Climate Change
IREDA	Indian Renewable Energy Development Agency
LHV	Lower Heating Value
MFS	Minor Field Study
MNRE	Ministry of New and Renewable Energy
MoEF	Ministry of Environment and Forest
MoU	Memorandum of Understanding
MoUD	Ministry of Urban Development
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
NGO	Non-Governmental Organisation
NEERI	National Environmental Engineering Research Institute
NO_x	Nitrogen oxides
O_2	Oxygen
PCB	Polychlorinated biphenyls
PCDD	Polychlorinated dibenzo-p-dioxins
PCDFs	Polychlorinated dibenzofurans
PDD	Project Development Document
PVC	Polyvinyl chloride
RBI	Reserve Bank of India
RDF	Refuse Derived Fuel
RES	Renewable Energy Sources
SCR	Selective Catalytic Reduction

Sida	Swedish International Development Cooperation Agency
SLF	Sanitary Landfill
SNCR	Selective Non Catalytic Reduction
SIPCOT	State Industries Promotion Corporation of Tamil Nadu
SO_x	Sulphur oxides
SWM	Solid Waste Management
TDB	Technology Development Board
TEDA	Tamil Nadu Energy Development
TNEB	Tamil Nadu Electricity Board
TNERC	Tamil Nadu Electricity Regulatory Commission
TNPCB	Tamil Nadu Pollution Control Board
TPD	Tons Per Day
UNFCCC	United Nations Framework Convention on Climate Change
VER	Voluntary Emission Reduction

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1 Introduction

Solid Waste Management (SWM) is one of the most essential functions of the local authorities in India to achieve a sustainable development in the country. Nevertheless, it has also been one of the least prioritized services during the last decades.

The largest part of the solid waste generated is Municipal Solid Waste (MSW), which is waste generated from the households and commercial establishments. The rapid urbanization and the economical development in India during the last years have resulted in an increase in MSW generation. The local authorities have had problems keeping in pace with the growing problems with MSW, resulting in overfilled dumpsites and uncontrolled burning. Since India has 18 percent of the world's population [4], but only 2 percent of the world's total land area [5], the problem becomes even more urgent.

When waste is not treated properly, the environmental and health impacts can be disastrous. Today, India is one of the world's largest methane emitters from solid waste disposal. Since methane is an aggressive greenhouse gas, it will affect global warming on a large scale. A functional SWM is also necessary to prevent the spreading of diseases and improve the standard of living of people. Every year thousands of people die in India of water borne diseases, caused by lack of sanitation. [6]

Another result from the rapid industrialization is the increased demand for electricity. Today India suffers major problems with shortage of electricity which results in daily power cuts all throughout India. In some cities these power cuts could last for hours leading to disturbances in the daily routines and productivity losses.

Chennai is the fourth largest city in India, with a population of 4.3 million (2001 census). [47] Like most of the municipalities in India today, the corporation of Chennai experiences difficulties handling the problems related to SWM and shortage of electricity. The two dumpsites in the city are overfilled and the environmental and health effects of the mistreatment of waste during the past have started to get more noticeable.

The last decade's pressure from the government of India with stricter regulations and standards concerning SWM has forced the municipalities to more actively work towards a change. What many municipalities advocate for future waste management is a solution that minimizes the waste going to the dumpsite and at the same time generates energy. Such solution is often referred to as an MSW-to-energy solution.

1.1 Background

This master's thesis is a Minor Field Study (MFS), which is a scholarship program for field studies in developing countries, funded by the Swedish International Development Cooperation Agency (Sida). The project is carried out on behalf of Borlänge Energy, which is an energy producing company situated in Borlänge, Sweden. They provide the city of Borlänge with electricity and district heating from an MSW-to-energy facility.

Borlänge Energy has been involved in several projects on sustainable development in developing countries during the past years. Since Borlänge Energy is a municipal owned company, their involvement is not based on potential financial profits. The only finance for these projects is subsidies from Sida. Borlänge Energy's engagement reflects the culture of the city and creates working opportunities for the citizens involved in these projects, which is the main incentive.

Borlänge Energy's engagement in India started with cooperation with the non-governmental organisation (NGO), Hand in Hand, situated in Chennai. Hand in Hand is an international organisation involved in many projects concerning sustainable development, including solid waste management. This cooperation enables Hand in Hand to get funding for their projects from Sida. Because of the fact that the engagement in India is relatively new, Borlänge Energy requested a pre-study of the current waste situation in 2008, in order to determine the feasibility for an MSW-to-energy project. Since Borlänge Energy has several years of experience from producing energy from waste, they could assist with technology transfer and know-how, if a future waste-to-energy project would be carried out in Chennai.

During the fieldwork in Chennai it became clear that one company had signed contract to take care of a large part of the MSW in Chennai. The company's name is Hydroair Tectonics Ltd and is situated in Mumbai. Most likely, they will also take care of the other part of the MSW in Chennai in the nearest future. Since their waste treatment methods were in line with Borlänge Energy's beliefs of sustainable waste management, the study changed focus and started to see the possibilities of cooperating with this company.

The cooperation between Borlänge Energy and Hydroair Tectonics started successfully. A Memorandum of Understanding (MoU) between the two companies was signed in October 2008. An MoU is a non-binding document that can be signed between organizations to facilitate sharing of information and technology. One of the purposes with this agreement is for Borlänge Energy to provide Hydroair Tectonics with technical knowledge, regarding energy recovery from waste. Since the head of international projects at Borlänge Energy, Ronny Arnberg, also is the chairman of the board in the international group at the Swedish trade association Swedish Waste Management (Avfall Sverige), the cooperation has now expanded to include even this association. Recently it was decided that the Swedish Waste Management will be partner with Hydroair Tectonics in an upcoming project funded by Sida.

1.2 Objective

The aim with this master's thesis is to do a feasibility study about the possibility to recover energy from MSW in Chennai, with focus on combustion. In order to evaluate the feasibility for building a combustion unit, the current waste and electricity situation in Chennai as well as the future MSW treatment plans are analysed. This information will be used to formulate a case study, in which the following questions are answered:

1. Should there be mass burning of MSW or only combustion of the burnable fraction of the MSW (RDF)?
2. Who should process the waste and which methods should be used?
3. Where should the plant be situated?
4. Should there be co-incineration with another fuel? In that case, which fuel is suitable for co-incineration?
5. Which technology should be used for combustion and what type of flue gas treatment should be used?
6. Which type of energy should be recovered?

When the case is formulated the technical and financial viability are analysed. The possible energy extracted from the plant is determined as well as the plant cost.

1.3 Expected result of the study

The study will result in an informative and analysing report of the current and future MSW situation in Chennai. It is meant to serve as informative material for those people interested in learning more about the MSW and electricity situation in Chennai as well as guidelines for future MSW management.

1.3.1 For whom is this report written?

This master's thesis is written on behalf of Borlänge Energy. It is written for decision makers, NGO's and private companies who might be involved in future MSW management in Chennai.

Since this report assumes that the Indian company Hydroair Tectonics will play an important role in future MSW management, the result of the case study is especially interesting for them.

1.4 Limitations

- MSW stands for the largest part of the waste generated in Chennai and causes difficult problems for the municipality. Therefore, the focus will be on energy recovery from MSW and not other waste types.
- Energy recovery from MSW can be achieved through different technologies such as biomethanation, gasification and combustion. Due to the fact that combustion has been proven successful in many developed countries and that it is an efficient method to reduce the volume of the waste, this study will focus on energy recovery from combustion.
- In the case study, only the technical and financial viability will be covered. The environmental gains from improving the waste situation in Chennai will not be evaluated, except from the carbon dioxide reductions, which will result in Certified Emission Reductions (CERs) and thereby give financial revenues.

1.5 Methodology

The information in this master's thesis is obtained through interviews, study visits and literature studies. The methodologies used for the three main sections are described below as well as the exchange rates used in this report.

1.5.1 Description of the current and future waste and electricity situation in Chennai

In this section the current and future waste and electricity situation in Chennai is described. To be able to get an overview of the waste and electricity situation, several interviews with companies, institutions and governmental actors involved in solid waste management in Chennai were made.

The information about future MSW management in Chennai was given by the company Hydroair Tectonics, since they are going to take care of at least half of the generated MSW in Chennai in the near future. A study visit to one of Hydroair Tectonics MSW treatment plants in Ichalkaranji, together with interviews and work at their head office in Mumbai made it possible to thoroughly analyse their treatment methods.

1.5.2 Setting up a waste-to energy plant

This chapter gives an overview of the regulations and support systems that need to be considered when setting up a waste-to-energy plant in India. The information is given by interviews.

1.5.3 The case for MSW incineration in Chennai

In this chapter, the case study is presented and the technical and financial viability is analysed. The presentation of the case is based on analysis of the information given in the sections above.

In the technical viability analyses, the potential energy that can be extracted from the plant is calculated. The methods used for the calculations are based on literature studies and known equations. In the technical viability analysis it is assumed that the company Hydroair Tectonics and the industry Orchid Chemicals & Pharmaceuticals Ltd will cooperate and exchange energy/fuel. Therefore this section is based on data from these two companies. Furthermore, standard values from Borlänge Energy's waste-to-energy facility are used.

In the financial viability analysis, an estimation of the maximum plant cost for the project is made, in order for the project to be profitable. The calculations are based on the possible revenues from the plant and on the alternative costs for not building the plant. These data were obtained from interviews and Internet sources.

1.5.4 Exchange rate

The financial calculations are based on the exchange rate on the 31 July 2009, given in Table 1. [43]

Table 1 The exchange rate as on 31 July 2009.

United States Dollar	Indian Rupee	Euro	Swedish Krona
USD	**INR**	**EUR**	**SEK**
1	48.1	0.707	7.31

2 Solid waste management and electricity production in Chennai

This chapter will give an overview of SWM in Chennai, with extra focus on management of MSW. The electricity situation will be described as well as the current and future situation concerning energy recovery from MSW.

2.1 Background

Chennai lies on India's southeast coast and is the capital of the state Tamil Nadu. Figure 1 shows Chennai´s location. [155] Chennai district borders to Tiruvallur in the north and Kancheepuram in the south, both within Tamil Nadu. The population of the city is 4.3 million (2001 census), which makes it the fourth largest city in India. [47]

The English language is widely spoken in Chennai along with the local language Tamil.

The city is known for its many IT and automobile manufacturing industries. Many foreign and national companies are located in large industrial areas in and in the outskirt of the city. [52]

Chennai has a hot and humid climate with a maximum temperature of 38-42 degree Celsius in June and a minimum temperature of 18-20 degree Celsius in January. The annual monsoon season is between mid-September and mid-December, which is when Chennai get its most rainfall. [52]

Figure 1 Map of India. [155]

The municipality of Chennai is divided into 10 administrative zones, as can be seen in Figure 2. Each zone is further divided into 15 wards, which totally gives 150 wards. The Corporation of Chennai (CoC) is the local elected government in Chennai. [46] The CoC provides Chennai with water supply, education, health care, water drainage, electricity and solid waste management. [49]

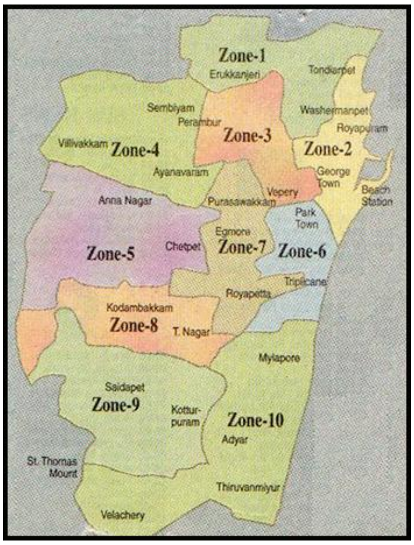

Figure 2 The zones of Chennai. [160]

The department of Solid waste management (SWM) at CoC takes care of all the handling of solid waste, from generation to final disposal. Like many municipalities in India, the CoC experiences a hard time handling the growing problem of waste. The insufficient management in Chennai during the past has put strain on the environment and peoples' health and the CoC has a heavy burden to carry on their shoulder to try to improve the system.

2.2 Solid waste generation

The solid waste in Chennai can be divided into the following categories: industrial waste, agricultural waste, hazardous waste, bio-medical waste, e-waste, construction and demolition waste and MSW. A study performed in 1996 by Chennai Metropolitan Development Authority (CMDA) in collaboration with the World Bank shows that the residences are the largest generator of solid waste in Chennai [54], which can be seen in Table 2.

Table 2 Solid waste generation sources in Chennai. [54]

Solid waste generation source	[%]
Residences	68
Commercial buildings	14
Restaurants, Hotels, Schools and other	11
Markets	4
Hospitals and Clinics (collected separately)	3
Total	**100**

The following section will shortly explain the different types of waste in Chennai.

2.2.1 Industrial Waste

Industrial waste is unwanted material from an industrial operation. It may be liquid, sludge, solid or hazardous waste. [55]

One of the largest industrial areas in Chennai is called Manali and is situated in the northern suburb in the Tiruvallur district. Major chemical industries are situated in this area, particularly petrochemical industries. [129]

No figures exist about how much industrial waste is generated every day in Chennai. The industries are themselves responsible for taking care of their waste. The industries often have private scrap dealers collecting their recyclable waste. The scrap dealers buy the waste from the industries and sell it to manufacturing industries that recycle the material. [121]

2.2.2 Agricultural Waste

Agricultural waste is waste produced as a result of various agricultural operations. It includes manure, harvest waste and other wastes from farms, poultry and slaughter houses. [56]

Within the ten zones of Chennai there is no land for agricultural purposes. Yet in the nearby districts in Tamil Nadu there are areas used for agricultural operations. The interesting crops for cultivation here are paddy, ground nut, prosopis juliflora and sugarcanes. [130]

In Tamil Nadu there are agricultural waste-to-energy projects from combustion, gasification and biomethanation. There are nine combustion power plants, that together stand for 109 MW. There is one gasification plant (1 MW) and two biomethanation plants; one that uses vegetable waste (0.25 MW) and one that uses poultry litter waste (4 MW). [130]

Figure 3 The biomethanation plant in Koyembedu wholesale market complex, Chennai. [57]

Figure 3 shows a 0.25 MW biomethanation plant that was set up at the Koyembedu wholesale market complex in September 2005. Around 100 tons of vegetable waste reaches the plant every day. [54] The plant is unique in India in the way that it produces electricity only from vegetable waste, no leather or other animal waste. [131]

2.2.3 Hazardous Waste

Hazardous waste is waste that can cause significant damage to environment and human health if it is not treated properly. [54]

During a long period of time the industries in Chennai disposed their hazardous waste together with the MSW on roadsides and in low-lying areas, as there was no infrastructure available. As an attempt to solve this problem the Supreme Court created the Hazardous Waste Handling Rules 1989, which forced the state governments to provide infrastructure such as landfills for disposal and treatment of hazardous waste. [54]

For fifteen years Tamil Nadu Government violated these rules allowing industrial expansion without taking any measurements for the hazardous waste generated. The proposal from Tamil Nadu Pollution Control Board (TNPCB), to establish common treatment storage and disposal facility for hazardous waste, became a difficult issue because of the public opinion that the nearby land and the groundwater would be polluted. Threatened by pressure from the Supreme Court, the Tamil Nadu Government finally selected Gummidipoondi in the Tiruvallur district for the treatment site. [58]

In January 2006 the work on a treatment facility in Gummidipoondi started, despite massive public opposition. The facility is situated on a 40 acre big area and consists of a sanitary landfill and an incinerator. [58]

2.2.4 Bio-Medical Waste

Bio-medical waste means any waste, which is generated during the diagnosis treatment of immunization of human beings or animals in research activities or in the production or testing of medication. [59]

Bio-medical waste is waste generated from healthcare centres. The 528 hospitals in Chennai city generate about 12 000 kg of bio-medical waste per day. It is considered hazardous firstly for its potential for infection and secondly for its ingredients of antibiotics, cytotoxic drugs, corrosive chemicals and radioactive substances. [54] According to the Bio-Medical Waste (Management and Handling) Rules, 1998, bio- waste needs to be treated in certain facilities. [60] Two sites were chosen by TNPCB for location of common treatment and disposal of biomedical waste from hospitals in Chennai and the nearby districts. They are situated in Thenmelpakkam and Chennakuppan in the Kancheepuram district. [54] The main processes in these facilities are incineration and autoclaving.[1] [61]

2.2.5 E-Waste

E-waste is the informal name of electronic products nearing the end of their useful life. Products such as mobile phones, computers, refrigerators etc fall under this category. [132]

E-waste contains over a thousand different substances, many of which are toxic to environment and human health. One of the primary sources of e-waste in Chennai is computer waste from the many western IT companies which have been established in the southern parts of the city.

Today there are no specific guidelines or environmental laws for e-waste in India. Since it is considered both “hazardous” and “non-hazardous” it falls under the Hazardous Waste Management Rules, 2003. [62] Thus, the creation of new guidelines for handling e-waste is in progress by the Central Pollution Control Board (CPCB), which most likely will be transformed into environmental laws later. [132]

TNPCB has authorized seven e-waste recycling industries, which receive e-waste scrap from industries in Tamil Nadu. They use mechanical tools to break the scrap and then manually segregate it into different components for recycling. The scrap is segregated into plastic components, glass, ferrous and non-ferrous material. Some of the components are not suitable for this process and are therefore exported to reprocessing facilities in Belgium, Singapore, Hong Kong, China and Taiwan for metal recovery. [54]

However there are informal scrap dealers and recyclers in residential areas in Chennai and in the outskirts of the city. With small tools and crude methods they manually sort out valuable materials from the scrap. In order to segregate aluminium from the e-waste they often burn the waste, which causes toxic air pollution. [54]

2.2.6 Construction and Demolition Waste

Construction and demolition waste is waste from building materials debris and debris resulting from construction, re-modelling, repair and demolition operations. [63]

Every day Chennai city generates around 500 tons of construction and demolition waste. There are a few sites identified by the CoC, where the generators of this waste can dump their waste, as well as collect the waste if they want to use the material for landfilling etc. This system does not work perfectly and it exists unauthorized dumping of construction debris along certain roads. [54]

2.2.7 Municipal solid waste

MSW includes residential and commercial waste generated in a municipal area, excluding industrial hazardous waste but including bio-medical waste. [63]

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[1] Autoclaving is a process of killing pathogenic microorganisms through saturation with steam under pressure. [42]

Low-income countries like India produce approximately 0.4-0.9 kg waste per person and day, while the waste generation rate in high-income countries ranges from 1.1-5 kg per person and day. [7] The average waste generation in Chennai is estimated to be 585 gram per person and day, which is the highest per capita generation of all cities in India [64] [54]. The population in Chennai 2008 was 5.03 million according to CMDA and the total amount of solid waste collected per day was 3400 tons [54]. Zones 10 and 5 are the largest zones by area but zones 5 and 8 generate the highest amount of waste which is shown in Figure 4.

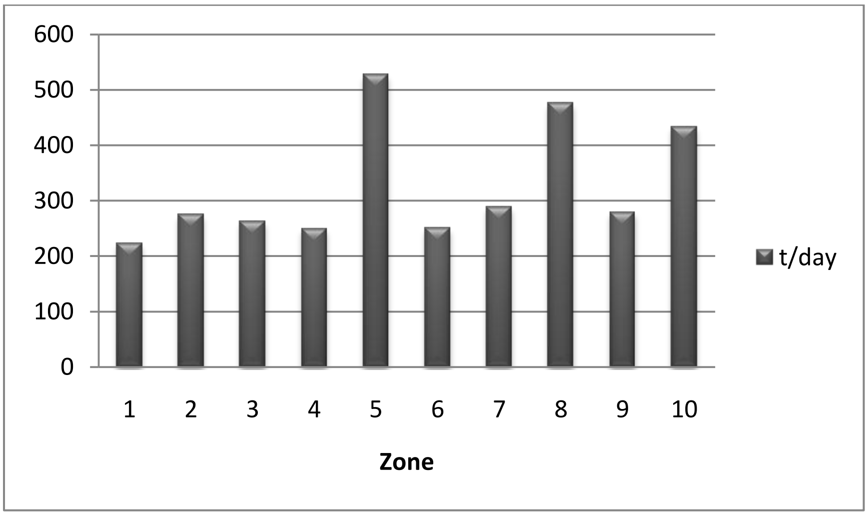


Figure 4 Zone wise garbage removal in Chennai. [128]

2.3 Municipal solid waste management in Chennai

The following text will explain the role of the governmental actors and the different aspects of MSWM in Chennai.

2.3.1 Governmental actors responsible for SWM

In India it is the local bodies that have the overall responsibilities for SWM in each city. Unfortunately, the municipal laws regarding SWM do not have adequate provision do deal effectively with the problems of solid waste in India today. [9] However, governmental actors provide the local bodies with certain directives and guidelines how the MSW should be handled. The governmental actors that are responsible for SWM are the Ministry for Environment and Forest (MoEF), Central Pollution Control Board (CPCB), the Ministry of New and Renewable Energy (MNER) and the Ministry of Urban Development (MoUD). [10]

2.3.1.1 The Ministry for Environment and Forest

The principle activities of the Ministry for Environment and Forest (MoEF) consist of protection of the environment in the form of legislations. This includes conservation of flora, fauna, forest and wildlife as well as control and prevention of pollution. MoEF created the Municipal Solid Waste (Management and Handling) Rules, 2000. [13]

Figure 5 illustrates the Municipal Solid Waste (M&H) Rules, 2000, in the form of Schedule (I-IV). Below each schedule there are specifications, standards and procedure descriptions how MSW should be handled. [20] The responsibility for the implementation of the Municipal Solid Waste (M&H) Rules, 2000, lies within every municipality. [19]

Schedule-I	Relates to implementation Schedule
Schedule-II	Specifications relating to collection, segregation, storage, transportation, processing and disposal of municipal solid waste (MSW).
Schedule-III	Specifications for landfilling indicating; site selection, facilities at the site, specifications for landfilling, pollution prevention, water quality monitoring, ambient air quality monitoring, plantation at landfill site, closure of landfill site and post care.
Schedule-IV	Indicate waste processing options including; standards for composting, treated leachates and incinerations

Figure 5 The Municipal Solid Waste (M&H) Rules, 2000. [157]

2.3.1.2 Central Pollution Control Board

Central Pollution Control Board (CPCB) is together with the State Pollution Control Boards responsible for the implementation and review of the standards and guidelines described in the Municipal Solid Waste (M&H) Rules, 2000. They shall make sure that the monitored data will be in compliance with the standards specified under Schedules II, III and IV. [19] In Tamil Nadu it is the Tamil Nadu Pollution Control Board (TNPCB), which has the responsibility on state level.

CPCB advises the Central Government on any matter concerning the improvement of the quality of air and prevention and control of air and water pollution. If a company wants to set up a facility that will cause pollution, it needs to get clearance from CPCB. [22]

2.3.1.3 The Ministry of New and Renewable Energy

The Ministry of New and Renewable Energy (MNRE) is responsible for both renewable energies and new fossil fuel technologies. Its main objectives regarding MSW management are

- to accelerate the promotion for MSW-to-energy projects
- to create favourable conditions with financial regime, to develop and demonstrate the viability of recovering energy from waste
- to realize the available potential of MSW-to-energy by the year 2017 [8]

Tamil Nadu Energy Development Agency (TEDA) implements The Ministry of New and Renewable Energy’s (MNRE’s) goals and visions on state level. They encourage research and development on renewable energy sources and implement such projects within Tamil Nadu as well as distribute subsidies to the projects. [89] TEDA promotes mainly four renewable energy sources: wind, biomass, solar energy and energy recovery from waste. [130]

2.3.1.4 The Ministry of Urban Development

The Ministry of Urban Development (MoUD) created the solid waste management manual, which serves as guidelines for the municipalities to handle their work more efficiently. It also provides the municipalities with technical guidelines on aspects of solid waste management. [10]

The urban local bodies, which are responsible for the SWM in each city, often lack adequate knowledge and expertise to deal efficiently with the problems of waste management. As an attempt to improve the situation, the MoUD decided in 1998 to create a solid waste management manual. The manual serves as guidelines for the urban local bodies to handle their work more efficiently. [15]

According to the solid waste management manual, the best method to deal with waste in India is to adapt the "hierarchy of waste management". This method is known throughout the world as a sustainable solution for the growing problem of solid waste. Figure 6 shows the hierarchy as it is described in the solid waste management manual.

Figure 6 Hierarchy of waste management. [15]

1. *Waste minimisation/reduction at source* means that the waste is prevented from entering the waste stream by the means of reusing products and using less material for manufacturing them.
2. *Recycling* means the act of sorting out recyclable materials like plastic, glass, metals and paper from the waste and reprocessing them into new products.
3. *Waste processing* includes biological and thermal processing and can result in useful products like energy and compost.

a) *Biological processing* includes composting and biomethanation.
b) *Thermal processing* includes combustion, pyrolysis and gasification.

4. *Waste transformation (without recovery of resources)* is for example combustion without energy recovery. Mechanical decomposition and autoclaving fall under this category.
5. *Disposal on land (landfilling)* should be the solution only if the waste cannot be treated with the four previous methods. The landfills should be designed to minimize the impact on the environment. [15]

2.3.2 Local bodies responsible for SWM in Chennai

In each state in India it is the local urban bodies that are responsible for solid waste management. They can choose if they want to have full responsibility of SWM in the community or outsource some of the responsibility to private contractors. In many cities in India there are also NGOs or other welfare organizations helping with SWM. This section will describe the different actors responsible for SWM in Chennai.

2.3.2.1 The CoC and private contractors

The overall responsibility of SWM in Chennai lies within the Solid Waste Management Department in the CoC. 7 percent of the CoC's total budget is allotted to this specific department. Each zone has an assistant commissioner responsible for the SWM in the corresponding zone. Yet, during the last decades the CoC has experienced difficulties keeping SWM at a good level, especially regarding MSWM. Therefore, the CoC has since a couple of years outsourced some of the collection and transportation of the MSW to private contractors. [64]

Chennai was the first city in India to outsource SWM to a private company. For seven years a Singaporean based company ONYX was responsible for sweeping, collecting, storing and transporting MSW in zone 6, 8 and 10, and to create public awareness in these zones. In 2007 the private company Neel Metal Fanalca replaced ONYX in the three zones. In July 2008 a fourth zone was privatised; zone 3, which is included in Neel Metal Fanalca's responsibility. [64] The privatised zones are seen in figure 7.

Neel Metal Fanalca is a joint venture between Fanalca SA of Columbia and JBM Group of India. Fanalca SA of Columbia has 20 years of experience in SWM and operates in Colombia, Panama, Chile, Venezuela and now India. [65]

The waste collection by the private company is more efficient due to more machines and less manpower. The total cost for street sweeping, collection and transporting of waste by the CoC is $33 per ton compared to $25 per ton by the private company. [64] According to R Umapathy, head of the waste management department at CoC, the CoC currently prefers a 50-50 distribution between private and governmental collection to balance efficiency versus unemployment. [128]

Figure 7 In the four zones marked, SWM is outsourced to the private company Neel Metal Fanalca. [65]

2.3.2.2 NGOs and welfare associations

NGOs and welfare associations have a significant role in the SWM in Chennai. In some areas they assist the CoC with collection of the waste at household level. Civic Exnora is an international NGO funded in Chennai and active on grass root level. They educate households in recycling and reusing waste as well as motivate communities to work towards Zero Waste. Another NGO in Chennai, Hand in Hand, employs former ragpickers to a low, but stable monthly salary. [64]

2.3.3 Collection and transportation of MSW

The collection and transportation of waste are similar in all zones, regardless if it is the government or the private company who is responsible. Both of them need to follow the Municipal Solid Waste (M&H) Rules, 2000. The structure of the transportation and collection system is described in this section.

2.3.3.1 Structure of collection and transportation

The collection and transportation of the waste is made in two different ways depending on how the waste is generated. Household waste is collected through door-to-door collection with tricycles. Waste thrown on the streets is collected through street bin collection with compactors. [128] The collection efficiency in Chennai is 73 percent, which means that 73 percent of all the MSW in Chennai is collected and transported to a final disposal. [76] A schematic view over Chennai's MSW collection and transportation is seen in Figure 8.

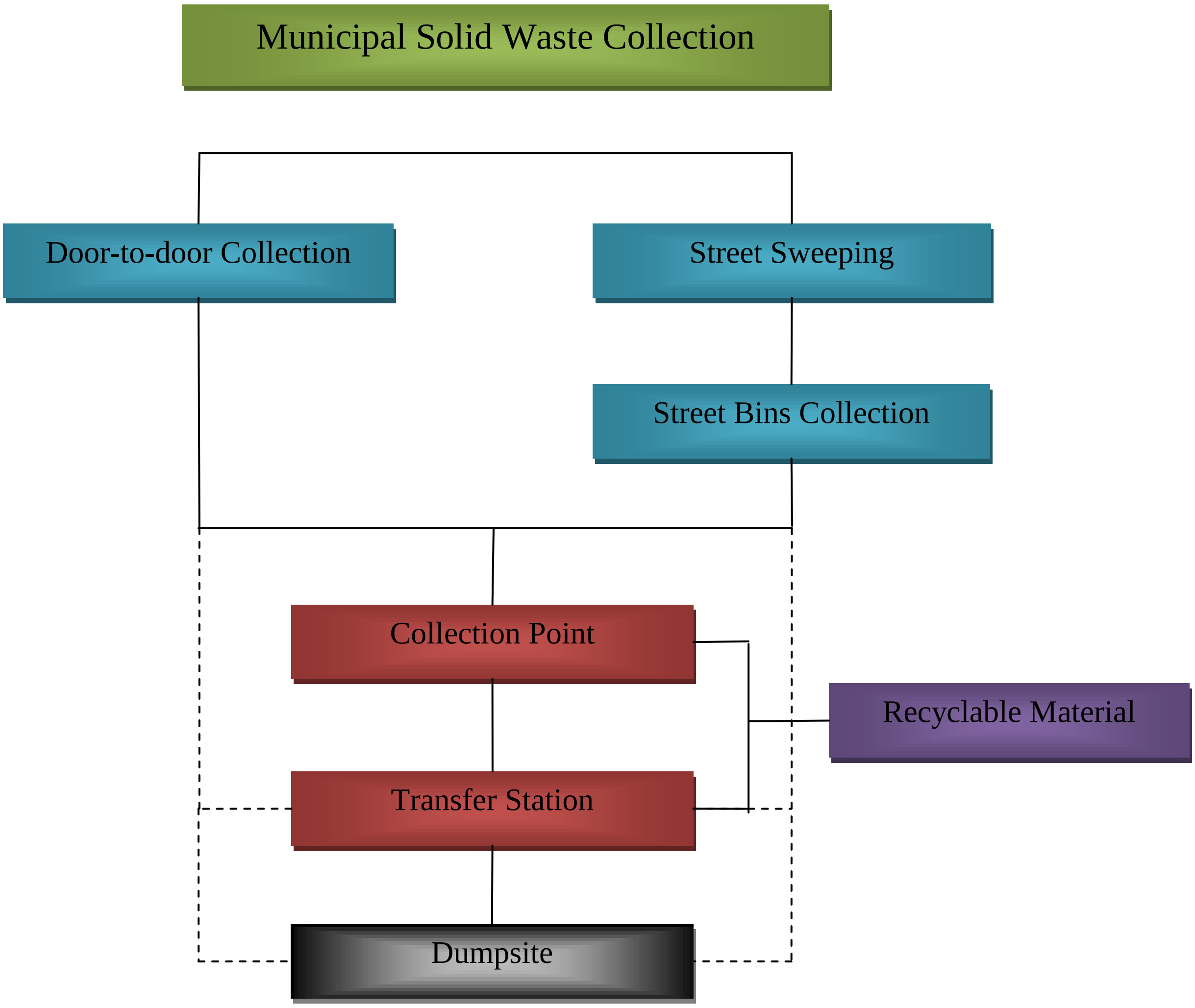


Figure 8 MSW collection scheme. [128]

- *Door-to-door collection:* Tricycles collect the waste from bins outside the households. These bins are emptied in larger bins placed on the tricycle. The households are supposed to segregate their domestic waste into two different bins, the organic waste in green bins and the recyclable waste in red bins. The bins are shown in figure 9. The tricycle then has corresponding red and green bins for the collected waste. This is however not totally implemented in Chennai at the moment. Few households have two

Figure 9 Bins used for segregation of waste. [39]

different bins. Nevertheless, the future goal is to implement two parallel waste streams, one organic and one inorganic. [128]

- *Street sweeping:* Street sweeping has become the principal method of primary collection in Chennai and other cities in India. [9] The street sweepers use short brooms to clear the streets from waste which then is put in bins along the roadsides. [39] Figure 10 shows an Indian street sweeper.

Figure 10 Indian street sweeper. [156]

- *Street bins collection:* Compactors collect the waste from the street bins. After the collection, the compactors transport the waste to a collection point, a transfer station or the dumpsite depending on which is closest. [128]

- *Collection point:* If the distance to the transfer station is far, the tricycles and compactors leave the waste at a collection point. At the collection point recyclable material such as plastic, paper and metal is segregated, often by ragpickers. The recyclable material is then sold to private scrap dealers. From the collection point, compactors transport the remaining waste to a transfer station. [64]

- *Transfer station:* At the transfer station machines lift the waste from the compactors or tricycles to a heavy vehicle, a four-wheel-drive lorry, which can be seen in figure 11. The Lorry transports the waste to a dumpsite for final disposal. Chennai has totally eight transfer stations, each for one zone, except for zones 6 and 10 that share transfer station. Zone 1 lies very close to Kodungaiyur dumpsite and therefore has neither collection point nor transfer station. [64]

Figure 11 Transfer station. [65]

2.3.3.2 Collection and Transportation by the CoC

The CoC is responsible for the collection of MSW in zones 1, 2, 4, 5, 7 and 9. The CoC has 9700 workers employed to handle the MSW in these six zones, most of whom are street sweepers. [128] The CoC's vehicles are coloured red, green and yellow. The tricycle used for door-to-door collection and the compactor can be seen in figure 12.

Figure 12 Tricycle collecting waste at door step (left) and compactor emptying a street bin (right). [128]

2.3.3.3 Collection and Transportation by Neel Metal Fanalca

Neel Metal Fanalca is responsible for the waste in the remaining four zones, except for demolition and construction waste and drainage water. 2700 people are employed by Neel Metal Fanalca to handle SWM in these four zones. The vehicles are white with a green leaf and marked Neel Metal Fanalca. [65] Figure 13 shows one of Neel Metal Fanalca’s vehicles.

Figure 13 Neel Metal Fanalca vehicle. [161]

2.3.4 Recycling

The CoC does not have a formal recycling program, whereas Neel Metal Fanalca recycles parts of their waste at their transfer stations. However, the informal sector takes care of the largest part of the recycling activities. This sector has formed a wide network with different hierarchical levels. Ragpickers, the lowest standing in this hierarchy, collect recyclable material in the streets, at collection points, transfer stations and dumpsites. [54] They sell the recyclable material to private dealers, who sell it to the recycling industry. This chapter will give an overview of recycling activities by Neel Metal Fanalca and recycling by the informal sector, in the form of ragpickers.

2.3.4.1 Recycling in the formal sector

Neel Metal Fanalca has employees working at the transfer stations to segregate the valuable material from the waste. The recycled fractions are sold to fixed prices shown in table 3.

Table 3 Market price for waste fractions. [133]

Waste fractions	[Rs./kg]	[$]
Plastic	13	0.27
Glass	1.5	0.031
Paper	3.5	0.073
Liquor bottles (coloured)	3	0.062
Liquor bottles (white)	11	0.23
Metal	7	0.15
Plastic bottles	11	0.23

Neel Metal Fanalca's vision is to segregate everything except the inert material. To be able to fulfil this goal, the public awareness has to increase. The segregation has to start at household level with segregation of organic and non-organic waste into separate bins. This is planned to be achieved through education campaigns to politicians, schools and people through public meetings. [133]

2.3.4.2 Ragpickers

About one fourth of the population in India live under the poverty line, which means that they have less than $1 per day per person. [2] For some of these people MSW becomes a source of income by recycling and reusing the waste. A large amount of the MSW generated is recycled through ragpickers. It is one of the poorest and marginalized groups of people in India. They are neither employed by the CoC nor do they get regular salaries. Because of this they are referred to as the informal sector. Nevertheless, they have a significant role in Chennai's MSWM. Each day ragpickers recycle approximately 400 tons of Chennai's MSW and thereby they reduce the transportation cost for the CoC. [54]

Since MSW contains hazardous waste including medical waste, the ragpickers are exposed to safety and health risks while walking around and segregating waste without any safety equipment. Ragpickers are not included in the general laws concerning employment, and therefore, will not get any help on the occasion of illness or accidents. [66]

Ragpickers scavenge for recyclable material such as paper, plastic, glass and metal. Each kilogram segregated waste is sold to waste dealers for a few rupees. Their daily income reaches from Rs. 40 to 100 ($0.83-$2.10). [67] The most valuable material is metal. In order to segregate the metals from the waste the ragpickers have historically started fires on the dumpsite. Burning of waste releases toxic compounds to the air, which cause health risks for the surrounding people. As an attempt to solve the problem the CoC decided in 2008 to ban the ragpickers from entering to the dumpsite. This decision has changed the livelihood for about 300 rag-picking families in Chennai and many of them are on the verge of starvation. [69]

2.3.5 MSW treatment

Today the management of MSW is going through a difficult phase in metropolitan cities because of the unavailability of facilities to treat and dispose the waste generated. The most common methods for treating MSW today in India are uncontrolled burning and unscientific disposal on open dumpsites.

The uncontrolled burning of waste is performed by locals in alleys in the city and in rural areas where MSWM is poorly developed. Furthermore, it is performed at dumpsites by ragpickers as a way to segregate the valuable metals from the waste.

In contrast to scientific landfills, open dumpsites do not have any collection of leachate water or capture of landfill gas, i.e. methane gas, neither do they use inert material to cover the waste. A description of the two dumpsites in Chennai is given in this section as well as future plans for MSW disposal.

2.3.5.1 Dumpsites in Chennai

At present, Chennai has two open dumpsites, Perungudi in the south and Kodungaiyur in the north, both of which are uncontrolled. These dumpsites are placed on marshy land, which used to be aquifers and bird sanctuaries. [37]

The northern zones dump their waste at Kodungaiyur dumpsite, which represent about half of the total amount of waste generated in Chennai. The other half comes from the southern zones and is dumped at Perungudi dumpsite. The characteristics of the two dumping grounds can be seen in table 4.

Table 4 Characteristics of Chennai´s two dumpsites. [70]

Dumping ground	Kodungaiyur	Perungudi
Location	North of Chennai (within the city) in zone 1	South of Chennai (outside the city)
Opening year	1980	1968
Neighbourhood within [km]	1	0.5
Daily Waste disposed [tons/day]	1400-1500	1500-1800
Disposal by [zones]	1-5	6-10
Area of disposal [ha]	140	80
Average height [m]	5	3.2

When the sun heats the glass material among the waste, the waste around get heated up which eventually starts small fires, as seen in figure 14. [120]

Figure 14 Perungudi dumpsite seen from outside. The second figure illustrates smoke from fires caused by glass material at the dumpsite [161]

2.3.4.4 Future MSW disposal
CMDA has not yet identified a new landfill site for future MSW disposal. The CoC is going to optimize and modernize the two existing dumpsites as well as minimize the waste going there, by processing and segregation (see chapter 5 for further description of future MSWM). This will extend the lifespan of the two existing dumpsites with 50-100 years according to CMDA. [135]

2.4 Environmental and health impacts of MSW treatment
Unscientific dumping and open burning are the least preferred treatments for MSW, causing severe environmental and health related problems. The following text will give an overview of how the MSWM in Chennai has affected the citizens and the surrounding environment.

2.4.1 Environmental and health impacts of open dumping
Because of the shortage of land in urban areas in India, areas not suitable for any other purposes are often chosen as dumpsites. Hence, these areas are often inappropriate for waste disposal. This is also the case in Chennai, where both the dumpsites are placed on marshland. This facilitates the spreading of toxic compounds to the groundwater. [120]

The Municipal Solid Waste (M&H) Rules, 2000, require that the site chosen for the dumpsite is suitable for this purpose. The site should be examined to make sure that it will meet certain criteria. The two dumpsites in Chennai only meet the requirements in the Municipal Solid Waste (M&H) Rules, 2000, on 4 out of 17 criteria. [37] Consequently pollutants are spread to the surrounding environment, affecting wildlife and humans.

The wetlands on which the two dumpsites in Chennai are placed are connected to the Bay of Bengal through canals and backwaters. Lead, mercury and dioxins affect the marine life as they bio-accumulate in fish and eventually also accumulate in humans while consuming fish. [37]

The contamination of the soil and groundwater as a result of not collecting the leachate water, leads to polluted water that people use for sanitary purposes. Every year thousands of people in India die from diarrhoea diseases caused by insufficient sanitation. [14] In Chennai, studies show that the residents around the dumpsites have to spend more money to purchase water and medicine than in other locations in the city. [73] Other problems due to open dumping are contamination of the surface water by the run-off from dumpsites, acidification of the soil, bad odour, pests, rodents and the spread of epidemics through stray animals. [15]

Another aspect is the biodiversity and ecological value that these areas had before they became dumpsites, considering the fact that these lands used to serve as aquifers and bird sanctuaries.

2.4.1.1 Emissions of methane (CH_4) due to open dumping
Dumpsites are also a large source of methane gas. Since methane is a 21 times more aggressive greenhouse gas than carbon dioxide it will have an impact on global warming on a large scale. India is currently one of the world’s largest methane emitters from solid waste disposal. [10] Appendix 4 shows the calculation of methane emissions from Chennai’s dumpsites with the first-order decay model. [75] The result shows that the methane gas

emitted in Chennai during 2008 was 28 000 tons (595 000 tons CO_2 eq). According to data from 2004, Chennai accounted for 6 percent of India's methane emissions from landfills.

2.4.2 Environmental and health impacts of uncontrolled burning

The health effects from open burning have become more noticeable the recent years in Chennai. In the daily newspapers there are constant articles about people living close to the dumpsites who complain about health problems such as rashes and suffocation, due to the pollution from the fires started by ragpickers. [68]

The emissions from uncontrolled burning of waste depend on the combustion process and on the composition of waste. Table 5 describes how different emissions are created and their effect on the environment and health.

If combustion takes place in an incineration plant, the burning process can be controlled and optimized for good incineration conditions. Moreover, the created pollutants can be reduced with flue gas treatment. Open burning on the other hand, will release the pollutants directly to the atmosphere. [17]

Table 5 Description of how different emissions are created and their effect on the environment and health. [152]

Emissions	The formation is due to:	Gives the following effect on health and environment:
Nitrogen oxides (NOX)	• The nitrogen content of the fuel	• Acidification • Eutrophication • Contributes to the formation of ambient ozone • Poisons the blood if inhaled
Sulphur dioxide (SO2)	• The sulphur content of the fuel • The combustion process: temperature, oxygen concentration and duration	• Acidification • Health effects for persons with inhalation problems
Carbon dioxide (CO2)	• The carbon content of the fuel	• Contributes to the greenhouse effect (only the carbon with fossil origin contributes)
Carbon monoxide (CO)	• The combustion process: Created when the supply is scarce	• Harmful to the cardiovascular system
Voltaic organic compounds (VOC)	• The combustion process: Created when the oxygen supply is scarce	• Cancerogenic • Contributes to the formation of ambient ozone • Methane is a VOC that contributes to the greenhouse effect
Dust	• The ash content of the waste • The combustion process	• Harmful if inhaled, heavy metals get stuck to particles which is transported to the lungs
Nitrous oxide (N2O)	• The combustion process: Crated at low combustion temperatures	• Contributes to the greenhouse effect
Heavy metals (Cd, Pb, Hg et al)	• The heavy metal content of the fuel	• Most heavy metals are toxic to human and wildlife
Hydrogen chloride (HCl)	• The combustion process: The combustion temperature, the oxygen supply, the presence of catalyst • The PVC content in the waste i.e. the chlorinated material in the fuel	• Acidification
Dioxins	• The chloride content in the presence of copper, which works as a catalyst	• Can cause cancer while accumulating in fatty tissues in human and wildlife

The most significant effect on the local environment and people's health around the dumpsite due to open burning are the emissions of dioxins. The following will give a deeper analysis of the dioxin concentration around one of the dumpsites in Chennai.

2.4.2.2 Emissions of dioxins due to open burning

Open burning is a significant source of high dioxin concentrations in the soil and air around the dumpsites. Dioxins are toxic pollutants which are created when MSW is burned. Appendix 13 gives a brief explanation of dioxins. The major source of dioxin is burning of chlorinated waste such as polyvinyl chloride (PVC). [79]

A study conducted by Minh et al. (2003) [79] in collaboration with Annamalai University in Tamil Nadu measured the concentrations of the dioxins PCDDs, PCDFs and PCBs around Perungudi dumpsite. The concentration of the dioxins in the soil at the dumpsite was compared to a reference site, a control site, at least 30 km away from any dumpsite. The result showed a 224 times higher concentration of PCDD/Fs at the dumpsite compared to the control site. For PCBs it was 238 times higher. The concentrations of PCDD/Fs and PCBs with the Toxic Equivalent (TEQs) can be seen in table 6.

Table 6 Concentration of PCDD/Fs and PCBs in soil samples from Perungudi dumpsite and a control site. [79]

	Perungudi dumpsite		Control site	
	[pg/g dry weight]	[TEQs]	[pg/g dry weight]	[TEQs]
Total PCDD/Fs	7 400	47	33	0.2
Range PCDD/Fs	2 200-34 000	9.9 -200	18-79	0.05-0.34
Total PCBs	6 670	5.1	28	0.022
Range PCBs	1 300-20 000	2.4-10	12-52	0.015-0.029

Furthermore the study looks at the exposure of dioxins to humans living near the dumpsite. Dioxins are lipophilic and enter fatty tissues in human and wildlife either direct through dermal absorption and inhalation of dust from polluted soil or indirect by consuming food grown in contaminated areas. The assessment was implemented on two groups of people, ragpickers at the dumpsite and people living far away from the dumpsite who were the control group. More than a hundred people were daily observed at Perungudi dumpsite when the study was conducted in 2000. The results are displayed divided into adults and children in table 7. It is seen that children's intake through ingestion is eleven times higher than for adults. The people at the dumpsite had around 260 times higher concentrations of dioxins in the fatty tissues compared to the control site for both children and adults. [79]

Table 7 Estimated intakes of PCDD/Fs for children and adults via soil ingestion and dermal exposure. [79]

	Perungudi dumpsite		Control site	
	Adult	Child	Adult	Child
Soil ingestion [pg TEQ/kg/day]	0.0152	0.1730	0.00006	0.00067
Dermal exposure [pg TEQ/kg/day]	0.0361	0.0310	0.00014	0.00012

2.5 Characteristics of MSW in Chennai

The waste composition depends on several factors such as income, climate, culture, food habits and lifestyle etc. [24] MSW in low-income countries contains a larger fraction of organic matter and less recyclable material than high-income countries due to different life style and consumption patterns. The waste in low-income countries also has a high percentage of inert material. The reason is first of all the high amount of ash from the traditional use of biomass as fuel and secondly the daily activities of street sweeping.

2.5.1 The Composition of MSW in Chennai

There are two main studies made analysing the composition and the chemical characteristics of the MSW generated in Chennai. The first analysis is made by the CoC in 2003 and the second analysis is made by the National Environmental Engineering Research Institute (NEERI) in 2006. [54] [128] Depending on where the analyses are made, if they are made on the dumpsite or earlier in the waste stream, the results could differ. In these cases the MSW is assumed to be from the dumpsite. Figure 15 illustrates the composition of the MSW generated in Chennai.

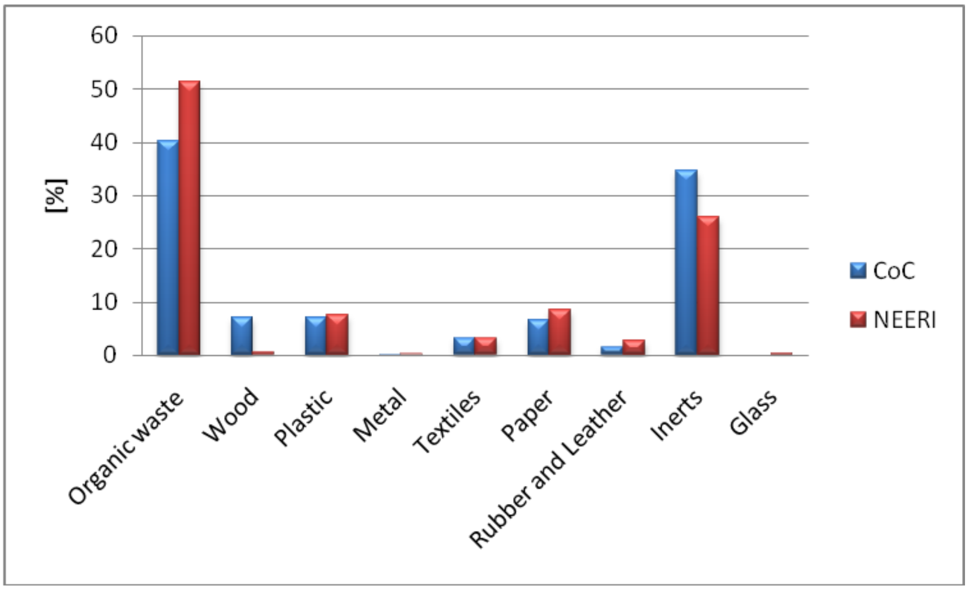


Figure 15 Analysis of the composition of MSW in Chennai, made by the CoC (2003) and NEERI (2006). [49] [54]

The result shows that the two largest fractions of the MSW are organic waste and inert material.

2.5.1.1 Organic waste

The organic components consist of kitchen waste and green waste. Green waste consists of garden waste and waste from agricultural operations. Figure 16 illustrates the relation between the two components. Since the year 2000, there has been a ban for dumping organic waste in India according to the Municipal Solid Waste (M&H) Rules, 2000. The rules require that all organic waste should be segregated and processed, with the aim to reduce methane production in the dumpsites. However, the CoC and other municipalities throughout the country experience difficulties monitoring and enforcing this rule. [10]

Figure 16 Analysis of the composition of organic matter in Chennai, made by the CoC 2003. [49]

2.5.1.2 Recyclable Waste

The recyclable waste in Chennai consists of plastic, paper, metals and glass. As shown in figure 17, the fraction of paper and plastic is very high. Since metal is removed by ragpickers for their high re-sale value, the fraction found on the dumpsites is very low.

The plastic waste can be divided in two different categories: thermoplastics and thermoset plastics. They stand for 80 percent and 20 percent respectively, of the consumer plastic waste generated in India. The thermoplastics are recyclable plastic and consist of Polyethylene Terephthalate (PET), Low Density Poly Ethylene (LDPE), Poly Vinyl Chloride (PVC) etc. while thermoset plastics are non-recyclable and contain alkyd, epoxy, ester, melamine formaldehyde, polyurethane etc. [81]

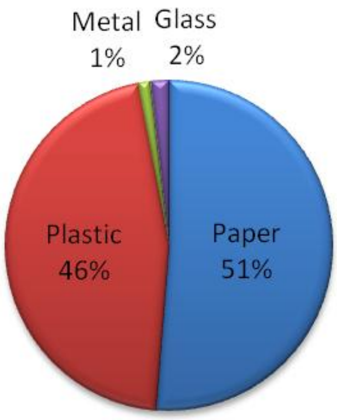


Figure 17 Analysis of the composition of the recyclable fraction in Chennai, made by NERRI (2006). [54]

2.5.1.3 Inert Material

The inert material in the MSW in Chennai consists of bricks, sand, stone and silt. The largest part of this waste comes from street sweeping and illegal dumping of construction and demolition waste. [128]

2.5.2 Chemical characteristics of MSW

The chemical characteristics of the MSW in Chennai are illustrated in table 8.

Table 8 The chemical characteristics of the MSW in Chennai, based on analysis made by the CoC (2003) and NEERI (2006). [49] [54]

Characteristics	CoC	NEERI
Moisture content [%]	27.6	47.0
Ph value	7.7	6.2-8.1
Volatile matter at 550°C [%]	no data	42.6
Carbon [%]	21.5	24.7
Nitrogen Content [%]	0.8	0.9
Phosphorus as P_2O_3 [%]	0.6	0.4
Potassium as K_2O [%]	0.6	0.9
C/N Ratio [%]	no data	29.3

2.5.3 Heating value

The heating value of a fuel is the amount of heat released by a specific quantity of the fuel at complete combustion. Two types of heating value are defined, a lower and a higher. The lower heating value takes into consideration the amount of energy needed to vaporize the moisture in the fuel. The higher heating value on the other hand includes this energy. It is thereby important to define if it is the higher or lower value that is given, to be able to make a comparison.

According to the CoC the lower heating value of the MSW in Chennai is between 1.1 and 1.2 MWh/ton, (946-1032 kcal/kg), which is a value given for India in general. [136]

Since knowing that the heating value of the MSW in Chennai is an important factor for deciding if this waste is suitable for combustion, the heating value has also been estimated numerically. There are different methods to calculate the heating value of a fuel. A common method is to use the Dulong's formula, as described in box 1. This method takes into account the content of moisture, carbon, hydrogen, oxygen, nitrogen and sulphur in the fuel. Given the information about the content of these substances in each component of MSW, given in appendix 6, and the information about the percentage of each component in the MSW, the total heating value of the mixed MSW can be calculated. The result shows that the lower heating value of the MSW in Chennai is 1.6 MWh/ton (1376 kcal/kg).

Box 1 Estimation of the heating value of MSW in Chennai
The heating value of a fuel can be calculated using the Dulong's formula [100]:

$$Hi = 0.339 \cdot c + 0.105 \cdot s + \left(h - \frac{o}{8}\right) - 0.0251 \cdot w$$

$$Hs = Hi + \frac{2.5}{100} \cdot (9 \cdot h + w)$$

Where:

Hi	Lower heating value [MJ/kg]
Hs	Higher heating value [MJ/kg]
c	coal [mass%]
s	sulphur [mass%]
h	hydrogen [mass%]
o	oxygen [mass%]
w	water [mass%]

Assumptions:

	Mass percentage of specific substances in MSW					
Study	m(w) (%)	m(c) (%)	m(h) (%)	m(o) (%)	m(n) (%)	m(s) (%)
CoC	31.7	16.8	2.4	12.1	0.6	0.06
NEERI	38.8	16.8	2.4	12.1	0.7	0.06

The mass percentage of the substances in MSW in Chennai, was calculated from the information about the energy content in each component of the waste. (see appendix 6)

Result:

	LHV (Hi)		HHV (Hs)	
Study	MWh/ton	kcal/kg	MWh/ton	kcal/kg
CoC	1.6	1376	2.0	1720
NEERI	1.6	1376	2.0	1720

According to Dulong's formula both the studies show that the lower heating value in Chennai is 1.6 MWh/ton (1376 kcal/kg) and the higher is 2.0 MWh/ton (1720 kcal/kg).

2.5.4 Future waste characteristics

Future waste characteristics in India and Chennai will be more similar to those in high-income countries, with more recyclable material, less inert components and the organic fraction will be proportionally smaller. Thus, the heating value will be higher. More packaging material will increase the need for more environmental friendly material for a sustainable development. Today, one fourth of the plastic material used in India consists of PVC, which is a chemical that is almost phased out in many high income countries. [25]

2.6 Electricity production in Chennai

This chapter will give an overview of the electricity situation in Chennai and the possibility to produce electricity from MSW.

2.6.1 The electricity situation in Chennai

Today Chennai suffers from daily power cuts, which can last for hours. The power cuts vary in length and differ between areas in Chennai, though a normal power cut lasts one to two hours. [86] Many of the power cuts are announced, meaning that the time and the area of a power cut are decided in advance. A consequence of this is that many citizens plan their working days after the power cuts, resulting in loss of productivity and disturbances in the daily life.

The shortage of electricity in Chennai and in many cities in India is partly because the government has not been able to keep up with the country's economic growth the recent years. Hence, the installed capacity of power stations has not been enough to cover the demand. In January 2009 Tamil Nadu suffered an electricity deficit of 7.3 percent and the shortage during peak hours was 853 MW which can be seen in table 9. [84]

Table 9 Tamil Nadu's power supply and peak demand in January 2009. [84]

Power Supply in Tamil Nadu January 2009			
		Surplus/Deficit (-)	
Requirement [MWh]	Availability [MWh]	[MWh]	[%]
5243	4860	-383	-7.3
Peak demand/Peak met in Tamil Nadu January 2009			
		Surplus/Deficit (-)	
Peak demand [MW]	Peak met [MW]	[MW]	[%]
9180	8327	-853	-9.3

The power disruptions are a problematic issue especially for the industries in Chennai. The city hosts 30 percent of India's automobile industry and 35 percent of India's auto component industry. [82] Moreover, 14 percent of India's total software exports come from Chennai. [83] The power interruptions affect the industries that get an irregular working week, resulting in loss of productivity. [134] For several industries the power disruptions have caused increased production costs. Nevertheless, for fear of losing business, the extra cost is not passed on to the consumers, resulting in closing of small-scale industries. [85] Besides from industries, other examples of sectors that suffer hard from the power cuts are hospitals and educational institutions, even though the government claims that essential service should not be affected. [86]

2.6.1.1 The governmental actors responsible for electricity production

The Central Electricity Authority (CEA) is the national authority responsible for matters regarding electricity production, transmission and distribution. They advise the government on questions relating to national electricity policy and they formulate plans for development of the electricity system. [27]

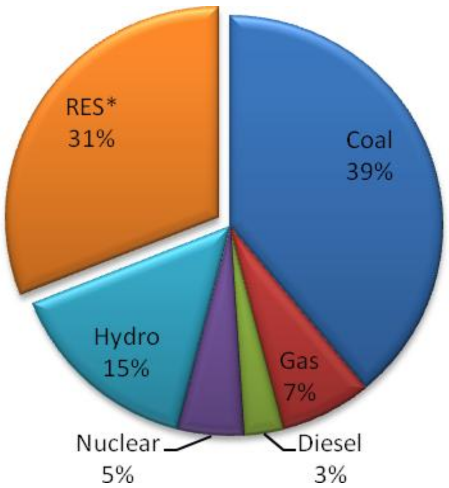
Tamil Nadu Electricity Board (TNEB), which is the state government energy supplier in Tamil Nadu, is the only licensed energy distributor in Tamil Nadu. TNEB generates, transmits and distributes electricity. [87] 50 percent of the electricity in Tamil Nadu is produced by TNEB. The remaining electricity is provided from the national grid or by private producers. [137]

2.6.1.2 The price for electricity

An electricity producing company can sell the generated electricity to TNEB for approximately Rs. 3/kWh ($0.062/kWh). Depending on what fuel this company uses, the price differs slightly. If the company uses renewable energy sources the price is Rs. 3.15/kWh ($0.065/kWh). The TNEB sells the electricity to the users of electricity in the state of Tamil Nadu. Depending on the user, the price for electricity differs. For industries the price is Rs. 6/kWh ($0.12/kWh) while it is Rs. 2.5/kWh ($0.052/kWh) for residences. For the agricultural sector, electricity is provided for free because of their difficult financial situation. [130]

2.6.2 Installed capacity of power stations in Tamil Nadu

The total installed capacity of power plants in Tamil Nadu was 14 GW on January 2009. A power station can be owned by the government of India, a state government or by private companies. The ownership of power stations in each energy sector is specified in appendix 1. Tamil Nadu's energy mix is seen in figure 18. The installed capacity from Renewable Energy Sources (RES) was slightly above 4 GW which corresponds to 31 percent. This makes Tamil Nadu the state in India with the highest rate of renewable energy sources. [88] Discounting larger hydropower plants, the main non-conventional energy source in Tamil Nadu is wind energy. [130]



*Renewable energy sources (RES) includes small hydro power plants (up to 25 MW), wind energy, bio energy and waste energy.

Figure 18 Installed capacity in Tamil Nadu, January 2009. [88]

2.6.3 Future electricity production

The Indian government has specified a goal in the 11th New and Renewable Energy five-year plan, which tells that 10 percent of the power generation capacity should come from renewable sources by the end of the year 2012. [16] This number does not include hydropower plants larger than 25 MW. Compared to Chennai which has a share of 31 percent renewable energy sources in their energy mix, India as a whole only has 9 percent, (as on 31 January 2009). The increased demand for electricity the upcoming years will impose the development for electricity production from renewable energies.

2.6.3.1 Potential for power generation from MSW

Waste-to-energy will play an important role to reach the target of 10 percent power generation from renewable sources. The installed power capacity from waste-to-energy plant in India was 90 MW on 31 January 2009, of which 31 MW was produced in captive power plants meaning that the power plant use the energy produced for their own use. [121], [29] Today, the largest part of the power generated from waste comes from agricultural waste. However, both industrial waste and MSW are interesting for power generation.

A few projects already exist in India with power generation from MSW, whereas in Chennai no such projects exist. Nevertheless, the growing amount of garbage and the electricity deficit in Tamil Nadu have opened the discussion further for future MSW-to-energy alternatives. Except for contributing with electricity to the grid, future electricity production from MSW would have benefits such as

- replacing fossil fuel, which is the most common fuel for electricity production in Tamil Nadu
- prolonging the lifespan of the two overfilled dumpsites in Chennai, since less waste will be dumped
- decreasing the pollution related to open dumping.

2.7 The current situation for MSW-to-energy

The technology of producing energy from MSW has been accepted and proven worldwide. In India on the other hand, the viability of this technology is yet to be demonstrated. As mentioned above, there are no current activities for producing energy from MSW in Chennai. Yet, in other cities in India MSW-to-energy projects have been commissioned, more or less successfully during the last decade. The following chapter will give an insight into these projects in order to better understand the challenges with implementing an MSW-to-energy project in Chennai.

2.7.1 Combustion

Combustion is an exothermic chemical reaction that occurs when a fuel is heated in an oxygen rich environment. When energy is extracted from burning of MSW, the combustion takes place in a closed combustion chamber with surplus of air and temperature range of 700-1300 degrees. The incineration techniques and flue gas treatments are described more thoroughly in chapter 5 and appendix 12. There are two options which are commonly used for combustion of MSW:

- Mass burning
- Combustion of RDF

Mass burning of MSW is a common method for waste reduction and energy recovery in high-income countries. The waste is burnt directly in a boiler without processing it further to pellets or “fluff”. It requires waste with sufficient heating value to sustain combustion. However, in India and other developing countries, this technology is not much practiced.

If the burnable fraction of MSW is sorted out and further homogenized the result is called Refuse Derived Fuel or shortly RDF. For a more detailed description of the segregation process see section 3.1.2. In developing countries it is more common to incinerate RDF than MSW, since the heating value of the MSW is often too low to sustain combustion. Since the inert and organic waste is sorted out from the RDF fraction, the heating value will be higher than for MSW. The RDF can be combusted in a fluidized bed or in a grate, co-incinerated in industrial boilers or used in pyrolysis and gasification systems. The steam generated from the process can be used to produce energy. [30]

2.7.1.1 Mass burning plants in India

Today there are no operating incineration plants for direct incineration of MSW in India. There have been failed projects in the past, which has strengthened the opinion that direct incineration is not suitable for Indian waste. [9] Box 2 describes one of these projects. Nevertheless, in many cities small incinerators are used for burning bio-medical and hazardous waste.

Box 2 Mass burning plant in Timarpur, New Delhi

The first large scale incineration plant in India was commissioned at Timarpur, New Delhi in 1987 by MNES, with the support of the Danish Firm Vølund Miljøteknik A/S. It cost about Rs. 250 million ($5.2 million) and was projected to produce 3.7 MW electricity. It was designed to process MSW that had an average heating value of 1.7 MWh/ton (1462 kcal/kg) and an approximate moisture content of 15 percent. [11] After 6 months the plant was out of operation and the Municipal Corporation of Delhi had to close down the plant. The main reason for the poor performance of the plant was a mismatch of the plant design and the waste processed. [31]

2.7.1.2 RDF plants in India

RDF plants are in the initial stage of development in India. There are numbers of projects that are operating all over India, more or less successful. The two projects described in box 3 are examples of plants that have been proven successful and have generated electricity to the grid.

Box 3 RDF plants in Hyderabad and Vijayawada

Hyderabad
A 6 MW power plant was set up in Hydrerabad in November 2003, based on combustion of RDF. The project was performed by SELCO International Ltd, Hyderabad and financed by soft loans from the Technology Development Board (TDB), the Department of Science and Technologies (DST) and the Indian Renewable Energy development Agency (IREDA). The plant cost about Rs. 400 million ($8.3 million) and is based on indigenous technology.

The MSW is firstly converted into fluff or pellets of RDF and then combusted in a boiler. The heating value of the RDF is around 3.5-4.1 MWh/ton (3010-3526 kcal/kg). The steam generated in the boiler is used to run a steam turbine and generate electricity. From November 2003 till January 2005 the plant had generated 35 GWh of electricity. [32]

Vijayawada
In Vijayawada a 6 MW power project was commissioned in December 2003, based on combustion of RDF. It was performed by Shiram Energy Systems, Hyderabad and financed with soft loans from TDB and IREDA. The cost for the project was about Rs. 450 million ($9.4 million).

A total amount of 500 tons of MSW is being collected from the urban areas of Vijayawada and Guntur every day. The MSW is firstly transported to various sites where the waste is processed and converted into fluff of RDF and thereafter transported to the plant site where the electricity generation takes place. The plant is operating at full capacity and had generated 28 GWh of electricity from the day it was commission until January 2005. [32]

2.7.2 Pyrolysis and gasification

Pyrolysis and gasification are similar to combustion in that manner that they are thermal processes that use high temperature to break down the waste. The main difference from combustion is that they use less oxygen. Pyrolysis degrades waste in the absence of air while gasification uses some oxygen, but not enough to start the combustion. Gasification refers to the production of gaseous components, whereas pyrolysis produces liquid residues and charcoal. The syngas generated from the gasification process mostly consists of carbon monoxide and hydrogen and could be used in gas turbines to produce electricity. Today, energy production from gasification of MSW is in the development stage and it has not yet been proven viable on a commercial scale. [33]

2.7.2.1 Pyrolysis and gasification plants in India

There are currently no commercial pyrolysis and gasification plants for treating MSW in India. [9] However, there exist gasifiers for biomass applications such as agricultural waste, sawmill dust and forest waste. [31]

2.7.3 Sanitary landfill with energy recovery

There are four basic conditions that need to be fulfilled in order for a landfill site to be called a sanitary landfill:

- The landfill site should either be located on land which naturally contains leachate security, or the site should have additional lining materials to prevent leachate to reach the ground water and surrounding soil. Leachate collection and treatment is a basic requirement.
- The design of the landfill should be developed from geological and hydro geological investigations made by engineers.
- Trained staff should be based at the landfill for regular maintenance of the plant and supervision.
- The waste should be spread in layers and compacted. [34]

The degradation of organic waste results in production of landfill gas, which has a methane content of 25-55 percent. The gas can be collected and used for energy recovery. [35]

2.7.3.1 Sanitary landfills with energy recovery in India

There was not a single sanitary landfill site in India, until just recently. All cities in India disposed their waste unscientifically in low-lying areas without pollution prevention measures taken. Along with the Municipal Solid Waste (M&H) Rules, 2000, the local bodies started to more actively take measures towards the treatments of MSW. Today there are landfill sites in Surat, Pune, Puttur and Karwar and some more sites are under construction. [9]

There are currently no projects in India that recover energy from the landfill gas captured. However, pre-feasibility studies and/or pump tests have been commissioned on dumpsites in Mumbai, Delhi, Ahmedabad, Hyderabad and Pune which speaks for the realisation of landfill gas-to-energy projects in the near future. [10]

2.7.4 Anaerobic biomethanation

Anaerobic digestion is a biological process where organic material is decomposed by microorganisms under anaerobic condition. The result is generation of biogas, which consists of 55-60 percent methane. The process is similar to the decomposition taking place in landfills, yet more advantageous since it has a more efficient methane formation. One ton of anaerobic digested MSW can produce 2-4 times more methane in three weeks than one ton of landfilled MSW in 6-7 years. The waste from the biomethanation process can be used as compost for soil conditioning. [31] The biogas can be used for energy production or alternatively engine fuel.

2.7.4.1 Biomethanation plants in India

Biomethanation is a relatively well-established technology for treatment of agricultural waste and sewage sludge in India. Even though the application for the organic fraction of MSW is less common, there exist smaller projects in the country for this purpose. [9]

Biomethanation on a small scale is a proven technology in Lucknow and in other cities in India. In these cities, selected organic waste from canteens, vegetable markets etc, is used. Box 4 gives more information about the plant in Lucknow. [9]

Box 4 Biomethanation plant in Lucknow
A 5 MW MSW-based power project was established at Lucknow in December 2003, based on high-rate biomethanation technology. It was executed by Asia Bio-energy Ltd, Chennai on BOOM (Build, Own, Operate and Maintenance) basis. The technology is developed and commercialized by Environment Technology (ENTEC), Austria and the project cost was about Rs. 740 million ($15 million). [32]

The plant is designed to take care of about 500-600 tons of MSW every day from Lucknow city. This amount of MSW is converted into 115 tons of dry volatile solids, which produce about 50 000 m^3 of biogas and 75 tons of organic fertilizer. The biogas generated is used for electricity production to the grid. Even though the plant is dimensioned for 5 MW electric power, it has only reached a maximum limit of 1 MW since it was commissioned. The main problem achieving its designed capacity has been the difficulties of getting segregated and source collected biodegradable MSW to the plant. [32]

2.7.5 MSW to products

By segregating, processing and recycling the MSW, the amount of waste that needs to be managed decreases. It is an energy conserving process, since recycling of material replaces the virgin material needed for the manufacturing of new products.

The segregation can be done manually in the households or mechanically in processing plants. In many developed countries it is common for each household to segregate the MSW manually in different bins. The separated fractions are then transported to industries for processing and recycling. In developing countries manual segregation has proven to be difficult due to lack of infrastructure. [128] An alternative method is mechanical segregation in processing plants. Besides from recyclables such as plastic, metal and paper that can be segregated manually, the plant enables mechanical segregation of inert material, organic and burnable fraction. Further processing of these fractions could give bricks, compost and RDF respectively, which can be sold on the open market. [37]

During the last years, numbers of processing plants have been set up in India that manually and mechanically segregates the MSW. The main incentives for these plants have been the income possibilities from selling recyclables, compost and bricks as well as selling RDF or selling the electricity generated from combusting RDF. Since these processing plants have numbers of environmental benefits, there are possibilities of getting subsidies from the government and income through CDM (see appendix 9 and section 4.2.1.3), which gives these project stronger financial viability.

2.7.5.1 Bricks

The inert material of the MSW can be recycled and used for manufacturing of bricks. These bricks are not as robust as cement bricks, which make them less suitable for quality construction work. Yet, they are interesting for less sensitive construction work such as sidewalks. [123]

2.7.5.2 Compost

Aerobic composting is the decomposition of organic material by microorganisms to produce humus-like material called compost. It is suitable for the organic fraction of the MSW and agricultural waste such as garden waste, waste from slaughter houses and dairy waste. The compost is most commonly used as soil conditioning.

There are different types of composting technologies, *windrow composting* and *vermi composting* being two common methods:

- *Windrow composting* is a method where the waste is piled in elongated rows to allow diffusion of oxygen and retention of heat. The piles are regularly turned to increase the porosity and facilitate the diffusion of air. It is suitable for large-scale applications. [38]
- *Vermi composting* is a process where the organic fraction is converted to compost through the action of worms. This method is especially suitable in smaller towns since it is easy to operate and the technology required is rather simple. [9]

Farmers in India have been using composting for many years to process agricultural waste and cow dung, for the purpose of soil conditioner improvement. The application for MSW has been proven successful and demonstrated in numbers of cities in India. Windrow composting has been found most relevant for large-scale applications and vermi composting more relevant in smaller scale. [9] 106 small scale composting units have been introduced in Chennai on ward level. [64]

2.7.5.3 RDF

As described earlier in the text, RDF is processed from the burnable fraction of the MSW. The RDF can be chopped to a fluffy fraction called RDF-fluff or it can be further processed to pellets, which can be sold on the open market or used directly. [37]

2.7.5.4 The processing plant in Ichalkaranji

An example of a processing plant in India is the one that the company Hydroair Tectonics Ltd from Mumbai, has set up in Ichalkaranji. The 300 tons of MSW per day that arrives to the plant is segregated into recyclables, inert material, burnable waste and organic waste. The recyclables are sold directly to scrap dealers for re-sale value while the other fractions are processed further to bricks, RDF-fluff and compost respectively. At present there is no electricity production from the RDF-fluff at the plant-site, instead the fluff is sold to industries as a substitute for coal. [123]

3 Future MSW-to-energy in Chennai

The problems that Chennai Corporation has been facing during the last years regarding solid waste management and electricity production have become more manifest today than ever. The two dumpsites in Chennai, Kodungaiyur and Perungudi, are overfilled with waste and the residents in Tamil Nadu are getting tired of planning their daily routines after the announced and unannounced power cuts. This, together with stricter regulation from the government has made Chennai Corporation more actively work towards changing the situation.

This chapter will describe future MSW management in Chennai. In the sections where the source is not given, the facts are based on Hydroair Tectonics internal documents. [37]

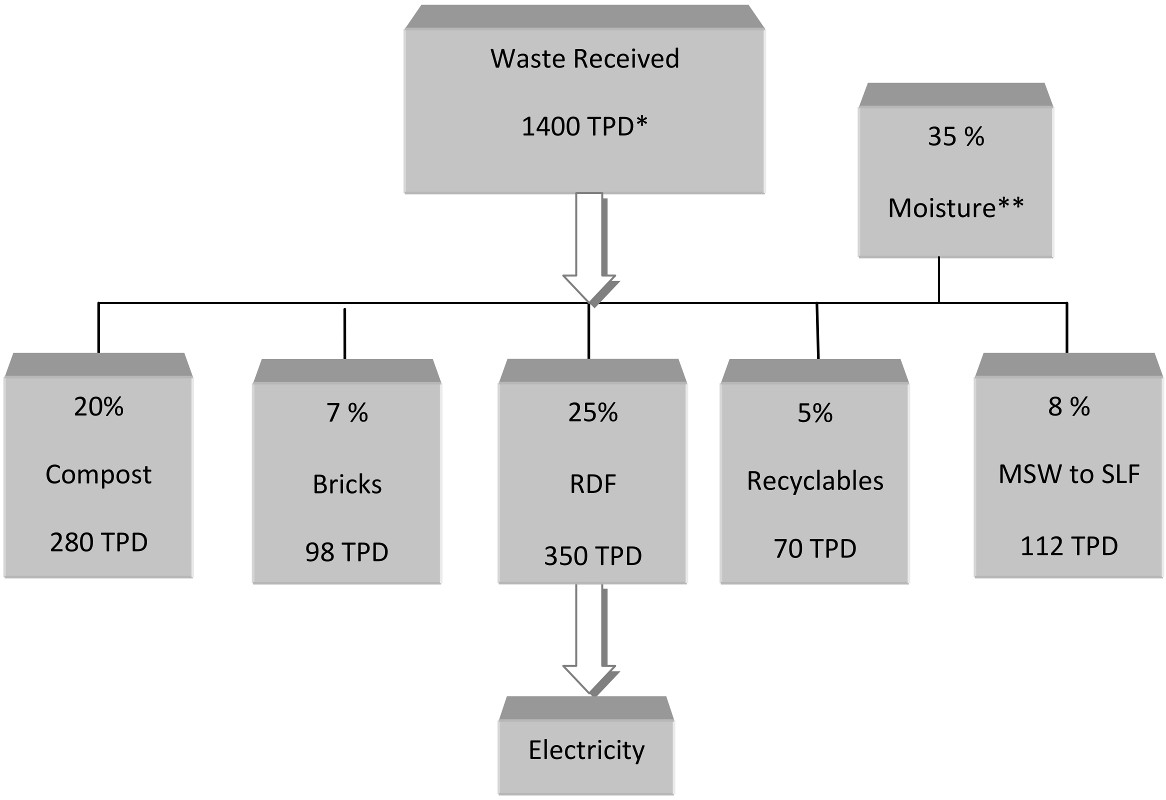
3.1 Hydroair Tectonics

Recently, the company Hydroair Tectonics Ltd from Mumbai has signed a contract with Chennai Corporation to take care of the waste going to Perungudi dumpsite. An area of 30 acres is provided by the CoC at Perungudi dumping ground. In return the company needs to pay a royalty fee to the CoC of Rs. 15/ton ($0.31/ton) of MSW.

3.1.1 The processing plant

The company will set up an integrated MSW treatment plant at Perungudi dumping ground in Chennai, which is going to process 1400 tons of MSW every day. It is going to be two segregation units, each processing 700 tons of MSW per day. M/S Shiram Energy Systems Ltd is an associate for this project. They have implemented the 6 MW processing plant in Hyderabad which has been operating successfully since 2003 (see box 3 section 2.7.1.2).

The MSW will be segregated into the following fractions: recyclables, inert material, compostable fractions and burnable waste. The segregation is made both manually and mechanically. The incoming waste is initially weighted on a weight bridge, tipped on a tipping ground and then processed according to figure 19.



*TPD=tons per day
**Here it is not sure whether this is the natural moisture in the waste or if this is moisture in excess of the natural moisture

Figure 19 Estimated flowchart of the processing of waste at Perungudi dumpsite in Chennai. [37]

The compostable and inert components are segregated and processed to compost and bricks respectively. The burnable material is separated and chopped to Refuse Derived Fuel (RDF) which can be used in a boiler to produce electricity. Most of the recyclable components will be segregated and sold to scrap dealers, for resale value. Larger inert components and other waste that is not suitable for recycling or biological processing will be put on a sanitary landfill. More than one third of the waste received at the plant consists of moisture. Leachate water will be collected and processed in a treatment plant.

3.1.1.1 Compliance with the Municipal Solid Waste (M&H) Rules, 2000

The technology used will meet the requirements of The Municipal Solid Waste (M&H) Rules 2000, in line with the following rules:

- Biodegradable Waste will be processed by composting only.
- Compost or any other end products will comply with standards as specified in Schedule-IV of The Municipal Solid Waste (M&H) Rules, 2000.
- Land filling shall be restricted to non-biodegradable, inert waste and other waste that are not suitable either for recycling or for biological processing.

3.1.2 MSW to products

A large part of the financial income of the plant will be revenues from selling the products generated from the segregation process. The products are recyclables, compost, RDF and bricks. If Hydroair Tectonics builds a unit for burning RDF with energy recovery in the future, the primary product will be electricity.

The following text will give a short description of the manufacturing process of the products and the segregation process, based on facts from the existing plant in Ichalkaranji.

3.1.2.1 Compost

1. When the large stone blocks and recyclables have been sorted out manually from the waste at the tipping ground, the segregation of the compostable fraction starts. The MSW is fed into a drum machine with holes measuring 80 mm in diameter. The compostable fraction, mixed with the inert material, passes through the holes. The remaining waste makes up the burnable fraction, which is going to be processed to RDF. The segregation unit is shown in figure 20.

Figure 20 Segregation unit for separation of the organic and inert components. [37]

The compostable fraction mixed with inert material is used for aerobic composting in windrows. The waste is processed for 35 days with regular stir and mixing with bio-culture, which accelerates the degradation, as seen in figure 21.

Figure 21 Bioculture is sprayed on the windrows. [37]

2. The processed waste is passed on to the second mechanical segregation step, which is a drum machine with holes measuring 20 mm in diameter. The larger fractions of inert material will be separated and sent to a sanitary landfill or to a stone crusher.
3. The remaining waste will continue to the next segregation step, which is based on gravity separation. Air is added from below and the inert fraction with higher density is separated from the compostable fraction.

4. The final segregation step, before the compostable fraction can be used as compost, is the magnetic separator which separates small components of metals from the organic fraction.
5. The compost is packed in plastic bags, as illustrated in figure 22, and sold to farmers as soil conditioner or organic fertiliser.

Figure 22 The compost ready to be sold to farmers. [65]

In Schedule-IV of The Municipal Solid Waste (M&H) Rules, 2000 there are standards specified for the maximum amount of heavy metals that is allowed in compost for the purpose of using it as fertilizer. There are also standards for pH value and C:N ratio. A sample taken on the 6th of June 2008 from the compost produced at Hydroair Tectonics' segregation plant in Ichalkaranji shows that the standard values were not exceeded. The values can be seen in table 10.

Table 10 Standard values of compost in India and specific values from the compost produced in Ichalkaranji. [37]

Physical characteristics	Standard	Ichalkaranji
C : N ratio	20 – 40	27.35
pH	5.5 – 8.5	6.54
Heavy metals	Should not exceed (mg/kg)	mg/kg
Arsenic	10	BDL
Cadmium	5	0.22
Chromium	50	0.19
Copper	300	90
Lead	100	BDL
Mercury	0.15	BDL
Nickel	50	BDL
Zinc	1000	212

*BDL=Below Detectable Level

3.1.2.2 RDF

The larger fractions of MSW, which are separated in the first segregation step, consist of larger stone blocks and burnable waste such as paper, plastic, textiles, coconut shells, rubber etc. The large inert fractions and the recyclable plastic and metals are sorted out manually and the remaining burnable waste is passed on to a mechanical separation unit. Air is added from below and the heavy non-combustible material, such as glass and inert material are separated from the light combustible fractions. Finally, the combustible material is mechanically crushed and chopped into a small fluffy fraction. The RDF processing machinery is illustrated in figure 23.

Figure 23 The RDF processing machinery. [37]

Figure 24 Bailed RDF fluff. [37]

The result is called RDF fluff and can be used as fuel in a boiler for electricity generation. Alternatively it can be sold to energy demanding industries as a substitute for coal.

For the purpose of storing and transportation, the RDF fluff can be bailed as seen in figure 24, or processed further to briquettes or pellets. If it is going to be sold directly to the market further processing of RDF fluff is preferable.

In table 11 the range of specific characteristics of RDF fluff is shown.

Table 11 Specific characteristics of RDF fluff. [37]

Characteristics	Range [%]
Moisture	10 - 30
Ash Content	20 - 30
Volatile Matter	50 - 65
Fixed Carbon	12 - 15
Mineral matter	20 - 30
Carbon	20 - 30
Hydrogen	3 - 5
Nitrogen	1 - 1.5
Sulphur	0.2 - 0.3
Oxygen	20 - 25

From the above characteristics of RDF fluff, the heating value can be calculated with Dulong's formula, see box 1 section 2.5.3. [100] The result gives a higher heating value of 2.2-3.7 MWh/ton (1900-3200 kcal/kg), as seen in table 12.

Table 12 The higher and lower heating value for RDF. [37]

RDF	LHV (Hi)		HHV (Hs)	
	MWh/ton	kcal/kg	MWh/ton	kcal/kg
Lower limit	2.0	1684	2.2	1905
Higher limit	3.1	2705	3.7	3152

When RDF fluff is processed further to pellets the characteristics change, as illustrated in table 13.

Table 13 Characteristics of RDF fluff and pellets. [37]

Product	Fluff	Pellets
Shape	Irregular	Cylindrical
Size	25 x 25mm to 150 x 150mm	8 mm to 25 mm in diameter
Bulk density	0.02-0.03 MT/m3	0.6 to 0.7 MT/m3

Hydroair Tectonics is considering building a plant for burning RDF fluff with the purpose of generating electricity. However, this plant will not be built in the initial stage, but after some years when the segregation plant has been proven viable. In the initial state the RDF generated from the segregation plant is going to be sold to energy demanding industries as a substitute for coal.

3.1.2.3 Eco bricks

The inert fraction is separated from the compostable fraction through the different steps described above. Ash which is received from industries to the dumpsite is mixed with inert particles larger than 4 mm, but smaller than 20 mm in diameter. The ash mixture is added to another mixture consisting of inert particles smaller than 4 mm in diameter, cement and water. Everything is blended together and processed mechanically to bricks. Figure 25 illustrates the process of making bricks. These bricks are not appropriate for the construction of houses but they are a good alternative for road work such as construction of sidewalks.

Figure 25 The mechanical processing of bricks. [37]

3.1.2.4 Recyclable material

The recyclable material is mostly segregated manually initially when the MSW arrives to the plant. Furthermore it is separated mechanically through magnetic separators. Around 5 percent of the incoming MSW is recyclable material, which will be sold to scrap dealers for a resale value.

3.1.3 Sanitary landfill

A sanitary landfill will be made at the dumpsite. The waste going to the landfill is restricted to certain inert material and other unusable waste and will stand for less than 8 percent of the incoming waste. Compactors will be used to arrange the waste in thin layers and to achieve high density of the waste. To minimize the run off to the ground water, the sanitary landfill will have a sealing system consisting of sheets made of plastic material and soil layer with low permeability. The site will be provided with a leachate collection and removal system, which will be explained in the next section. Sand, silt and soil, which are separated during the segregation steps, are going to be used as earth cover to prevent infiltration. A cover of 10 cm is provided daily and an intermediate cover of 40-64 cm during monsoon.

3.1.4 Leachate treatment

A large part of the waste is moisture, which will result in runoff from the plant, in the form of leachate water if it is not collected. The leachate from the project facility and sanitary landfill site will be collected through a drainage layer, a perforated pipe collector system and a sump collection area. It is carried to collection tanks and later on to a treatment plant. At the plant, the leachate will be treated so that it can meet certain standards as specified in the Schedule-IV of The Municipal Solid Waste (M&H) Rules, 2000. These are illustrated in table 14.

Table 14 Standard for leachate treatment. [37]

Parameter	Standards (Mode of Disposal)		
	Inland surface water	Public sewers	Land disposal
Suspended solids, mg/l, max	100	600	-
Dissolved solids (inorganic) mg/l, max.	2100	2100	-
pH value	5.5 - 9.0	5.5 - 9.0	-
Ammonium nitrogen (as N), mg/l, max.	50	50	-
Total nitrogen (as N), mg/l, max.	100	-	-
Biochemical oxygen demand (3 days at 27 deg C) max.(mg/l)	30	350	100
Chemical oxygen demand, mg/l, max.	250	-	-
Arsenic (as As), mg/l, max	0.2	0.2	0.2
Mercury (as Hg), mg/l, max	0.01	0.01	-
Lead (as Pb), mg/l, max	0.1	1.0	-
Cadmium (as Cd), mg/l, max	2.0	1.0	-

4 Setting up a waste-to-energy plant

During the last decade major reforms have been made in the field of investment in India, which have improved the investment climate for both domestic and foreign companies. [94]

When a foreign company wants to set up a waste-to-energy facility in India there are certain regulations that need to be considered before setting up the plant. There are also financial and infrastructural support systems, which could be good to have in mind when calculating the budget for the project. This chapter will describe the main regulation and support systems in India.

4.1 Regulations

The company needs to get clearances from the federal government and from specific state authorities before starting the business in India. These regulations are specified further in appendix 7. The environmental clearance is one of the most important regulations, when plants that will pollute toxic gases are going to be implemented. It is the State Pollution Control Board that will give these clearances, by following the national emission standards. [140]

4.1.1 Emission standards

Each country has specific national standards for how much pollutants are allowed from a waste incineration plant. The emission standards for waste incineration in India are specified in table 15. These values are compared to the corresponding values for Sweden, which is an industrial country that has practiced MSW incineration for many years. Both the Swedish and the Indian values refer to an oxygen concentration of 11 percent in the flue gases. The Indian values are specified for hazardous waste. Nevertheless, according to Mr S.Balaji TNPCB, incineration of MSW will fall under this category as well. The Swedish values are for waste incineration in general.

Table 15 The emissions standards for waste incineration in India and Sweden. [107] [108]

PARAMETER	EMISSION STANDARDS				SAMPLING DURATION
	India	Sweden			
			(A*)	(B*)	
Particulates [mg/m3]	50		30	10	30 Minutes
HCl [mg/m3]	50		60	10	30 Minutes
SO2 [mg/m3]	200		200	50	30 Minutes
CO [mg/m3]	100		100	150**	30 Minutes/ **10 Minutes
	50	50			Standard refers to daily average value
Total Organic Carbon [mg/m3]	20		20	10	30 Minutes
HF [mg/m3]	4		4	2	30 Minutes
NO_X (NO and NO_2 expressed as NO_2) [mg/m3]	400		400	200	30 Minutes
Total dioxins and furans [ng/m3]	0.1	0.1			6-8 hours sampling.
Cd + Th + their compounds [mg/m3]	0.05	0.05			Sampling time anywhere between 30 minutes and 8 hours.
Hg and its compounds [mg/m3]	0.05	0.05			Sampling time anywhere between 30 minutes and 8 hours.
Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V + their compounds [mg/m3]	0.5	0.5			Sampling time anywhere between 30 minutes and 8 hours.

* The company can choose between two cases, A or B. The 30 minutes sampling values during one year, that are below the standard value, should be 100 % in case A and 97 % in case B.

** For CO there is an alternative that 95 % (instead of 97 %) of the 10 minutes sampling values during one year should be below the standard value.

4.2 Funding for MSW-to-energy projects

Except from revenues that MSW-to-energy projects can get from selling energy and segregating products generated from the process, a company that sets up an MSW-to-energy plant could also get financial and infrastructural support from the federal and state government. There is also a possibility to get revenues through CDM.

4.2.1 Support systems

The company can get support from the federal and state government to start the business in the form of subsidies and infrastructural support.

4.2.1.1 Subsidies

If a company produces energy from renewable energy sources there are subsidies that they can apply for. The company can apply for subsidies from the following agencies:

- *Federal level:* Indian Renewable Energy Development Agency (IREDA)
- *State level:* Tamilnadu Energy Development Agency (TEDA)

Both IREDA and TEDA are under the administrative control of the Ministry of New and Renewable Energy (MNRE). [90] The company needs to be inspected by TEDA before the application can be approved and sent to MNRE. [130]

For projects regarding energy recovery from MSW, there are possibilities to get financial assistance of Rs. 20 million ($0.4 million), per MW subject to ceiling of 20 percent of project cost and Rs. 100 millions per project ($2 million), whichever is less. [50]

4.2.1.2 Infrastructural support

Every state provides infrastructural support for the companies that are about to be established in the state.

The infrastructural support, which is provided by the state government and paid by the company, is in the form of land, power, water and roads.

Guidance bureau provides help with all infrastructural support except for land. For the land requirements the company needs to contact State Industries Promotion Corporation of Tamil Nadu (SIPCOT). The price for land varies depending on where the waste-to-energy plant is going to be built. The prices are generally higher in the central and the southern part of Chennai. If the area needed for the plant is 2 ha, the estimated price for land to build a waste-to-energy plant is Rs. 11 250 ($230) (see box 5). [138] However, if the CoC consider the area is required for a good cause they could even give the land to the company for free. [128]

Box 5 Estimation of the price for land to build a waste-to-energy plant

$$P = (P_{land} \cdot A) + P_{process} + C$$

Where:

P	Price for the land needed for the waste-to-energy plant [Rs.]
P_{land}	Average price for land in Chennai [Rs./ha]
$P_{process}$	Processing charge [Rs.]
C	Cost for application [Rs.]
A	Area needed for plant [ha]

Assumptions: [138]

P_{land}	Rs. 5000/ha
$P_{process}$	Rs. 1000
C	Rs. 250
A	2 ha

Result:
The calculated price for the land needed for the waste-to-energy plant is Rs. 11 250 ($230).

4.2.1.3 CDM

The Clean Development Mechanism (CDM) is an arrangement under the Kyoto Protocol and the United Nations Framework Convention on Climate Change (UNFCCC). CDM allows developed countries to reduce greenhouse gases in developing countries to be able to achieve their emission reduction targets. [91] In appendix 9, CDM is described more thoroughly.

An MSW-to-energy project that treats waste, which otherwise would be sent to a landfill, would prevent methane emissions to the atmosphere. Since methane is a 21 times more aggressive green house gas than carbon dioxide, this project would reduce the carbon dioxide emissions and thereby account for as a CDM project. A successfully implemented CDM project generates carbon credits, Certified Emission Reductions (CERs), to the project owner. Each CER is equivalent to one ton reduced carbon dioxide. The CERs can be used by the investor to manage the reduction target within the Kyoto protocol or be sold on the International Emission Trading (IET) market to generate income. [92] The price for a CER was 11-12 EUR as on the first month of 2009. [110]

The baseline is the amount of carbon dioxide emitted per produced unit energy and is often described in kg CO_2/MWh. The project's baseline is compared to the baseline estimated for the area where the project is going to be set up.

The baseline in Tamil Nadu, including import and export was 0.85 kg CO_2/MWh in 2008. If a project in Chennai should be classified as a CDM project, the project's baseline has to be less than 0.85 kg CO_2/MWh. The difference between the Tamil Nadu baseline and the project's baseline corresponds to the CERs that can be issued. [139]

5 The case for MSW incineration in Chennai

As mentioned previously, Hydroair Tectonics has recently signed a contract with the CoC to take care of the waste at Perungudi dumpsite and it is a great chance that they will get a similar contract at Kodungaiyur dumpsite. They are planning to process the waste and produce RDF, which initially will be sold to energy demanding industries as a substitute for coal. When the segregation plant has been proven financially viable Hydroair Tectonics is discussing whether or not to build a plant for burning RDF fluff and generate electricity.

There are many possibilities to produce energy from incineration. This chapter will analyse which method would be most suitable for Chennai. A case will be presented, in which the best solution for MSW incineration with energy recovery in Chennai will be discussed and analysed. Thereafter the technical and financial viability will be analysed for this specific case.

5.1 The case study

The case for MSW incineration with energy recovery in Chennai is presented by answering the following questions.

- Should there be mass burning of MSW or only combustion of the burnable fraction of the MSW (RDF)?
- Who should process the waste and which methods should be used?
- Where should the plant be situated?
- Should there be co-incineration with another fuel? In that case, which fuel is suitable for co-incineration?
- Which technology should be used for combustion and what type of flue gas treatment should be used?
- Which type of energy should be recovered?

5.1.1 Should there be mass burning of MSW or only combustion of the burnable fraction of the MSW (the RDF)?

Mass burning of MSW is a common method in developed countries to reduce the volume of MSW and at the same time generate energy. Box 6 illustrates the strengths and weaknesses with mass burning of waste. [118]

Box 6 Strengths and weaknesses with mass burning of MSW

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- No pre-treatment is required
- Reduces the volume of waste by ~ 90%
- Proven and commercially available technology in developed countries

-

- High capital costs. To cover the costs it is advantageous if the plant has:
  1. high utilization factor
  2. tipping fee for MSW
  3. production of another energy source except from electricity, such as heat, cold and/or process steam.
- Negative public perception in certain countries
- The characteristics of the MSW need to be suitable for incineration
- Produces toxic residues, though bottom ash can be recycled
- Minimum recovery of material, except for ferrous materials

In developing countries mass burning of waste is not common. However, there exist RDF plants that generate energy from combusting the burnable fraction of the MSW. Depending on the MSW characteristics and system for MSW management in the country different methods are suitable. Whether mass burning of MSW or combustion of RDF is most suitable for the conditions in Chennai will be discussed below in respect of public opinion, waste characteristics, infrastructure and possibilities for combined recycling activities. In the end of the section, a comparison is made between the conditions in Sweden, to illustrate why one method could be suitable in one country and not in another.

5.1.1.1 Public opinion

Many citizens and decision makers in Chennai do not consider incineration of MSW as an option for energy recovery. Firstly they believe waste incineration is bad for the environment and human health. Since open burning along roadsides and at dumpsites have been common treatments for MSW in the past, the citizens associate incineration with toxic pollution. Secondly, the memory of failed waste incineration projects in India has made the people doubt that the waste characteristic in India is suitable for combustion. Even though combustion of RDF is a type of waste incineration, it is considered more acceptable by the public than direct incineration of MSW. RDF is often referred to as “green coal” by decision makers. The CoC opposes direct incineration, but they have accepted Hydroair Tectonics future plans to build a unit for burning RDF at Perungudi dumpsite. [136] Therefore, setting up an incineration plant for burning RDF would probably be less problematic than setting up a plant for mass burning of MSW.

5.1.1.2 Waste characteristics

Composition: The composition of MSW in India is not optimal for combustion, due to high content of inert and compostable material and high moisture content. Furthermore, the MSW contain some hazardous waste, because of insufficient segregation of MSW at source. Segregation of hazardous waste is very important before burning MSW in order to minimize toxic pollution. The composition of RDF in India is more suitable for combustion. Since RDF contains less inert material it will cause less operational problems during the combustion process. RDF also contains less sulphur and chlorine than MSW, which lowers the risk for corrosion problems in the boiler. [98] The lower content of inert and organic material will also give the RDF lower moisture content, which is more beneficial for incineration.

Heating value: The lower heating value of a fuel should preferably be about 3 MWh/ton (2580 kcal/kg), in order to operate an incineration plant without additional fuel. [143] The average lower and higher heating values of MSW and RDF in Chennai, which also were presented earlier in the study, is summarized in table 16.

Table 16 The average lower heating value of MSW and RDF in Chennai. [100]

Waste type	LHV [MWh/ton]	HHV [kcal/kg]
MSW	1.6	1376
RDF	2.6	2236

The heating value of MSW or RDF could be increased by reducing the moisture content. This could be done by air drying during the dry seasons. During the wet seasons this could be done by using hot flue gases from the combustion process. Another pre-treatment method is to mix the MSW or RDF with another fuel with a higher heating value. Since the lower heating value of MSW in India only is 1.6 MWh/ton, compared to 2.6 MWh/ton for RDF, more pre-treatment is needed for MSW to sustain the combustion. Nevertheless, incineration of RDF could be sufficient in Chennai without pre-treatment, if the boiler used for incineration allows a slightly lower heating value.

Uncertainties in data: Since the climate in Chennai varies from dry and hot weather to monsoon climate, there will be great variations in moisture content of the waste during the year which will affect the heating value. Different studies show great variations in characteristics and composition of MSW in India, depending on the season and the area where the study was performed. This complicates the process of designing an incineration plant. A misjudgement in design could cause a project failure, which was what happened 1987 when the Danish Firm Vølund Miljøteknik set up a plant for mass burning of MSW in Delhi. The main reason for the failure of this plant was that the MSW was very different in composition, moisture and energy content than the waste that was initially tested. It had a higher percentage of inert material in the form of sand, silt, rock and ashes. The energy content was only about 50 percent of the designed value which could not sustain combustion. Large quantities of auxiliary fuel were needed as well as combustion air. This put strain on the burner and the air supply arrangements and the high content of inert material caused problems in the ash handling systems. [11]

5.1.1.3 Infrastructure

Since the capital cost for a mass burning plant with good flue gas treatment is high, the plant needs to get revenues in order to cover the cost. The revenues could for example come from selling electricity, process steam, district heating and cooling and/or from receiving a tipping fee from those dumping the waste at the plant. Considering the electricity deficit in Chennai, the main product from the plant will be electricity. Process steam could be sold to a nearby industry; however, the feasibility for this purpose needs to be investigated. Because of the warm climate, there is no need for district heating in Chennai. There is a need for district cooling, although there is no infrastructure in Chennai today for that. Since there is no fee for dumping MSW at the dumpsite in Chennai, there is no possibility for receiving a tipping fee when dumping MSW at the plant. Regarding RDF, the investment cost for building a combustion unit will be lower (see section 5.1.5.1).

5.1.1.4 Combined recycling activities

According to the hierarchy of waste management, which is described in section 2.3.1.4, waste minimization, recycling and biological processing should be prioritized before thermal processing. Production of RDF is combined with recycling activities and biological processing, which gives other products that can be sold to the market such as recyclables, bricks and compost. For a developing country like India, with a lack of an organized system for segregation of MSW at source, producing RDF would give better use of resources. Better use of resources gains both the environment and the economy. The financial incentives, in the form of revenues from selling products generated from the process, are strong in developing countries. Besides from selling waste products, there is also the possibility of getting revenues through CDM. Since the processing of MSW decreases the waste going to the dumpsite, methane emissions to the air will be prevented. The CO_2-eqs that are prevented correspond to the CERs that the company is eligible for. [92]

5.1.1.5 Developed vs. developing countries

Since mass burning of MSW has been proven both technically and financially viable in developed countries, many western companies want to expand their business and apply the same technology in India. Somehow, all projects regarding mass burning of MSW that have been implemented in India the past years have failed. (see section 2.7.1.1). Table 17 summarizes the conditions in Chennai together with a comparison of the conditions in a developing country (Sweden). See appendix 11 for further explanations of the different conditions in Sweden.

Table 17 The conditions for mass burning of MSW in Chennai compared to Sweden.

Parameter	Chennai	Sweden
Positive public perception of mass burning of MSW	no	yes
Segregation of MSW at source	no	yes
Efficient segregation of hazardous waste	no	yes
Suitable MSW characteristics for combustion	no	yes
~ Heating value MWh/ton (LHV)	1.6	3
Possibility of getting revenues from:		
Tipping fee	no	yes
Selling electricity	yes	yes
Selling district heating	no	yes
Selling district cooling	uncertain	yes
Selling process steam	uncertain	yes

5.1.1.6 Conclusion

The following arguments speak for the alternative that there should be combustion of RDF and not mass burning of MSW in Chennai. Compared to MSW, RDF has

- more positive public perception
- more suitable characteristics for incineration
- higher heating value
- better possibility of material recovery

- less content of hazardous waste
- less investment cost when building a combustion plant.

➡ **Combustion of RDF**

5.1.2 Who should process the waste and which methods should be used?

Considering that there should be combustion of RDF, a processing plant for producing RDF needs to be built. Hydroair Tectonics has several years of experience of processing waste and their concept has been proven viable, both financially and technically. [122] They have recently signed a contract with the CoC to take care of the waste at Perungudi dumpsite and it is a good chance that they will get a similar contract at Kodungaiyur dumpsite. In this case study it is therefore assumed that this company build a processing plant at either one or both of the dumpsites in Chennai in the nearest future.

Hydroair Tectonics has experience from producing bricks from the inert material, compost from the organic material and RDF from the burnable material. Furthermore, they have experience from separating the recyclable fraction (see chapter 3). This concept has been proven successful, thus it is assumed that they will continue with the same concept. The RDF should initially be sold to coal fired industries as a substitute for coal. Depending on the financial and technical viability for building a combustion unit, the RDF should in the future either continuously be sold to coal fired industries or combusted with energy recovery. Because of the electricity deficit in Chennai, a future alternative for compost could instead be to use the organic waste for electricity production in a biomethanation plant.

5.1.2.1 Conclusion

Hydroair Tectonics should build a processing plant for MSW at either one or both of the dumpsites in Chennai. In the initial stage they should segregate the inert, compostable and burnable fraction and produce bricks, compost and RDF, respectively. The recyclables should be separated. RDF should be sold to coal fired industries or burnt with energy recovery. Biomethanation of the organic waste could be a solution for the future.

➡ **Hydroair Tectonics – The method that they should use is the same as described in chapter 3**

5.1.3 Where should the plant be situated?

There are several factors that need to be considered when deciding the location of the plant, such as price, transportation and characteristics of the building ground.

The price for land differs greatly depending on the location and the building purpose of a new establishment. If the CoC consider that the building will gain the society, they can even give the land for free. [128] Taking into consideration that the plant for burning RDF will provide the city with electricity, there is a great chance that the land will be given by the CoC for free. [135]

However, because of the land deficit in Chennai, the best solution would be to build the plant on the existing dumping ground, since this land area is not suitable for many other purposes. Another advantage with building the plant on the dumping ground is that the existing transportation routes for collecting and dumping the MSW do not need to change. The problem though is that the two dumping grounds in Chennai are built on wetland, meaning that these grounds are not suitable to build on. The processing plant for RDF will consist of several small segregation units. Considering their light weight, they will not be a problem to set up at the dumpsite. Whether the plant for burning RDF is suitable to build on the dumping ground or not needs further investigations. If the plant, because of its heavier weight, has to be placed elsewhere, the RDF could easily be transported. To minimize the transportation costs the RDF-fluff could be processed further to briquettes or pellets. The plant in the case study could be situated at either one of the two dumpsites in Chennai.

5.1.3.1 Conclusion

The RDF plant should preferably be situated on the dumpsite or close to the dumping ground to avoid unnecessary transportation and straining on the environment. Considering the availability and price for land, the dumping ground is a good alternative.

The plant in the case study could be situated at either one of the dumpsites in Chennai or close to them

5.1.4 Should there be co-incineration with another fuel? In that case, which fuel is suitable for co-incineration?

Considering the case of building a unit for burning RDF with energy recovery, the heating value of RDF could be sufficient if the type of boiler used can handle a slightly lower heating value. Yet, if suitable fuel is available, co-incineration is positive for increasing the heating value and producing more energy.

Agricultural or industrial wastes are examples of fuel that could be suitable for co-incineration with RDF. Alternatively, small amounts of coal could be added. The following text will discuss the potential for these alternatives.

5.1.4.1 Agricultural waste

In a study made by Anna University, the future potential in Tamil Nadu for using agricultural waste for energy production was made. The result shows that the potential is low. Within the ten zones in Chennai the potential is 0 MW, since there is no land for agricultural purposes there. In the nearby districts Kancheepuram and Tiruvallur the potentials are 9.47 MW and 8.33 MW, respectively. On the other hand, there are already smaller agricultural waste-to-energy projects planned here which results in a zero potential. [130]

5.1.4.2 Industrial waste

To determine if a certain industrial waste is suitable for co-incineration with RDF there are some issues that need to be considered:

- If the difference in viscosity and density is too large between the RDF and the industrial waste, this can result in thermal straining of the boiler.
- The content of heavy metals and other hazardous waste should be limited.
- The waste should not have high content of chlorine, since chlorine causes problems with high temperature corrosion. [143]

Most of the industrial areas are situated outside the ten zones of Chennai. One of the largest industrial areas is called Manali and is situated north of Chennai. Here there are numbers of industries which produce waste that could be interesting for co-incineration with RDF.

5.1.4.3 Coal

A large part of the electricity produced in Chennai comes from coal fired power stations. All power stations in this area use sub-bituminous coal, with a heating value of about 5 MWh/ton (4300 kcal/kg) As Chennai lies on the coast, there is a good possibility to import coal, which can be mixed with MSW to increase the heating value. [137]

5.1.4.4 Conclusion

Whether there should be co-incineration with another fuel or not depends on the allowed heating value for the chosen boiler and on the price and supply of suitable fuel in the surrounding areas.

Since there is no potential for using agricultural waste, it leaves the alternatives of using industrial waste or coal. If a suitable industrial waste could be found, it would be the best solution both environmentally and financially.

RDF is preferably co-incinerated with suitable industrial waste, if it is available.

5.1.5 Which technology should be used for combustion and what type of flue gas treatment should be used?

There exist different technologies for waste combustion. In the following sections the best alternatives regarding combustion technology and flue gas treatment for Chennai will be discussed.

5.1.5.1 Combustion technology

The two main technologies for burning waste are moving grate and fluidized bed. The strength and weaknesses with these technologies are described in box 7. Other technologies for waste incineration are described in appendix 12.

Box 7 Moving grate and fluidized bed - Strength and weakness

Moving grate

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- Can handle MSW without pre-treatment
- Easy to operate
- Proven and commercially available in developed countries

-

- High maintenance costs due to many moving parts
- Minimum material recovery except for ferrous material
- Slow response to operational changes

Fluidized bed

+

- Can be used in combination with recycling operations [104]
- High combustion efficiency [30]
- Less ash because of the high combustion efficiency [30]
- Reduced NOx emissions due to lower temperatures[30]
- Low maintenance needed due to no moving parts [150]
- Fast respons to operational changes [150]

-

- Require pre-treatment of the waste
- High capital cost (The pre-treatment plant stands for a large part of the costs) [30]
- High temperatures can cause problems with sintering [150]

When the solution is to burn RDF, fluidized bed is a good choice of technology, which is described in box 8. Except from environmental benefits, the fluidized bed has financial advantages. When burning mixed MSW in a fluidized bed, the waste needs to undergo pre-treatments to make it more homogenous. The pre-treatment facility is a large part of the investment costs. Since RDF fluff is already homogenised, there is no need to have this facility in this case, which makes it a cheaper choice than a moving grate. [144]

A large difference in operating a fluidized bed compared to a moving grate is that the response from operational changes can be seen faster, which is an advantage. However, operating a fluidized bed can be difficult for inexperienced technicians. According to Björn Petterson at Händelöverket in Norrköping they had problems with sintering in their fluidized bed during the first years due to inexperience, which was very costly. [126] To avoid these problems knowledge transfer is important.

The fluidized bed should be bubbling and not circulating. The extra cyclone in the CFB increases the investment costs, which makes it more profitable for larger applications. Since the plant in Chennai will be relatively small it is therefore more motivated with a BFB. [150]

Box 8 Fluidized bed
The fluidized bed (FB) consists of a chamber with a bed of inert material. The fuel is distributed inside the bed and pre-heated with a gas or oil burner until it reaches the ignition temperature. The bed mixture, which is supported by a plate, is fluidized by air or other gas being blown through the plate. The combustion has no flames and temperature is about 700-900 degrees Celsius. The flue gas carries particles out of the vertical chamber into a cyclone, from where the inert bed material is carried back to the chamber again. [35]

There are two types of fluidized bed combustor: bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) (see figure 26). The main difference is that the airflow is higher in a CFB, allowing more particles to be carried over the vertical chamber. The higher turbulence increases the contact area of the fuel particles and the combustion air. The result is an increase in thermal efficiency to 90 percent compared to 89 percent with the BFB and a decrease in emissions of CO and NO_x. [30]

The extra cyclone, which is a part of the CFB, means higher investment costs. Therefore, BFB is suitable for smaller applications of 1-50 MW plants while CFB is better for larger applications of 10-200 MW. [97]

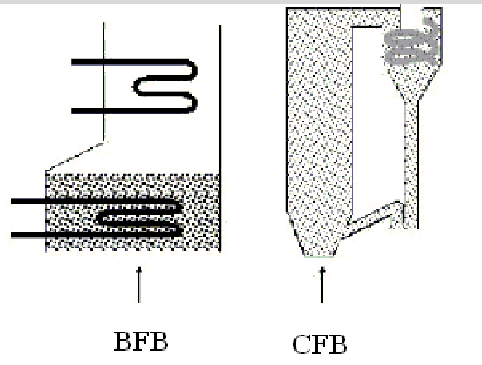


Figure 26 Bubling bluidized bed and circulating fluidized bed. [172]

5.1.5.2 Flue gas treatment

When waste is burned in an incineration plant with good flue gas treatment, the pollution will be much less compared to open burning, which is common in India today.

As specified in section 4.1.1, the emission standards for waste incineration in India are similar to those in Sweden. In other words, if a plant for burning RDF is going to be built in India, it will need the same flue gas treatment as a plant in Sweden.

One of the challenges to set up an RDF-boiler for energy generation in Chennai is for the project to be profitable. Since flue gas treatment is a large part of the investment cost, it is important to choose a system with low investment and operational costs. Another issue is that the availability of water in many areas in India is limited, which speaks for a flue gas treatment that does not need waste water treatment. A semi-dry system with low investment cost could therefore be a suitable choice. An example of a semi-dry system is the NID-system, which is explained more in box 9. The advantage of this system is that it is simple and efficient and it does not need any waste water treatment. Moreover it has low investment and operational costs. [145]

Box 9 The NID-system
The NID-system consists of a NID reactor, fabric filter, lime and activated carbon. The layout can be seen in figure 27. In this system lime, active carbon and water are mixed to slurry and added to the flue gases before the fabric filter through the NID-reactor. The slurry will bind to the acid components and the dioxins, which later are removed in the fabric filter. The slurry is then re-circulating to save chemicals. [145]

A NID-system can be provided by Alstom, which is an international provider of power generation and rail infrastructure technology. [95] The price for a NID-system from Alstom is about Rs. 300 million ($6 million). [154]

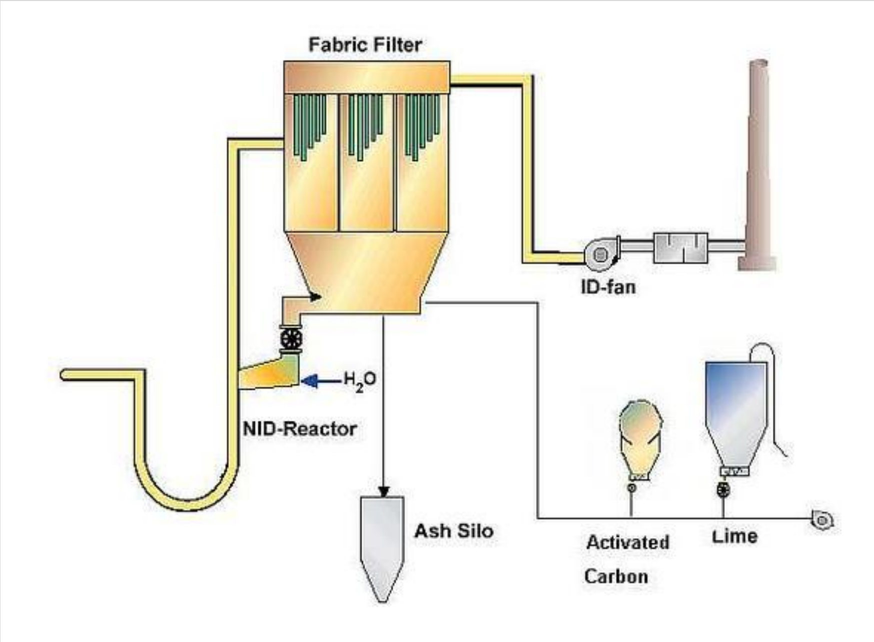


Figure 27 The NID-system. [170]

Regarding NO_x reduction, SCR is more efficient but since it is expensive, it is only motivated if the requirement for NO_x reduction is very high. [145] Considering that SNCR has been sufficient to meet the standards for several plants in Sweden, SNCR should be sufficient for this specific case in Chennai.

5.1.5.3. Conclusion

The RDF should be incinerated in a bubbling fluidized bed and the flue gas treatment should be semi-dry with low investment cost.

Bubbling fluidized bed and semi dry flue gas treatment.

5.1.6 Which type of energy should be recovered?

Considering the electricity deficit in Chennai, the plant should first of all generate electricity. Though, it could be difficult to find profit in this type of project, if selling electricity is the only income.

In Chennai it is common that certain industries use coal for the production of process steam, which is used in their production. If an industry of this kind would be situated close to the RDF plant, the steam generated from the plant could be delivered directly to the industry. This would be a cheaper and a more environmental friendly alternative for the industry than using coal. If the same industry also generates waste suitable for combustion it could be co-incinerated with RDF. A co-operation between an industry and an energy producing company is thereby a win-win situation.

Because of the warm weather in Chennai, district heating is not an alternative. On the other hand district cooling could be an alternative. Yet, considering the large investment cost for district cooling pipelines and the current infrastructure in Chennai today, this alternative might be more suitable in a few years from now.

5.1.6.1 Conclusion

In the initial stage electricity and/or steam should be generated. In the future, district cooling could be a good alternative.

Electricity and/or steam

5.2 Presentation of the case

According to this study, the answers to the questions in the section above represent the best solution for future MSW incineration in Chennai. The case can be summarized as follows:

- It should be combustion of RDF.
- Hydroair Tectonics should process the waste according to the methods described in chapter 5.
- The plant should be situated on or close to one of the dumpsites.
- RDF could be combusted separately or co-incinerated with industrial waste or coal if the heating value is not sufficient.
- The RDF should be combusted in a bubbling fluidized bed (BFB) with semi dry flue gas treatment.
- Electricity and/or steam should be recovered.

5.2.1 Alternative case

An alternative to building an incineration plant with energy recovery is to sell the RDF generated from the processing plant to coal firing industries as “green coal”. These industries could use RDF as a substitute for coal in the existing coal boilers.

5.2.2 Problem formulation and system boundaries

The next part of the case study will try to answer the question:

- Should Hydroair Tectonics invest in a combustion unit burning RDF with recovery of electricity and/or steam or should they sell their RDF to industries?

To be able to answer the question, the technical and financial viability for this specific case will be analysed.

The technical and financial viability will be determined for two scenarios. In scenario 1, only electricity is sold whereas in scenario 2, both electricity and steam is recovered. In scenario 2 it is assumed that a nearby industry buys the steam.

The result will be compared to the alternative case, which is that Hydroair Tectonics should sell the RDF to coal fired industries. The case study with system boundaries is illustrated in figure 28. As seen in the figure, the processing plant (that separates the waste fractions and produces the RDF fluff) is not included in the case study.

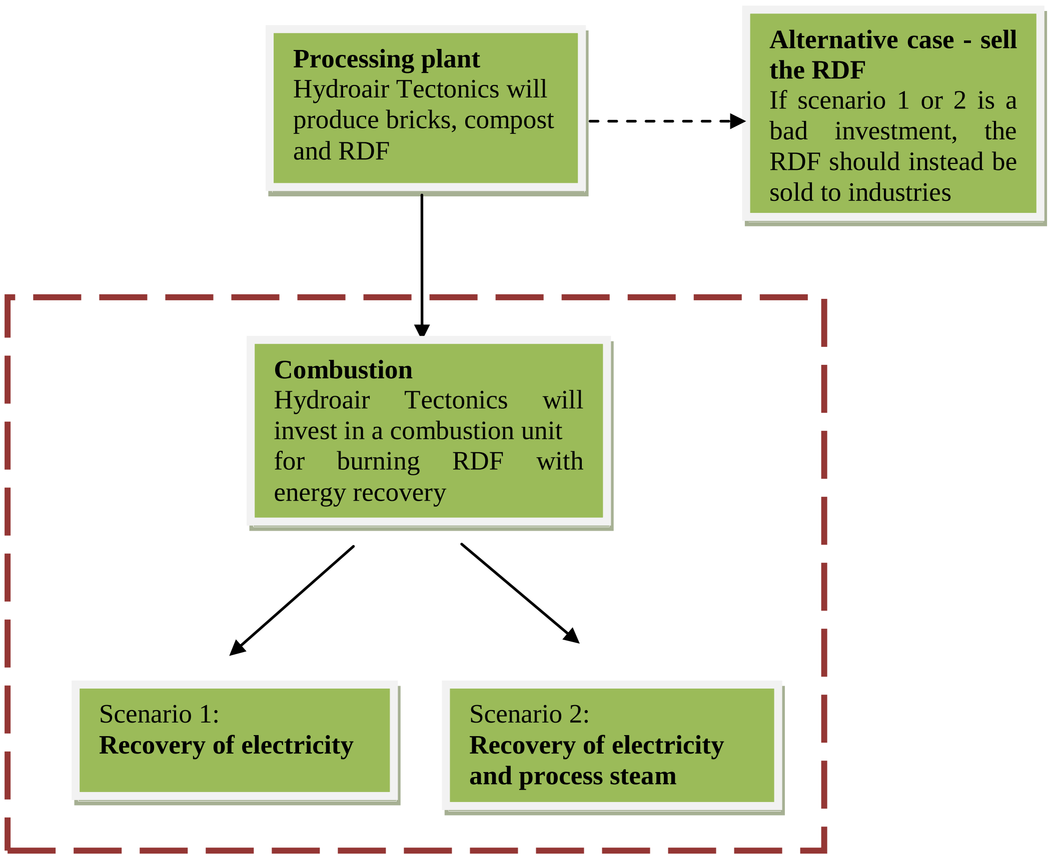


Figure 28 The flow chart and the system boundaries of the case study.

5.3 Technical viability

This section will analyze the technical viability of the project. To begin with, the technical parameters will be specified and thereafter the potential power that could be extracted from the plant will be determined.

5.3.1 Specification of technology and parameters

To be able to determine the potential power that could be extracted from the plant, the following parameters must be specified:

- Efficiency of boiler, turbine and generator [%]
- Heating value of fuel [MWh/ton] (kcal/kg)
- Flow rate of waste to the plant [kg/s]
- Enthalpy of working medium at different stages in the steam power process [kJ/kg]

The following sections will determine these parameters for scenario 1 and scenario 2.

5.3.1.1 Efficiency of boiler, turbine and generator

The efficiency of the boiler, turbine and generator can vary slightly from different manufacturers. Below are examples of suitable technology for the plant in this case study. Further information about price estimations and other suitable technologies can be seen in appendix 8.

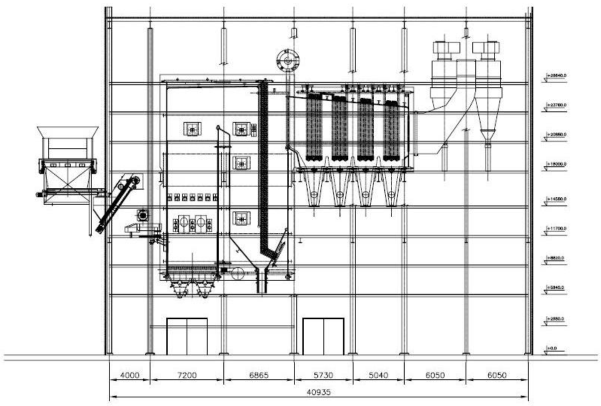


Figure 29 Ecofluid bubbling fluidized bed with attaching parts. [144]

When electricity and process steam are required, a steam boiler is necessary. The boiler efficiency can vary for different boiler types. Figure 29 illustrates an example of a BFB boiler type called Ecofluid, which is manufactured by AE&E Group. This company is an international provider of systems for thermal power generation and environmental technologies and has a manufacturing unit in Chennai, AE&E Chennai Works. [109] This boiler can burn fuel with lower heating value down to 2.2 MWh/ton (1892 kcal/kg) and the boiler efficiency is about 89 percent. [144] Further details about the boiler can be found in appendix 8.

Figure 30 Alstom turbine. [171]

The turbine and generator can be provided by Alstom, which is a global provider of power generation technology. Figure 30 illustrates a turbine, though a larger one than this project will require. An average turbine and generator from Alstom have efficiencies of 85 and 98 percent, respectively. [154]

5.3.1.2 Heating value

The heating value in scenarios 1 and 2 is assumed to be different, due to different conditions in the scenarios.

Scenario 1: In scenario 1 there will only be production of electricity. RDF has an average lower heating value of 2.6 MWh/ton (2236 kcal/kg) (see section 3.1.2.2). The BFB boiler in appendix 8 can handle waste with a lower heating value down to 2.2 MWh/ton (1892 kcal/kg), which indicates that combusting RDF should be sufficient most of the time without auxiliary fuel. Therefore it is assumed in this scenario that RDF will be burnt without additional fuel, which means that the lower heating value of the fuel will remain at 2.6 MWh/ton (2236 kcal/kg).

Scenario 2: In scenario 2 it is assumed that there will be production of process steam, which will be delivered to a nearby industry. If the same industry produces waste with a heating value higher than the heating value for RDF, this waste could be co-incinerated with RDF. Thereby the energy content of the fuel mix will be higher and the potential generated energy will increase.

An example of an industry, that could be interested in buying steam generated from an MSW-to-energy plant and also produces suitable waste for co-incineration, is Orchid Chemicals & Pharmaceuticals Ltd, situated in Alathur south of Chennai. They burn coal to produce process steam, which is used in their manufacturing processes. This company generates industrial waste, which consists of carbon compounds such as toluene and ethanol. The heating value of this waste is about 4.2 MWh/ton (LHV) (3612 kcal/kg). [153]

In Scenario 2 it is assumed that Orchid Chemicals & Pharmaceuticals Ltd will expand their business and build a production unit close to the RDF plant. Instead of producing steam from coal, they will buy the steam generated from the RDF plant. The RDF plant will co-incinerate industrial waste with RDF, which will increase the heating value of the fuel mix.

It is assumed that the infusion of industrial waste will be about 25 percent of the total waste mix consisting of RDF fluff and industrial waste. This will give a heating value of 3 MWh/ton (2580 kcal/kg) (LHV).

5.3.1.3 The flow rate of waste

The amount of MSW going to Kodungaiyur dumpsite is approximately 1400-1500 tons per day compared to 1500-1800 tons per day to Perungudi dumpsite. The company Hydroair Tectonics has signed a contract with the CoC to take care of 1400 tons of MSW per day at Perungudi dumpsite resulting in 350 tons of RDF. [37] If there will be a similar contract for waste processing at Kodungaiyur dumpsite in the near future it can be assumed that the amount of RDF will be about the same. With this assumption the incineration plant in the case study could be situated at either one of the dumpsites.

The generation of waste in Chennai is most likely to increase with time. The segregation plant will probably have the capacity to increase the production of RDF but as the incineration plant is dimensioned for 350 tons per day it will not be possible to increase the amount of RDF going to the incineration plant. However, the RDF could then be sold to industries and thereby replace fossil fuels like sub-bituminous coal, which is widely used by industries in Tamil Nadu.

Scenario 1: In scenario 1 it is assumed that the amount of RDF going to the plant will be 350 tons per day.

Scenario 2: With an infusion of industrial waste, which increases the heating value of the fuel mix to 3 MWh/ton (2580 kcal/kg), the total amount of fuel going to the plant will be 466 tons per day.

5.3.1.4 Parameters in the Rankine cycle

The process in an incineration plant is a steam power process, which is explained more in box 10. The parameters in the different stages in the Rankine cycle can be optimized for maximum energy recovery. Nevertheless, compared to the ideal process, there are factors in the real process that limit the possibilities of extracting maximum of energy. The fuel, construction material and economy are examples of such factors. The principal rule for maximum energy recovery is that the difference between the warmest and coolest point in the Rankine cycle is as large as possible, i.e. that the steam should have a high temperature before the turbine and a low temperature in the condenser.

Box 10 The Rankine cycle

The cycle consists of four processes which take place in four different components in a closed system. The four components are: feed water pump, steam boiler, turbine and condenser, all which can be seen in figure 31. The feed water pump increases the pressure of the working medium. In the boiler the water is heated and vaporized into steam. The steam goes through a turbine where it expands to overheated pressure and temperature, as work is extracted. In the condenser the steam condenses into water when heat is transferred to a cooling medium. From this stage, the condense water goes to a feed water tank before it continues to the feed water pump and the Rankine cycle is completed.

To decide the electric and thermal power of a steam power plant, a temperature-entropy diagram, T-s diagram, can be used. By deciding the pressure and temperature at stage *a, b, c* and *d* in figure 31 it is possible to find out the enthalpy in the working medium at these specific stages.

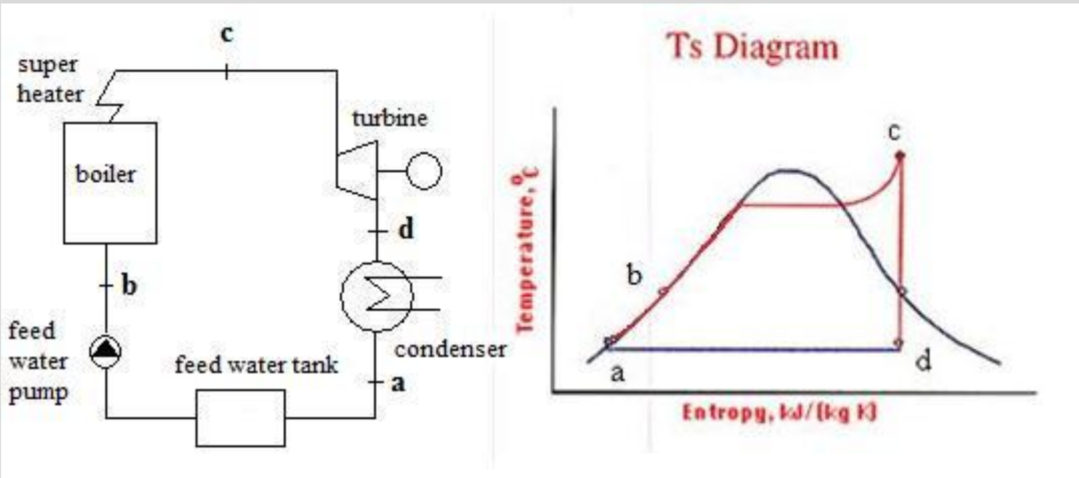


Figure 31 The Rankine cycle and T-s diagram. [167] [168]

The following section will specify the different stages in the Rankine cycle (as illustrated in box 10) for the steam process in the case study.

Stage a: Stage a occurs after condenser when the working medium is saturated liquid. The temperature at this stage is the same as in the condenser. For optimal energy recovery the temperature in the condenser should be as low as possible. The highest dew point[2] of the surrounding area decides the lowest temperature for the system. [149] The average dew point in Chennai can be seen in figure 32.

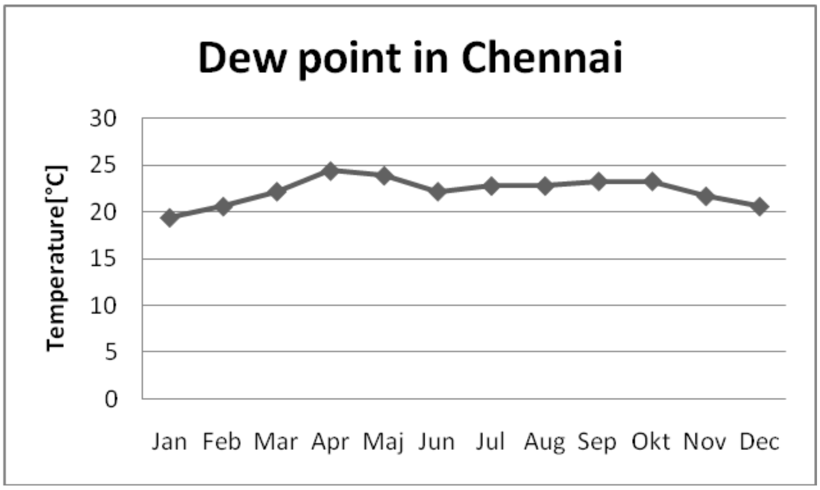


Figure 32 The dew point in Chennai through a year. [44]

The highest dew point in Chennai occurs in April and is 24.4 degrees Celsius. [44] This gives the lowest possible temperature in the condenser to 35 degrees Celsius as some degrees have to be added for the loss in the heat exchanger. [149]

When the temperature is decided, the pressure and enthalpy is given in a T-s diagram. The values are presented in table 18.

Table 18 Characteristics of water in stage a in the Rankine cycle. [100]

Stage	T [°C]	P [bar]	h [kJ/kg]
a	35	0.056	146.6

Stage b: The feed water pump increases the pressure of the water before it is fed into the boiler at stage b. In order to get a flow of the feed water into the boiler, there has to be a pressure difference before and after the boiler. Since it is a marginal pressure difference, this is neglected. [149] The temperature of the feed water at stage b is the same as after the condenser (stage a) and the pressure is the same as after the boiler (stage c). The enthalpy is given in a T-s diagram and the values are presented in table 19.

Table 19 Characteristics of water in stage b in the Rankine cycle. [100]

Stage	T [°C]	P [bar]	h [kJ/kg]
b	35	45	506.8

[2] The dew point is the lowest temperature humid air can have without condensing into water.

The efficiency of the process could increase if steam is tapped off from the turbine to preheat the feed water in preheaters, thus the temperature at stage b would increase. This is a financial deliberation, where the profitability will depend on the price for electricity. In this study preheating of the water is only performed in scenario 2, because the condensate from the industry has a high temperature that would be senseless not to use.

Stage c: Stage c occurs after the boiler and before the turbine, when the working medium is saturated vapour. For optimal energy recovery, the temperature at this stage should be as high as possible. The maximum temperature that could be reached depends on the fuel. When coal is incinerated, it is possible to reach temperatures around 530 degrees Celsius [149]. However, when the fuel is waste, which gives corrosive flue gases, the maximum temperature is lower, around 400 degrees Celsius. [145] Better material or chemical additives would make it possible to use higher temperatures. [149]

For the values in stage c in the Rankine cycle, Borlänge Energy’s values from their waste-to-energy plant will be used. These values can be seen in table 20.

Table 20 Characteristics of saturated vapour in stage c in the Rankine cycle. [145] [100]

Stage	T [°C]	P [bar]	h [kJ/kg]
c	400	45	3208

Stage d: Stage d occurs after the turbine and before the condenser when the working medium is wet vapour. Hence, the temperature at this stage will be the same as in the condenser, i.e. 35 degrees Celsius. Figure 33 shows the steam power process in a T-s diagram. The blue line illustrates the ideal process, while the red line illustrates the real process, assuming that the isentropic efficiency of the turbine is 85 percent. In the ideal or isentropic process the steam expands trough the turbine to the surrounding temperature and pressure (stage d_{is}). Because of the efficiency of the turbine the real process allows the steam to expand longer through the turbine (stage d).

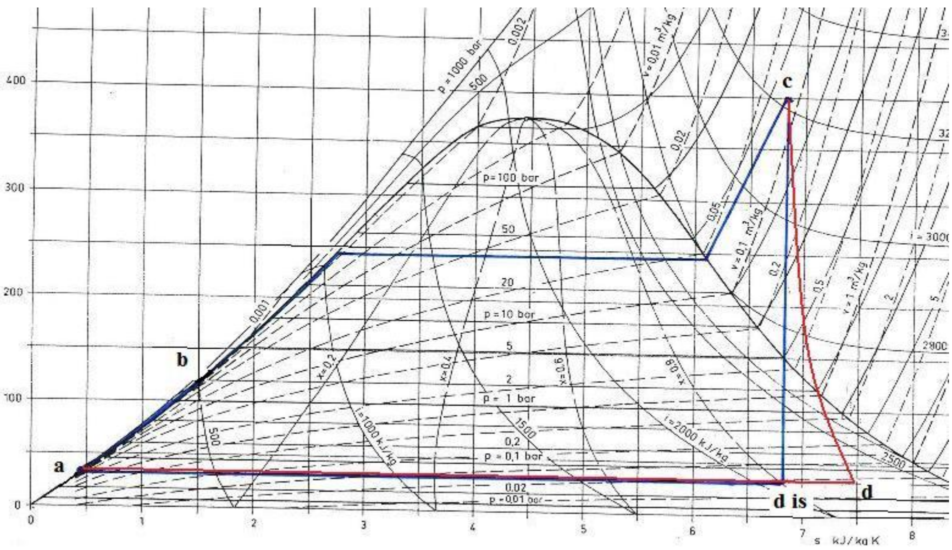


Figure 33 The steam process illustrated in a T-s diagram. [100]

The enthalpy in stage d_{is} is read from the T-s diagram to 2 100 kJ/kg, which gives the enthalpy in stage d to 2 270 kJ/kg. The calculations are presented in box 11.

Box 11 Calculations of the enthalpy after the turbine.

$$\eta_t = \frac{h_c - h_d}{h_c - h_{d_{is}}}$$

Where:

η_t	The isentropic efficiency of the turbine [%]
h	Enthalpy [kJ/kg]

Assumptions:

η_t	85 % [154]

Stage	T [°C]	P [bar]	h [kJ/kg]
c	400	45	3208
d_{is}	35	0.056	2100

Result:
The enthalpy in stage d is 2 270 kJ/kg.

The data for stage d is presented in table 21. The pressure and enthalpy is read from the T-s diagram.

Table 21 Characteristics of the wet vapour in stage d in the Rankine cycle. [100]

Stage	T [°C]	P [bar]	h [kJ/kg]
d	35	0.056	2270

Technical and financial limitation: There are financial and technical aspects that limit the lowest possible temperature in the condenser. The lower the chosen temperature is in the condenser, the larger cooling tower is needed, which makes this a financial deliberation.

Whether the chosen temperature in the condenser is too low or not can be illustrated in a T-s diagram. As seen in figure 33 the point after the turbine (stage d) is in the wet area which is below the line. This means that the steam will start to condense in the turbine and cause erosion. To prevent this, steam could be extracted from the turbine (2), reheated in the boiler and then sent back to a low pressure turbine (2'), as illustrated in figure 34. [167]

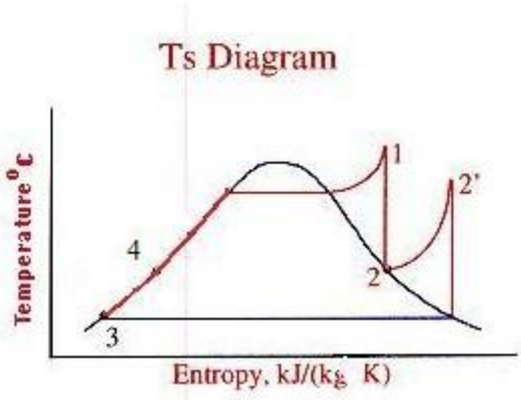


Figure 34 T-s diagram with two turbines. [167]

If two turbines are used, more of the energy content in the waste can be extracted and less needs to be cooled away. The revenue from electricity will be bigger with two turbines, but the extra turbine will increase the investment cost. Two turbines are only financially viable for larger applications [144], hence this will not be an alternative for this specific case in Chennai.

There is also a possibility to increase the pressure before the turbine. However, an increased pressure means higher internal electricity costs and increased investment costs in the form of more robust pipes. [149]

Additional parameters in scenario 2: In scenario 2, when both electricity and process steam will be produced, the energy extracted from the plant will increase. Nevertheless, the maximum extracted electric power will decrease when steam is tapped off the turbine. The decrease in electric power produced depends on the pressure, temperature and flow of the process steam leaving the turbine. Table 22 specifies the steam requirements of Orchid Chemicals & Pharmaceuticals Ltd.

Table 22 Steam requirements of Orchid Chemicals & Pharmaceuticals LTd. [153]

Required steam characteristics	
Pressure [bar]	10
Temperature [°C]	180
Mass flow [kg/s]	6

Steam with this specific characteristic will be tapped off at an outlet of the turbine. The rest of the steam flow will expand totally through the turbine and generate electricity. At the industry, the steam will go to a steam generator, which functions as a condenser. Considering losses in the steam generator, the steam pressure drawn from the turbine has to be slightly higher. Assuming that the steam is drawn at 12 bar, this gives the temperature to 220 degrees Celsius.

Hence, the Rankine cycle in scenario 2 will have two more stages, x and y, which are specified in table 23 and figure 35. The enthalpy in stage x is read from the T-s diagram.

Table 23 The two extra stages in the steam cycle. [100]

Stage	T [°C]	P [bar]	h [kJ/kg]
y	220	12	2866
x	188	12	798.6

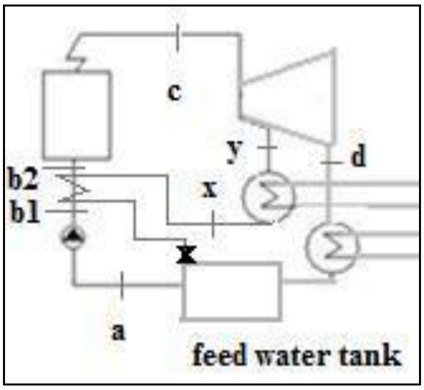
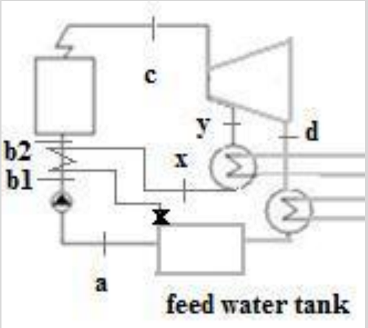


Figure 35 The steam cycle in scenario 2. [100]

The water after the industry has a temperature of 190 degrees Celsius. This water can be used to preheat the feed water before the boiler. As the water from the industry has a pressure of 12 bar, a valve is necessary before the feed water tank to lower the pressure. The new value for the enthalpy in stage b with preheaters is 380.9 kJ/kg and is calculated in box 12. This gives the temperature of the feed water before the boiler to 90 degrees Celsius. However, this makes only a small difference for the efficiency of the plant and is neglected in the further calculations.

Box 12 Calculation of the enthalpy before the boiler in the presence of a preheater

$$\dot{m}_b \cdot (h_{b2} - h_{b1}) = \dot{m}_x (h_x - h_a)$$



Where:

Stage	T [°C]	P [bar]	h [kJ/kg]	ṁ [kg/s]
a	35	0.056	146.6	17.0
b1	35	45	150.8	17.0
x	188	12	798.6	6.0

Result:
The enthalpy after the preheater before the boiler (h_{b2}) is calculated to 380.9 kJ/kg.

5.3.1.5 Summary of parameters

Table 24, 25 and 26 summarize the parameters that will be used to determine the potential thermal and electrical power that could be extracted from the MSW incineration plant in the two scenarios in the case study.

Table 24 Boiler efficiency.

Parameter	
Boiler efficiency [%]	89
Turbine efficiency [%]	85
Generator efficiency [%]	98

Table 25 Fuel specifications for scenarios 1 and 2.

Parameter	Scenario 1	Scenario 2
Fuel	RDF	RDF + industrial waste
Heating value [MWh/ton] (kcal/kg)	2.6 (2236)	3 (2580)
Heating value [MJ/kg]	9.4	10.8
Flow rate of waste [tons/day]	350	466
Flow rate of waste [kg/s]	4.1	5.4

Table 26 Parameters in the Rankine cycle.

Stage	T [°C]	P [bar]	h [kJ/kg]
a	35	0.056	146.6
b (scenario 1)	35	45	150.8
b (scenario 2)	90	45	380.9
c	400	45	3208
d	35	0.056	2270
y	220	12	2866
x	188	12	798.6

5.3.2 Potential power generation

This section will calculate the potential electric and thermal power that could be extracted from an MSW incineration plant in scenarios 1 and 2. Firstly, the fuel power, steam flow and the thermal and electric efficiency are estimated.

5.3.2.1 The fuel power of the plant

The fuel power of the plant can be estimated if the flow rate and heating value of the fuel is known, as well as the efficiency of the boiler.

The fuel power of the plant in scenarios 1 and 2 is 34 MW and 52 MW, respectively. The calculations are presented in boxes 13 and 14.

Box 13 The fuel power of the plant in scenario 1

$$P_F = \dot{B} \cdot H_i \cdot \eta_b$$

Where:

P_F	Fuel power [MW]
$\dot{B}$	Flow rate of waste [kg/s]
H_i	Lower heating value [MJ/kg]
η_b	Efficiency of the furnace in a BFB [%]

Assumptions:

$\dot{B}$	350 ton/day (4.1 kg/s)
H_i	2.6 MWh/ton (9.4 MJ/kg)
H_b	89.5 % [111]

Result:
The fuel power of the plant is 34 MW in scenario 1.

Box 14 The fuel power of the plant in scenario 2

$$P_F = \dot{B} \cdot H_i \cdot \eta_b$$

Where:

P_F	Fuel power [MW]
$\dot{B}$	Flow rate of waste [kg/s]
H_i	Lower heating value [MJ/kg]
η_b	Efficiency of the furnace in a BFB [%]

Assumptions:

$\dot{B}$	466 ton/day (5.4 kg/s)
H_i	3 MWh/ton (10.8 MJ/kg)
η_b	89.5 % [111]

Result:
The fuel power of the plant is 52 MW in scenario 2.

5.3.2.2 Steam flow

The steam flow can be calculated from the enthalpy difference over the boiler (stages a and c in the Rankine cycle) and the fuel power of the plant.

This gives a steam flow of 11.3 kg/s and 17.0 kg/s in scenarios 1 and 2, respectively. The calculations are presented in box 15.

Box 15 The steam flow in scenarios 1 and 2

$$\dot{m} = \frac{P_F}{(h_c - h_a)}$$

Where:

$\dot{m}$	Steam flow [kg/s]
h	Enthalpy [kJ/kg]
P_F	Fuel power [kW]

Assumptions:

h_c	3208 kJ/kg
h_a	146.6 kJ/kg
P_{F1}	34 MW (34 493 kW)
P_{F2}	52 MW (52 196 kW)

Result:

The steam flow in scenario 1 and 2 is 11.3 kg/s and 17.0 kg/s, respectively.

5.3.2.3 Electrical and thermal efficiencies

The efficiencies of the plants in scenarios 1 and 2 are calculated from data of the steam flow and the enthalpy at different stages in the steam cycle.

In scenario 1 the total mass flow of the steam is 11.3 kg/s throughout the whole cycle. In scenario 2 the total mass flow of the steam after the boiler is 17.0 kg/s. Since the industry needs steam with a mass flow of 6 kg/s at 180 degrees Celsius and 10 bar, steam with characteristics shown in table 22 will be tapped off at an outlet of the turbine. The rest of the flow (11 kg/s) will expand through the turbine to stage (d) and generate electricity.

The electric efficiency in scenario 1 is 31 percent and 24 percent in scenario 2. The thermal efficiency in scenario 2 is 24 percent. The calculations are presented in boxes 16 and 17.

Box 16 Calculation of the electric efficiency in scenario 1

$$\eta_e = \frac{\dot{m} \cdot (h_c - h_d)}{\dot{m} \cdot (h_c - h_a)}$$

Where:

η_e	Electric efficiency of the plant [%]
$\dot{m}$	Steam flow [kg/s]
h	Enthalpy [kJ/kg]

Assumptions:

Stage	T [°C]	P [bar]	h [kJ/kg]	ṁ [kg/s]
a	35	0.056	146.6	11.3
b	35	45	150.8	11.3
c	400	45	3208	11.3
d	-	-	2270	11.3

Result:

The electric efficiency in scenario 1 is 31 %.

Box 17 Calculations of the electric and thermal efficiencies in scenario 2

$$\eta_e = \frac{\dot{m}_c \cdot (h_c - h_y) + \dot{m}_d \cdot (h_y - h_d)}{\dot{m}_c \cdot (h_c - h_a)}$$

$$\eta_{th} = \frac{\dot{m}_x \cdot (h_y - h_x)}{\dot{m}_c \cdot (h_c - h_a)}$$

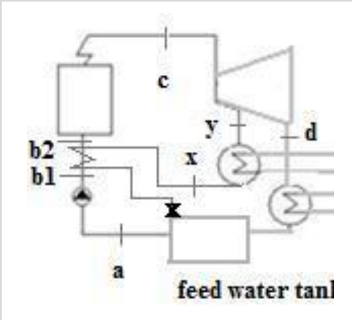
Where:

η_e Electric efficiency of the plant [%]

η_{th} Thermal efficiency of the plant [%]

Assumptions:

Stage	T [°C]	P [bar]	h [kJ/kg]	$\dot{m}$ [kg/s]
a	35	0.056	146.6	17.0
b2	90	45	380.9	17.0
c	400	45	3208	17.0
d	35	0.056	2270	11.0
y	220	12	2866	6.0
x	188	12	798.6	6.0



Result:

The electric efficiency is 24 % and the thermal efficiency is 24 % in scenario 2.

5.3.2.4 The potential electric and thermal power extracted from the plant

When electricity is produced, only a part of the energy in the fuel can be extracted. How much depends on the electric efficiency and the efficiencies of the turbine and generator. The thermal power possible to extract depends on the thermal efficiency.

The potential electric power in scenario 1 is 10.5 MW, whereas it is 12.2 MW in scenario 2. The thermal power in scenario 2 is 12.5 MW. The calculations are presented in boxes 18 and 19.

Box 18 The potential electric power in scenario 1

$$P_{tot} = \dot{m}_c \cdot (h_c - h_a)$$

$$P_e = \eta_e \cdot \eta_g \cdot P_{tot}$$

Where:

P_e	Electric power [kW]
η_e	Electric efficiency of the plant [%]
η_g	Efficiency of the generator [%]
P_{tot}	Maximum power of the plant [kW]
$\dot{m}$	Steam flow [kg/s]
h	Enthalpy [kJ/kg]

Assumptions:

η_e	31 %	
η_g	98 %	[154]
$\dot{m}$	11.3 kg/s	
h_c	3208 kJ/kg	
h_a	146.6 kJ/kg	

Result:

The electric power in an incineration plant producing electricity is 10.5 MW.

Box 19 The potential electric and thermal power in scenario 2

$$P_{tot} = \dot{m}_c \cdot (h_c - h_a)$$

$$P_e = \eta_e \cdot \eta_g \cdot P_{tot}$$

$$P_{th} = \eta_{th} \cdot P_{tot}$$

Where:

P_e	Electric power [kW]
P_{th}	Thermal power [kW]
η_e	Electric efficiency of the plant [%]
η_g	Efficiency of the generator [%]
η_{th}	Thermal efficiency of the plant [%]
P_{tot}	Maximum power of the plant [kW]
$\dot{m}$	Steam flow [kg/s]
h	Enthalpy [kJ/kg]

Assumptions:

η_e	24 %	
η_g	98 %	[154]
η_{th}	24 %	
$\dot{m}$	17.0 kg/s	
h_c	3208 kJ/kg	
h_a	146.6 kJ/kg	

Result:
The electric power in scenario 2 is 12.2 MW and the thermal power is 12.5 MW.

The power that needs to be cooled away can be determined by knowing the enthalpy and mass flow of the steam before the condenser and the water after the condenser. This knowledge will determine the required size of the cooling tower. The calculations in box 20 show that the power that needs to be cooled away are 24.0 MW and 23.4 MW in scenarios 1 and 2, respectively.

Box 20 The power that needs to be cooled in scenarios 1 and 2

$$P_c = \dot{m} \cdot (h_d - h_a)$$

Where:

Data	Scenario 1	Scenario 2
h_a [kJ/kg]	146.6	146.6
h_d [kJ/kg]	2270	2270
$\dot{m}$ [kg/s]	11.3	11.0

Result:
The power that needs to be cooled is 24.0 MW for scenario 1 and 23.4 MW for scenario 2.

5.3.2.5 Summary of the estimated technical parameters

The result of technical calculations is presented in table 27.

Table 27 The estimated technical parameters.

Parameters	Scenario 1	Scenario 2
Total amount of fuel [tons/day]	350	466
Fuel power of plant [MW]	34	52
Steam flow [kg/s]	11.3	17.0
Electric efficiency [%]	31	24
Thermal efficiency [%]	-	24
Cooling power [MW]	24.0	23.4
Electric power [MW]	**10.5**	**12.2**
Thermal power [MW]	**-**	**12.5**

5.4 Financial viability

The costs for setting up and operate a waste incineration facility can vary greatly in different parts of the world. Labour costs and the price of manufacturing resources in the country where the facility will be set up are example of factors that will determine the final cost for the project. According to Bengt Heike at EON in Norrköping, Sweden, the facility described in this case study would cost about Rs. 5 billion, ($100 million) if it would be set up in Sweden. This price includes everything such as flue gas treatment, piping, labour costs and material for the construction work etc. [150] See appendix 8 for price estimations of specific components needed in an MSW-incineration plant.

Because of the difficulties finding relevant data for the investment and operational costs in India and the uncertainties applying the same data from developed countries on India, this case study will focus on the revenues from the plant. The estimated revenues will determine which plant cost is financially viable for the project.

5.4.1 Revenues

The possible revenues that the investor can get from building the plant are profits from selling electricity and/or steam, CERs and from getting subsidies. The revenues from de two scenarios are given in table 28.

Table 28 Revenues from scenarios 1 and 2. [37]

Scenario 1	Scenario 2
Electricity	Electricity and steam
CERs (electricity)	CERs (electricity and steam)
Subsidy	Subsidy

5.4.1.1 Revenues from selling electricity and steam

The generated electricity will be sold to the state electricity board in Tamil Nadu, TNEB. The price for selling electricity generated from burning MSW in Chennai is currently Rs. 3.15/kWh ($0.065). [130] The process steam which is generated in scenario 2 will be sold to the company Orchid Chemicals & Pharmaceuticals Ltd. At the moment they generate steam to a price of Rs. 1/kWh ($0.021). Therefore, this process steam will be sold to a lower price, which is assumed to be Rs. 0.8/kWh ($0.017). The number of working hours per year is specified to 8000.

The calculations of the revenues from electricity and steam are presented in box 21. The result shows that the annual revenue from selling electricity is Rs. 265 million ($5.5 million) in scenario 1 and Rs. 307 million ($6.4 million) in scenario 2 and the annual revenue from selling process steam is Rs. 80 million ($1.7 million).

Box 21 The revenues from selling electricity and process steam

$$R_e = p_e \cdot P_e \cdot h_{op}$$

$$R_{th} = p_{th} \cdot P_{th} \cdot h_{op}$$

Where:

R_e	Revenues from selling electricity [Rs./year]
R_{th}	Revenues from selling process steam [Rs/year]
p_e	Price for electricity [Rs./kWh]
p_{th}	Price for process steam [Rs./kWh]
P_e	Electric power of the plant [kW]
P_{th}	Thermal power of the plant [kW]
h_{op}	Working hours per year [h]

Assumptions:

Parameter	Scenario 1	Scenario 2
Price for electricity (p_e) [Rs/KWh]	3.15	3.15
Price for steam(p_{th}) [Rs/KWh]	-	0.8
Electric power (P_e) [MW]	10.5	12.2
Thermal power (P_{th})[MW]	-	12.5
Working hours/year (h_{op})	8000	8000

Result:
The annual revenue from selling electricity is Rs. 265 million ($5.5 million) in scenario 1 and Rs. 307 million ($6.4 million) in scenario 2. The annual revenue from selling process steam is Rs. 80 million ($1.7 million).

The company Orchid Chemicals & Pharmaceuticals Ltd will profit by switching from their old system to buying steam generated from the incineration plant. Considering that they will buy steam to a Rs. 0.2/kWh ($0.0042) lower price, they will save about Rs. 20 million ($0.42 million) each year.

5.4.1.2 Revenues from getting subsidies

As explained in section 4.2.1.1, there are possibilities to get subsidies for an MSW-to-energy project from MNRE. As formulated by MNRE, it is possible to get financial assistance of Rs. 20 million ($0.42 million) per MW, subject to ceiling of 20 percent of project cost or Rs. 100 million ($2.1 million) per project, whichever is less. [50] Since the plants in scenarios 1 and 2 both are larger than 5 MW, it is assumed that the revenues from subsidies will be Rs. 100 million ($2.1 million).

5.4.1.3 Revenues from selling CERs

The prevented tons of CO_2 emissions for a project correspond to the amount of CERs that can be issued (section 4.2.1.3). The calculations of the prevented CO_2 emissions for scenario 1 and scenario 2 can be seen in appendix 10. The market price for a CER, January to April 2009, was 11-12 Euros [110]. The CERs generated for a project will be sold before the project has been realized, i.e. before the actual emission reduction has occurred and the CERs have been issued. The buyer thereby takes a risk, as the project could fail to reduce the projected emission reductions. Because of the involved risk the CERs have to be sold to less than the market price. [146] The CERs are in this study assumed to be sold for 10 Euros (Rs. 680). The revenues from CERs in both scenarios can be seen in table 29.

Table 29 The potential revenues from CERs. [110] [146]

Parameter	Scenario 1	Scenario 2
Prevented CO_2 emissions [tons/year]	66 076	104 056
Revenues from CERs [Rs/year] (million $)	**44 931 680 (0.93)**	**70 758 080 (1.5)**

The CERs are issued annually and can be issued more than once for a specific project. The project proponent can choose between two crediting periods:

- A fixed crediting period of 10 years
- A renewable crediting period of 7 years renewed thrice (that is $7 \cdot 3 = 21$ years) [147]

In the second option the project proponent needs to justify baseline and calculate the CO_2 emissions once every 7 years and then apply for renewal. Therefore, the most common is to choose a straight 10 years period, which also is chosen for this case.

5.4.2 Alternative cost

In Hydroair Tectonics existing plant in Ichalkaranji they sell their produced RDF to industries for Rs. 1000 ($21) per ton. In the case study it is assumed that Hydroair Tectonics has the option to sell their produced RDF for the same price. If the revenue from the incineration plant is less than the revenue from selling the RDF directly to the industries, the plant should not be built. Therefore, in this case study, the price Rs. 1000 ($21) per ton will be used as an alternative cost in order to estimate the allowed plant cost of the project.

5.4.3 Estimation of allowed plant cost

The revenues and costs described in the past sections will be used to estimate the allowed plant cost. The allowed plant cost is the total cost (investment costs including operational costs) that the project is allowed to have to be profitable, for a chosen payback time. A summary of the known revenues and costs is presented in table 30.

Table 30 The known revenues and costs for the plant.

Parameter	Scenario 1	Scenario 2
Annual revenues	**[Rs/year]**	**[Rs/year]**
Revenues from electricity* [Rs/year]	264 600 000	307 440 000
Revenues from steam*[Rs/year]	-	80 000 000
Revenues from CERs** [Rs/year]	24 125 687	51 825 539
One time revenue	**[Rs]**	**[Rs]**
Subsidies [Rs)	100 000 000	100 000 000
Annual cost	**[Rs/year]**	**[Rs/year]**
RDF	116 550 000	116 550 000

***the revenue will increase with the price of electricity and steam (see section 5.4.3.1)**
****max 10 years**

By using the data in table 30, the allowed plant cost is estimated for scenarios 1 and 2, for different chosen payback times.

5.4.3.1 Assumptions

- The price for electricity and steam will most likely increase with time. In the calculations it is assumed that the price for electricity and steam each will increase with 2.5 percent annually, from the values in 2009 which was Rs. 3.15/kWh ($0.065) and Rs. 0.8/kWh ($0.017) respectively.
- The incineration plant could only operate for 8000 working hours per year due to maintenance work etc. It is assumed that the working hours are the same for the industry.

5.4.4 Result

The aim with the case study was to answer the following question:

- Should Hydroair Tectonics invest in a combustion unit burning RDF with recovery of electricity and/or steam or should they sell their RDF to industries?

The answer depends on which payback time the investor allows. Considering that the investor allows a payback time of 15 years for setting up an incineration plant, the allowed plant cost is Rs. 3546 million ($74 million) for scenario 1 and Rs. 6007 million ($125 million) for scenario 2, as seen in table 31. If the investor estimates that the total plant costs (investment costs and operational costs) will be less than this amount, the plant should be built. If not, the RDF should be sold to industries. The result is shown graphically in figure 36.

Table 31 Allowed plant costs for different payback times.

Payback time	Scenario 1		Scenario 2	
[year]	[M Rs]	[M USD]	[M Rs]	[M USD]
5	1133	24	1908	40
10	2348	49	3983	83
15	**3546**	**74**	**6007**	**125**
20	4977	104	8374	174

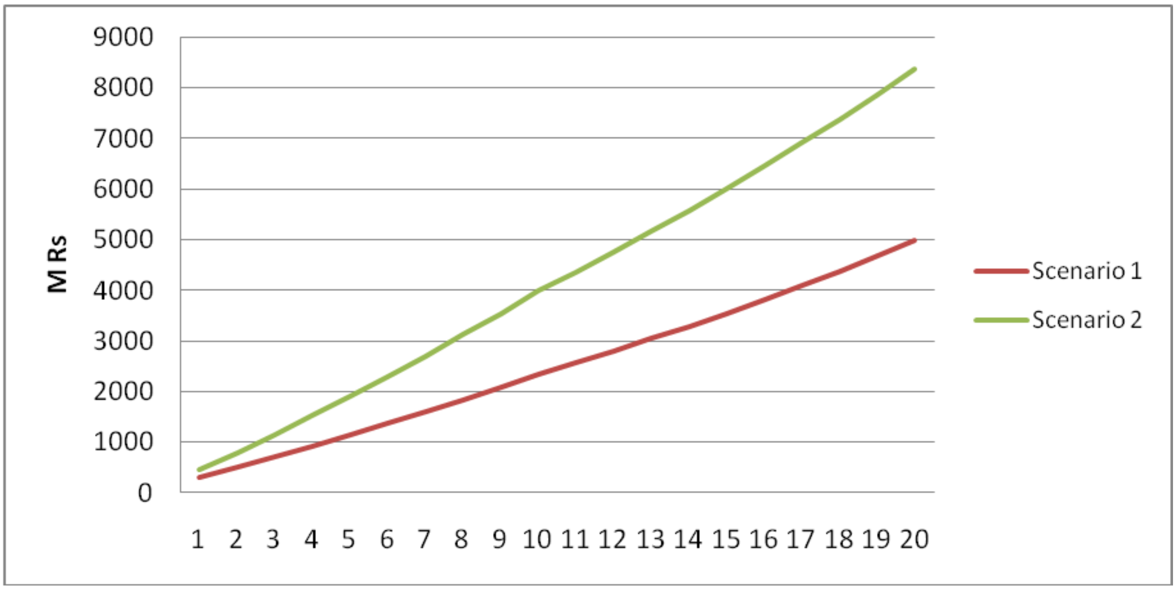


Figure 36 Allowed plant costs for different payback times in million Rupees.

5.4.4.1 Discussion of result

The result shows that in scenario 2, when both steam and electricity are recovered, the allowed plant costs are considerably higher. However, since additional components will come with scenario 2 such as an extra steam piping system, modifications of the current steam system in the industry, a more expensive back pressure turbine etc, the investment cost will be higher. Nevertheless, most likely the extra cost will not exceed the revenues that will come with scenario 2; hence, this scenario is probably the most profitable. In reality, finding a steam demanding industry that could establish a production unit close to one of the dumpsites in Chennai and at the same time generates suitable waste for co-incineration could be difficult. The most realistic scenario is scenario 1.

Whether or not the real costs for setting up a plant will be less than “the allowed plant cost” can be difficult to say. The investment cost for the plant described in scenario 1 would be about Rs. 4808 million ($100 million), if it would be built in Sweden. [150] (The plant in scenario 2 would be slightly more expensive.) This price only includes the investment cost, not the operational cost during the plant’s lifetime. Considering scenario 1 (when only electricity is produced) the total allowed plant cost during 15 years is Rs. 3546 million, which is less than just the investment cost if it would have been built in Sweden. An assumption of this could be that this plant should not be built. However, the costs in India could be considerably lower due to lower labour costs and the possibility of using domestic resources. As seen in box 3 in section 2.7.1.2 the plant costs for setting up the 6 MW RDF plant in Hyderabad in 2003 was Rs. 400 million ($8.3 million), which is a lot cheaper than the investment cost of the plant in Sweden. [32] In that case it could be profitable to build this incineration plant. One aspect that could be questioned, regarding the price difference, is if the plant in Hyderabad has the same flue gas treatment as a plant in Sweden, since the flu gas treatment is a large part of the investment cost.

Another aspect of consideration is the environmental situation of the alternative method, i.e. selling RDF to coal-firing industries. Which flue gas treatment do these coal boilers have? Selling RDF to industries has certain environmental benefits. An advantage of burning RDF in existing coal boilers is that a new plant does not need to be build, which causes less stress on the environment with respect of building material. Furthermore when RDF is burnt in existing coal boilers, it will replace coal and thereby also decrease the carbon dioxide emissions to the atmosphere.

To sum up from the discussion above: It could be difficult to get profitability from setting up an RDF-plant in India, if the same standard and the same flue gas treatment are demanded, as in Sweden. Nevertheless, by using domestic labour and natural resources in India, the price could be significantly lower and should therefore be analyzed further. Besides from analyzing the financial gains, the environmental gains from building the plant could also be compared to the alternative method of selling the RDF to industries, in order to determine the feasibility of the project.

6 Conclusions

Based on the analysis in the case study, the following conclusions can be drawn on which is the best solution for future MSW management in Chennai.

The best solution for waste incineration in Chennai is combustion of RDF and not mass burning of MSW. The production of RDF should take place in a processing facility, set up by Hydroair Tectonics. The products generated from the plant should be compost, bricks, RDF and recyclable material.

The RDF generated from the processing plant should be sold to coal fired industries or burnt with energy recovery. Considering that the RDF should be burnt with energy recovery, it should be combusted in a bubbling fluidized bed. Since the amount of RDF is the same from both of the dumpsites, the plant could be situated at either one of the dumpsites. It should be situated close to the processing plant at (or close to) the dumpsite to minimize the transportation costs. The plant should have a semi-dry flue gas treatment system, which has low investment cost but sufficient flue gas treatment in order to meet the national emission standards. The combustion process should generate energy in two different scenarios:

- *Scenario 1:* The fuel should consist of RDF with an average lower heating value of 2.6 MWh/ton (2236 kcal/kg). There should be recovery of electricity, which will be sold to TNEB. 350 tons of RDF per day will be combusted in an incineration plant with an electric power of 10.5 MW.
- *Scenario 2*: The fuel should consist of a fuel mix of RDF and industrial waste with a lower heating value of 3 MWh/ton (2580 kcal/kg). There will be recovery of electricity which will be sold to TNEB, and process steam which will be sold to a nearby industry. Every day, 466 tons of RDF and industrial waste will be combusted in an incineration plant with an electric power of 12.2 MW and a thermal power of 12.5 MW.

Considering a payback time of 15 years the produced RDF should be

- combusted in an incineration plant with recovery of electricity
  - if the total plant cost does not exceed about Rs. 3546 million ($74 million)
- combusted in an incineration plant together with industrial waste, with recovery of electricity and process steam
  - if there would be an industry close to the incineration plant, with suitable waste for co-incineration as well as a demand for process steam. Considering the specific case which assumes that Orchid Chemicals & Pharmaceuticals Ltd will expand their business and build a production unit close to the dumpsite, the plant should be built if the total plant cost does not exceed about Rs. 6007 million ($125 million).
- sold to industries for Rs. 1000 ($21) per ton
  - if the plant costs exceed the above mentioned.

7 Conclusive discussion

This section will discuss the result of the master's thesis with respect of method criticism, source of errors and suggestions of further studies.

7.1 Method criticism

The conclusion regarding if the RDF should be incinerated or sold to industries, is only based on the financial viability. However, there are other aspects besides the financial that could be considered, such as the environmental. This could be further analyzed.

In scenario 1, it is assumed that the lower heating value of the RDF is sufficient to sustain combustion in the chosen boiler. It is said, that this specific boiler can handle heating values, as low as 2.2 MWh/ton (1892 kcal/kg) (LHV). The average lower heating value of RDF is 2.6 MWh/ton (2236 kcal/kg) and it is therefore assumed that the RDF could be co-incinerated without additional fuel. According to table 12 in section 3.1.2.2 the lower heating value of RDF ranges from 2.0 to 3.1 MWh/ton (1720-2666 kcal/kg). It means that in the monsoon time, when the heating value of RDF is at its minimum, there could be a need for co-incineration. This is not considered in this study.

As mentioned in the case study, RDF could be co-incinerated with coal in order to increase the heating value. Considering scenario 1 when 350 tons of RDF is incinerated every day, a 15 percent infusion of sub-bituminous coal with a lower heating value of 5.25 MWh/ton (4515 kcal/kg) would give a total lower heating value of 3 MWh/ton (2580 kcal/kg). This corresponds to about 62 tons of coal per day, which with a cost of Rs. 3000 ($63) per ton will give an extra annual cost of Rs. 62 million ($1.3 million). Whether or not this is financially viable could be further analyzed.

In the case study in scenario 2, it is assumed that the industrial waste is co-incinerated with RDF. The method for feeding the industrial waste into the combustion unit is not specified. Depending on the characteristics of the waste, the boiler might need to be modified. A sprinkler system could be necessary if the waste is fluent and pelletation could be the case if it is heterogeneous. This needs to be considered in order to determine the financial and technical viability. Another issue is that the industrial waste might not even be suitable for incineration, for certain reasons. The specifications described in section 5.1.4.2 should preferably be fulfilled.

The incineration plant in the case study is situated at, or close to the dumpsite. It would be most advantageous if it would be situated at the dumpsite, considering the lack of land area in Chennai and because it would minimize the transportation costs. If the incineration plant is suitable to place on the dumping ground or not needs further investigations.

The choice of flue gas treatment in the case study was determined from the fact that the emission standards in India and Sweden were at the same level, which would mean that the plant in India should have the same flue gas treatment as in Sweden, in order not to exceed these standards. How strict these standards are followed in India is unknown. According to Mr S. Balaji at TNPCB, depending on where the plant is located, different emission limits are allowed. It is TNPCB that will decide whether or not it is possible to build the plant in the requested area. Since the two dumpsites in Chennai are rigorously polluted, getting a clearance from TNPCB to build an incineration plant at or close to one of these dumpsites can be difficult. As Mr S. Balaji was saying, it would require a plant with very good flue gas treatment. [132]

7.2 Sources of errors

The calculations of the heating value of the MSW in Chennai are based on the percentage of the different components' fractions in the MSW. In the studies where these data were found, it does not say where in the waste stream the analyses were made. If they were made on the dumpsite, the fraction of recyclable material would be less than in the beginning of the waste stream considering that the ragpickers have sorted them out. A lower fraction of the recyclable material, such as plastic, will decrease the heating value of the waste.

The calculations of the heating value of RDF are based on data about the content of specific substances in the RDF. The quality of these data is unknown. Information about the heating value of the industrial waste comes from personal communication with employees at Orchid Chemicals & Pharmaceuticals Ltd. Also in this case, the quality of the data is unknown. Since the calculation of potential power of the plant depends on the heating value of RDF and the fuel mix of RDF and industrial waste, uncertainties in these values will affect the result.

7.3 Suggestions of further studies

- Investigate the possibility of using the organic fraction in a biomethanation plant for electricity generation instead of producing compost at one of Hydroair Tectonics' processing plants. Regarding the electricity deficit in India, this technique is to prefer.

- Examine the possibility to build an incineration plant at the processing plant in Ichalkaranji. In Ichalkaranji, where one of Hydroair Tectonics processing plants is situated, there are many textile industries that are in need of steam for their production. Furthermore, there are large areas where they cultivate sugarcanes near the processing plant. The waste from the sugarcanes could be used for co-incineration with RDF to increase the heating value, while process steam could be provided to the textile industries. In this area the ground water level is relatively high, meaning that water is not so scarce compared to other places in India, which is advantageous if setting up an incineration plant. [123]

- Study the potential for building an incineration plant with co-generation of electricity and district cooling. Because of the warm climate in Chennai, district heating is not an alternative. District cooling on the other hand could be an alternative. However, considering the large investment costs for district cooling pipelines as well as the current infrastructure in Chennai today, this alternative might be more suitable in a few years from now.

- Investigate the possibility for using hot flue gases, generated from the incineration process in the case study, to dry the RDF further and thereby increase the heating value.

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Appendix 1 The ownership of the power stations in India

The ownership of the power stations in India is seen in table A1.

Table A1 The ownership of the power stations in India in GW. [28]

Ownership sector	Thermal			Total Thermal	Nuclear	Hydro	RES*	Total
	Coal	Gas	Diesel					
State	42598	3912	603	47112	0	26826	2248	76186
Private	5241	4183	579	10022	0	1230	10995	22246
Central	29620	6639	0	36259	4120	8592	0	48971
Total	77459	14734	1182	93393	4120	36648	13242	147403

Appendix 2 Annual waste dumped in Chennai

The calculations of the annual population are based on the growth rate in table A2 with 2001 as reference year. The population was 7.04 million in Chennai metropolitan area according to census 2001. [54] The reference year for per capita waste generation is 1996. The waste generation in 1996 was 585 g/cap/day. [54] The waste growth rate per year is assumed to be 1 percent. [7]

Table A2 Annual waste generation in Chennai.

Year	Population	[g/cap/day]	[tons/year]
2009	7806349	666	1394128
2008	7702367	659	1361939
2007	7599770	653	1330493
2006	7498540	646	1299773
2005	7404503	640	1270765
2004	7311645	633	1242405
2003	7219951	627	1214677
2002	7129408	621	1187569
2001	7040000	615	1161065
2000	6954460	609	1135601
1999	6869960	603	1110696
1998	6786486	597	1086337
1997	6704026	591	1062513
1996	6622569	585	1039210
1995	6542101	579	1016318
1994	6462611	573	993929
1993	6384087	568	972034
1992	6306516	562	950621
1991	6208423	556	926476
1990	6111856	551	902945
1989	6016791	545	880011
1988	5923204	540	857660
1987	5831073	534	835877
1986	5740375	529	814647
1985	5651088	524	793956
1984	5563190	519	773790
1983	5476658	513	754137
1982	5391473	508	734983
1981	5275414	503	711970
1980	5161853	498	689677
1979	5050737	493	668082
1978	4942013	488	647164
1977	4835629	483	626901
1976	4731535	478	607272
1975	4629682	474	588257
1974	4530022	469	569838
1973	4432506	464	551996
1972	2700124	460	332894
1971	2642000	455	322470

Appendix 3 Carbon content of MSW in Chennai

Table A3 shows the carbon content in each fraction of Chennai's MSW composition as well as the total organic carbon content in Chennai's MSW. The MSW composition is based on survey conducted by NEERI.

$$C_0 = \sum_i 1000 \cdot SW_i \cdot dm_i \cdot CF_i \cdot OCF_i$$

Where:

SWi	Fraction of waste type *i* (wet weight) [%]
dmi	Dry matter content in the waste (wet weight) [%]
CFi	Fraction of carbon in the dry matter (total carbon content) [%]
OCFi	Fraction of organic carbon in the total carbon [%]
i	Type of waste
C_0	Organic carbon content [kg/ton]

Assumptions:

Table A3 Characteristics of Chennai's MSW.

Component	SWi [%]	dmi [%]	CFi [%]	OCFi [%] default [113]	C_o [kg/ton]
Food	10.3	25	11.7	100	3
Paper/cardboard	8.4	77	33.1	99	21.2
Plastic	7.5	80	48	0	0
Textiles	3.1	90	49.5	80	11
Wood	0.5	80	39.2	100	1.6
Yard	41.1	35	16.7	100	24.1
Other fuel-wastes	0.2	90	48.4	0	-
Glass	0.3	98	0.5	-	0
Metals	0.2	97	4.4	-	0
Other waste	2.5	79.5	20.9	80	3.3
Inerts	26	100	0	-	0
Mixed MSW	100	61.2	16.8	0	0
				Total	64.2

Result:

The organic carbon content in the MSW in Chennai is 64 kg per ton.

Appendix 4 The total methane emission in Chennai

The total methane emissions from the dumpsites in Chennai for 2008 are seen in Table A4, and were 28 348 tons. C_0 is calculated in appendix 3.

$$\alpha_t = \zeta \cdot 1,87 \cdot A_i \cdot C_0 . k . e^{-k} \cdot t$$

Where:

α_t	Landfill gas formation at a certain time [m^3/year]
ζ	Landfill gas formation factor
A	Amount of waste deposited each year [ton]
C_0	Amount of degradable organic carbon in the waste at the time of deposition [kg/ton]
k	Degradation rate constant [$year^{-1}$]
t	Time elapsed since deposition [year]
1.87	Amount of landfill gas produced per kilogram of organic carbon that degrades [m^3/kg]
i	A specific year after disposal

Assumptions:

A	The amount of MSW generated per year is taken from appendix 2
ζ	A typical value for ζ is 0.5. In this study ζ = 0.58 has been used which is estimated from a study in the Netherlands and a value used in other studies in India [75]
k	0.094 $year^{-1}$ is chosen on the same grounds as above [75]
C_0	912 kg/ton [appendix 3]

- 50 % of the landfill gas consists of methane [75]
- Both the landfills opened in year 1971
- The collection efficiency in Chennai is 73 % [76]

Table A4 Calculated methane emissions in Chennai for 2008.

Year of disposal	t [years]	A [tons]	A*C_0 [tons]	α(t) [m^3/year]	CH_4 [tons]
2008	0	1361939	87164	8886589	3173
2007	1	1330493	85152	7902533	2822
2006	2	1299773	83185	7027446	2510
2005	3	1270765	81329	6254198	2233
2004	4	1242405	79514	5566033	1988
2003	5	1214677	77739	4953588	1769
2002	6	1187569	76004	4408532	1574
2001	7	1161065	74308	3923450	1401
2000	8	1135601	72678	3493123	1247
1999	9	1110696	71085	3109994	1111
1998	10	1086337	69526	2768887	989
1997	11	1062513	68001	2465193	880
1996	12	1039210	66509	2194809	784
1995	13	1016318	65044	1953885	698
1994	14	993929	63611	1739407	621

Year of disposal	t [years]	A [tons]	A*C_0 [tons]	α(t) [m^3/year]	CH_4 [tons]
1993	15	972034	62210	1548473	553
1992	16	950621	60840	1378497	492
1991	17	926476	59294	1222951	437
1990	18	902945	57788	1084957	387
1989	19	880011	56321	962533	344
1988	20	857660	54890	853924	305
1987	21	835877	53496	757569	271
1986	22	814647	52137	672087	240
1985	23	793956	50813	596251	213
1984	24	773790	49523	528971	189
1983	25	754137	48265	469284	168
1982	26	734983	47039	416331	149
1981	27	711970	45566	367113	131
1980	28	689677	44139	323713	116
1979	29	668082	42757	285444	102
1978	30	647164	41418	251699	90
1977	31	626901	40122	221943	79
1976	32	607272	38865	195705	70
1975	33	588257	37648	172569	62
1974	34	569838	36470	152168	54
1973	35	551996	35328	134179	48
1972	36	332894	21305	73660	26
1971	37	322470	20638	64952	23
Total	-	34026945	2177724	79382641	28348

Result:
By adding the amount of methane gas produced from the waste disposed each year, the methane gas for year 2008 can be estimated. The total methane emissions in Chennai from MSW in year 2008 were according to the first-order decay method 28 348 tons.

Analysis of methane emission calculations:

- Methane generation in a landfill is a complex process depending on many variables, for example the anaerobic and aerobic processes on different depths in the dumpsite. These processes are not totally included in the calculations.
- The landfill gas factor needs to be estimated for Indian conditions, the current value is estimated from developing countries.
- Ragpickers remove approximately 20 % of the waste before it is landfilled, which is not considered. On the other hand, the current carbon content in the waste was used for every year. Previous studies show that using the actual value for the carbon content for each year gives about 20 % more landfill gas. It is assumed that these two factors cancel each other. [73]

Appendix 5 Calculations of the carbon dioxide emissions from open dumping in Chennai

The calculations for fossil CO_2 emissions are based on 73 % collection efficiency. It is assumed that the amount of waste which is not collected is open burned in alleys.

The amount of MSW that is open burned:

$$MSW\ open\ burned = population \cdot MSW\ generation \cdot 365 \cdot \frac{100 - collection\ efficiency}{100}$$

CO_2 emissions from open burning, based on 2006 IPCC Guidelines for National Greenhouse Gas Inventories [113]:

$$CO2\ emissions = \sum_i MSW\ open\ burned \cdot (SWi \cdot dmi \cdot CFi \cdot OFi) \cdot 44/12$$

Where:

population	The population in Chennai 2009
MSW generation	Amount of MSW generated per capita per day [tons/cap/day]
365	Days per year
collection efficiency	Collection efficiency of MSW in Chennai [%]
SWi	Fraction of waste type *i* (wet weight) incinerated or open-burned [%]
dmi	Dry matter content in the waste (wet weight) incinerated or open-burned, (fraction)
CFi	Fraction of carbon in the dry matter (total carbon content), (fraction)
OFi	Oxidation factor, (fraction)
44/12	Conversion factor from C to CO_2
i	Type of waste incinerated/open-burned specific as follows

Assumptions:

population	7702367 [appendix 2]
MSW generation	666 g/cap/day [appendix 2]
collection efficiency	73 % [76]

- The Tier 2b in 2006 IPCC Guidelines for National Greenhouse Gas Inventories are used: SWi, dmi and CFi are country specific while for OFi default parameter is used. [113]. Table A5 specifies these parameters.
- All the waste in Chennai not collected is open burnt.

Table A5 Specifications of SWi, dmi, CFi and OFi in Chennai.

Component	SWi [%]	dmi [%]	CFi [%]	OFi [%] default [113]
Food	10.3	25	11.68	58
Paper/cardboard	8.4	77	33.11	58
Plastic	7.5	80	48	58
Textiles	3.1	90	49.5	58
Wood	0.5	80	39.2	58
Yard	41.1	35	16.73	58
Other fuel-wastes	0.2	90	48.42	58
Glass	0.3	98	0.49	58
Metals	0.2	97	4.37	58
Other waste	2.5	79.5	20.91	58
Inerts	26	100	0	58
Mixed MSW	100	61.23	16.79	58

Result:
The amount of waste that is going to be open burned in Chennai in 2009 is 500 225 tons/year. The total amount of CO_2 emissions from this waste will be 213 400 tons/year.

Appendix 6 Characteristics of the waste in Chennai analysed by the CoC and NEERI

Table A6, A7and A8 specify the content of different substances in MSW and RDF, in order to determine the heating value with Dulong's formula.

Table A6 Calculations of the heating value of MSW in Chennai based on a study made by the CoC.

Component	Content (%)	m(w) (%)	m(c) (%)	m(h) (%)	m(o) (%)	m(n) (%)	m(s) (%)	LHV	HHV
Food	8	75	11.68	2	9.72	0.53	0.03		
Paper/cardboard	6.5	23	33.11	5.39	33.88	0.15	0.02		
Plastic	7.0	20	48	8	18.24	0	0		
Textiles	3.1	10	49.5	5.94	28.08	4.05	0.18		
Wood	7.0	20	39.2	4.8	34.16	0.16	0.08		
Yard	32.3	65	16.73	2.1	13.3	1.19	0.11		
Other fuel-wastes	1.5	10	48.42	8.01	20.97	0.75	0.51		
Glass	0	2	0.49	0.1	0.39	0.1	0		
Metals	0.03	3	4.37	0.58	4.17	0.1	0		
Other waste	0	20.5	20.91	2.39	12.78	0.4	0.1		
Inert	34.7	-	-	-	-	-	-		
Mixed MSW	100	31.71	16.84	2.39	12.11	0.59	0.06	**1.61**	**1.98**

Table A7 Calculations of the heating value of MSW in Chennai based on a study made by NEERI.

Component	Content (%)	m(w) (%)	m(c) (%)	m(h) (%)	m(o) (%)	m(n) (%)	m(s) (%)	LHV	HHV
Food	10.3	75	11.68	2	9.72	0.53	0.03		
Paper/cardboard	8.4	23	33.11	5.39	33.88	0.15	0.02		
Plastic	7.5	20	48	8	18.24	0	0		
Textiles	3.1	10	49.5	5.94	28.08	4.05	0.18		
Wood	0.5	20	39.2	4.8	34.16	0.16	0.08		
Yard	41.1	65	16.73	2.1	13.3	1.19	0.11		
Other fuel-wastes	0.2	10	48.42	8.01	20.97	0.75	0.51		
Glass	0.3	2	0.49	0.1	0.39	0.1	0		
Metals	0.2	3	4.37	0.58	4.17	0.1	0		
Other waste	2.5	20.5	20.91	2.39	12.78	0.4	0.1		
Inert	26.0	-	-	-	-	-	-		
Mixed MSW	100.0	38.77	16.79	2.40	12.08	0.69	0.06	**1.56**	**1.98**

Table A8 Calculations of the heating value of RDF made from MSW in Chennai based on a study made by Hydroair Tectonics.

Component	m(w) (%)	m(c) (%)	m(h) (%)	m(o) (%)	m(n) (%)	m(s) (%)	LHV	HHV
RDF	20	25	4	22.5	1.25	0.25	2.55	2.94
Lower limit	10	20	3	20	1	0.2	1.96	2.22
Higher limit	30	30	5	25	1.5	0.3	3.15	3.67

Appendix 7 Regulatory systems for setting up an incineration plant in India

The regulatory systems in India differ both on federal and state level. The state level systems can differ from various states while the federal systems are the same throughout all India. In every state there is a guidance bureau that can provide help with enquiries regarding state level regulations and support. [135]

A 7.1 Pre-project clearances

The pre-project clearances need to be dealt with before the company can get the approval to start a business.

A 7.1.1 Federal level

The company needs to have

- *a registered office in India.* The company can be 100 percent foreign owned or it can be a joint venture with an Indian partner
- *an approval from the Reserve Bank of India (RBI) and a bank account.* This is necessary when the company wants to transfer money out from India. [93]

A 7.1.2 State level

The company needs to have

- *a building plan permit*
- *environmental clearance*
- *safety clearance for fire, electricity, boilers* [140]

Guidance bureau can assist with all the above listed enquiries. Table A9 shows the responsible authorities/agencies for each enquiry, to which the guidance bureau will send an application for the company. [140]

Table A9 The responsible authority/agency for the specific enquiry.

Enquiry	Responsible authority/agency
Building plan permit	Chennai Metropolitan Development Agency (CMDA) or Corporation of Chennai (COC)
Environmental clearance	Tamil Nadu Pollution Control Board (TNPCB)
Safety clearance for:	
Fire	Directory of fire and rescue services
Electricity	Chief electrical inspector
Boilers	Boilers' directory

A 7.2 Post-project clearances

The post-project clearances can be dealt with when the company has got the approval to start a business. The main post-project clearance is *tax registration.* The tax registration should be made both to the federal and state government.

Appendix 8 Example of suitable technology with price estimations

This chapter will give examples of suitable technology for this specific case, together with price estimations of specific components.

A 8.1 Boiler

A suitable boiler for this specific case of MSW incineration in Chennai is Ecofluid bubbling fluidized bed. This boiler is manufactured by AE&E Group, which is an international provider of systems for thermal power generation and environmental technologies. An advantage with choosing this company is that they have a manufacturing unit in Chennai, AE&E Chennai Works. [109] This boiler can burn fuel with lower heating value down to 2.2 MWh/ton (1892 kcal/kg) and the boiler efficiency is about 89 percent. [144]

The boiler is delivered with attaching parts. The principal parts which are included are fuel feeding system, overheaters and economizer. Furthermore, there will be a feed water system with a tank, pumps and piping. The excluding parts are roughly spoken those situated before the feed water system and after the superheaters in the steam cycle. The including components in the boiler package are specified below in figure A1.

The boiler package from AE&E Group will cost about Rs. 2193 million ($44 million), if it would be delivered to Sweden. [144] Since the company also has a manufacturing unit in Chennai, the prices could be lower considering that it will be built there.

AUSTRIAN ENERGY
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Scope of Supply and Services:

+ Bubbling Bed Fluidised Bed **ECOFLUID®-RC** boiler including pressure parts, combustion system, SNCR, flue gas and air ducts, heating surface cleaning, boiler auxiliaries (from Economiser inlet to main steam shut-off-valve)
+ Fuel feeding system for waste and sludge within boiler house including dosing silos and start-up fuel system for light fuel oil (within boiler house)
+ Feed water system including tank, pumps and piping etc. (inside boiler house)
+ Ash handling system (mechanical, pneumatic ash system inside the boiler house)
+ Sand storage and dosing system (inside the boiler house)
+ Steel structure for boiler house
+ Cladding and roofing boiler house
+ Refractory lining and insulation
+ Feed and boiler water dosing
+ Water and steam sampling
+ Field instruments and motors
+ Engineering, manufacturing, delivery, erection and commissioning

Excluding:

- Flue gas cleaning system (bag house filter, scrubber etc.)
- Live steam pipeline to steam turbine outside the boiler house
- low pressure steam supply (3 bar) to the boiler house and condensate handling
- External feed water and condensate handling (feed water is supplied with 105°C at the boiler house wall 8 bar)
- Steam Turbine (existing)
- pressurised air supply (pressurised air is supplied at the boiler house wall)
- Flue gas emission monitoring
- Fuel preparation and handling outside the boiler house
- HVAC boiler house
- ID-fan including motor and FC (located near the flue gas cleaning)
- Power cabling, transformers, MCC's and control system
- Cabling for instruments and control system (DCS)
- Civil works

Figure A1 The including components in the boiler package from AE&E Group.

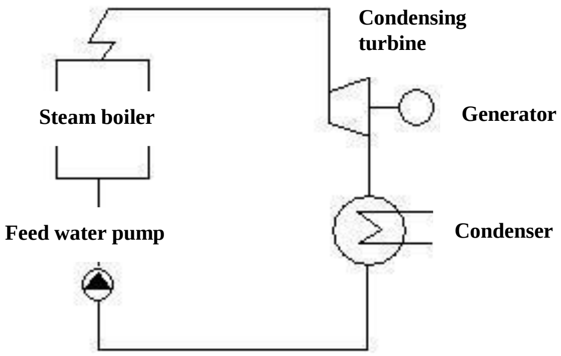
A 8.2 Turbine and generator

The turbine can be provided by Alstom, which is a global provider of power generation technology. The price for a turbine (including a generator) depends on the type and size. For this case, the cost will be about $13 million or Rs. 645 million.

A 8.3 Examples of other components involved in the steam power process

Besides the boiler package, turbine/generator and the flue gas treatment systems the plant needs other components such as preheaters, condensate storage tank, accumulator, condenser, piping, pumps etc. Because of the limited amount of water at the dumpsite, a cooling tower will be used as a cooling devise. No price estimations have been made for these components.

In scenarios 1 and 2 the components used in the steam cycle will differ. The main differences in the two scenarios are the turbine type, the piping system and the extra components needed for energy transfer in the industry. The differences in the two scenarios are illustrated in figures A2 and A3.



- There will only be electricity production. Hence, there will be a **condensing turbine.**

Figure A2 The steam process of scenario 1.

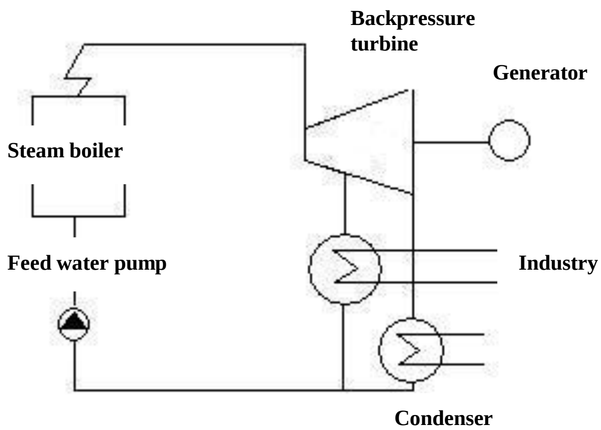


Figure A3 The steam process of scenario 2.

- Some of the steam will be tapped off the turbine and sent to an industry. Therefore a backpressure turbine is used. The rest of the steam will be used for electricity production and will therefore follow the same route as for scenario 1.
- Steam pipes will be used to deliver the process steam to the industry, and water pipes in which the condensate returns to the plant.
- The industry will have a steam generator and a heat exchanger. The condensate that returns from the industry to the plant will have a relatively high temperature. Therefore it will go directly to the feed water tank.

Appendix 9 Clean Development Mechanism (CDM)

A 9.1 What is CDM?

The Clean Development Mechanism (CDM) is an arrangement under the Kyoto Protocol and the United Nations Framework Convention on Climate Change (UNFCCC). CDM allows developed nations to reduce greenhouse gases in developing countries to be able to achieve their emission reduction targets. The countries recited in Annex 1 of the Kyoto protocol, EU, Australia and New Zeeland, have individual commitments to reduce or limit their greenhouse gas emissions [91]. Parts of those emission reductions can be obtained in developing countries, non-Annex 1 countries, where the emission reduction cost is lower. The emission reductions can be achieved by making the energy production more efficient or by exchange the electricity produced from fossil fuel to electricity produced from biofuel. The CDM projects are a way for the Annex 1 countries to compliment the national commitments under the Kyoto protocol, i.e. the CDM projects shall not be more significant than the arrangements in the home country. The host country's government has to approve the proposed CDM project and evaluate whether the project leads to sustainable development. [92]

CDM does not only contribute to a more cost efficient emission reduction for the developed country, it also assists the developing country to achieve sustainable development. The CDM projects provide the developing country with new technology and contribute thereby to a modernization of the industrial sector and the energy production sector. [92]

A 9.2 Supervisory bodies

The CDM Executive Board (EB) is the international agency to monitor the CDM projects. They approve the methodologies, register and monitor the CDM projects and issue carbon credits, CERs. Countries with commitments under the Kyoto protocol must have a responsible authority, Designated National Authority (DNA), to approve and authorize the CDM project. Developing countries who want to be a host country for CDM projects must as well have a DNA to monitor the projects. A third part agency, Designated Operational Entity (DOE), validate the CDM project before it gets registered at the CDM Executive Board, to ensure the project results in long term and real emission reductions. [92]

A 9.3 Requirements to become a CDM project

The CDM project has to be approved by the host country which is the developing country where the project is going to be set up and by the CDM Executive Board. To get approval from the CDM Executive Board some criteria have to be fulfilled [148]:

Additionality: The first requirement for being considered as a CDM project is additionality. There are two interpretations of additionality. The first refers to the emission reductions that will not occur in absence of the project, environmental additionality, i.e. the emissions from the project have to be lower than the baseline. The second interpretation, project additionality, means that the project would not be realized without CDM due to financial deficit without the income from carbon credits. At present the second interpretation is used by the CDM Executive Board when evaluating a project proposal.

Contribute to sustainable development: The function of CDM is not only to reduce greenhouse gas emissions; it must also contribute to sustainable development in the host country.

An upcoming project: The project must be identified as an Upcoming Construction or Ready for Construction. The project cannot be in operation already. This would contradict the additionality criterion.

Eligibility of the project owner: The CDM project owner can be a country with commitments under the Kyoto protocol or an industry with emission limits within an Annex 1 country. The project owner has to be approved by the host country's DNA. The eligibility of the project owners is decided by the DNA and varies between countries. For example in some countries the project owner has to be a national entity or a joint venture.

Eligibility of the host country: The host country must have ratified the Kyoto protocol and be a non-Annex 1 country. An accrediting entity, a DNA, is as well required in the host country to approve and monitor the projects and the project owners, and to confirm that the proposed project will lead to sustainable development for the country.

Identification of a buyer: Before the project can become a CDM project the buyer of the CERs must be identified.

A 9.4 Project cycle for CDM

It is important that the procedure to become a CDM project is not too bureaucratic. This could result in default emission reductions or that the most effective option is rejected. However, if projects that would have happened anyway are registered as CDM projects the net effect of global greenhouse gas emissions will increase as there will be no change of emissions in the developing country, but emissions in the home country can proceed corresponding to the amount of CERs hold from the CDM project. The cycle to become a CDM project is explained below and an overview is seen in figure A4 [114]:

The developing of the project: The project owner formulates an idea of the project, a Project Idea Note (PIN), and presents it to the project developer. The idea is further developed by the project developer to a project description, Project Development Document (PDD).

Validation of the PDD: The PDD is validated by an independent entity, Designated Operational Entity (DOE), to make sure that the CDM project is in accordance with the framework for CDM and that the estimated emission reductions are correct. The DOE has to be accredited by the CDM Executive Board.

Registration of the project at the CDM Executive Board: The DOE present the PDD for the CDM Executive Board with the validation report. Before the CDM Executive Board decides whether the project is a CDM project or not, the PDD must be published for 30 days for possible comments. If the project is approved PDD is registered as a CDM project at the CDM Executive Board.

Verifying the CDM project's emission reductions: CERs will not be issued until the corresponding emission reductions are verified, to confirm that the emission reductions are real. This is performed ones a year at the time of issuing and transfer of the CERs. The verifying is performed by a DOE which cannot be the same one that did the validation. A validation report is then sent to the CDM Executive Board.

Issuing and transferring of CERs to the buyer: Verified emission reductions are certified as CERs and registered and are then issued to the buyer. The CDM Executive Board deducts a part of the CERs generated by the CDM project before they are sold to the buyer. This is done to cover for the adjustment costs for developing countries exposed for negative consequences by the climate change. The project participants are bound to pay a fee to the CDM Executive Board, based on issued CERs to cover the administrative costs. [92]

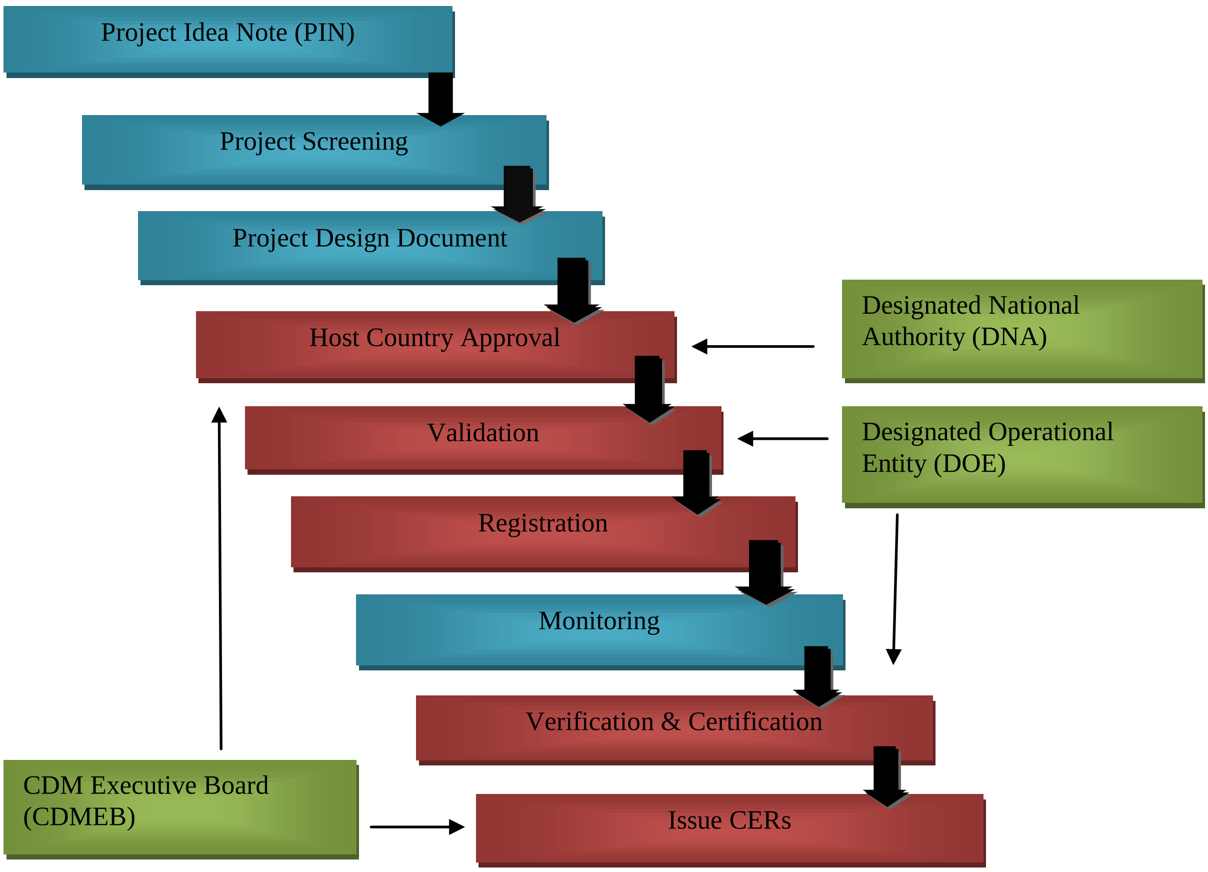


Figure A4 The project cycle for CDM.

A 9.5 Certified Emission Reductions (CERs)

A successfully implemented CDM project generates carbon credits, Certified Emission Reductions (CERs), to the project owner. Each CER is equivalent to one ton reduced carbon dioxide and is issued in exchange for real emission reductions. These credits can be used by the investor to manage the reduction target within the Kyoto protocol or be sold on the International Emission Trading (IET) market to generate income. All CERs have individual serial numbers guaranteeing that they cannot be sold twice. [92] The value of a CER is not fixed, it varies with the market. The price for a CER was 11-12 EUR the first months in 2009. [110]

A 9.6 Baseline estimation

To know if the CDM project is environmental additional, it is necessary to estimate the project's baseline. The baseline is the amount of carbon dioxide emitted per produced unit energy, i.e. kg CO_2/MWh. The project's baseline is then compared to the baseline estimated for the area where the project is going to be set up. If the electricity produced from the CDM project replaces electricity from the national grid, the national baseline is used to calculate the gained emission reductions. On the other hand, if the CDM project produced electricity is replacing the regional grid the comparison then has to be made with the regional baseline. If the CDM project totally replaces coal or oil, the CDM project's emissions are compared to the emissions from the corresponding fuel. [92]

A 9.7 Methodology

The proposed CDM project needs to use an approved methodology and be written in the form prescribed by the UNFCCC. The CDM methodology describes the methodologies used for determination of potential emission reductions achieved by the proposed CDM project. Basically it describes the methodologies for baseline estimation, monitoring plans and project boundaries. Since the projects vary a lot one specific methodology might not be suitable for more than one project. But with validation of an approved methodology it could be possible to approach the new methodology to an upcoming project. If no existing methodology is suitable for a project the project developer can propose a new methodology. The new methodology then first has to be approved by the CDM Executive Board. All the current methodologies are possible to view at UNFCCC's homepage. New methodologies are constantly approved by the CDM Executive Board. [115]

A 9.8 CDM for a WTE project in India

Incineration of MSW demands a more advanced fluegas treatment then incineration of oil or coal. MSW is a mixture of the society's rest products and contains many different materials, some of them with toxic components. In India the hazardous waste is not sorted out and follows the MSW stream. Incineration of hazardous waste results in creation of dioxins. Many other pollutants are formed while incinerating MSW. The nitrogen in meat products gives rise to the formation of nitrogen hydroxides, and sulphur in plastics form sulphur dioxide. Both of these harm the environment. The fluegas treatment of a WTE facility is approximately fifty percent of the investment cost. To be able to build a WTE facility with good fluegas treatment, CDM can be a way of financing the project. CDM will cover approximately ten percent of the invested capital cost. CDM can never be the main financing but it gives an incentive to invest in more environmentally-friendly technology.

At the moment India has 360 CDM projects registered at the CDM Executive Board and 1 426 at or after the validation stage. [116]

A 9.8.1 The Designated National Authority (DNA)

The Ministry of Environment and Forest (MoEF) is the accredited Designated National Authority (DNA) in India. They have the power to invite specialists from different areas as the government, industries, financial institutions, NGOs, commerce, consultants, civil society and legal profession, as they need technical and professional input. [116]

A 9.8.2 Baseline

The national baseline in India is estimated from India’s energy mix. The corresponding calculation for the state level is estimated from the energy mix in that specific region. In the total baseline for an area import and export are included. The biggest energy source in India is sub-bituminous coal which then also is the biggest contributor to the national baseline. [117] [7] The estimation of the national and regional baselines is done by the Central Electricity Authority (CEA). To estimate the baselines CEA uses the “Tool to calculating the emission factors for an electricity system” developed by the CDM Executive Board. The baseline database is annually updated as it changes when new projects are implemented. [117]

Appendix 10 Revenues from CDM in scenarios 1 and 2

If a project that will lower the net emissions of CO_2 eq have problems getting founded, it is possible to become a CDM project. By replacing fossil based energy production with energy production from renewable sources carbon credits can be generated, i.e. the total amount of CO_2 eq with fossil origin that can be reduced gives the same amount of CERs. The CER can be sold to market price to generate income to the project.

The CERs are issued annually and can be issued more than once for a specific project. The project proponent can choose between two crediting periods:

1. a fixed crediting period of 10 years or
2. a renewable crediting period of 7 years renewed thrice (that is $7 \cdot 3 = 21$ years). [147]

In the second option the project proponent needs to justify baseline and calculate the CO_2 emissions once every 7 years and then apply for renewal. Therefore, the most common is to choose a straight 10 years period, which also is chosen for this case. A baseline for the crediting period is then estimated based on the predicted future baseline. The baseline does not change drastically and therefore it is possible to assume a realistic value. The Tamil Nadu baseline has varied between 0.85 and 0.86 tons CO_2/MWh since 2000 [139], and it is thereby assumed that the baseline for the crediting period in this project will be 0.85 tons CO_2/MWh.

According to IPCC Guidelines only the fossil carbon fraction should be taken into consideration when calculating CO_2 emissions from waste incineration. [113] As RDF is derived from waste the same is considered in our case. The most significant greenhouse gas emission from incineration of waste and coal is CO_2. [113] In this study only a rough estimation of CO_2 eq will be made and therefore only CO_2 emissions are taken into consideration.

In the following section, the CO_2 eq for the two scenarios are estimated and compared with the present system to estimate how many CO_2 eq that can be prevented. Thereafter the potential revenues from CERs for both scenarios are estimated.

A 10.1 Prevented CO_2 emissions for the two scenarios

In this section the prevented CO_2 emissions for both scenarios are calculated.

A.10.1.1 Scenario 1

In scenario 1, only electricity is produced. The electricity produced replaces the electricity from Tamil Nadu's gridmix. By calculating the annual amount of emissions from the fuel, i.e. the fraction of RDF with fossil origin, and compare this with the baseline for Tamil Nadu, the net emission reduction can be estimated. The regional baseline for Tamil Nadu is 0.85 tons CO_2 eq/MWh. The annual CO_2 emissions from scenario 1 are 5 324 tons/year. The calculations are presented in box A1.

Box A1 CO_2 emissions from incineration of RDF

Fossil CO_2 emissions from RDF based on IPCC Guidelines for National Greenhouse Gas Inventories [113]:

$$CO_{2_{RDF}} = \sum_i MSW \cdot (CF \cdot FCF \cdot OF) \cdot \frac{44}{12} \cdot \eta_b$$

Where:

MSW	Annual amount of RDF [tons/year]
CF	Fraction of RDF that has fossil origin, (fraction of plastic) [%]
FCF	Fossil carbon fraction in plastic [%]
OF	Oxidation factor, (fraction) [%]
44/12	Molecular weight ratio [CO_2/C]
η_b	Boiler efficiency [%]

Assumptions:

MSW	116550 tons of RDF per year	
CF	5 %	[112]
FCF	48 %	
OF	58 % (default)	[113]
η_b	89.5 %	[111]

Result:
The amount of CO_2 emissions from incineration of RDF is 5 324 tons/year.

The net emission reduction of CO_2 in scenario 1 are 66 076 tons/year. The calculations are presented in box A2.

Box A2 The estimated net emission reduction from scenario 1

Emissions from electricity produced from Tamil Nadu's gridmix:

$$CO_{2_{gridmix}} = Electric\ power \cdot h_{op} \cdot baseline_{TamilNadu}$$

Prevented CO_2 – emissions from scenario 1:

$$CO_{2_{prevented}} = CO_{2_{gridmix}} - CO_{2_{RDF}}$$

Where:

Electric power	The potential electric power [MW]
h_{op}	Operating hours for the plant [h]
$baseline_{TamilNadu}$	The baseline for Tamil Nadu, estimated from the gridmix [tons of CO2/MWh]
$CO_{2_{RDF}}$	The CO_2 – emissions from scenario 1 [tons/year]

Assumptions:

Electric power	10.5 MW	[box 14]
h_{op}	8000 hours	
$baseline_{TamilNadu}$	0.85 tons of CO_2/MWh	[137]
$CO_{2_{RDF}}$	5324 tons/year	[box A1]

Result:

If electricity is produced with Tamil Nadu's gridmix, the CO_2 emissions will be 71 400 tons/year. The prevented CO_2 emissions in scenario 1 will be 66 076 tons/year.

A 10.1.2 Scenario 2

In scenario 2, electricity and process steam are produced. The electricity produced replaces the electricity from Tamil Nadu's gridmix. By calculating the annual amount of emissions from the fuel, i.e. the fraction of RDF with fossil origin and comparing it with the baseline for Tamil Nadu, the net emission reduction can be estimated. The regional baseline for Tamil Nadu is 0.85 tons CO_2 eq/MWh. It is assumed that the industrial waste is free from fossil carbon.

In scenario 2, the industry's present steam production has to be considered. The industry produces steam from sub-bituminous coal. If the industry buys process steam generated at the RDF plant CO_2 emissions can be prevented. The CO_2 emissions prevented are the difference between the CO_2 emissions from sub-bituminous coal that the industry currently uses to produce their process steam and the CO_2 emissions from the fuel in the RDF plant to generate the required steam. The CO_2 emissions from sub-bituminous coal incinerated in the industry is 37 251 tons/year. The calculations are presented in box A3.

Box A3 CO_2 emissions from the sub-bituminous coal incinerated in the industry
The annual amount of sub-bituminous coal for the steam production in the industry:

$$Steam\ power = (h_b - h_a) * \dot{m}$$

$$Size\ of\ plant = \frac{Steam\ power}{\eta_b}$$

$$Coal = \frac{Size\ of\ plant * h_{op}}{LHV}$$

CO_2 emissions from sub-bituminous coal in the industry:

$$CO_{2_{sub-bituminous}} = Coal \cdot CF \cdot \frac{44}{12} \cdot \eta_b$$

Where:

Steam power	The industry's steam demand [MW]
Size of plant	The needed size of the plant for the required steam [MW]
Coal	Amount of sub-bituminous coal needed [tons/year]
$\dot{m}$	Mass flow [kg/s]
h_b	Enthalpy for steam before the industry [MJ/kg]
h_a	Enthalpy for condense after the industry [MJ/kg]
η_b	Efficiency of coal boiler [%]
h_{op}	Operating hours
LHV	Lower heating value for sub-bituminous coal [MWh/ton]
CF	The carbon fraction in the sub-bituminous coal [%]
44/12	Molecular weight ratio CO_2/C

The industry needs steam at 180 degrees Celsius and 10 bar. Considering losses in the steam generator, the steam temperature drawn from the turbine has to be 190 degrees Celsius and 12.6 bar.

Assumptions:

$\dot{m}$	6 kg/s	
h_b	2.778 MJ/kg	
h_a	0.808 MJ/kg	
η_b	89 %	[119]
h_{op}	8 000	
LHV	5.25 MWh/ton	[72]
CF	40 %	[72]

Result:
The amount of sub-bituminous coal needed for the industry's steam production will be 20 240 tons/year. The CO_2 emissions from sub-bituminous coal for steam production in the industry will be 26 420 tons/year.

The net emission reduction of CO_2 in scenario 2 is 87 007 tons/year. The calculations are presented in box A4.

Box A4 The net emission reduction from scenario 2

Emissions from electricity produced from Tamil Nadu's gridmix:

$$CO_{2_{gridmix}} = Electric\ power \cdot h_{op} \cdot baseline_{TamilNadu}$$

Prevented CO_2 emissions in scenario 2:

$$CO_{2_{prevented}} = \left(CO_{2_{sub-bituminous}} + CO_{2_{gridmix}}\right) - CO_{2_{RDF}}$$

Where:

Electric power	The potential electric power calculated in Box X [MW]
h_{op}	Operating hours for the plant
$baseline_{TamilNadu}$	The baseline for Tamil Nadu, estimated from the gridmix [tons of CO2/MWh]
$CO_{2_{RDF}}$	The CO_2 emissions from RDF [tons/year]
$CO_{2_{sub-bituminous}}$	The CO_2 emissions from sub-bituminous coal incinerated in the industry [tons/year]

Assumptions:

Electric power	12.2 MW	[box 15]
h_{op}	8 000	
$baseline_{TamilNadu}$	0.85 tons of CO_2/MWh	[137]
$CO_{2_{RDF}}$	5 324 tons/year	[box A1]
$CO_{2_{sub-bituminous}}$	26 420 tons/year	[box A3]

Result:

The CO_2 emissions from Tamil Nadu gridmix are 82 960 tons/year. The prevented CO_2 emissions in scenario 2 will be 104 056 tons/year.

Appendix 11 MSW management in developed countries

Many western companies within the waste sector are interested in expanding their business and in setting up waste incineration plants in developing countries. Somehow, very few of these companies experience that their projects are successful. A technology which is proven successful in one country could be complicated to just apply on another country with different waste characteristics, infrastructure and climate.

To better understand the differences between MSW management in developed and developing countries and their different choice of technology, this chapter will give an overview of MSW management in developed countries with focus on Sweden.

A 11.1 MSW management in Sweden

Sweden, which is seen in figure A5, is a small country in the north of Europe with about 9 million inhabitants. It has a temperate climate with cold winters and cool summers. Residential heating is necessary during the winters while cooling during the summers is more common in public buildings such as offices and other institutional buildings.

Figure A5 Map of Sweden

Around 20 years ago, the most common method in Sweden to treat waste was mechanical segregation and processing of RDF. Along with improved waste management, increased heating value and increased demand for energy the method of direct incineration became more financially viable. Today the most common way to treat MSW in Sweden is direct incineration of mixed MSW. [124]

Waste incineration in Sweden is always combined with energy recovery. The largest part of the energy recovered is heat, which is used as district heating. Electricity generation is sometimes combined with production of heat, which is delivered to the grid. During the last years, production of cold has become more common in Sweden, which is used as district cooling in public buildings. Many incineration plants also deliver process steam directly from the plant to industries.

A 11.1.1 MSW treatments

The total amount of MSW treated in Sweden in 2007 was 4 717 380 tons, which is about 514 kg per person. Figure A6 illustrates that the largest parts of the MSW treated in Sweden was recycled and incinerated with energy recovery. Only 4.0 percent of the MSW was sent to sanitary landfills. [23]

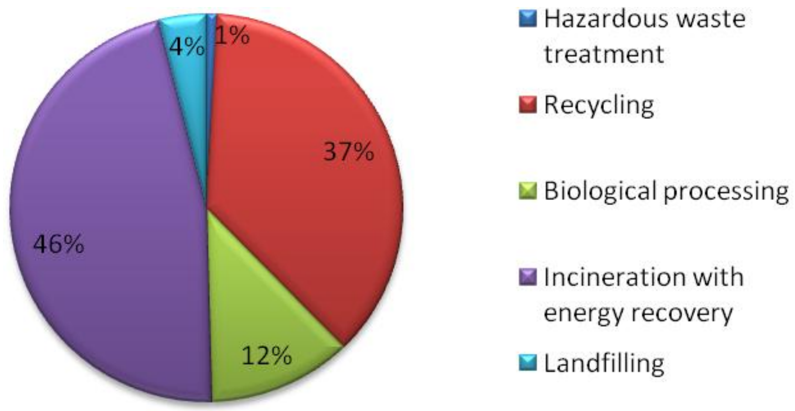


Figure A6 MSW treatments in Sweden in 2007. [23]

A 11.1.2 Hazardous waste treatment

An important factor in the MSW management strategy in Sweden is to sort out the hazardous waste from the MSW generated. 40 880 tons of hazardous waste was collected from the households in 2007. Even though the hazardous waste stands for less than 1 percent of waste generated, it contributes to more that 90 percent of the environmental stress from MSW. [124]

The hazardous waste is treated differently depending on the possible damage they can cause. Impregnated tree and biomedical waste are often burned together with MSW in incineration plants with certain permission. Material recycling and separation processes of hazardous components are used for batteries, fluorescent lamps, paint bottles and oil filter. The Electronic waste (E-waste) is firstly dismantled and thereafter the different components are recycled, treated or incinerated. It occurs that the E-waste is donated to developing countries, where the possibilities of taking care of the waste properly are limited. The hazardous components that cannot be recycled or rendered harmless are put on sanitary landfills. [23]

A 11.1.3 Material recycling and biological processing

The government of Sweden has set up a goal that at least 50 percent of the MSW generated should be recycled through material recycling or biological processing, by the year 2010. During 2007 this amount was 2 299 020, which was 48.7 percent of the total amount of MSW generated. [23]

A 11.1.3.1 Material recycling

The amount of material recycled in Sweden in 2007 was 1 737 720 tons. Segregation of paper, metal, plastic, glass and E-waste is done in the households using different bins for each fraction. Figure A7 shows the recycling degree of specific materials. [23]

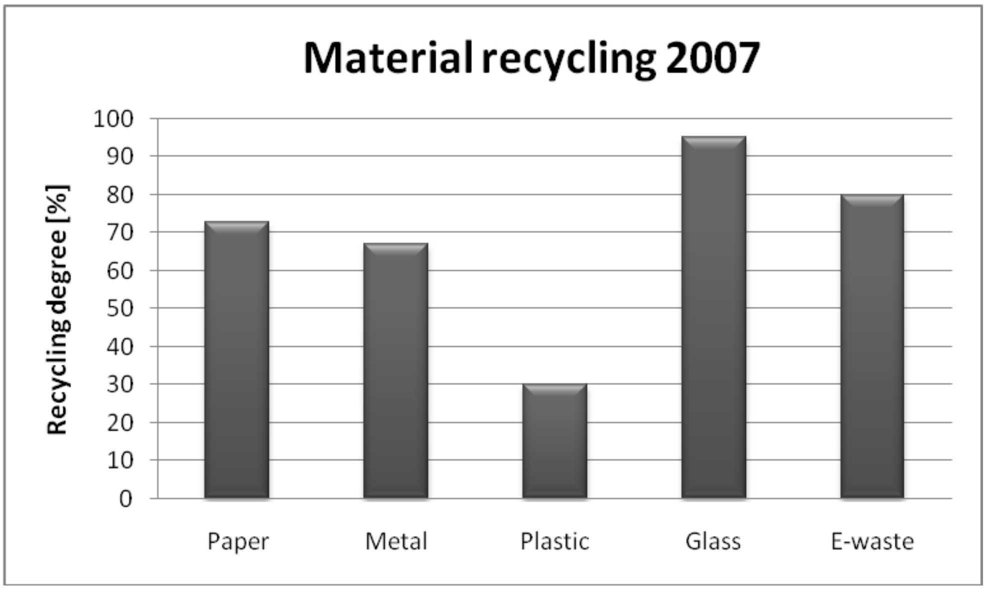


Figure A7 Recycling degree of specific materials in Sweden in 2007. [23]

A 11.1.3.2 Biological processing

The total amount of organic waste (food waste and green waste) that was biologically processed in 2007 was 561 300 tons. [23]

228 8110 MWh of biogas was produced in biomethanation plants throughout Sweden in 2007, which is equal to 26 million litres of petrol. Today the biogas is mostly used as automotive fuel. [23]

During 2007, 336 100 tons of fertilizer was produced in compost plants in Sweden. The produced compost was primarily used as soil conditioner. [23]

A 11.1.4 Incineration with energy recovery

The principal method for treating waste in Sweden is mass burning of mixed MSW in a moving grate or in a fluidized bed (the technology is described in chapter 7 and appendix 12). There are about 30 incineration plants in Sweden, of which most are moving grates. [23]

The share of the MSW generated in 2007, that was incinerated with energy recovery, was 46.4 percent. In Sweden it is common to incinerate other types of waste together with MSW in the same plant, mostly industrial waste but also bio-medical and other less harmful hazardous waste types. [23]

The total amount of electricity and heat generated in 2007 was 13.6 TWh, of which 90 percent was heat and 10 percent electricity. [23] About 60 percent of the incineration plants do not have electricity production at all. Table A10 specifies the amount of waste incinerated in Sweden in 2007 and the electricity and heat recovered.

Table A10 The amount of waste incinerated and the energy recovered in Sweden in 2007. [23]

Incineration	[tons]	Production	[MWh]
MSW	2 190 980	Heat	12 151 270
Other waste	2 279 710	Electricity	1 482 750
Total amount of waste incinerated	4 470 690	Total energy production	13 634 020

A 11.1.4.1 Emissions from waste incineration

Since the middle of 1980s there have been strict emission standards in Sweden for how much emission that is allowed from an incineration plant. This has resulted in improved flue gas treatment and better sorting out of hazardous waste from the MSW. Most of the emissions have been reduced by 90-99 percent during the last decades. Table A11 illustrates the emissions from waste incineration during 2007.

Table A11 Emissions to air from waste incineration in Sweden in 2007. [23]

Substance	Value	Unit
Particles	5	g/ton
HCl	13	g/ton
SOx	44	g/ton
NOx	470	g/ton
Hg	8	mg/ton
Cd+Tl	1	mg/ton
Pb	11	mg/ton
Dioxines	0.1	µg/ton

Figure A8 shows the reduced dioxin emissions from waste incineration over time in Sweden. Between the years 1985 and 2002 the emissions have decreased with 99.4 percent.

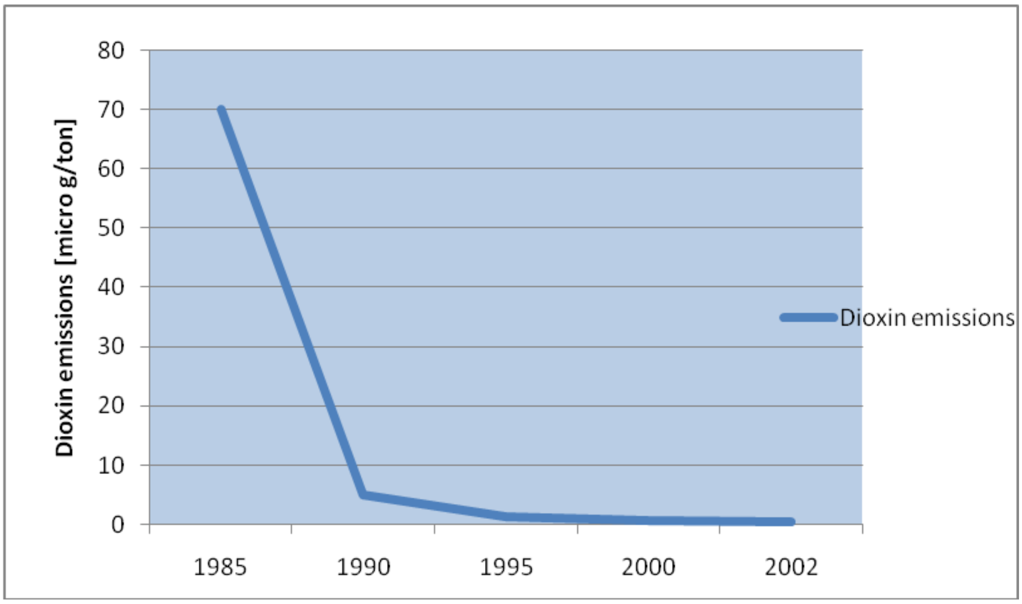


Figure A8 Dioxin emissions from waste incineration in Sweden 1985-2002. [40]

A 11.1.5 Landfilling

186 490 tons of MSW was landfilled during 2007. On 60 sites out of the total of 140 active landfill sites throughout the country, there was extraction of landfill gas. The energy generated from the gas was 290 100 GWh, of which 92 percent was heat and 8 percent electricity. [23]

A 11.1.6 Gasification/pyrolysis

Today there are no large scale plants in Sweden for treating MSW through gasification or pyrolysis. However, the company Mälarenergy plans to build a 200 MW gasifier in Västerås for treating MSW and industrial waste. The plant is going to treat waste with low moisture content in a Circulating Fluidized Bed (CFB). [41]

A 11.2 Swedish waste characteristics

The composition of MSW in Sweden is given in figure A9. It is based on analysis of the MSW from 7 different municipalities in Sweden. [125]

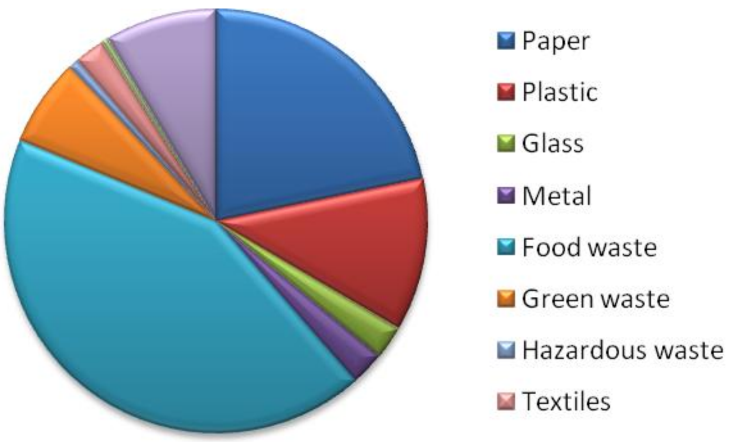


Figure A9 The composition of MSW in Sweden.

A 11.2.1 Heating value

The lower heating value of the waste that is incinerated in the incineration plants in Sweden is no less than 3 MWh/ton (2580 kcal/kg). [124] Before the MSW is fed into the incineration plant it is often mixed with industrial waste to increase the heating value. In box A5 the waste fed into the fluidized bed plant in Norrköping is described. [126]

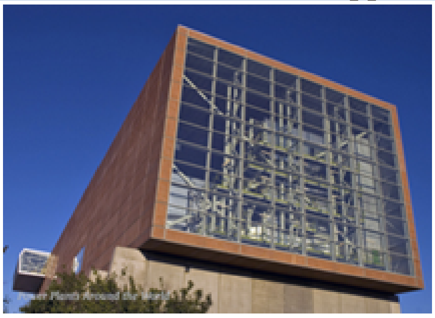
Box A5 Händelöverket in Norrköping [126]

Händelöverket (EON) in Norrköping, Sweden is a fluidized bed. They incinerate a mixture (50/50) of MSW and industrial waste. The lower heating value of the MSW is approximately 3 MWh/ton, whereas the industrial waste has a lower heating value of approximately 4 MWh/ton. Hence, the waste mixture fed into the plant has a lower heating value of 3.5 MWh/ton or 3010 kcal/kg.

Figure A10 Händelöverket in Norrköping. [158]

Box A6 explains the type of waste and the heating value of the waste fed into the moving grate plant in Uppsala.

Box A6 AFA Block 5 in Uppsala [127]



AFA Block 5 (Vattenfall) in Uppsala, Sweden is a moving grate. They incinerate a mixture of MSW and industrial waste. When the MSW arrives to the plant it has a lower heating value of approximately 2.8 MWh/ton. After adding industrial waste the final waste mixture gets a lower heating value of 3.2 MWh/ton or 2750 kcal/kg.

Figure A11 AFA Block 5 in Uppsala. [159]

A 11.3 Mass burning vs. combustion of RDF

The conclusion of chapter 7.1.1 was that there should be combustion of RDF and not mass burning of MSW in India. The choice for Sweden is the opposite. Box A7 discusses why mass burning of waste is a good choice in a developed country like Sweden.

Box A7 Should there be mass burning of MSW or only combustion of the burnable fraction of the MSW (RDF) in Sweden?

Incineration of MSW is widely accepted in Sweden. Because of the advanced flue gas treatment, people are generally not afraid of toxic compounds from the plant. Proposals of building new plants are most often welcomed by the public.

The segregation of different fractions of MSW takes place in the households. The fractions which are segregated are recyclables, organic and hazardous waste. This minimizes the moisture and toxic compounds of the MSW going to the incineration plant, which makes it more suitable for incineration.

Since the MSW in Sweden and other high income countries have a lower heating value close to 3 MWh/ton (2580 kcal/kg) it is neither necessary to pre treat the MSW before combustion, nor is it critical to add auxiliary fuel to sustain the combustion. However, if suitable fuel is available it could be mixed with MSW to increase the energy content of the fuel mix. Sweden has a large forest industry that produces waste with a high heating value, commonly used for co-incineration with MSW.

The Swedish waste incineration companies receive a tipping fee for each kilogram of MSW that is tipped at the plant. Mass burning of waste in Sweden is always combined with energy recovery. Because of the cold climate, most of the energy produced is district heating. Nearly half of the incineration plants in the country also have electricity production. Furthermore, many incineration plants have started to produce process steam and district cooling, due to an increased demand during the past years.

→ **Mass burning of MSW**

Appendix 12 Technologies for treating MSW

This section will describe alternative technologies for waste incineration, other than fluidized bed technology. It will also cover the most common flue gas treatment systems. Moreover, the components in the steam process will be described.

A 12.1 Combustion technologies

The main combustion technologies for MSW are fluidized bed and moving grate. The fluidized bed technology is described in section 7.1.5.1. Both of the techniques require that the heating value of the waste is at least 3 MWh/ton (2580 kcal/kg) (LHV). The combustion processes generate bottom ash and fly ash. The fly ash is very toxic and needs to be treated or landfilled. The bottom ash, which is less toxic can be recycled and used for road material. The products that could be generated from these plants are electricity that can be sold to the grid, process steam that could be used by a nearby industry and district heating and/or cooling that could be delivered to close residential or industrial areas.

A 12.1.1 Moving grate

The majority of the incinerators operating in Europe are moving grates. They are designed to handle large volumes of MSW with no pre-treatment. A typical grate has two to three combustion units, which range from 100 tpd to 3000 tpd. A crane is used to feed the waste into the grate, which consists of fixed and movable grate bars that constantly push the waste forward. Before the waste reaches the combustion zone it is dried, by re-using the warm flue gases from the combustion process. The waste is constantly fed at one end and the bottom ash is discharged in the other, as seen in figure A12. [30] The temperature in the grate is about 1000 degrees Celsius. [100]

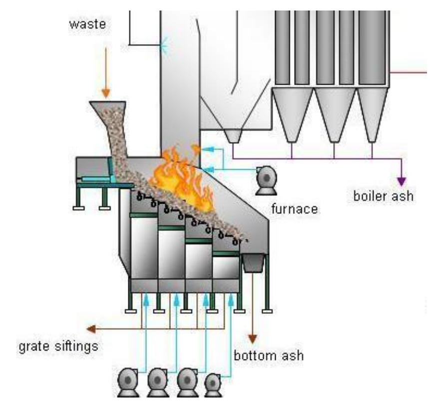


Figure A12 Moving grate. [162]

A 12.1.3 Coal boiler

RDF can be mixed with coal and incinerated with energy recovery. It is a proven technology worldwide with both financial and environmental benefits compared to coal-firing. The main advantage is that the existing coal fired boiler can be used and the expenses of building a new plant can be avoided. Since the sulphur content and the level of heavy metals is lower in RDF, the environmental benefits of co-firing compared to burning only coal is significant. The main disadvantages are that the coal boiler must be modified and that there could be difficulties handling RDF compared to coal. [96] Figure A13 shows a coil boiler.

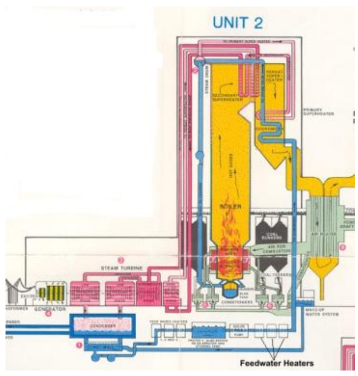


Figure A13 Coal boiler. [163]

A 12.1.4 Gasifiers

Gasification of MSW or RDF can be done in a fixed bed or in a fluidized bed. The choice of technology depends on the size of the plant. For application larger than 12 MW, a fluidized bed is the best solution. BFB is suitable for smaller applications of 1-50 MW plants while CFB is better for larger applications of 10-200 MW. [97] An existing fluidized bed for combustion could be reconstructed for gasification. [141]

Gasification works best when the MSW is carbon-rich and the non-combustible fraction is sorted out, which is why RDF is suitable for gasification. The process is pressurized and the temperature is usually above 750 degrees Celsius. Gasification has several advantages over traditional combustion. First of all it takes place in an oxygen poor environment which decreases the formation of dioxins, SOx and NOx. The lower volume of oxygen added also results in a lower volume of syngas generated. Hence, smaller and less expensive gas cleaning is required compared to the flue gas treatment from the combustion process. However, during the gasification, tars, heavy metals and alkaline compounds are released which can cause environmental and operational problems in the boiler and gas turbine. Before gasification can be a solution for future energy production from MSW or RDF these problems need to be solved. [97] A fluidized bed can be used for gasification as well as for combustion. If gasification turns out to be more viable in the future, an existing fluidized bed boiler for combustion could be reconstructed for gasification. [141] The strength and weaknesses using gasification over combustion is summarized in box A8. [30]

Box A8 Gasification and pyrolysis vs combustion

+

- Syngas can generate electricity more efficiently via gas turbine, whereas steam from combustion processes generates electricity less efficiently in steam turbines
- Fewer air emissions are produced by using less oxygen
- Other products except energy can be generated through gasification and pyrolysis, such as oils and chemicals
- Gas can easily and environmentally friendly be transported in pipes
- Cheaper gas cleaning system is required

-

- Require pre-treatment of waste
- Uncertainties of financial and technical viability
- Problems due to release of tars, heavy metals and alkaline compounds

A 12.2 Flue gas treatment

There are many different types of pollutants in the flue gases. There are those that depend on the waste composition, such as dust, metals and acid gases and there are those that depend on incineration conditions, for example NO_x [98]. These substances are hazardous for human health and/or the environment and need to be removed before released to the atmosphere, in order to meet the regulatory standards. The pollutants may differ in size, inertia, electrical and absorption properties compared to the carrying stream. The removal device must therefore be scientifically properly designed to be able to perform the separation. Hence, different equipment is needed to get an effective removal or of the varying pollutants. [17] The following section will give an overview of the technical equipment used to remove the pollutants.

A 12.2.1 Removal of dust pollutants

Dust in the flue gas is correlated to the ash content of the waste as well as the burnout of the fuel. The burnout depends on the optimization of the incineration. The different technologies to eliminate dust are presented below.

A 12.2.1.1 Cyclone

The cyclone separates bigger particles through the gravitation force occurring while the flue gas is forced into circulation, shown in figure A14. The particles are hurled to the cyclone walls and fall down to the bottom of the cyclone where they are discharged. [17] The flue gas leaves the cyclone in the outlet in the top. The elimination is 90 percent for particles over 5 μm but extensively lower for smaller particles. [99]

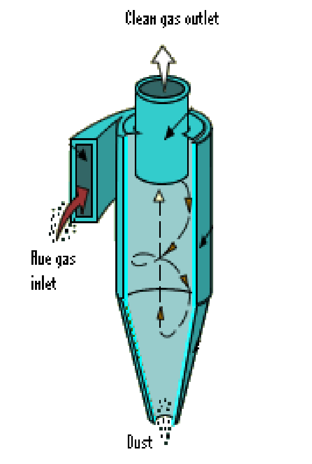


Figure A14 Cyclone. [164]

A 12.2.1.2 Electrostatic filter

In the electrostatic filter also called electrostatic precipitator, the particles get charged by emission electrodes when the flue gas enters the device. The charged particles then get attached to metal plates with the opposite charge. By knocking on the plates, the particles fall down and are discharged from the hoppers. The principle is seen in figure A15. The main advantage with an electrostatic precipitator is that the separation rate is very high, over 99.5 percent. The negative aspect is that the device is sensitive to operational changes, space demanding and expensive compared to other treatment methods. [100]

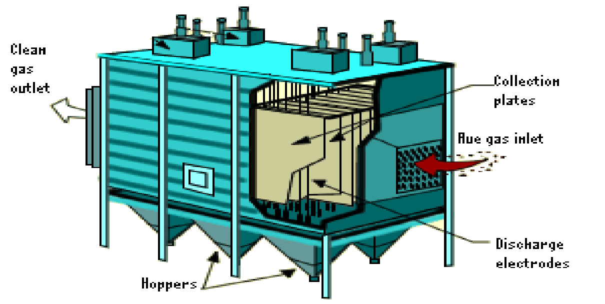


Figure A15 Electrostatic filter. [162]

A 12.2.1.3 Fabric filter

The principle for a fabric filter also called bag filter, is comparable with a vacuum cleaner. The flue gas passes through heat-resistant textile socks or cylindrical bags, which prevent the particles to pass, see figure A16. The dust cakes formed on the fabric filter is removed by shaking or blowing. The separation rate is high, 99.95 percent [100] even for small particles. The high temperature of the flue gas involves a risk for fire. The bag filter is therefore put in the end of the flue gas treatment where the temperatures are lower. Another problem is condensation of the flue gas which can cause corrosion or clogging. [101]

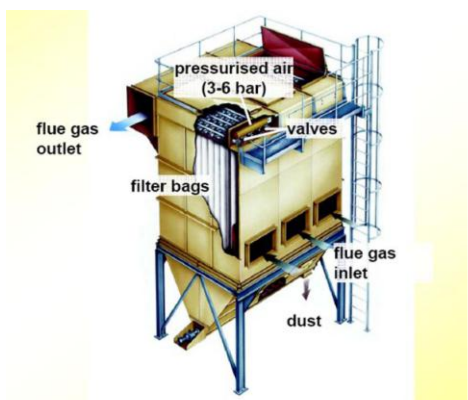


Figure A16 Fabric filter. [165]

A 12.2.2 Reduction of acid gases

Acid gases, e.g. hydrogen chloride (HCL), hydrogen fluoride (HF) and sulphur oxides (SO_x), are generally reduced with alkaline reagents. Three different cleaning processes are applied; dry, semi-wet and wet process which are described below.

These methods reduce the acid gases by adding a chemical or a physical sorption agent that absorb the pollutants, dissolve them or turn them into dry salts which are separated from the flue gas in a later stage. [102] All the three methods mentioned above efficiently remove mercury and dioxins. [103]

A 12.2.2.1 Dry process

The sorption agent in the dry process is lime or sodium bicarbonate, which is fed into the furnace in the form of a dry powder. The reaction products are solid, which are removed from the flue gas in the fabric filter. [102] The reduction efficiency is no more than 50 percent for a grate but significantly higher for a fluidized bed, 70 to 90 percent, due to the possibility to mix the absorbent with the inert bed material. The investment cost is low but the process consumes a lot of chemicals. [98]

A 12.2.2.2 Wet process

In the wet process illustrated in figure A17, water or neutralization liquid is sprayed over the flue gas. The acid pollutants condense and get mixed with the sprayed liquid. This is normally performed in one or more scrubbers. It is common to have one acetic acid scrubber where dust, HCl, HF, metals and dioxins are removed and one neutral scrubber where lime is added to remove SO_2. This method generates waste water which is highly polluted and has to go through a special treatment to remove metals and get neutralized. [102] [103]

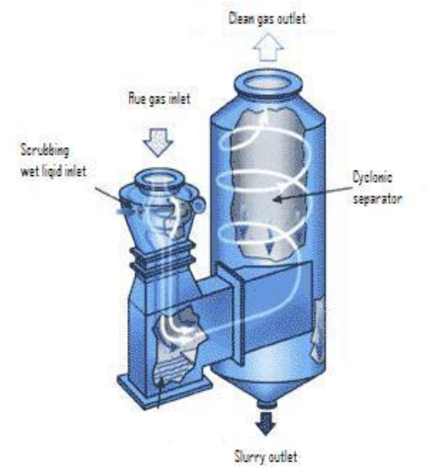


Figure A17 Wet scrubber. [166]

A 12.2.2.3 Semi-wet process

The semi-wet process is an alternative to the wet process in order to get a more efficient removal of SO_2. At the same time HF, HCl and SO_3 are removed as well as metals like mercury, lead, cadmium, copper, and zinc. [100] The sorption agent, which in this case is lime water, is mixed with water to slurry which is sprayed on the flue gases. The heat of the flue gas makes the solvent evaporate and the reaction product becomes solid and could be removed in a dust separator. [102] The removal efficiency is 70 - 90 percent. [98]

A 12.2.2.4Wastewater treatment

The wet flue gas treatment generates polluted wastewater and treatment of this water is necessary. This is done similar to the treatment of municipality wastewater and the process is very efficient. Most of the pollutants get removed or dissolved. The wastewater treatment includes neutralization, precipitation, flocculation, sedimentation, ammonia cupellation, sand filter and carbon filter. The cleaned water passes through a final control before it can be let out in the nearby sea or river. The process creates sludge that needs to be treated. [104]

A 12.2.3 Removal of nitrogen oxides

The formation of NO_x depends mainly on the combustion temperature. By optimizing the incineration, the technical system and the operation of the plant the NO_x formation could be reduced. The technical removal of NO_x can be obtained through selective non-catalytic reduction (SNCR) or selective catalytic reduction (SCR). [103]

A 12.2.3.1 SNCR

The SNCR reduces NO_x without catalyst through injection of ammonia and urea in the furnace. The injection takes place in the upper part of the furnace where the temperature is high, 900-1050 degrees Celsius, as the reduction increases with the temperature. SNCR has lower investment and operational costs than SCR, but the reduction of NO_x is also lower (40-60%). Furthermore, the flue gases from waste incineration contain many different pollutants which can destroy the catalyst which further speaks for SNCR. [142]

A 12.2.3.2 SCR

The SCR takes place after the furnace and reduces the NO_x concentration with 70-90 percent. The NO_x catalyst is placed in the end of the flue gas treatment to avoid other pollutants that could put strain on the material. Before the catalyst, ammonia is added to the flue gases. The desired temperature in the catalyst is 300-400 degree Celsius which often requires reheating of the flue gases. The main advantage with SCR is the high reduction rate. The negative aspect is the high capital costs as well as its sensitivity to other pollutants that could destroy the catalyst. [142]

A 12.2.4 Removal of dioxins

Reduction of the formation of dioxins can be made through optimization of the operation of the incineration plant. High incineration temperature (above 800 degrees Celsius), turbulence and long incineration time are factors that prevent the formation of these pollutants. [17] Removal of dioxins can be done through different techniques which are described below. Once the dioxins have been removed they need to be disposed in a safe final disposal, due to its toxicity.

A 12.2.4.1 Active carbon

Active carbon is normally injected before the fabric filter. The dioxins get absorbed by the active carbon and are separated from the flue gas in the fabric filter. [106] This method has a relatively high operating cost. [105] Nevertheless, this is the most common method for dioxin reduction.

A 12.2.4.2 SCR and additives

SCR, sulphur and urea reduce dioxins, though they are primarily used for other purposes. SCR is used to reduce $NO_{x,}$ while sulphur prevents corrosion on heat transferring surfaces and urea is injected to prevent NO_x formation. These methods give therefore a cost efficient reduction of dioxins. [105]

A 12.3 The steam power process

The process in an incineration plant is a steam power process, which means that electricity is produced from steam and that the working medium appears in both liquid and steam phase. There are many components involved in a steam power process. This section will describe the steam cycle and the different components included in the process.

A 12.3.1 The Rankine Cycle

The steam power process in an incineration plant is a Rankine process. In the Rankine cycle the working medium appears in both liquid- and steam phase. This is to prefer, as the process then can be pressurized on the liquid side which increases the efficiency. [149]

The cycle consists of four processes which take place in four different components in a closed system. The four components are: feed water pump, steam boiler, turbine and condenser, all of which can be seen in figure A18. The feed water pump increases the pressure of the working medium which is water, called feed water. In the steam boiler the water in the tubes is heated and then vaporized into steam. The steam goes through a turbine where it expands to a lower pressure and temperature, as work is extracted. In the condenser the steam condenses into water when heat is transferred to a cooling medium. From this stage, the condense water goes back to the feed water pump again and the Rankine cycle is completed.

For the purpose of estimating the electric and thermal power of a steam power plant, a temperature – entropy diagram, T-s diagram, can be used. By knowing the pressure and temperature at stage *a*, *b*, *c* and *d* in figure A18 it is possible, through a T-s diagram, to find out the enthalpy in the working medium at these specific stages. [167] [168]

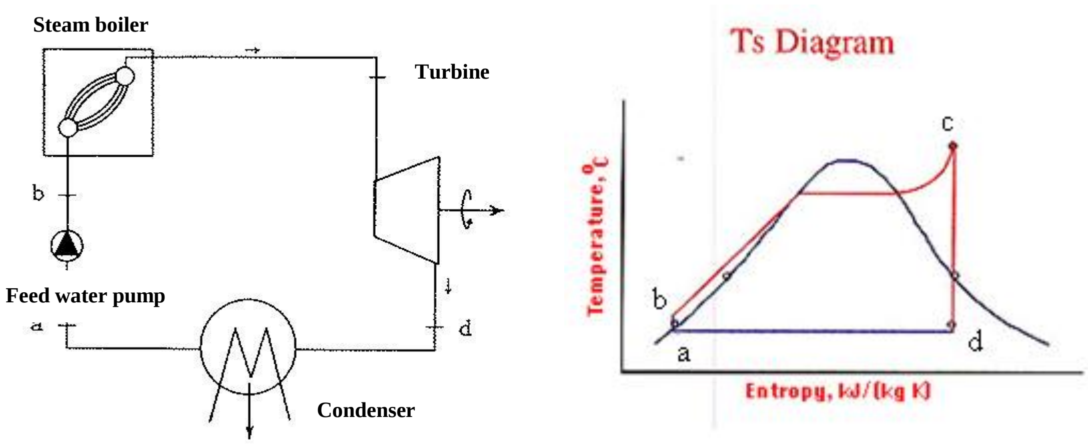


Figure A18 The Rankine cycle and T-s diagram.

A 12.3.2 The components in the steam cycle

The principal components in the Rankine cycle, pump, boiler and turbine, are described below, together with other components that often are involved in a steam cycle.

A 12.3.2.1 Feed water pump

After the condenser, the feed water returns to the boiler again. However, since it has a low pressure, it cannot be fed into the boiler. There has to be a pressure difference before and after the boiler in order to get the water to flow, where the pressure before the boiler has to be higher. Therefore one or two pumps are used to increase the pressure. [149]

A 12.3.2.2 Steam boiler

There are two types of boilers, steam boiler and hot water boiler. A hot water boiler is less expensive but can only produce hot water. A steam boiler can produce electricity, process steam, heat and cold, depending on the demand in the area.

In the steam boiler there are several tubes through which the feed water runs. As the temperature increases the water gets vaporized into steam, which is tapped off in the steam dome situated on top of the boiler.

A 12.3.2.3 Steam turbine

The principal use of a turbine is to convert the energy in the hot steam into a rotary motion. A generator is attached to the turbine which generates electricity. There are two main types of turbines, condensing turbine and back pressure turbine.

Inside a condensing turbine, the steam expands below the atmospheric pressure. After the turbine the pressure of the steam is so low that it cannot be used for industrial applications. The backpressure turbines allow the possibility to tap off part of the steam, before it has fully expanded in the turbine. Hence, this way the high pressurized steam could be used for industrial processes such as drying and heating. [115]

An incineration plant could use one or more turbines, and with more turbines it is possible to extract more electricity. For smaller plants it is common to use only one turbine, because it is not financially viable with more. [151]

A 12.3.2.4 Condenser

A condenser is put after the turbine to condense the steam into water before the boiler and to maintain a low pressure after the turbine. The lower the pressure and temperature is in the condenser, the higher is the potential electricity generation.

If the power plant would be situated close to the ocean, sea water could be used as cooling medium in the condenser. Nevertheless, if water is scarce, which often is the case in developing countries, a cooling tower could be used.

A cooling tower is a heat exchanger that removes the heat from water and transfers it to air. The process is illustrated in figure A19. [169] As the hot water falls through the cooling tower some of it evaporates, which cools the remaining water. The cooled water is collected at the bottom of the cooling tower and returned to the plant. The process water is cooled to near the dew point.

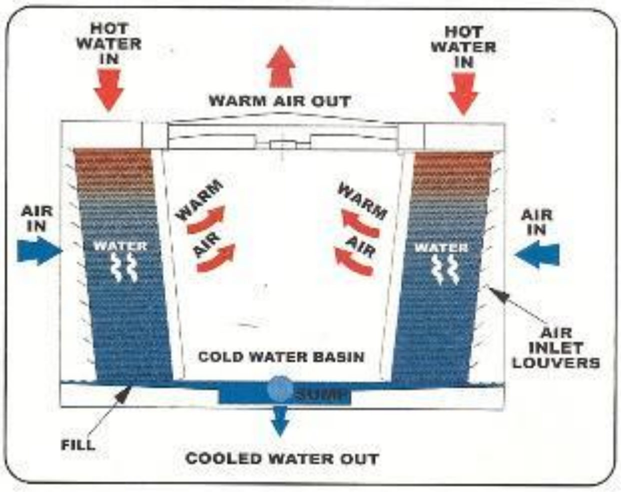


Figure A19 The process of cooling in a cooling tower.

A 12.3.2.5 Other components

The steam process described above is a simplification of the real process, which often contains several more components. Below are some of the most important components described.

Condensate storage tank: When the steam has expanded in the turbine and condensed to water in a condenser, the water is collected in a condense tank. If the plant produces more products than electricity, such as process steam, district heating and cooling the plant could have more than one condensate storage tank, if there are great variations of the characteristics of the condensate. In the tanks, hot steam is fed from below to remove oxygen from the water. [150]

Feed water tank: The feed water tank is placed after the condense tank and before the boiler. Here, more oxygen is removed in the same way as for the condense tanks. [150]

Economizer: The principal use of an economizer is to heat the feed water. In the economizer the hot flue gases give their energy to the feed water, which runs in pipes inside the devise. Another use for this energy is for district heating/cooling purposes. The process of taking care of the energy in the flue gases, which otherwise would be lost, "economizes" or saves energy. [149]

Preheaters: If the feed water has a high temperature when it is fed into the plant, the efficiency of the process increases. The steam generated in the process could be tapped off at different points in the steam process cycle and be used to pre-heat the feed water in so called preheaters. An incineration plant could have one or more preheaters. [149]

Superheaters: Superheaters are used after the boiler to convert saturated steam into dry steam, so that it can be fed into the turbine for electricity generation. One or more superheaters can be used. [149]

Fuel bunker and feeding system: When the fuel arrives to the plant it needs to have a bunker for storage. Furthermore, a feeding system for the fuel into the plant is required.

Accumulator tank: An accumulator tank is an energy storage device, which is required if there are large fluctuations in the requirements for steam. The main reason for using an accumulator is to make the system respond more quickly to temporary demand. [145]

Appendix 13 Dioxins

The term dioxin is used to refer to *2,3,7,8–tetrachlorodibenzo para dioxin* (TCDD), the most toxic compound in the group dioxins. Dioxins is the collective name for chemical compounds with several toxic responses similar to TCDD, namely *polychlorinated dibenzo para dioxins* (PCDDs), *polychlorinated dibenzofurans* (PCDFs) and some *polychlorinated biphenyls* (PCBs) that are dioxin-like. Totally there are 419 types of dioxin-related compounds but only 30 of these have significant toxicity. [7]

Dioxins are formed when organic and chlorinated material is burned together. [80] PCDD/Fs are not produced intentionally but are formed in some industrial processes, while incinerating coal, oil, wood or MSW and through some natural processes such as forest fires. PCBs, however, are manufactured on purpose but are banned in many countries today. Dioxins are persistent pollutants and will therefore remain in the environment for a long time after the actual emission. [7]

Dioxins are toxic to human and wildlife. They are lipophilic, which means that they are soluble in fats, oils and lipids and can therefore bio-accumulate in fatty tissues in humans and wildlife. The toxicity of dioxins is often measured in Toxic Equivalents (TEQs). [80]

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