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Modeling and Simulation of Small Scale Waste-to-Energy Plant

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Modeling and Simulation Small Scale Waste-to-Energy Plant

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DECLARATION

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ABSTRACT

With increasing demand of energy and global issue of pollution due to municipal solid waste, the idea of energy from waste is attracting the attention of many researchers. This is due to the fact that, generation of energy in the form of electricity or heat from waste has a dual effect: getting energy and changing environmentally polluting waste in to harmless and usable material which is ash. At the moment a 50 MW Waste to Energy plant is under construction in Addis Ababa at 'Rappi, Koshe' site which is previously used as land fill site. There is also a landfill site at 'Sendafa' which is by now closed as surrounding people not accepted the project. However as both these plants sites are at outskirts of Addis Ababa city, delivering of such amount of waste to these plants needs complicated transport management and traffic congestion. Due to this, localized waste management is preferable. This is possible with the application of Small Scale Waste to Energy plant.

Thus, in this thesis, Addis Ababa's municipal solid waste was characterized, detailed modeling and simulation of Small Scale Waste to Energy plant for Ethiopian Cities are performed. Various ways to maximize the energy performance of Small Scale Waste-to-Energy plants has been done.

Different data has been collected through literature. Thermoeflex® Software has been used for modeling and Simulation. The model has also been validated by using literature data from actual operating Small Scale Waste to Energy Plants. Thus, based on the simulation result, the proposed model plant can generate approximately 2.4 MW net electric power at 21.27 % net electric efficiency with waste throughput of 1.7 Kg/s. As a result, the electric generation potential of regional towns of Ethiopia was assessed by varying the waste throughputs. Detailed simulation has been done by varying the waste input from 23.04 tons/day to 97.92 tons/day. Thus, based on the result, net electric power of 0.5 - 1MW can be obtained for Bahir Dar, Awasa, and Harar and net electric power of 1 – 1.5MW can be obtained for Mekelle, Dire Dawa and Jimma and 2 - 2.45 MW can be obtained from a sub city of Addis Ababa. The result also shows that fuel's lower heating value, moisture and ash content, ambient temperature, and size of the plant affects the plant's performance significantly. Thus, by adopting a Small Scale Waste-to-Energy plant with a generating capacity of 2.45 MW, around 2,000 town houses can be electrified with the

assumption that each house will consume 1.2KW electric power. In conclusion, adopting small scale waste-to-energy plant for Ethiopia not only generates electricity but also it helps in reducing waste to be land filled.

Keywords: Small-Scale Waste-to-Energy Plant, Efficiency, Simulation

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ACRONYMS

A	Ash content of MSW
AACA	Addis Ababa City Administration
C&I waste	Commercial and Industrial waste
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine
CEMS	Continuous Emissions Monitoring System
CHP	Combined Heat & Power
CSA	Central Statistical Agency of Ethiopia
EEA	European Environment Agency
EEP	Ethiopian Electric Power
EPC	Engineering Procurement and Construction
EGSL	Ethiopian Geological survey Laboratory
ESP	Electrostatic Precipitator
EU	European Union
FC	Fixed Carbon
GWh	Giga watt hour
ICS	Interconnected system
ISWA	International Solid Waste Association
LHV	Lower Heating Value
LW	Liquid waste
MSE	Micro and Small Enterprises
MSW	Municipal Solid Waste
MW	Megawatt
NIMBY	Not In My Back Yard, A term for a person who resists unwanted development
OPEX	Operational Expenditure
PCDSWGR	Per capita per day solid waste generation rate

RWCD	Representative Waste Character Data
SCS	Self-contained system
SNCR	Selective Non Catalytic Reduction
SRF	Solid Recovered Fuel
SSWTE	Small Scale Waste to Energy
TOC	Total Organic Carbon content
VM	Volatile Matter
WTE	Waste to Energy

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1. INTRODUCTION

1.1 BACKGROUND

Rapid urban population growth has resulted in a number of land-use and infrastructural challenges, including municipal solid-waste management. National and municipal governments often have insufficient capacity or funding to meet the growing demand for solid-waste management services [1]. Solid-waste management is the single largest budget item for many cities [2]. The World Bank estimates that in developing countries, it is common for municipalities to spend 20-50 percent of their available budget on solid waste management (open dumping with open burning is the norm), even though 30-60 percent of all the urban solid wastes remain uncollected and less than 50 percent of the population is served [3]. In low income countries, collection alone drains up 80-90 percent of municipal solid waste management budget. In mid-income countries, collection costs 50-80 percent of municipal solid waste management budget. In high-income countries, collection only accounts for less than 10 percent of the budget, which allows large funds to be allocated to waste treatment facilities[4].

According to Ethiopian Electric Power (EEP) power sector development report made in 2014, Ethiopia's electricity generation, existing and expected from projects under execution in total is 11,085MW. From this Hydropower contribute 10,102MW, Diesel 112MW, Geothermal 77MW, Wind 444MW, Solar 300MW, and WTE 50MW. It also stated that Ethiopia's electricity peak demand forecast will grow from 1,237MW in 2012 to 32,486MW by 2037 [5]. As per presentation of UK-ETHIOPIA TRADE & INVESTMENT FORUM 2015, Ethiopian population access to electricity is 55% and so far exploited renewable energy potential of Hydro power is less than 5%, and others Wind, Solar, Geothermal, and WTE remain almost unexploited. As per this presentation, the major energy consumers for the forecasted electric demand are Transport Sector (Railway), Agriculture Sector, Industrial Sector, Large-scale Housing Programs, Universal Electricity Access Programs, and Electricity Export Market.

A fast-track implementation to increase capacity is therefore necessary. As a short-run solution to cover the increasing demand, EEP has evaluated two alternatives: waste-to-energy technology and diesel power. EEP has determined that waste-to-energy technology must be pursued for both economic and environmental reasons. EEP is making particular efforts to diversify its source of energy and building alternatives that will allow EEP to mitigate weather related shortages. It is

important to first test new projects in small scale and expand throughout the country. It was decided to construct a 50MW waste-to-energy facility to diversify the current renewable energy sources and start on a sample level. Thus EEP could gather lessons learned in future projects that can allow WTE to contribute significant power generation share from EEP's future power supply. This will allow Ethiopia to build distributed power sources in areas with concentrated population and thus not be dependent on large scale hydro power that can be freed up by exporting to neighboring countries.

In this context, the energy conversion of Municipal Solid Waste in WTE power plant is one of the principal means of an integrated waste management; its potential is increasing throughout World, both in terms of plants number and capacity, furthered by legislative directives. This Thesis aims at determining the electric generation efficiency and capacity of Addis Ababa municipal solid waste. Thermoflex18 software is employed for the analysis and optimization. The software further determines basic plant components size and specification and operational parameters which can be used to realize actual plant.

In many countries waste is considered as a problem causing great difficulties, politically as well as environmentally. Local people are afraid of the possible pollution from the thermal treatment of waste. At the same time the consumption of energy is increasing steeply in Ethiopia and the need for new energy resources is urgent. If this way of thinking is shared in a local community, then waste becomes a source of new energy and a valuable economic and environmental asset. We can then move from waste management to resource management [6].

What if we could use waste as a resource and thereby scale down the demand for extraction of new resources? Extracting fewer materials and using existing resources would help avert some of the impacts created along the chain. In this context, unused waste also represents a potential loss. Turning waste into a resource by 2020 is one of the key objectives of the EU's Roadmap to a Resource Efficient Europe [7]. The roadmap also highlights the need to ensure high-quality recycling, eliminate land filling, limit energy recovery to non-recyclable materials, and stop illegal shipments of waste.

An EEA study from 2011 looked at the potential gains from better management of municipal waste. Its findings are striking. Improved management of municipal waste between 1995 and

2008 resulted in significantly lower greenhouse gas emissions, mainly attributable to lower methane emissions from landfill and emissions avoided through recycling. If, by 2020, all countries fully meet the Landfill Directive's landfill diversion targets, they could cut an additional 62 million tons of CO₂ equivalent of greenhouse gas emissions from the life cycle — which would be a significant contribution to the EU's climate change mitigation efforts [8].

Combustion of Solid Waste on a moving grate of “as-received” municipal solid wastes is the dominant technology especially for large Waste-to-Energy plants. The plants burn waste on specially designed grates and the hot flue gases generate steam in a boiler [9] [10]. However, there are circumstances where a low-capacity plant (<100,000 tons per year) is required. One of the biggest advantages of small-scale Waste-to-Energy plant is that they can exist within residential communities. Besides, installing Small-scale Waste-to-Energy plant can complement local waste recycling initiatives. Other benefits offered by small scale Waste-to-Energy plants includes, treatment of solid waste in the vicinity of waste generation, the creation of jobs in the local community and lower transport distances. Thus, Small scale waste to energy plants can be more easily integrated in to existing residential areas or condominium houses [11].

Considering Ethiopia, where most of the people lives in rural areas and delivering large amount of waste to large scale waste-to-energy plants needs complicated transport management systems and traffic congestion. Due to this, localized waste management is preferable. This is possible with the application of Small Scale Waste-to-Energy plant. However, it is worth mentioning that there is no Small Scale Waste-to-Energy plant in Ethiopia. It has to be noted that Reppi Waste-to-Energy plant of Ethiopia is a large scale waste-to energy plant. Therefore, assessing the full potential of small scale Waste-to-energy plants in the Ethiopian context helps the country a lot. Thus, in this thesis, a detailed simulation of Small-Scale Waste-to-Energy will be performed and the possible means to improve the efficiency of Small Scale Waste-to-Energy plants will be performed.

1.2 THESIS OBJECTIVE

1.2.1 Main Objective

The overall objective of this thesis is to determine the recoverable megawatt electricity from Addis Ababa MSW and other cities of Ethiopia and the amount of waste eliminated per day using a small scale WTE.

1.2.2 Specific Objectives

The specific objectives of this thesis are.

1. Performance estimation of small scale Waste-to-Energy plants at design conditions
2. Determination of optimized operating parameters
3. Performing sensitivity analysis to see the effects of main operating parameters on performance of WTE plant: operating parameters like moisture content, ash, and Lower heating value, ambient temperature, condenser pressure, and excess air.
4. Finding ways to improve performance of small scale Waste-to-Energy plant

1.3 PROBLEM STATEMENT AND RESEARCH GAP

In an ideal world all waste would be prevented. However, in reality, for a range of social, economic and practical reasons, this does not happen. Where waste does exist it is usually best to reuse it if possible, and if not, to recycle it. What can't be recycled, the residual waste, could either go to energy recovery or as a last resort, landfill. This general order of preference is known as the waste hierarchy: prevention, reuse, recycling, recovery, and disposal.

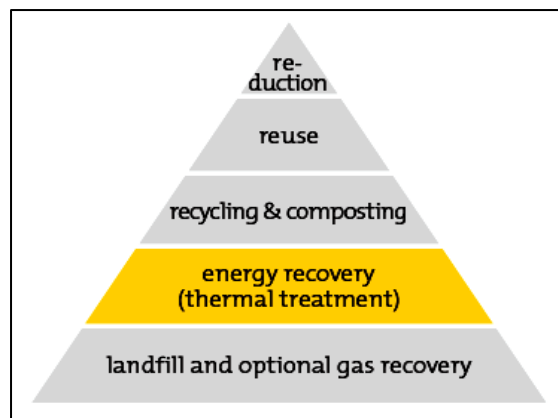


Figure 1 : Waste management hierarchy

MSW consists of many materials with entirely different properties. Under ideal circumstances of sorting, processing, and recycling, these materials should go to different destinations. To accomplish an integrated solid waste management, MSW should be classified under four categories of “recyclable”, “combustible,” “compostable,” and “land fillable.” In a WTE plant, non-recyclable MSW is combusted at high temperatures. The heat of combustion is used to produce steam that drives a turbine generator of electricity. In this process, a sophisticated air pollution control system is used to remove particulate and gaseous pollutants before the process gas is released into the atmosphere. Trash volume is reduced by 90% and the remaining residue is regularly tested and consistently meets strict Environmental Protection Agency (EPA) standards allowing beneficial use or disposal in landfills. In this thesis, due to comparative assessment made under section two, (literature review) a WTE plant employing combustion is going to be used. This type of WTE plant is practical in Japan, Europe and USA. Worldwide, and over 130 million tons of MSW are combusted annually in over 600 WTE facilities that produce electricity and steam for district heating, recover metals for recycling, and substantially reduce the volume of waste that is finally disposed [12]. Waste-to-energy has been recognized by the U.S. Environmental Protection Agency (EPA) as a clean, reliable, renewable source of energy [13]. In addition, the combustion of municipal solid wastes for generating electricity has been recognized by several US states as a renewable source of energy. The search for renewable energy sources is motivated by the desire to reduce use of fossil fuels. This type of WTE plant is under construction in Ethiopia, Addis Ababa: Reppie waste-to-energy facility.

Even though there are so many literatures and studies that discuss above type of WTE plant, it is not easy to understand how such type of plant is operating and it is difficult to optimize or customize to specific conditions. As a matter of fact, even for the one which is going to be operational in Addis Ababa, basic information is kept secret by the company which is executing the plant construction (Cambridge Industries). Basic WTE plant information includes operating parameters which vary with site conditions and plant component technology and technical specification. For example, such type of plant usually practical for part of large scale MSW integrated management. This thesis is intended to realize optimized small scale combustion WTE plant which so far never realized in Ethiopia. The realization will be attempted for the order of 2 - 3MW electricity generation utilizing 60 - 90 ton/day of municipal solid waste.

1.4 WHY SMALL SCALE WASTE TO ENERGY?

A localized approach to waste management is beneficial as there is both expense and negative environmental impact associated with the long distance transfer of waste. This type of facility has a very small footprint so it can be built in urban areas without looking out of place. The result of this is that the problem of waste treatment can be addressed at a local level, close to the waste source, rather than spending huge amounts of the tax payer's money transporting waste around the country to landfill sites-an activity, in itself, that creates more traffic congestion and produces even more greenhouse gases [14].

The forecasted waste generation of Addis Ababa city by 2030 is 541,295 ton/year [15]. But the waste consumption capacity of the newly under construction Waste to Energy plant in Addis Ababa 'Reppi, Koshe' site is 350,000 ton/year [16]. This shows that the plant under construction will be incapable to handle all generated waste in the city in the coming years. This shows again, it is mandatory to think for implementing localized small scale waste to energy plants in sub-cities.

2. LITERATURE REVIEW

2.1 INTRODUCTION

Solid waste is material, which is not in liquid form, and has no value to the persons who is responsible for it [17]. From the days of primitive society, humans and animals have used the resources of the earth to support life by disposing waste. In early times, the disposal of human and other waste did not pose a significant problem, for the population was small and the amount of land available for the assimilation of waste was large. Problems with the disposal of waste can be traced from the time when humans first began to congregate in tribes, villages, and communities and the accumulation of waste become a consequence of life [18].

The booming growth of cities of the developing world has outpaced the financial and manpower resources of municipalities to deal with provision and management of services, of which solid waste is the major one. Lack of these services greatly affects the urban poor, women and children who are vulnerable to health hazards. Improper management of solid waste has direct adverse effects on health. Uncontrolled fermentation of garbage creates a food source and habitat for bacterial growth. In the same environment, insects, rodents, and some birds' species proliferate and act as passive vectors in the transmission of some infectious diseases [19]. About 22 human diseases are related to improper solid waste management and to large extent ecological phenomena such as water and air pollution have also been attributed to improper management of solid waste [20].

Waste to energy technology is the best available technique for municipal solid waste management. It is the recovery of the energy content, preferably for non-recyclable municipal solid waste components. This is achieved by combustion of the waste to recover its chemical energy and then transferring this energy to water/steam in a boiler to produce power through turbine generator set. As compared to commercial fuels, municipal solid wastes are low grade fuels due to their low energy content, their large variations in fuel properties and high content of chlorine and heavy metals. But, there are established technologies available for WTE such as grate-type combustion, fluidized bed combustion, gasification, and pyrolysis/ash-melting [21]. Other energy recovery technologies are also available to increase the fuel quality of wastes and their flexible use, such as production of SRF and gasification [22]. After recovery of power or heat, the solid residue (bottom ash and fly ash) can be utilized as good input for construction [23]

or properly disposed with a minimal environmental impact [24]. Interesting feature of WTE is that it can replace the consumption of fossil fuels for heat and power production. Moreover, MSW contains biogenic fractions such as paper and wood. The energy produced from such waste is carbon-neutral, which can reduce greenhouse gas emissions [25]. Also, in many countries, WTE has been an important source of renewable energy [26].

Small scale WTE plants are also applicable worldwide for the sake of localized treatment of waste [27]. The survey analysis made over 330 WTE plants in Europe by the ISWA showed that there are about 170 small scale plants in Europe. Out of these, 84 plants have an annual capacity of less than 50,000 tons and another 85 plants range in capacity from 50,000 and 100,000 tons. Also, 24 plants in the ISWA survey co-combust sludge cake (from wastewater treatment plants) and 25% are of low capacity, ranging from 50,000 to 79,000 tons per year [27].

Some of already operational novel small scale WTE plants are from: *Novo Energy* which have both combustion and advanced gasification technologies [28], *JFE Engineering Corporation* which have both mass burn and gasification technologies [29], *Toplarna Celje* which employ combustion [30], and *Envikraft/Scan American Corp.* [31]. From this all it can be concluded that, under certain circumstances, the construction of small scale WTE plants is beneficial because it avoids the economic and environmental impacts associated with the long distance transfer of waste. Instead, a localized approach to waste management is beneficial as there is both expense and negative environmental impact associated with the long distance transfer of waste. In comparison to the traditional mass burn incinerators that are generally used at the moment, this type of facility uses small plot and it can be built in urban areas without looking out of place which shows that the problem of waste treatment can be addressed at a local level, close to the waste source, rather than spending money for transporting waste to landfill sites which creates more traffic congestion and produces even more greenhouse gases [27]

Previous studies conducted for Small scale WTE are predominantly based on gasification and pyrolysis. High Temperature Air/Steam Gasification proved to be very useful technology for gas fuel generation, which can be used later to produce heat and electricity. It is applicable to biomass gasification as well as to treatment of municipal wastes [32]. Besides the economic benefit of MSW gasification process, there is the clear environmental benefit, which is the reduction of land filling and the reduction in net CO₂ emissions [33].

Despite these benefits, there are significant concerns about gasification. The most difficult operational problem results from the formation of heavy organic compounds referred to as tars [34]. These tars cause significant fouling in downstream gas cleaning system and energy recovery devices. As a result, finding cost-effective and thermally efficient gas cleaning techniques for the syngas components remain difficult. And before it can be considered to be a clear-cut solution for waste thermal treatment, its long-term reliability must be demonstrated [34].

Mass burn waste-to-energy plants are more popular, not just for proper disposal of municipal solid waste but also to co-incinerate non-hazardous industrial waste in order to maximize the use of the plant facilities, hence to save costs from building facilities specifically for treating industrial wastes [35]. It is the most well developed and practical WTE technology [36]. However, detail operation principles of a large scale as received mass burn WTE technologies is not known and also, methods on how to down size large scale to small scale mass burn waste to energy plants is also not known.

2.2 MUNICIPAL SOLID WASTE OF ADDIS ABABA

In Addis Ababa, the contribution to the total generation of waste by the different sources is estimated to be around 76% for households, 18% for commercial, institutional and industrial sources, and 6% from streets and public areas [37]. As per the study made for Addis Ababa city government by ‘ARTELIA, L’union de Coteba et Sogreah’ [15] household waste generation varies from 0.21 to 0.59 kg/cap/day for household of low income to high income in Addis Ababa City and from 0.41 or 0.46 kg/cap/day to 0.49 to 0.70 kg/cap/day in Oromya special zones as indicated in Table 1.

Table 1 : Households waste generation by population’s level

PCDSWGR (kg/cap/day)	Low Income	Middle Income	High Income
AACA Average	0.21	0.33	0.6
Oromia special zones Burayu	0.46	0.49	0.49
Oromia special zones Sebeta	0.41	0.41	0.7

2.3 MUNICIPAL SOLID WASTE OF OTHER TOWNSIN ETHIOPIA

Per capita income level and solid waste generation rates have direct relationship [38]. Households that have better life standard use more consumption materials than low income households do, through which they generate higher wastes. The current condition of municipal solid waste management service in different towns of Ethiopia is also becoming a challenge for municipalities. For instance, according to Yami Birke, a study on municipal solid waste management practices in towns of Ethiopia, in most of towns a controlled solid waste disposal system is not practiced [39]. That means small proportions of the urban dwellers are served and a large quantity of solid waste left uncollected. In addition, a study conducted by Ministry of Health revealed that percentage of solid wastes which are left uncollected as shown in Table 2 and disposed anywhere without due attention regarding their consequences in different towns of Ethiopia [40].

Table 2 : % of uncollected solid waste in major towns of Ethiopia

Towns	% of uncollected solid waste
Jijiga	82
Hawassa	75
Dessie	70
Dire dawa	63
Jimma	63
Harar	53
Mekele	52
Addis Ababa	32

The urban waste characteristics may be conveniently considered under two headings: waste generation, and composition of the generated waste [41]. For instance the waste generation and waste management is discussed for selected towns as shown below.

Bahir Dar:

The capital city of Amhara regional state with a total population of 220,000 and an annual growth rate of 6.6% is one of the fastest growing cities in the country [42]. The average daily solid waste generation rate of the city is 0.25kg/c/day and 53% of the total waste generated is from households. The remaining 27, 17 and 3% are from the commercial sector, institutions and street sweeping respectively. The need for adequate solid waste management was unquestionable and well acknowledged by the municipality which pioneered the idea of introducing MSEs in the sector [43].

Dessie:

According to the national census conducted by Central Statistical Agency of Ethiopia in 2007 E.C., Dessie has a total population of 151,174 with a growth rate of 3.38% per annum. The daily solid waste generation rate is 0.231 kg/person/day and mainly produced from households which account for 60% of the total generated waste. Commercial areas account for 19%, street sweeping 11%, institutions 8%, while small scale industry contribute the rest (2%). Generally 136.11m³ of waste is generated per day in the town and only 32 m³ (23.51%) is collected. The fast population growth combined with expansion of the town precipitates an increase in the volume of solid waste. This in turn results in greater infrastructural demand, institutional setup and community participation in its management [44].

Mekelle:

It is the capital city of Tigray state which has a total population of 215,546 and an annual growth rate of 5.4% is among the fastest growing cities in Ethiopia according to Central Statistical Agency of Ethiopia in 2007 E.C. The daily solid waste generation rate is 0.22 kg/c/d. Like other cities mentioned above solid waste collection and disposal was limited in the city. The municipality was able to collect only 33.4% of the total waste generated until recently. There was no involvement of organized enterprises in waste collection until 2009 E.C.

Jimma:

According to CSA, population projection of 2006 E.C. is 159,009. Taking this figure into account, the daily, monthly and yearly solid waste generation rate of Jimma town will be 25, 750 and 9,125 tons respectively. From the study 67.6% of the wastes are easily decomposable organic

matter, indicating large potential for compost making. Municipality was able to collect only 33.4% of the total waste generated until recently [45].

Adama:

The 2007 E.C. national population census reported that this town has a total population of 222,035. The per-capita solid waste generation rate for the town was estimated at 271 gram/day (0.271kg/day) in 2005. The total amount of solid waste generated in the town was estimated at 54200kg/day and 1.98 million kg/year in 2005 [46]. Out of the total solid waste generated in the town, about 40-50% remains uncollected. Furthermore the formal dumpsite, located some 8 km away from the center of the town (towards west on the road from Adama to Addis Ababa in a place called ‘Qobbo Luxo’), does not appear to have proper measures to control runoffs from rainfall, which may result in the pollution of underground water and land surface in its neighborhoods[47].

2.4 WASTE TO ENERGY OVERVIEW IN ETHIOPIA

In Ethiopia, except recent activities at Addis Ababa, the solution to the waste situation is unmonitored landfills with smaller sorting operations [48]. Environmentally, this is a poor solution and although there are informal plans for change, no specific strategy has been presented or found. Another important issue is Ethiopia dependence on high investment energy resources like Hydropower [49]. What makes the waste to energy so interesting is that it contributes to an improvement in both of these issues by using the waste as fuel to reduce energy dependency and creating green cities and towns.

Waste management in Addis Ababa is fundamentally different from other emerging cities of Ethiopia [50]. There has been no form of waste management in emerging cities until very recently. A few of these new municipalities were designed to decrease human exposure to unsanitary conditions and environmentally degrading practices [51]. Yet, as Table 3 illustrates, the collection and management of waste in most of the municipalities is still quite inefficient. Two exceptions, Mekele and Dire Dawa, have recently experienced promising results for improved waste management and waste-to-energy conversion through biogas capture from landfills using both technical and institutional strategies [51].

Table 3 : Ethiopian municipalities and waste generation, 2010

City	Region	MSW generation	MSW collection
Addis Ababa	Addis Ababa	1,132 tonnes/day	70% collected
Mekelle	Tigray	78 tonnes/day	82% collected
Dire Dawa	Dire Dawa	77 tonnes/day	48% collected
Jimma	Oromia	87 tonnes/day	30% collected
Nazret	Oromia	59 tonnes/day	48% collected
Bahir Dar	Amara	27 tonnes/day	58% collected
Awasa	SNNPR	46 tonnes/day	44% collected
Harer	Harari	32 tonnes/day	45% collected
Source: (Fikreyesus, 2011; Getahun et al., 2011)			

Development Mechanisms could support the transition to sustainable waste management in these emerging cities, similar to the Addis Ababa municipality [51]. Although most emerging cities have not developed formal waste management systems comparable to that of Addis Ababa, it is important to recognize what has been established thus far so that all systems can develop more sustainably. It is increasingly apparent that local institutions, the Ethiopian federal government, nongovernmental organizations, and international organizations dedicate themselves to sustainable waste management in Ethiopia. As Table 4 illustrates, a number of projects are underway to convert or construct sanitary landfills in the cities of Addis Ababa, Dire Dawa, Mekele, and Adama. Since 2009, sanitary landfill projects have been established in each of these municipalities [52]. Sanitary landfills include the following characteristics:

- Leachate management
- Landfill gas management
- Soil cover applications
- Environmental monitoring systems

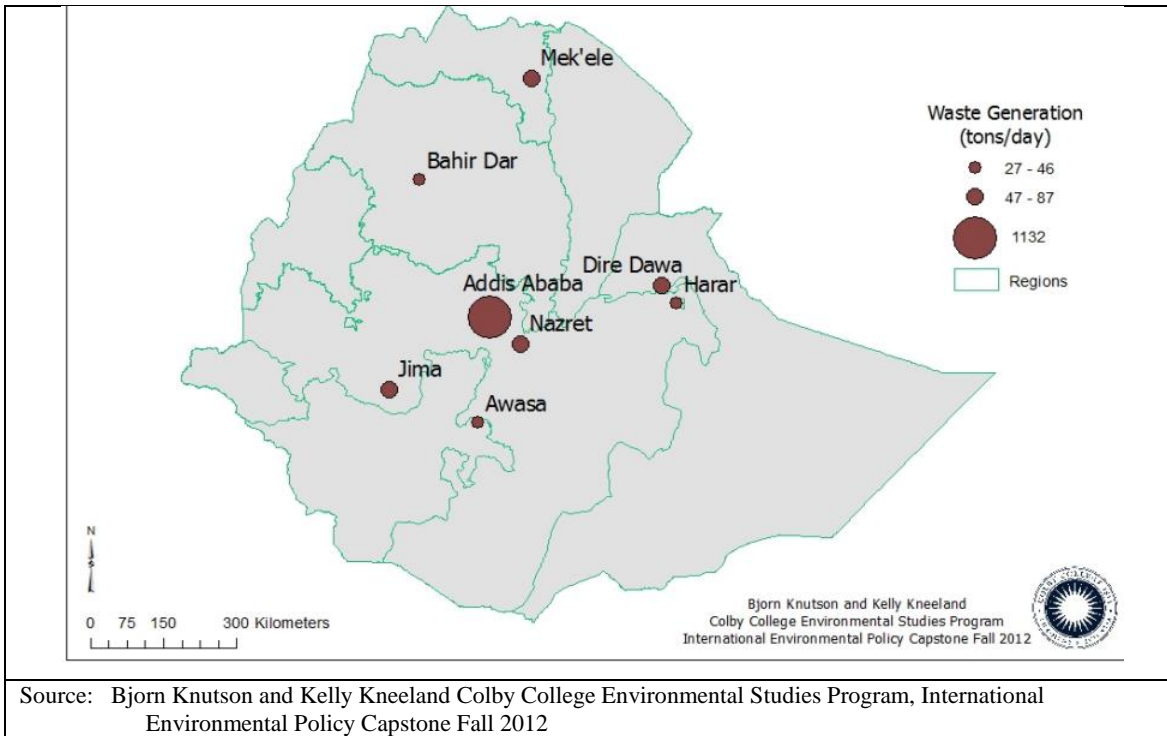


Figure 2 : Waste generation in eight Ethiopian cities

Table 4 : Technologies utilized by Ethiopian towns municipalities, 2010

City	Year Landfill Established	Sanitary Landfill	Secured Perimeter	Pre landfill Sorting	Landfill Gas Management	Leachate Managed
Addis Ababa	1964	Currently In Construction			Flaring System Proposed	Currently In Construction
Dire Dawa	2007	✓	✓		Venting System (Flaring System Proposed)	✓
Mekelle	2008	✓	✓	✓	Venting System	✓
Adama	2010	✓			Venting System	✓
Source: (Fikreyesus, 2011 & HoAREC, 2012)						

At the moment only in Addis Ababa a new state of the art WTE plant is under construction at Reppie or “Koshe” site which is previously a MSW land fill site. It is a 120 million USD deal project signed by the Ethiopian Electric Power Corporation (EEP) with Cambridge Industries, a United Kingdom based firm, in January 4, 2013. The plant aimed to produce 50 megawatts of clean energy through a controlled combustion. The Reppie Waste-to-Energy project is the first of its kind in Ethiopia as it produces green energy within city limits from municipal solid waste (MSW). It will also be the first base load power in the country providing electricity 24 hours of the day for over 330 days of the year. The facility will be a modern waste disposal system eliminating over 1,000 tons of waste every day. It will operate with two lines running at a nominal design throughput of 41 tons per hour (tph) on 24 hours bases for a design Net Calorific Value (NCV). Waste is combusted at a minimum temperature of 850°C with the released heat generating superheated steam. The steam is then fed to a condensing turbo-generator to produce electricity [16].

There is also a modern land fill project started operation which is funded by Agence Française de Développement - AFD with over 337 million USD secured from the government of France in the form of loan for the implementation of the project. It is forecasted that Sendafa landfill would receive approximately 9,000,000 tons of waste over the next 20 years. Table 5 provides a summary of the anticipated annual tonnage as well as the cumulative tonnage expected to be disposed of at the Sendafa landfill [15].

According to the design and detailed in the dedicated report, airspace available for the Sendafa landfill is around 9 500 000 m³. Thus, actual operation would not start before 2015. Taking into account airspace requirements including waste, temporary and final cover, lifespan would be 20 years, until 2034: Based on simulations (Poyry, 2010), the methane production will start within 3 – 4 years from the opening of the site. The methane production is expected to reach, with 50% utilization rate, 17,820 Nm³/hour after 22 years of operation i.e. 2 years after the closure of the site. The landfill is expected to produce methane approximately 20 years after the closure [15].

Table 5 : Forecasted waste ton of Addis Ababa city and surrounding special zones

Year	Ton/day	Ton/year	Tons
2015	983	358864	358864
2016	549	200428	559292

2017	598	218271	777564
2018	650	237141	1014705
2019	704	257104	1271808
2020	762	278228	1550037
2021	824	300590	1850626
2022	888	324267	2174893
2023	957	349348	2524241
2024	1026	374573	2898814
2025	1099	401222	3300036
2026	1169	426620	3726656
2027	1242	453415	4180072
2028	1320	481692	4661764
2029	1399	510712	5172475
2030	1483	541295	5713770
2031	1571	573535	6287305
2032	1664	607528	6894833
2033	1763	643376	7538209
2034	1866	681190	8219399
2035	1976	721084	8940483
Source: SOLID WASTE MANAGEMENT STRATEGY AND INSTITUTIONNAL REPORT R5, OCTOBER 2013, ARTELIA Ville et Transport ECHIROLLES International Activities, Sendafa landfill			

2.5 BASICS OF WASTE TO ENERGY POWER PLANT

2.5.1 INTRODUCTION

The first waste incineration plant, known as “Destructor” was built in Nottingham, UK, in 1874 [53]. Waste incineration became established in many European countries at the end of 19th century, as a device to minimize waste’s volume and to make it hygienic [54]. Since then, as environmental awareness has grown, Waste-To-Energy technology has continuously developed and improved, increasing the importance of efficient energy generation [55].

In the traditional sense, renewable sources of energy are those that nature can replenish, such as waterpower, windpower, solar radiation and biomass (wood and plant waste). However, MSW contain a large fraction of paper, food wastes, cotton and leather, all of which are renewable materials under proper stewardship of the Earth. At this time, the US Department of Energy (DOE) categorizes WTE as one type of biomass, as shown in the following definition: The term biomass means any plant derived organic matter available on a renewable basis, including dedicated energy crops and trees, agricultural food and feed crops, agricultural crop wastes and

residues, wood wastes and residues, aquatic plants, animal wastes, municipal wastes and other waste materials. The objective of renewable status legislation is to provide an economic incentive that encourages the development of alternative energy resources in order to reduce the environmental impacts resulting from the extraction and combustion of fossil fuels. WTE provides this environmental advantage, because, on the average, the combustion of one ton of MSW produces electricity equivalent to 0.3 tons of coal or one barrel of oil. WTE is the only renewable energy source to offer an additional environmental advantage: the avoidance of the environmental impacts of land filling of MSW [56].

3.5.1 WASTE TO ENERGY TECHNOLOGY OPTIONS

There are three principal ways to recover the energy content of MSW by treating it thermally, as shown below. These include pyrolysis, gasification and combustion. These processes are differentiated by the ratio of oxygen supplied to the thermal process divided by oxygen required for complete combustion. This ratio is defined as the “lambda” ratio and in the case of pyrolysis, it is equal to zero. Gasification is conducted at sub-stoichiometric conditions and full combustion is carried out using a lambda greater than one.

- Pyrolysis $\lambda = 0$, no air, all external heat
- Gasification $\lambda = 0.5$, partial use of external heat
- Combustion $\lambda = 1.5 +$, no external heat

Despite the fact that Waste to Energy (WTE) is a very broad term that covers any process that converts waste into energy, or an energy-carrying product, such as a gas or oil, the aims of all WTE processes are essentially the same [57]:

- Reduce the volume of waste and hence reduce the volume requiring disposal in landfill;
- Reduce the biodegradable fraction of waste to zero, and
- Produce a useful commodity (typically electricity and/or heat) from non-recyclable waste.

WTE can be split into two main categories [57]:

- Thermal - includes combustion, gasification and pyrolysis, related processes all of which subject waste to high temperatures but with varying oxygen concentrations.

- Biological – anaerobic digestion (AD). AD is can be used to recover energy from wet, biodegradable waste streams (such as food waste and farm slurry). AD uses micro-organisms in carefully controlled conditions to convert biomass into biogas consisting primarily of methane and carbon dioxide, and a stabilized residue known as digestate.

WTE relative to other waste treatment technologies has the following advantage and disadvantage[57].

Advantages:

Potential to treat a wide range of post-recycling municipal, commercial and industrial wastes, High landfill diversion (>90% possible), Compact solution for residual waste management, Potential to use majority of outputs, Generally compatible with high recycling rates providing correctly sized to take into account targets, Very low emissions possible, all modern plant treating municipal and commercial wastes should be capable of meeting stringent air and water emissions limits, Generation of electricity and heat, which is partly renewable (usually around 50-70% biomass).

Disadvantages:

High CAPEX, May require fiscal measures or incentives to be financially competitive with landfill, usually requires a long-term waste supply contract (often 25 years +) which can limit flexibility to both producer of waste and the operator of the plant, uncertainty around bottom/bed ash classification and hazardous fly ash/FGT residues require careful disposal/treatment, Negative public perception of WTE persists in many areas. NIMBYism can restrict or slow development process

The dominant technology for energy recovery from MSW is direct combustion over a moving grate with the generation of superheated steam feeding a steam turbine. Based on detail comparison for different technology option for WTE under Table 6, combustion is selected and used in this Thesis.

Table 6 : Advantages and disadvantages of different WTE technologies [57]

	Advantages	Disadvantages
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<p>Combustion</p>	<ul style="list-style-type: none"> • Mature, established, many reference plants worldwide • No feedstock preparation required; relatively simple, robust technology • Numerous reputable experienced technology suppliers & EPC contractors, competitive market • Relatively low CAPEX & OPEX compared with some more advanced technologies (especially slagging and plasma gasification) 	<ul style="list-style-type: none"> • Electrical efficiency is limited • Suffers from poor perception, primarily due to legacy of older generation of incinerators but also from advocates of ‘zero waste’ strategies • Generally better suited to larger scales (>100,000tpa)
<p>Gasification (Close-coupled)</p>	<ul style="list-style-type: none"> • Not seen as incineration (primarily a perceived advantage) • Despite few established technology suppliers, recent years have seen several suppliers begin commercial operation, or close to & there is increasing acceptance of such technologies (i.e. easier to finance). Gasification (with steam turbine) appears on the verge of competing with traditional combustion in some markets. • Good combustion control possible & less potential for formation of dioxins and NO_x than direct combustion due to lower temperatures in gasifier. 	<ul style="list-style-type: none"> • Feedstock preparation necessary for most plants, particularly those using a fluidised bed reactor • Existing commercial plants have not demonstrated significant practical advantages over conventional combustion plant in terms of air emissions, efficiency or residues.
<p>Gasification (Advanced)</p>	<ul style="list-style-type: none"> • High electrical efficiency possible by use of syngas engines or turbine compared to steam turbines • Inherently low emissions for most pollutants and low formation of dioxins given low temperature of combustion, though NO_x emissions relatively high • Suitable at small scales, potentially feasible at throughput capacities where traditional combustion is not 	<ul style="list-style-type: none"> • Expensive with high capital and operational costs • Cleaning syngas to a purity required for use in gas engines and turbines continues to be a major barrier to commercial deployment • Waste feedstock preparation often

	<p>viable</p> <ul style="list-style-type: none"> • Low building profile possible due to the lack of a boiler, and no requirement for high stack • Potentially more acceptance of technology due to the above 	<p>required to produce a consistent fuel (high quality SRF may be necessary)</p> <ul style="list-style-type: none"> • Many technologies struggling to gain the considerable funding and financing required to overcome technical challenges and move to commercial deployment
Gasification Slagging	<ul style="list-style-type: none"> • Maximizes landfill diversion potential • High quality, stable slag produced by melting ash which has many potential applications • Technically and commercially mature technology in Japan with a number of technology suppliers 	<ul style="list-style-type: none"> • Expensive, high CAPEX/OPEX. Query viability outside Japan, very few plants elsewhere • Needs oxygen and/or support fuel e.g. coke to generate high temperatures required to melt ash, negative impact on OPEX & CO₂ performance.
Gasification Plasma	<ul style="list-style-type: none"> • Potential to produce a clean syngas for use in engines or turbine • Can produce a high quality slag similar to slagging processes • Able to ‘add-on’ plasma units to more established combustion or gasification plants (to polish syngas or melt ash) 	<ul style="list-style-type: none"> • Expensive with high capital and operational costs • High parasitic electrical load • Achieving high availability may be challenging

2.5.3 BASIC WORKING PRINCIPLE OF COMBUSTION WASTE TO ENERGY PLAT

Moving grate furnace technologies have been the ‘workhorse’ of waste thermal treatment with more than 1,000 operational plants worldwide. A schematic representation of a moving grate combustion plant is shown in Figure3. The moving grate mechanism (normally inclined although

horizontal grate designs are operating) moves the burning solid waste from the inlet to the outlet. Primary combustion air passes from below the grate underneath the burning solids and flow through the waste bed into the freeboard zone above the bed. Secondary and tertiary air injection ports are used to ensure complete combustion of the gas phase components volatilized from the solid waste. The flue gas usually held at a minimum temperature of 850⁰C for two seconds after the last injection of combustion air[9].

The hot flue gas then passes into the water tube waste heat recovery boiler. Various boiler designs have been used that utilize horizontal and vertical boiler configurations. Both types of boiler configuration are capable of meeting all performance requirements[9].

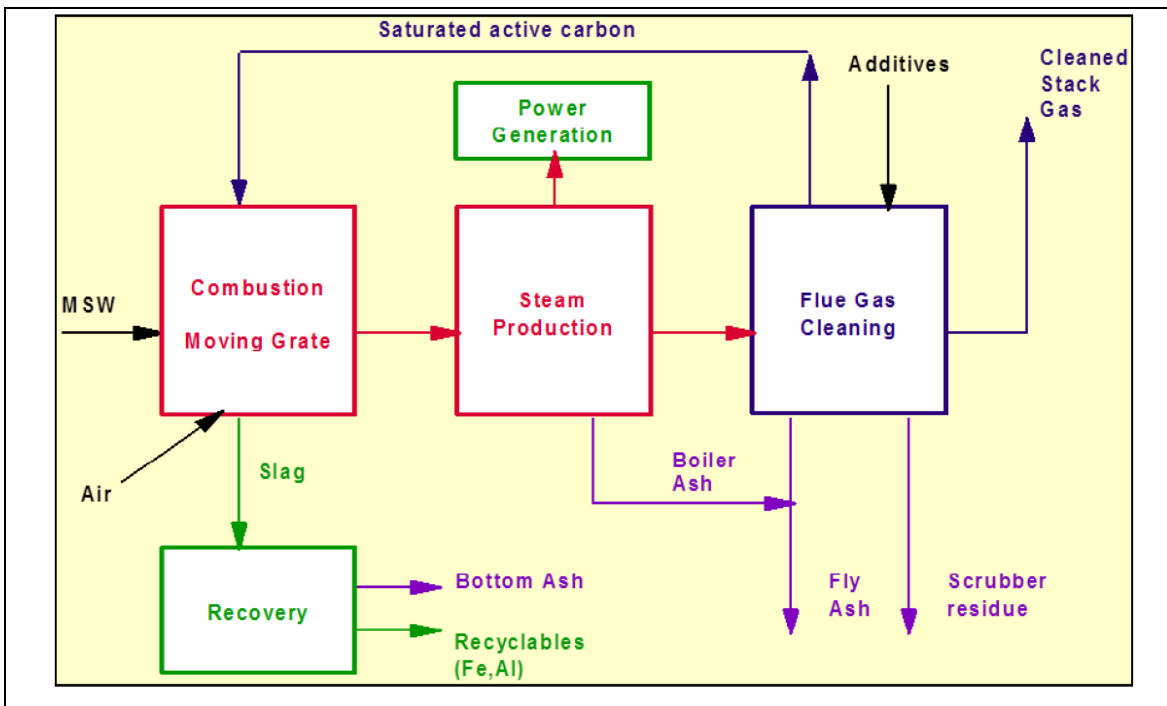


Figure 3 : Conventional Moving Grate Combustion Process [9]

In combustion processes, hot flue gases exit the furnace used to generate steam. The gases exit at temperatures in excess of 850⁰C and pass through the boiler where heat is transferred to the super heater, evaporator and economizer tube bundles respectively. Superheated steam is transferred to a steam turbine generator where electricity is generated. Steam can also be extracted from the turbine at an intermediate lower pressure stage for process optimization or to export offsite and supply a district heating network or feed an industrial need.

The steam conditions in a WTE combustion plant have typically been limited to 40bar, 400°C in most installations to avoid serious corrosion problems due to the high moisture content and plastics content of the waste; consequently, in conventional modern plants electrical efficiency is usually limited to around 22-25% (gross)[9]. There are a significant number of plants in the USA that operate boilers at 60 bar and plants in Europe have recently implemented similar high pressure boilers to increase the overall thermal efficiency of the WTE plant[9]. There are a number of means by which the efficiency can be increased and these techniques have been developed by WTE suppliers, particularly for large scale moving grate combustion process[9], [59]. These methods are:

- **Advanced combustion control** – the use of enhanced process control will maximize combustion efficiency to ensure maximum burn-out of the organic waste content, reduced excess air levels; and optimum oxygen levels can be achieved using flue gas recirculation;
- **High steam pressure and superheat temperature** – increasing steam pressure and temperature will increase the enthalpy of the steam and allow greater energy to be recovered in the steam turbine. Extreme care with the boiler design needs to be taken to protect the super heaters and increase the overall thermal efficiency of the plant. Locating the super heater tubes in the furnace can also boost steam temperatures beyond that usually possible. The tubes require considerable protection (Inconel) to avoid major corrosion problems, and may be located behind protective tiles;
- **Reheat cycle** – using a reheat cycle can increase the efficiency by several percent. Steam from the outlet of the high pressure stage of the turbine is sent back to the boiler where it is heated back to the original temperature, before being expanded in the low-pressure stage. This is a relatively high cost option, so the balance between cost and benefit of increased electricity generation has to be considered carefully;
- **Reduced boiler exit temperature** – the boiler exit temperature is established by sizing of the economizer and is typically set well above the dew points for hydrochloric and sulfuric acids and moisture. Preventing condensation of acid gases reduces corrosion and

preventing condensation of moisture prevents agglomeration of particulate on the boiler tubes. However, keeping the exhaust gas temperature well above the dew points means that energy recovery from the flue gases is reduced. Careful control and reduction of this temperature has been employed on recent plants to maximize energy recovery with additional corrosion protection provided in the economizers;

- **Reduced steam condenser pressure** – the condenser temperature has a strong influence on the plant efficiency, the lower the condenser temperature, the greater the pressure drop across the turbine which increases power generation. Water cooled condensers can create the lowest temperatures but air cooled condensers are used where no water cooling source is available. However where the temperature of near-by water bodies is too high, warmer water temperatures may not provide a significant improvement in power cycle efficiency and will not offset the increased maintenance effort of a pumped once-through ocean water cooling system
- **Integration with fossil fuelled fired power plant (external superheating)** – there are some plants in Europe that are integrated with a gas turbine CCGT system using the high temperature exhaust gases from the GT to provide additional heat. This can help boost the efficiency of energy recovery from the combustion of waste
- **Combined Heat & Power (CHP) operation** – the recovery of heat as well as electricity can produce the greatest increase in efficiency. Steam can be extracted from the turbine and used directly for process heating in industry or used to produce hot water for a district heating network.

All of the above techniques come at a cost, and there will always be a balance between additional capital, operational cost and increased revenue from electricity (and potentially heat) sales.

2.6 SMALL SCALE WASTE TO ENERGY PLANTS

Large WTE facilities have tended to be developed in proximity to major urban areas. However when the volume of waste, transportation costs, or public opposition rule out large-scale mass-burn WTE, small-scale technologies can offer smaller communities in rural, semi-urban or remote areas an alternative to landfill. The challenge for small scale systems is to effectively

meet emissions limits and regulations while dealing with the higher specific capital costs that developer of small scale systems often face[9].

Small scale WTE plants are not uncommon; however the presence of small scale WTE plants varies significantly between different countries [60]. In an energy efficiency report produced by Confederation of European Waste to Energy Plants report, approximately one third of the 314 plants included were plants with an annual capacity <100,000 tonnes [61]. In Japan, at least 60% (more than 1000 plants) of waste incineration plants were small scale, and were only in operation for 8 hours per day [9]. Many of these have since closed, as the Japanese Ministry of Environment reported that in 2009 there were 1243 incinerators in Japan in total, compared to earlier reports,[9]. There are 48 WTE facilities in Italy that treat MSW, 19 of which have a treatment capacity of < 100,000 ton/year[62]. In comparison, the Netherlands only has two small scale WTE plants, as per report from International Solid Waste Association [63]. In the UK, there are 13 small scale WTE facilities, with a combined capacity of 798,000 tonnes[9]. The following table shows three actual small scale combustion WTE plants technical data.

Table 7 : Representative Small Scale WTE plants technical data [9], [64]

Plant name	Waste Treatment capacity (tons/year)	Type of waste treated	Lower heating value (MJ/kg)	Electrical capacity of the plant (MW)	Steam data (°C/bar)	Availability (operational hours)
EXETER ENERGY RECOVERY FACILITY, UK	60,000	99% MSW, 1% C&I	9.08 - 10.7	4.2	390/40	89%
PONTENX-LES-FORGES, FRANCE	43,000	MSW, C&I	8.5	2.5	355/34	95.7%
SKÖVDE VÄRMEVERK, SWEDEN	60,000	50% MSW, 47% C&I, 3% Hazardous	12	2	215/16	99%
Envikraft Thermal Processing Plant, USA, Canada	20,000	MSW, LW, Hazardous	11.5	6.5	--	--

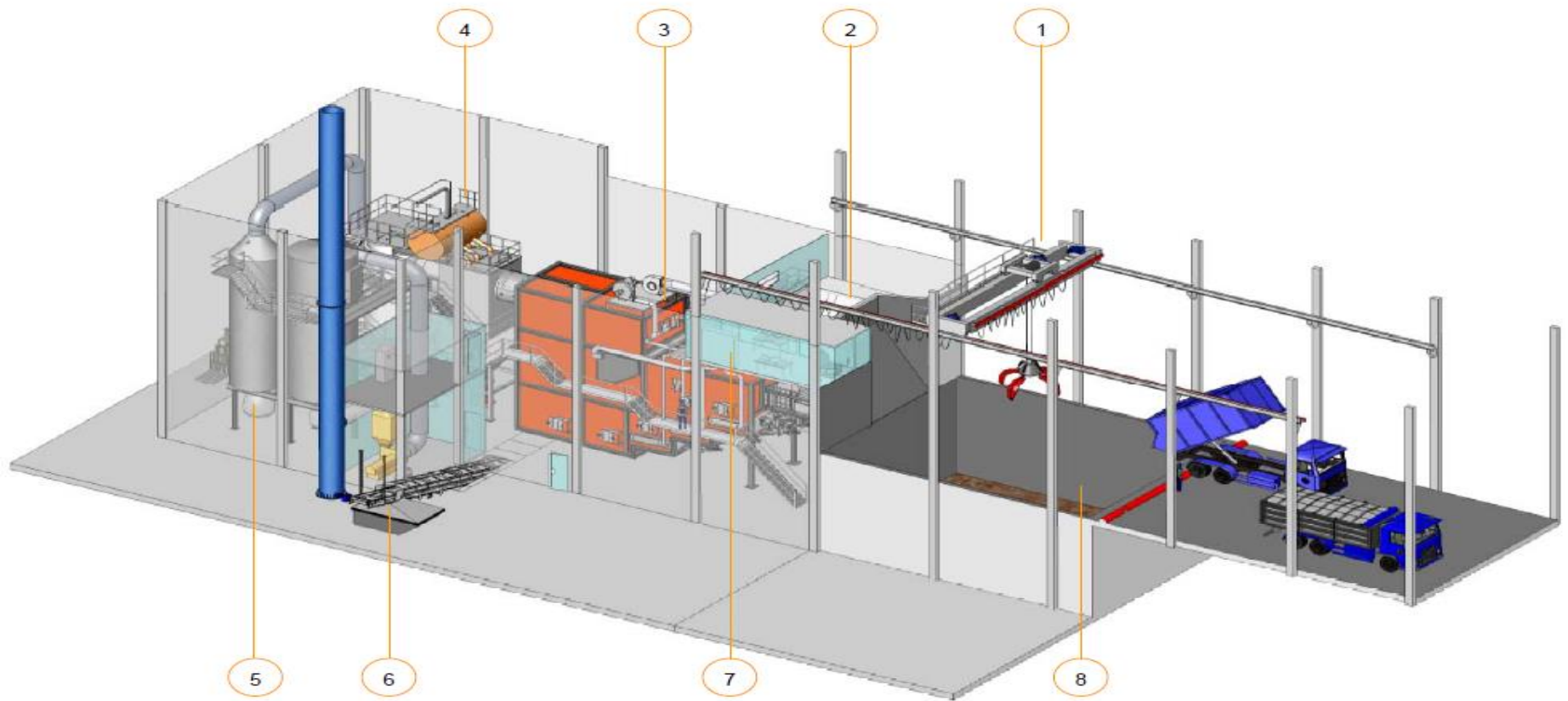
ForusEnergigjenvinning KS Forusbeen 202 NO-4313 Sandnes, Norway	43,560 (5.5 ton/hr)	MSW	10.7	8.478 MWh	380/21	91%
AVØ A/S Knivholtvej 14 DK-9900 Frederikshavn, Denmark	39,600 (5 ton/hr)	MSW		15.98 MWh	400/48	98%
Castelnuovo di Garfagnana (LU), Italy	11,880	MSW		0.8MW	250/40	
Tolentino (MC), Italy	19,800	MSW		1.2MW	310/28	
Arezzo (AR), Italy	39,600	MSW		2.9MW	380/40	

2.1 SMALL SCALE WASTE TO ENERGY CONFIGURATION

Generally, a small scale WTE power plant includes the following main operations and sections:

- Incoming waste reception
- Storage of waste and raw materials
- Pre-treatment of waste (where required, on-site or off-site)
- Loading of waste into the process
- Thermal treatment of the waste
- Energy recovery and conversion
- Flue-gas cleaning
- Flue-gas cleaning residue management (from flue-gas treatment)
- Flue-gas discharge
- Emissions monitoring and control;

Figure 4 and Figure 5 show small scale WTE plant and process flow diagram respectively.



1 - Waste Feeding Crane

2 - Waste Feeder

3 - Thermal Processor

4 - Boiler and electric generator

5 - Flue gas cleaning system

6 - Ash discharge and transportation

7 - Control room

8 - Waste bunker

Figure 4 : Typical small scale WTE plant [56]

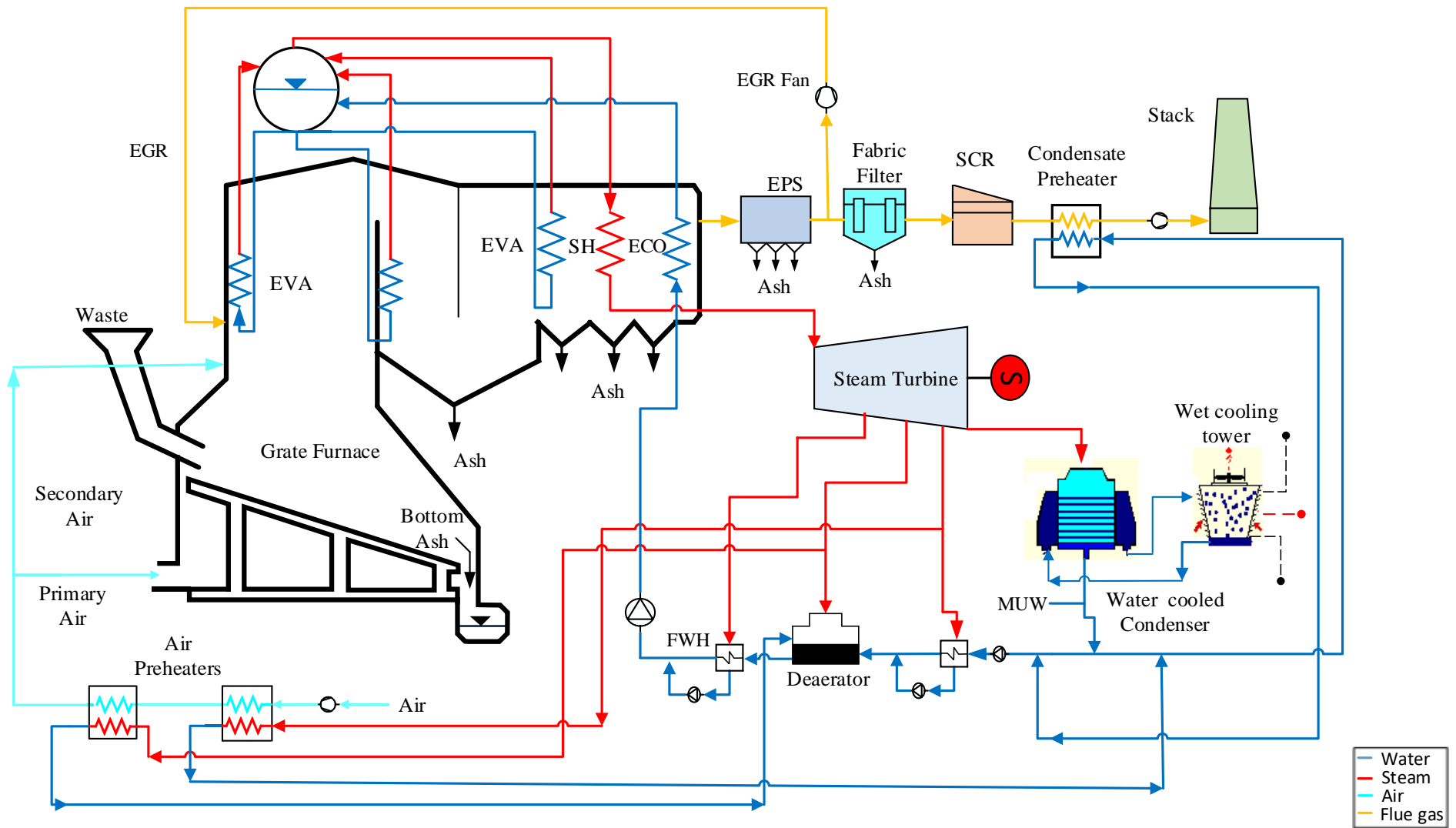


Figure 5 : A small scale WTE process flow diagram

2.7.1 WASTE RECEPTION, STORAGE AND PREPARATION

The waste reception area is where the delivery trucks, trains or containers arrive in order to dump the waste into the bunker (storage or pretreatment place), usually after visual control and weighing. Figure 6 shows a typical municipal solid waste bunker device. Enclosure of the delivery area can be one effective means to avoid odor, noise and emission problems from the waste. The bunker is usually a waterproof, concrete bed. The waste is piled and mixed in the bunker using cranes equipped with grapples. The mixing of wastes helps to achieve a balanced heat value, size, structure, composition, etc. of the material dumped into the incinerator filling hoppers. The cab has its own ventilation system, independent from the bunker. In order to avoid excessive dust development and gas formation (e.g. methane) from fermenting processes, as well as the accumulation of odor and dust emissions, the primary incineration air for the furnace plants is often extracted from the bunker area. Depending on the calorific value of the waste as well as the layout and the concept of the plant, preference is most often given to supplying the bunker air to either the primary or secondary air. The bunker usually has a storage capacity of several days (commonly 3 - 5 days) of plant operational throughput, thus its depth can reach a few dozen meters. This is very dependent on local factors and on the specific nature of the waste[57].



Figure 6 : A picture of a typical municipal solid waste bunker device

2.7.2 FEEDING SYSTEM

Feeding means dosing the right quantity of fuel to the grate for steady combustion and energy production. Proper feeding is continuous and adjusted to the grate transport capacity to ensure an even fuel layer across the grate, thus enabling a steady energy output. This consistent feeding ensures minimal environmental impact because it promotes ideal, controllable combustion. The correct design of the feed hopper prevents waste clogging and ensures a continuous waste transport to the water-cooled chute. Two powerful hydraulic gates are placed between chute and hopper. These gates can be closed in the event of a fire in the chute, and they will close automatically in the event of power failure. The water-cooled feed chute is made of heavy steel plates. The smooth sides have a negative inclination to ensure a free waste transport through the chute to the feed platform. The chute cooling system makes it fire-resistant. The grate is fed at a variable rate adjusted to the energy production by means of a hydraulic pusher. The front and top sides of the feed pusher are covered by exchangeable wear plates. The sides of the water-cooled feed chute are covered by exchangeable cast-iron plates up to the height of the top of the feed pusher. The continuous slow forward movement of the feed pusher at a variable rate adjusted to the energy production results in a steady and continuous feeding to the grate[57].

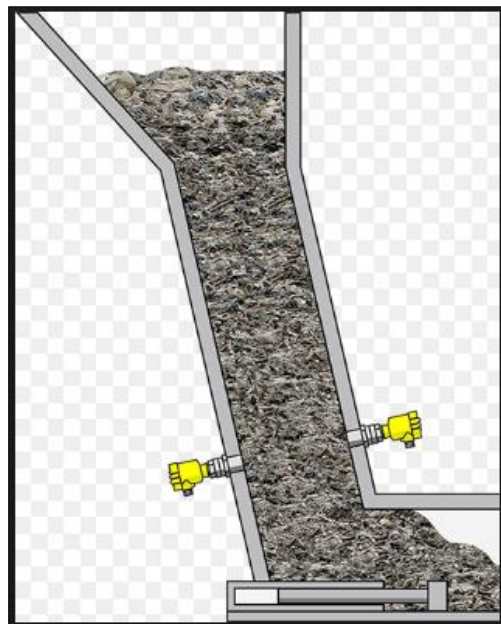


Figure 7 : A typical waste feeder

2.7.3 BASICS OF THE COMBUSTION PROCESS

Waste incineration is the oxidation of the combustible materials contained in the waste. Waste is generally a highly heterogeneous material, consisting essentially of organic substances, minerals, metals and water. During incineration, flue-gases are created containing the majority of the available fuel energy as heat. Burning of organic fuel substances occurs once they have reached the necessary ignition temperature and come into contact with oxygen. The combustion process takes place in the gas phase, in fractions of seconds, and simultaneously releases energy where the calorific value of the waste and oxygen supply is sufficient. This can lead to a thermal chain reaction and self-supporting combustion, i.e. there is no need for the addition of other fuels. The main stages of an incineration process, schematically shown in Figure 8, are [65]:

- A. Drying and degassing – here, volatile content is evolved (e.g. hydrocarbons and water) at temperatures generally between 100 and 300 °C. The drying and degassing process do not require any oxidizing agent and are only dependent on the supplied heat;
- B. Pyrolysis and gasification - pyrolysis is the further decomposition of organic substances in the absence of an oxidizing agent at approximately 250 °C – 700°C. Gasification of the carbonaceous residues is the reaction of the residues with water vapors and CO₂ at temperatures, typically between 500 °C and 1000 °C. Thus, solid organic matter is transferred to the gaseous phase. In addition to the temperature, water, steam and oxygen support this reaction;
- C. Oxidation - the combustible gases created in the previous stages are oxidized, depending on the selected incineration method, at flue gas temperatures generally between 800 °C and 1450 °C.

Figure 8, is a simplified illustration of the refuse bed processes on the grate [6]. The process is mainly controlled by mass and heat transfer. In the illustration a large part of the grate length has a deficit of oxygen (fuel rich condition) resulting in formation of combustible gases. The energy of the waste is released partly in the fuel layer and partly in the furnace room as combustible gases. Although the thermal treatment process in the waste on the grate receives a certain amount of excess combustion air, gasification will take place in certain areas. Consequently, controlling

the injection of primary air enable distribution of the individual reaction zones to obtain optimal combustion.

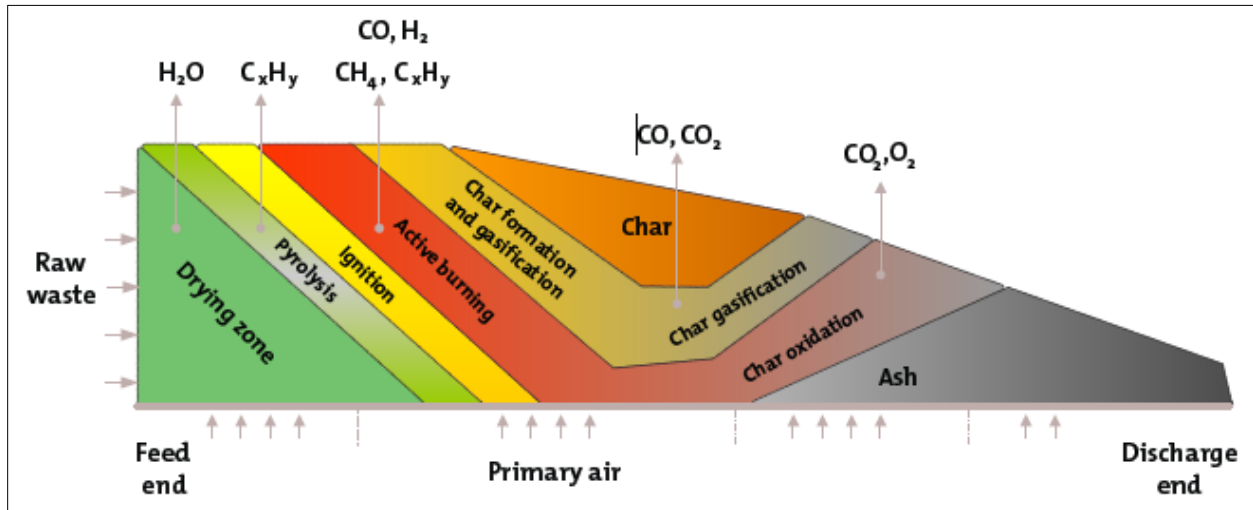


Figure 8 : Simplified process of the combustion process on the grate [6]

Staged combustion can be provided in several ways. One method for staging the combustion is a stepwise addition of combustion air to prevent complete combustion at the first stage. The change in stoichiometric rate will result in an increased flow of unburned gases into the furnace room. The energy released from the combustion process will move from the fuel bed to the furnace room, and a large part of the furnace room will be operating under slightly fuel-rich conditions. The individual stages generally overlap, meaning that spatial and temporal separation of these stages during waste incineration may only be possible to a limited extent. Indeed the processes partly occur in parallel and influence each other. Nevertheless it is possible, using in-furnace technical measures, to influence these processes so as to reduce polluting emissions. Such measures include furnace design, air distribution and control engineering. In fully oxidative incineration the main constituents of the flue-gas are: water vapor, nitrogen, carbon dioxide and oxygen. Depending on the composition of the material incinerated and on the operating conditions, smaller amounts of CO, HCl, HF, HBr, HI, NO_x, SO₂, VOCs and heavy metal compounds (among others) are formed or remain. Depending on the combustion temperatures during the main stages of incineration, volatile heavy metals and inorganic compounds (e.g. salts) are totally or partly evaporated. These substances are transferred from the input waste to both the flue-gas and the fly ash it contains. A mineral residue fly ash (dust) and heavier solid ash

(bottom ash) are created. In municipal waste incinerators, bottom ash is approximately 10% by volume and approximately 20% to 30% by weight of the solid waste input. Fly ash quantities are much lower, generally only few per cent of input. The proportions of solid residue vary greatly according to the waste type and detailed process design. For effective oxidative combustion, a sufficient oxygen supply is essential. The air ratio of the supplied incineration air to the chemically required (or stoichiometric) incineration air, usually ranges from 1.2 to 2.5, depending on whether the waste composition and furnace system. The incineration air accomplished the following objectives:

- Provides the oxidant;
- Cooling;
- Avoidance of slag formation in the furnace;
- Mixing of flue-gas.

Air is added at various places in the combustion chamber. It is usually described as primary and secondary, although tertiary air, and re-circulated flue-gases are also used. The primary air is generally taken from the waste bunker. Primary air is blown by fans into the areas below the grate, where its distribution can be closely controlled using multiple wind boxes and distribution valves. The primary air will be forced through the grate layer into the fuel bed. It cools the grate bars and carries oxygen into the incineration bed. Secondary air is blown into the incineration chamber at high speeds via, for example, injection lances or from internal structures. This is carried out to assure complete incineration and it is also responsible for the intensive mixing of flue-gases, and prevention of the free passage of unburned gas streams. Preheating the combustion air is particularly beneficial for assisting the combustion of high moisture content wastes. The pre-warmed air supply dries the waste, thus facilitating its ignition. The preheating of primary combustion air can have a positive influence on overall energy efficiency in case of electricity production. Figure 9 shows a typical 'capacity diagram' for a waste incineration plant where the operating area is highlighted as a function of waste mass flow rate, for different waste Lower Heating Value (LHV). The couple of variables waste mass flow rate and LHV, identify on vertical axis, the thermal input in the system. The diagram highlights also different area of operation where air preheating is required or auxiliary fuel is necessary [6].

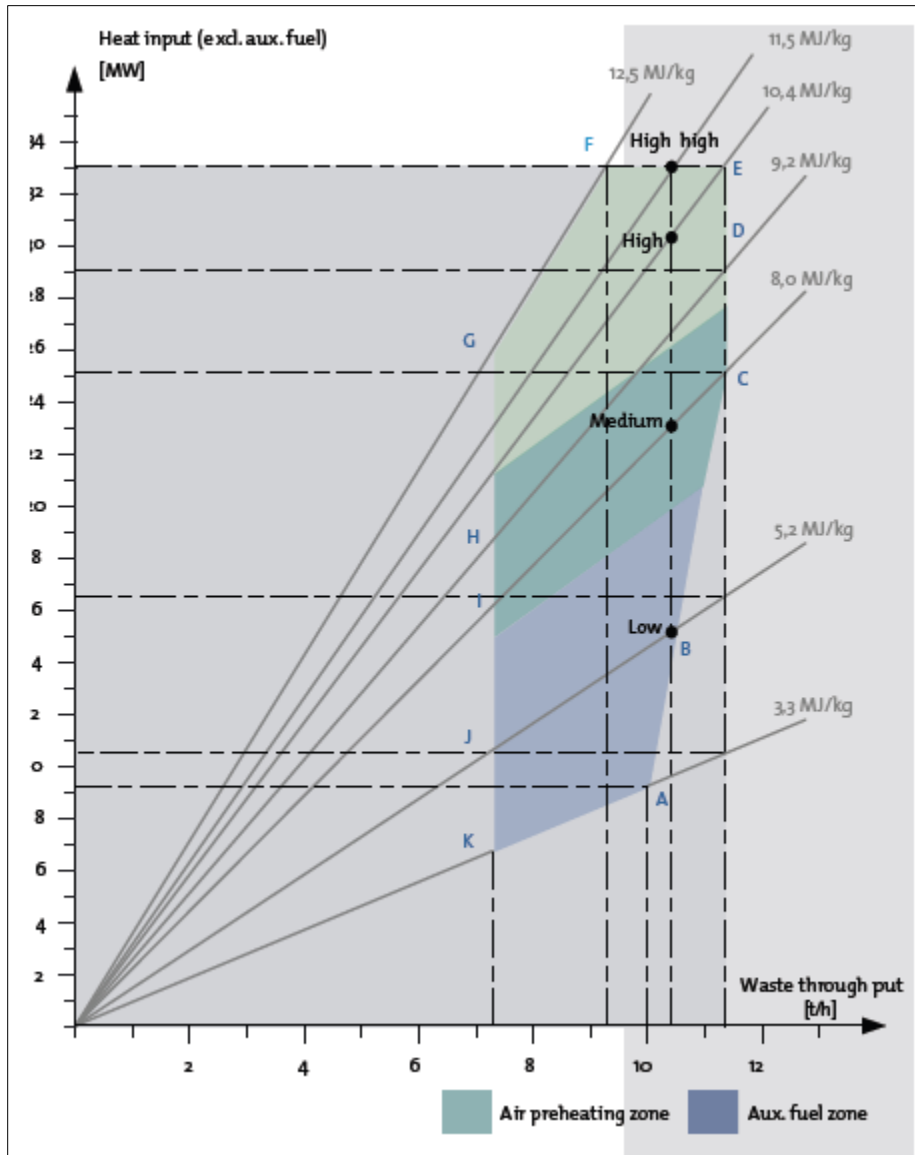


Figure 9 : A typical 'capacity diagram' for a waste incineration plant [6]

2.7.4 COMBUSTION GRATES

A combustion grate is a transport device that moves the burning fuel from the inlet through the furnace to the bottom ash outlet. During transportation waste is mixed, and combustion air is added. Volatile material is released to the furnace and fixed carbon is burned on the grate. The grate is an integrated part of the furnace, where the fuel is converted into energy. Grate incinerators are widely applied for the incineration of mixed municipal wastes. In Europe

approximately 90% of installations treating MSW use grates [66]. Grate incinerators usually have the following components, Figure 7:

- Waste feeder
- Incineration grate
- Bottom ash discharger
- Incineration air duct system
- Incineration chamber
- Auxiliary burners.

When introduced onto the grate, as described above, the waste is first dried, then partly pyrolysed under formation of combustible as well as incombustible gases. The combustible gases burn above the grate. The remaining waste is subsequently burned out on the grate to a total organic carbon (TOC) content of less than 3% before it falls into the – normally wet – bottom ash system. Primary combustion air is supplied from underneath through small openings in the grate. The air supply is determined by two considerations: firstly, enough air must be supplied to cool the grate (air-cooled grate), and secondly, enough air must be supplied to sustain the (primary) combustion. Thus, by partly cooling the grate by water (water-cooled grate), it is possible to adjust the primary air supplied to exactly the flow needed for the primary combustion process, only. Most grates are cooled, most often with air. In some cases a liquid cooling medium (usually water) is passed through the inside of the grate. The flow of the cooling medium is from colder zones to progressively hotter ones in order to maximize the heat transfer. The heat absorbed by the cooling medium may be transferred for use in the process or for external supply.

Water cooling is most often applied where the calorific value of the waste is higher (e.g. >12 - 15 MJ/kg for MSW). The design of the water cooled system is slightly more complex than air cooled systems. The addition of water cooling may allow grate metal temperature and local combustion temperature to be controlled with greater independence from the primary air supply.

This may then allow temperature and air (oxygen) supplied to be optimized to suit specific on-grate combustion requirements and thereby improve combustion performance. A better control of grate temperature can allow incineration of higher calorific value waste without the normally increased operational and maintenance problems.

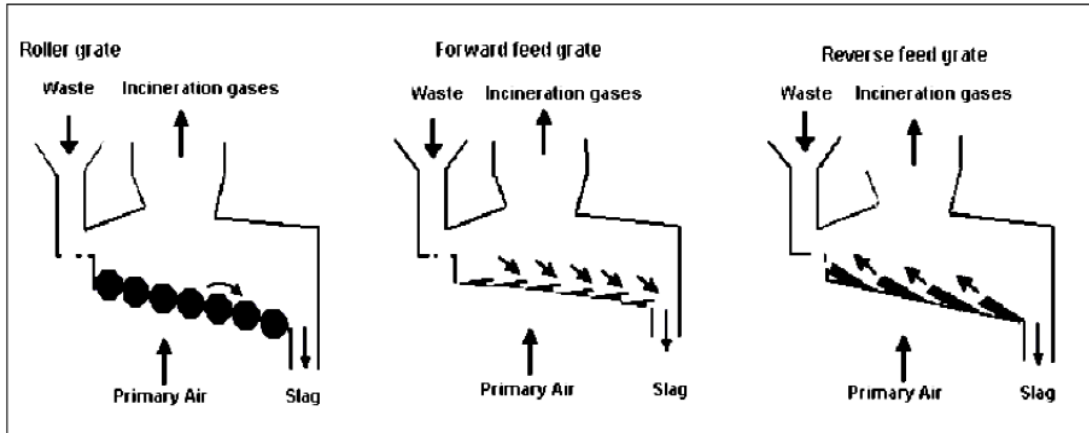


Figure 10 : Different types of grate

The residence time of waste on the grates is not more than 60 minutes. In general, one can differentiate between continuous (roller and chain grates) and discontinuous feeder principles (push grates). Figure 10 shows different types of grates while in Figure 11 a picture of a push forward grate is presented. Different grate systems can be distinguished by the way the waste is conveyed through the different zones in the combustion chamber. Each has to fulfill requirements regarding primary air feeding, conveying velocity as well as mixing of the waste. Modern small scale WTE plant employ auger type grate that utilize horizontal ramp pushing for waste feeding and rotating augers above the incinerator bed in order to mix the waste and provide for complete ash burnout [56].

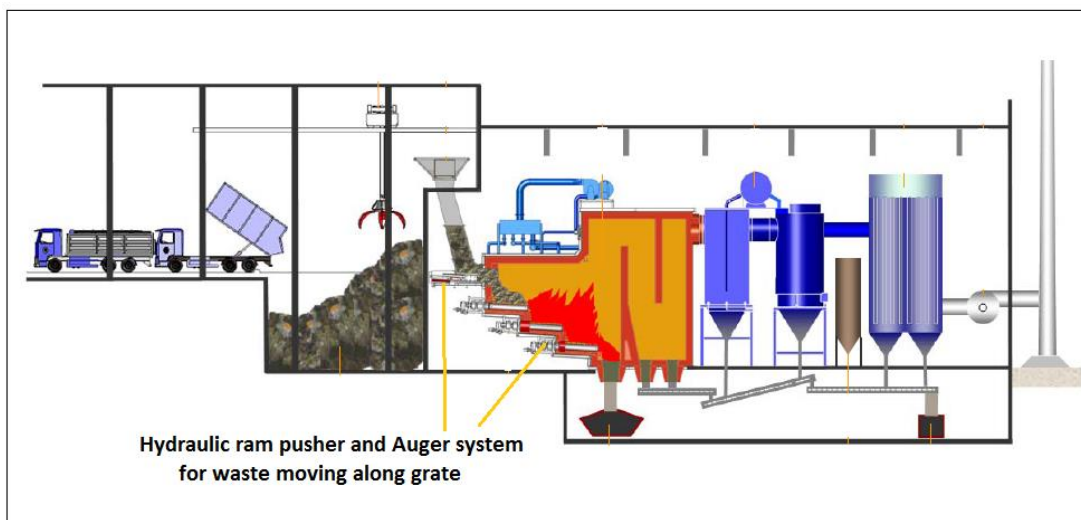


Figure 11 : Type of Grate for small scale WTE plant

2.7.5 INCINERATION CHAMBER AND BOILER

Combustion takes place above the grate in the incineration chamber (see Figure 12). As a whole, the incineration chamber typically consists of a grate situated at the bottom, cooled and non-cooled walls on the furnace sides, and a ceiling or boiler surface heater at the top. As municipal waste generally has a high volatile content, the volatile gases are driven off and only a small part of the actual incineration takes place on or near the grate. The following requirements influence the design of the incineration chamber:

- Form and size of the incineration grate - the size of the grate determines the size of the cross-section of the incineration chamber;
- Vortex and homogeneity of flue gas flow - complete mixing of the flue-gases is essential for good flue-gas incineration;
- Sufficient residence time for the flue-gases in the hot furnace;
- Sufficient reaction time at high temperatures must be assured for complete incineration;
- Partial cooling of the flue gases in order to avoid fusion of hot fly ash at the boiler; the flue gas temperature must not exceed an upper limit at the incineration chamber exit.

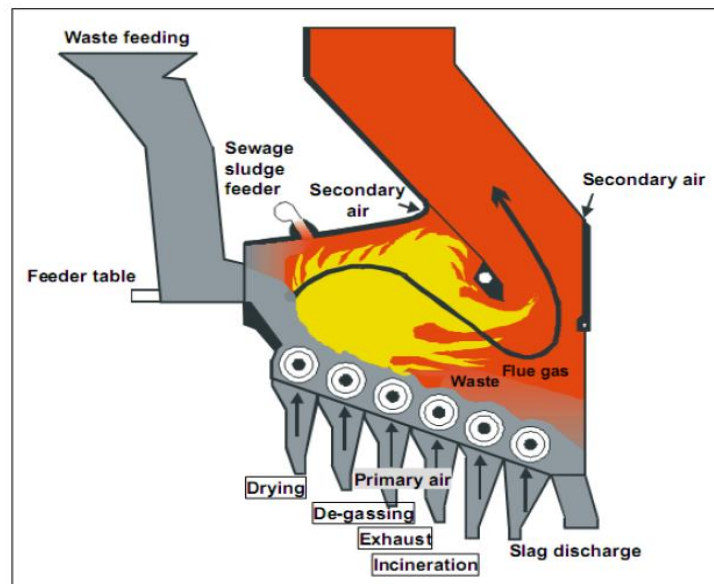


Figure 12 : Incineration chamber

2.7.6 POST COMBUSTION CHAMBER

Modern standards require that the flue gas be exposed to a temperature of minimum 850°C for a minimum residence time of 2 seconds after the last secondary air injection [65]. The furnace must therefore have a post combustion or afterburning chamber of a certain height above the grate. The final burnout of the flue gas takes place in that chamber, and secondary combustion air is added in the required amount and in a way that ensure maximum turbulence. Auxiliary burners, if installed, are located in the post combustion chamber; also the injection of ammonia (NH₃) or urea for NO_x reduction, according to the Selective Non Catalytic Reduction (SNCR) process, is carried out in this zone.

2.7.7 FLUE GAS RE-CIRCULATION

The total air supply to the combustion process is the sum of the primary and secondary air. To secure complete burnout, it is necessary to operate at a certain surplus of air. The excess air passes all the way through the boiler and the flue gas treatment system to the chimney and, depending on the flue gas temperature in the chimney, it represents a loss of energy and hence a loss of thermal efficiency. The excess air ratio can be reduced, on the primary side, by using a water-cooled grate and on the secondary side by re-circulating a part of the treated flue gas (Flue Gas Recirculation, FGR). It is also of importance whether the entire gas flows through the furnace is counterflow or parallel flow. A proportion (approx. 10% – 20% by volume) of the (usually cleaned) flue-gases is re-circulated, normally after pre-dusting, to replace secondary air feeds in the combustion chamber. This technique is reported to reduce heat losses with the flue-gas and to increase the process energy efficiency by around 0.75% - 2%.

2.7.8 BOILER

Boilers for WTE power plants are normally water tube boilers and most often they have four passes: 3 vertical radiation passes and a convective pass. The first of the radiation passes is integrated in the furnace as the post combustion chamber. The convection pass, in which the evaporators, super heaters and economizers are located, may be vertical or horizontal. When designing a boiler for waste firing, the most important aspect to take into account is the special risk of corrosion. In practice, corrosion problems, as will be described in details later, limit the steam parameters to a maximum of around 450 °C - 500 °C and 40 bar - 60 bar. Tubular water

boilers are generally used for steam and hot water generation from the energy potential of hot flue-gases. A WTE boiler typical feature includes[57]:

- Optimized flue gas flow in the system
- Uniform temperatures and heat loads
- Minimized corrosion risk
- Good burn-out, Low CO and TOC
- Optimized and integrated SNCR NO_xreduction process
- Very low NO_x emission

In steam generation, it is usually possible to differentiate between the three heat surface areas shown in Figure 13.

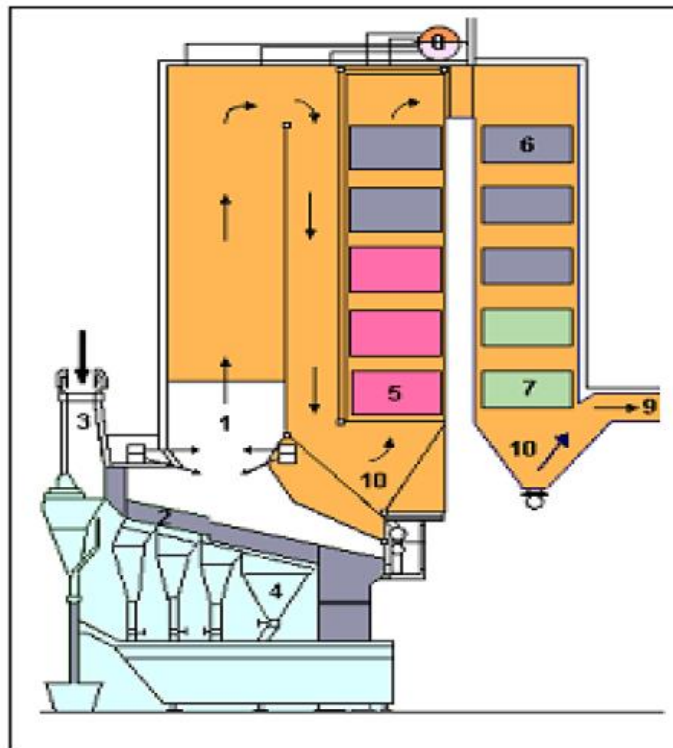


Figure 13 : Boiler heat surface areas

Feed-water preheating (Economizer) (7 in Figure 14):

In this area, the boiler feed-water is heated by flue-gases to a temperature close to the boiling point (designed as a bundled heating surface).

Evaporation (5 in Figure 14):

In this area, the water coming out from the economizer is heated until it reaches the saturated steam temperature (designed as a bundled heating surface, envelopment wall of the incineration chamber).

Superheating (6 in Figure 14):

In this area, the saturated steam coming from the evaporator is superheated to the maximum temperature. Spray coolers and surface coolers are used in circulation boilers in order to maintain the exact required steam temperature. It is their function to balance the fluctuations of the steam temperature, these fluctuations being the consequences of load fluctuations, changes in the waste quality, the surplus air, as well as contamination of the heat surfaces (clean or dirty surface).

The preparation of boiler feed water and make up water is essential for effective operation and to reduce corrosion (inside the tubes) or risk of turbine damage. The quality of boiler water must be higher when increased steam parameters are used. A compromise is required when determining steam parameters from waste fired boilers. This is because, while the selection of high temperatures and pressures increase waste conversion efficiency into electrical energy, these higher steam parameters can lead to significantly increased corrosion problems, especially at the super heater surfaces and the evaporator; thus, a compromise between high steam cycle parameters and corrosion problems must be looked for. In municipal waste incinerators it is common to use 40bar and 400 °C, when there is electricity production although higher values are used, especially with pre-treated MSW and prepared Refused Derived Fuel (RDF) (value of 60 Bar and 520 °C are in use with special measures to prevent corrosion)[59].

Based on these rather low (compared to most common fossil fuel power plants) steam parameters, almost exclusively, natural circulation steam boilers are selected. A feature of waste incineration is the high dust load in flue-gases. The high proportion of ash in flue-gas causes a risk of a correspondingly high contamination of the heat transfer surfaces. This leads to a decline in heat transfer and therefore a performance loss. Thus, heat transfer surface cleaning plays an important role. This cleaning can be accomplished manually or automatically with lances (compressed air

or water jet), with agitators, with soot blowers using steam, with a hail of pellets (sometimes shot cleaning), with sound and shock waves, or with tank cleaning devices.

2.7.9 CORROSION PROTECTION

Household and industrial wastes are fuels that contain most of the elements in the periodic system. Depending on the character of the combustion, various chemical combinations will be formed. Depending on local temperatures and oxygen supply, the Na, Ca, Cu, K, Cl, S, Cr, Pb, Zn, Fe, Sn and Al contents in particular will take part in various chemical reactions, the end-products of which may cause corrosion. The use of waste as fuel therefore makes major demands on the plant's resistance against corrosion. This section deals exclusively with the flue gas area. Corrosion attacks in a waste-fired boiler can in principle be divided into two main types.

- Low-temperature corrosion
- High-temperature corrosion

Low-temperature corrosion appears in the boiler and on other surfaces where the temperature is under approx. 135°C. It is caused by condensation of the acidic sulfurous and chlorine-containing gases. This type of corrosion is temperature-dependent. New plants are being designed in order to avoid low-temperature corrosion [57].

High-temperature corrosion (HT-corrosion) is more complex and only appears on the heating surfaces in steam boilers in particular on:

- Evaporator heating surfaces
- Superheater tubes

Depending upon local conditions tube wall temperatures (metal temperature) above 260°C may cause attacks of various HT-corrosion. In general, increasing metal temperatures and increasing gas temperatures will increase the corrosion rate as indicated in Figure 14, which is measured in mm tube wall per year, where the metal temperature being the most important factor [54]. The corrosion rate is influenced by the thickness and composition of the ash layer, the HCl and H₂SO₄ content of the gas, and the surplus/deficiency of oxygen in the gas at the tube wall.

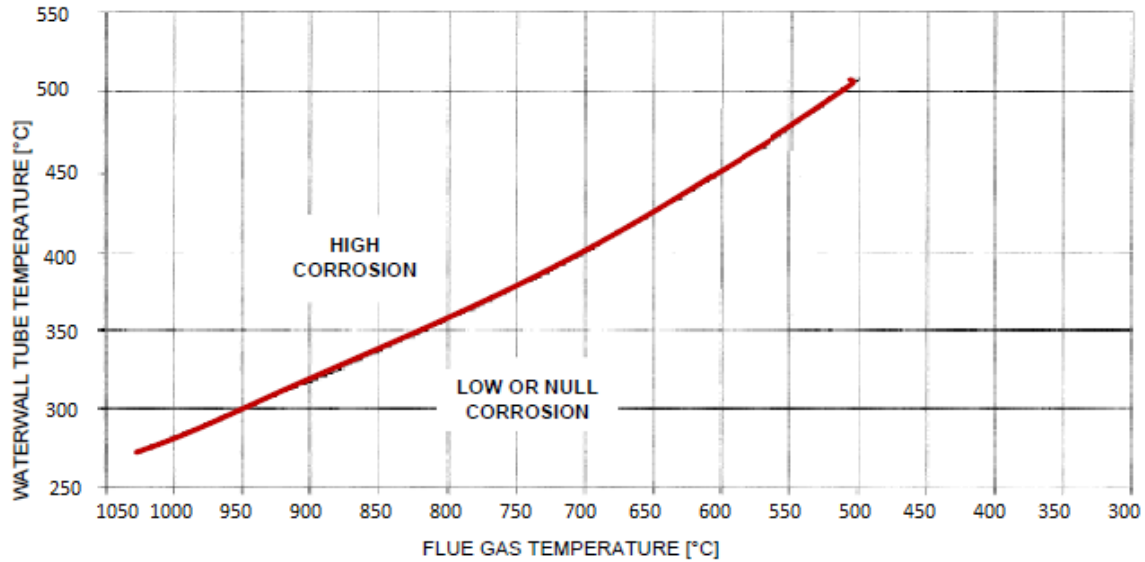


Figure 14 : Typical Corrosion diagram [54]

Metal tube corrosion is the major operating problem because it results in downtime and periodic shutdowns in WTE plants and accounts for a significant fraction of the total operating cost of WTE plants. High temperature corrosion has also environmental impacts. Metallic coatings and corrosion resistant alloys such as stainless steels and nickel-base alloys are often used to protect boilers from corrosion and represent a large use of valuable resources. The conversion efficiency of steam energy into electricity increases with higher steam temperatures and pressures. However, increasing steam temperature, the heat transfer surfaces are subjected to severe high temperature corrosion, caused by both the metal chlorides in the ash particles deposited on the gas tubes and by the high concentration of HCl in the process. The incineration chamber, the water walls of the first passes and the superheater are boiler's components more affected by corrosion. Under the same operating conditions, superheater tube bundles in a vertical design boiler, which has fewer gas passes will have more critical corrosion problems than the tubes in a horizontal design boiler, because the former are subjected to higher metal temperatures and flow velocities of flue gas. The disadvantage of the horizontal design is that it needs more floor space than the vertical design. The chlorine concentration in the combustion gas depends entirely on the MSW composition and varies somewhat from region to region. Approximately, one half of the Cl content of MSW is due to natural organics and the other half to chlorinated

plastics, mostly PVC. During combustion, nearly all of the chlorine content in the various components of the MSW, both natural organics and chlorinated plastics is volatilized and converted to HCl gas.

Beyond corrosion problems, other negative aspect occurring in a WTE plant is represented by erosion, which is the abrasion of surface material through vertical wear-and-tear, is caused primarily by the ash particles present in flue-gas. Erosion appears mostly in the area of gas redirection. Tube wear is caused by a combination of corrosion and abrasion.

The corrosion rate can be reduced by using high-alloy tubes and/or by protecting the tubes with refractory lining or welded high alloy materials such as Inconel®. The choice between refractory lining and Inconel® depends on:

- The plant size
- Regulatory requirements on the retention time of the flue gases
- Variation in heating values
- Which type of heating surface and design is chosen

If refractory lining is chosen as protection, the choice between the different lining types will be based on requirements regarding the resulting heat conduction, the residual porosity and the smoothness of the lining surface [57]. This shows that increased steam parameters pressure and temperature result in increased power output. However, the characteristics of the produced steam, pressure and temperature, play a fundamental role in corrosion generation. Because of this, steam cycle parameters are bounded and conversion efficiency of a Waste-To-Energy power plant hardly exceeds 30%, with a net electric efficiency, typically, lower than 25% [59].

2.7.10 FLUE GAS CLEANING

During combustion when fuels are burned a certain number of gas components remains beside the ash. These are after the heat is extracted called flue gases and are cleaned in a flue gas cleaning (FGC) system. Flue gases include: carbon dioxide (CO₂), carbon monoxide (CO), nitrogen oxides (NO_x), nitrogen (N₂), sulfur (S), sulfur dioxide (SO₂), water vapor, soot, hydro carbons and heavy metals etc. Tremendous advancements have been done in the field of FGC and

emission monitoring. Many emissions can now be measured continuously for online monitoring of compliance with regulations.

These pollutants can be effectively reduced to below the acceptable and regulated emission levels (example, set by the EU Waste Incineration Directive) by a range of physical and chemical processes. The capture and removal of the flue gases are generally based around the following basic steps:

- 1) Addition of ammonia to the combustion chamber,
- 2) Cooling of the flue gas,
- 3) Acid neutralization,
- 4) Addition of activated carbon, and
- 5) Filtration.

Most of these pollutants are removed by specific treatments: neutralization for acid gases, filtration for fly ashes and absorption with activated carbon for dioxins and other micro pollutants like metals [67]. Powder emissions must be controlled by means of fabric filters, because electrostatic precipitator's have efficiencies up to 99.5–99.8% [68] and often cannot meet the regulatory limits. Also fabric filters allow a strong enhancement of micro-pollutant absorption because active carbon is added before filtration and the filter cake acts like a thin fixed bed reactor to collect the pollutants [67]. NO_x reduction is achieved normally by means of urea or ammonia both in the post-combustion chamber itself and in a catalytic reactor, which is often installed downstream of all the other cleaning processes in the WTE (waste-to-energy) plants. Normally the flue gas, filtered and neutralized, is heated at the catalyst working temperature by means of a regenerative heater coupled with a burner. The additional fuel used in the burner increases flue gas temperature of less than 50°C . For this reason the presence of a catalytic reduction has a similar influence on the electrical efficiency of the plant regardless of the technologies used for the removal of other pollutants. Traditional technologies for acid gas removal are semi-dry neutralization with $\text{Ca}(\text{OH})_2$ and wet scrubbing. In WTE plants, dry processes based on neutralization with NaHCO_3 are also used. All these listed technologies for acid gas scrubbing are able to fulfill the limits imposed by the European and Italian regulations [69], but, as reported by Poggio and Calì [70], dry treatments (in particular based on $\text{Ca}(\text{OH})_2$) are not able to ensure pollutant concentrations remarkably smaller than the most stringent

regulatory limits (European directive 2000/76/CE: 10 mg/Nm³HCl, 50 mg/Nm³ SO₂). Wet scrubbers are more powerful but produce wastewater. In many recent plants wet scrubbing is applied down-stream of a dry neutralization with Ca(OH)₂ in order to reduce strongly both the amount of acid gases and the waste water production.

Flue gas cleaning system can affect the electrical efficiency of the plant because of the heat losses related to the introduction of liquid water within flue gas or because of additional steam requirements. The injection of liquid water is always present in semi-dry neutralization. This is one of the most disadvantageous technologies because lime drying leads to about 50 °C reduction of flue gas temperature. Dry neutralization with Ca(OH)₂, when the water content of waste is very low, requires to increase the flue gas humidity by means of water injection, leading to a reduction of the available heat for energy recovery. NaHCO₃ neutralization is not affected by water content in waste, it has no requirement on flue gas humidity and it leads to the highest electrical efficiency. Wet treatments can have a direct influence on the electrical efficiency because of the increase of consumption of steam: final heating of flue gas before stack can require a large amount of steam; this aspect can reduce the electrical efficiency to a value similar to that one corresponding to semi-dry neutralization. When flue gas heating is obtained by means of a regenerative gas/gas heater, a final wet scrubbing has reduced effects. On the other hand, regenerative heater is not commonly applied because it is affected by strong corrosion problems due to the presence of saturated acid gases.

2.8 EFFICIENCY ENHANCEMENT METHODS FOR SSWTE PLANTS

Originally, waste incinerators had the sole function of reliably burning the waste while meeting the statutory emission limits. In the meantime, however, there has been growing awareness of the waste's recoverable energy potential. These days it is imperative to optimize energy recovery from waste not only to meet the efficiency criterion and thus secure the recovery status of the operation as defined by the European waste hierarchy [59]. But also to further reduce CO₂ emissions in line with the climate protection targets. In this respect, thermal waste treatment plants are at an advantage in that more than fifty percent of the waste is of biogenic origin and therefore classifies as climate neutral [59].

WTE plants typically use conventional water – steam circuit for energy conversion and recovery known from other power generation process. However, energy optimization through raised steam parameters – the typical approach adopted in the power plant sector – has limited applicability for WTE plants because of the highly corrosive nature of the combustion flue gases from waste incineration. Nevertheless, optimization measures are worthwhile consideration as they not only provide ecological benefits but also generate additional income from increased energy sales. Other optimization techniques are also being in application as discussed below.

2.8.1 OPTIMIZATION WITH THE WATER – STEAM CIRCUIT

The majority of the WTE plants currently in operation is designed for live steam temperatures in the range of 380°C to 420°C and pressures between 40 bar and 60 bar [59]. In the T – s diagram shown by Figure 15, a reference plant for steam parameters of 400 °C / 40 bar (line along P2), feed water temperature of 130 °C, boiler outlet temperature of 190 °C, flue gas oxygen content of 8.0 %, dry basis, condensation pressure of 70 mbar (line along P1).

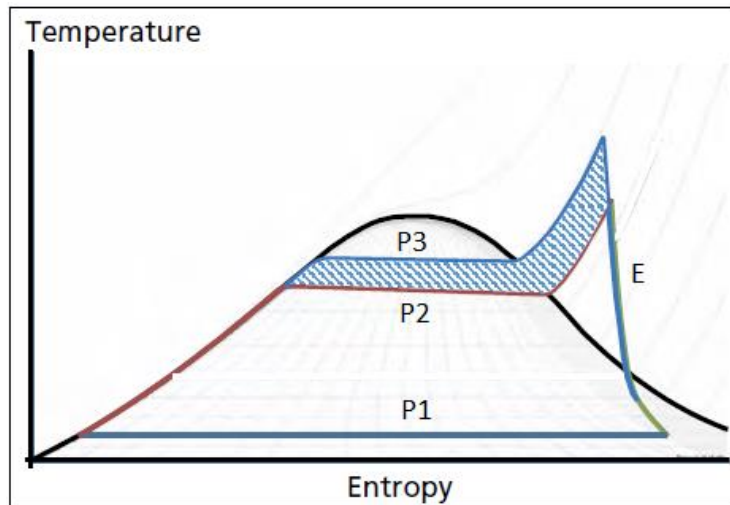


Figure 15 : A T-s diagram showing reference plant and optimized steam condition

The line along P2(or the area underneath) stands for the heat transferred from the flue gas to the water and/or steam. The line along P1 at the bottom designates the energy losses to the atmosphere on condensation of the exhaust steam in the air condenser at a low temperature level. The line along E in turn describes the mechanical energy recovered through steam expansion in

the turbine for electricity generation. Energy efficiency improvements are identified, inter alia, by a larger bounded area.

Higher steam parameters, i.e. increasing the live steam temperature and pressure, translate into improved efficiency. The line along P3 represents the thermodynamic cycle with the higher steam parameters. The efficiency improvement is proportional to the larger area bounded by the curve. Live steam parameters up to temperatures of approximately 520 °C and pressures of up to approximately one hundred bar are technically feasible in WTE plants[59]. This would translate into a twenty percent increase in power production compared to the standard process. The main limiting factor for higher steam parameters is the corrosion risk imposed by corrosive components present in the combustion gases. Corrosion problems increase disproportionately with rising live steam temperatures. For this reason, special measures are needed to protect the heating surfaces located in the high-temperature zone. Protection of the heating surfaces is provided in the form of ceramic lining or overlay-welded metallic coatings with elevated nickel and chromium contents[59]. The implementation of higher steam parameters requires a careful tradeoff between higher profit due to improved efficiency and the cost of the additional protective measures including increased maintenance requirements. Where steam at high temperatures is required – which is frequently the case at power plant and industrial sites – and the corrosion risk is to be kept at bay, the use of an external superheater may be a viable option. Using external superheaters, live steam temperatures of 530 °C and higher can be achieved[59]. Higher live steam temperature is attained by the input of external energy (shaded area in Figure 15). The external superheater can be installed in the immediate vicinity of the boiler in such a way that the flue gases from the additional firing system are directly led to the boiler after having passed through the superheater, united with the main flue gas stream and routed to the stack via the flue gas cleaning system.

2.8.2 OPTIMIZATION WITH STEAM REHEAT CONFIGURATION

Where high electrical generation efficiencies are the objective, steam reheating as known from thermal power plants is an interesting alternative. With the steam reheat configuration, the live steam is returned to the boiler after partial expansion through the first turbine stage and once

again heated to live steam temperature by heat exchange with the hot flue gases. The reheat steam is then led to the second turbine stage followed by condensation in the air condenser [59].

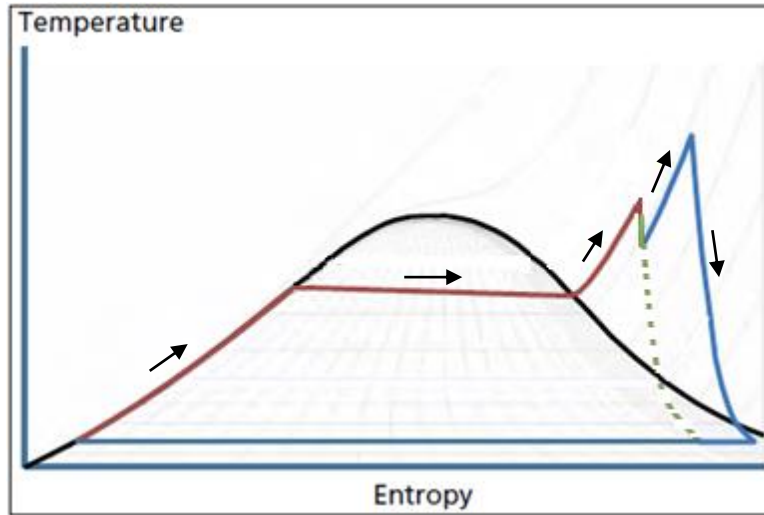


Figure 16 : Plant with reheat configuration and higher steam parameters [59]

The process is depicted in Figure 16 and relates to the conditions at a realized plant. Steam reheating makes it necessary to install heating surfaces in the high-temperature zone. At the same time, the high live steam pressure results in a correspondingly high temperature of the evaporator heating surfaces. In either case it is necessary to provide both the evaporator waterwalls and the superheater heating surfaces with effective corrosion protection by coating heat transfer surfaces with ceramics and Inconel materials.

2.8.3 OPTIMIZATION WITH FEED WATER AND COMBUSTION AIR PREHEATING

The feedwater can be preheated with steam extracted from the turbine. The resulting energy savings for feedwater heating translate into an increased live steam rate and ultimately into improved electrical generation efficiency. In WTE plants, it is common practice to preheat the condensate returned to the feedwater tank. However, for the energy optimization of a plant, it makes sense to also include the preheating stage downstream of the feedwater tank – more precisely downstream of the feed water pumps [59].

Primary air preheating is also used for waste with calorific values of less than about ten MJ /Kg in order to improve the ignition and combustion behavior of the fuel. At the same time, the energy input associated with primary air preheating increases the live steam rate going to the turbine. Preferably, low-pressure steam should be used as a heating medium for primary air preheating as it has already given off part of its energy content in the turbine. Figure 17 shows arrangement of preheating combustion air and feed water [59].

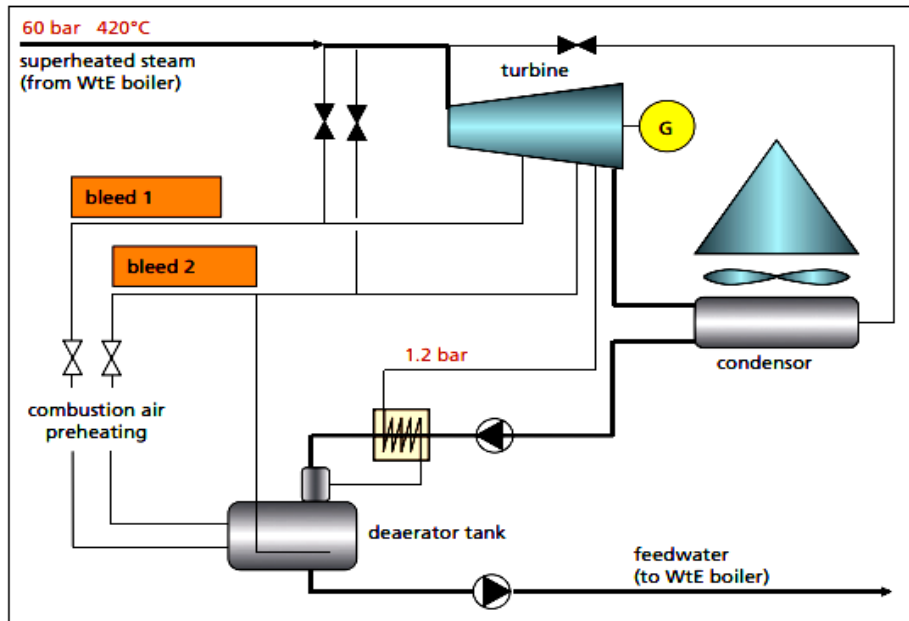


Figure 17 : Typical WtE Rankine cycle as used for steam cycle [59]

2.8.4 OPTIMIZATION WITH DISTRICT HEAT GENERATION

The heat loss by condensation can be minimized or avoided altogether if there is a demand for district heat. With such a combined heat and power concept, i.e. the cogeneration of electricity and heat, the turbine exhaust is condensed at a higher temperature level than would be the case with exclusive power production. The condensate obtained at a higher temperature level gives off its heat content to a district heating system that supplies adjacent residential buildings or industrial plants with heating and process energy. However, the plant must be located in the vicinity of heat consumers, on the other, there should be a year-round demand for district heat. This is frequently the case in the Scandinavian countries with a low average annual temperature. This is why this type of plant is frequently encountered in these countries [59].

2.8.5 REDUCTION OF THE FLUE GAS O₂ CONTENT AT THE BOILER OUTLET

WTE plants currently in operation are typically operated with a flue gas O₂ content of about eight percent (STP, dry) corresponding to an excess air factor of approximately 1.6. The flue gas oxygen content is controlled via the combustion air rate. When treating low-calorific waste, the O₂ reduction potential is limited because of the need for sufficient primary air to dry and burn the waste. Above calorific values of about 9 MJ/kg, such limitations no longer play a role.

Energy losses due to flue gas decrease with decreasing flue gas O₂ content due to the lower combustion air rate. Care must however be taken to ensure that lowering the flue gas oxygen content and the associated reduction of the combustion air rate does not compromise the air-flue gas mixing conditions in the area of the secondary air ports. Here, suitable measures are needed. Frequently, flue gas recirculation is used to improve mixing and control the flue gas temperature in the radiation pass [59].

2.8.6 FLUE GAS CONDENSATION

When using a wet flue gas cleaning system, the flue gas exiting the system has high latent energy content in the form of condensable water vapor. The share of the latent energy accounts for approximately fifty percent of the total flue gas energy content. This energy can be recovered by condensation [59]. This presupposes, however, a suitable infrastructure preferably with a district heating grid operated year-round and with return flow temperatures in the range of 40 °C to 60 °C as needed for condensation. Systems available for recovering the heat of condensation from the flue gas include direct-contact condensers where the flue gas is directly contacted with the process water or systems consisting of one or several heat exchangers [59]. The use of a condenser scrubber arranged downstream of the actual flue gas cleaning system is also possible; Figure 18.

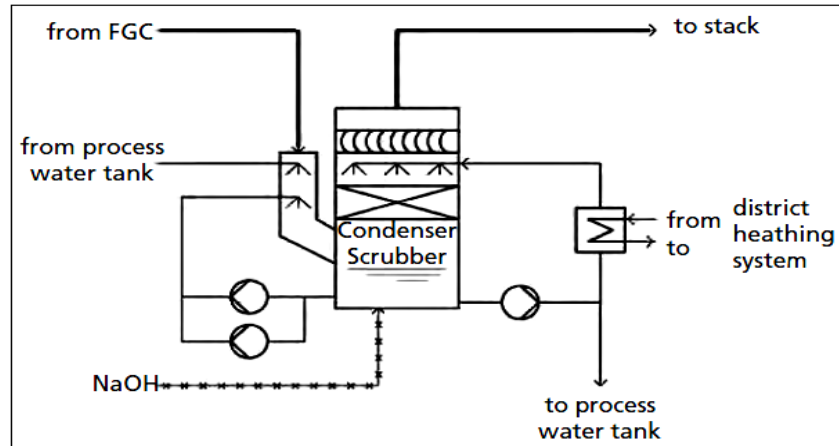


Figure 18 : Schematic of a Condenser scrubber [59]

The condenser scrubber is composed of two stages. In the first stage, the flue gas is quenched to saturation temperature by means of process water re-circulated through the condenser. The process water is then cooled in heat exchange with the return flow from the district heating grid and enters the second stage where it trickles through the scrubber packing in countercurrent with the flue gas. In the process, the moisture contained in the flue gas condenses and collects in the scrubber sump. As condensation occurs by direct contact, the return temperature of the district heating grid is the sole factor determining the water vapor condensation rate of the condenser scrubber. The latter increases with decreasing return temperature. Figure 19 shows the amount of heat transferred to the district heating grid as a function of the flue gas temperature downstream of the condenser scrubber.

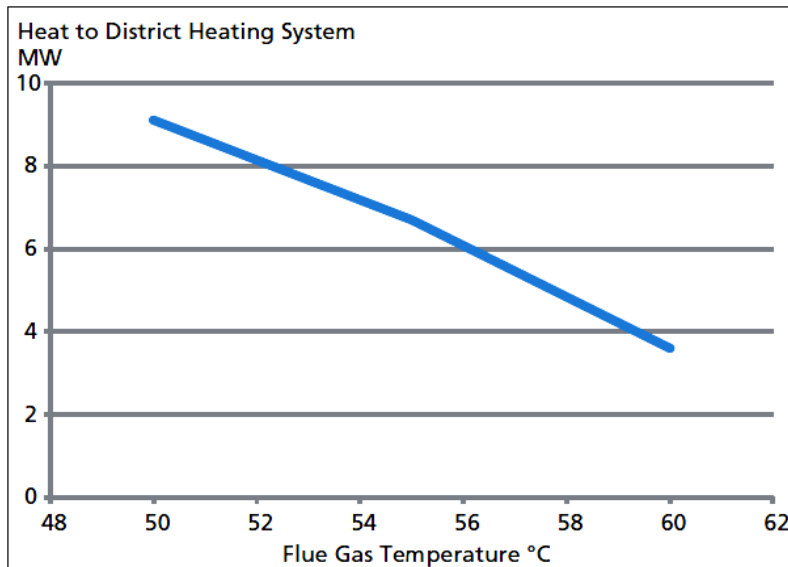


Figure 19 : Heat recovery through flue gas condensation [59]

2.8.7 OPTIMIZATION WITH COMBINED WET AND DRY COOLING SYSTEM

As is well known, heat rejection in the condensing system of a steam cycle based power plant is almost twice the generated electric power [71]. Since energy flows in power plants are typically high, small improvements to the cooling system can lead to large fuel savings and consequently efficiency enhancement. As a consequence a proper optimization of condensing system operation could lead to significant gain in net power production and electric efficiency. Options available for the condensing unit are [72]:

- a. once through cooling, i.e. cooling water that is discharged back to the source of water,
- b. a wet cooling tower that provides evaporative cooling,
- c. an air cooled condenser (dry cooling) or a hybrid wet and dry cooling system.

The first type of condenser withdraws water from the source at a very great rate and returns it to the source, but at an elevated temperature. It is the simplest system and has the least initial costs. The wet cooling tower requires much less cooling water withdrawal from the source since the withdrawal rate is replacement for only the water evaporation into the atmosphere [71]. The air cooled condenser eliminates the need for water use for cooling at the expense of a reduction in plant output and efficiency in hot weather. Hybrid wet and dry cooling systems allow plants to

save water with respect to a wet cooling tower, while avoiding the performance penalty of completely dry cooling systems [72]. The hybrid cooling system consists of an air cooled condenser and an evaporative cooling tower coupled with a water cooled condenser. The key point is to handle the cooling load between the air condenser and the cooling tower in an efficient way. This calls for an optimization of the condensing system operation. Net power gain from an optimization is shown in the following Figure 20.

Operating conditions ($T_{in} = 450\text{ }^{\circ}\text{C}$, $T_{DH} = 55\text{ }^{\circ}\text{C}$)	Optimal operation	Non-optimal operation	Optimal operation	Non-optimal operation
Steam flow rate at turbine inlet (m_{in})	480 (t/h)		120 (t/h)	
DH water flow rate (m_{DH})	4500 (t/h)		140 (t/h)	
Ambient temperature (T_{amb})	15 ($^{\circ}\text{C}$)			
AC fan load (I_{AC})	0.4	1	0.4	1
CT fan load (I_{CT})	0.7	1	0.8	1
Cooling water flow rate (m_{CW})	1500 (kg/s)	6500 (kg/s)	1500 (kg/s)	6500 (kg/s)
Net power (P_{elN})	103.3 (MW)	100.2 (MW)	23.6 (MW)	20.8 (MW)
DH : District Heating CT : Cooling Tower AC : Air cooled Condenser el : electric				

Figure 20 : Net power gain from optimization of Wet and Dry Cooling System [72]

3. METHODOLOGY

In this section, the procedural steps or methods for energy recovery from waste and optimization of WTE plant is discussed. First, waste is collected and characterized; second typical WTE plant is modeled and assumptions set. Then the model and assumptions are inserted in the software Thermoflex for simulation. Finally sensitivity analysis is carried out with selected parameter conditions. The basic principles of the software together with the main inputs and the basic assumptions are explained in intermediate sections.

3.1 GENERAL METHODOLOGY

For the sake of analyzing the performance of the WTE plant specific to Addis Ababa municipal solid waste condition, wastes were collected by their type and mixed proportionally. The mixed waste further characterized by determining its Proximate, Ultimate, and Lower heating value

analysis. Elaborated model of the plant has been carried out using a Thermoflex® software. Basic performance parameters: mass flow rate, energy input or output, temperature and pressure at the inlet and exit of each component or subsystem have been calculated. The software allow in calculating the power output of the whole plant and each component that comprises the system. It is important to note that the model considers all the factors that affect the energy performance of Waste-to-Energy plants, such as operating site conditions, heat transfer, combustion process, heat losses, losses due to unburnt carbon both in the bottom and fly ash, pressure drop in each component, etc.

The model has been calibrated to account the entire chemical and physical processes that take place in the real plant. Several data have been collected from literatures, before performing the simulation. Even though the data that are available are usually not complete or scarce, the codes reasonably predicts the performances of each components and the overall system by using few input parameters and based on built-in correlations and models. However, a lot of sensitivity analysis has been performed for the main operating parameters to understand their effects on performance of the whole plant. Based on these few parameters the model is calibrated to reproduce the energy performance of the state-of-the-art and highly efficient Waste-to-Energy plants. This is very important to compare the results of the proposed configuration with the-state-of-the-art technologies when they work under the same operating conditions. The model has been validated with data tabulated in Table 7, and the capability of the software has been thoroughly validated before simulation commencement.

3.2 WASTE COLLECTION AND SAMPLE PREPARATION

For this Thesis municipal solid waste is collected manually with the help of five people. The collection places are from nearby shops, condominium houses, market place, streets, etc. in Arada sub city, in the locality of “Aware”. Eight labeled bags were prepared for sorting wastes by type during collection as shown in Figure 21. After collection the wastes are dried to avoid decay and bad smells and then each finely shredded for a better homogenized mixing of waste components. The wastes then mixed proportionally according to available study (Yitayal Beyene, 2005). Figure 22 shows shredded waste components and Figure 23 shows mixed waste labeled sample.



Figure 21 : Sorted and labeled `municipal waste



Figure 22 : Shredded waste components



Figure 23 : Mixed and labeled municipal waste

3.3 WASTE CHARACTERIZATION

Waste characterization is a method used to determine the types of materials being discarded in a waste stream and in what proportion. Characterization further answers other information like moisture and ash content, fixed carbon and volatile matter present in waste, and elemental composition of the waste. This can help policy makers and city planners reduce landfill waste, set up waste management programs, and conserve money and resources. In fact, a waste characterization study typically precedes waste diversion studies and strategies.

The mixed waste sample shown in Figure 23 was given to Ethiopian Geological survey Laboratory for the determination of heating value and proximate analysis determination. Part of

this sample is given to Addis Ababa University; Chemistry Department for ultimate analysis. The test results are shown in the following tables.

Table 8 : Test result of proximate analysis

Sample code	Lab no.	Moisture %	Volatile matter %	Fixed carbon %	Ash %	Calorific value cal/gm	Sulfur %
W2009	7331/16	7.82	71.85	12.57	7.76	4062.75	0.13
W2009	7331/16dup	7.96	71.68	12.59	7.77	4023.58	0.15

Table 9 : Test result of ultimate analysis

Sample code	N(%)	C(%)	H(%)	S(%)
Waste 1	2.019	44.182	6.475	0.266
Waste 1a	2.098	45.524	6.788	-

When this laboratory analysis result compared with studies “Stefano Consonni, Federico Viganò 2011”, “Yitayalbeyene 2005”, “Samuel ShimelisTeka 2006”, and generalized municipal solid waste character data from “Tchobanoglous et al. 1993”, the result suggest that many as received waste samples has to be analyzed. But as the cost for lab analysis is unbearable, Addis Ababa municipal solid waste character is estimated as depicted in Table 10, due considering all above studies.

Table 10 : Generalized Addis Ababa City waste character data

Combustible Component of MSW	% H ₂ O	% by weight	weighted LHV (MJ / Kg)	% weighted VM	% weighted A
Paper, Card board	22	6.8	0.77	3.82	0.53
Wood	22	1.51	0.21	0.70	0.02
Plastic	14	6.75	2.07	10.69	0.44
Glass and inert materials	1	0.604	0.00	-0.47	0.58

Metals	1	0.662	0.00	-0.47	0.64
Food waste	40	59.17	3.00	18.66	3.66
Garden trimmings	75	12.02	0.33	2.49	0.05
Organic fines	59	1.56	0.09	0.12	0.10
Inert fines	30	9.13	(0.07)	-0.48	6.39
Textiles	14	1.61	0.26	0.92	0.07
Rubber, leather	32.5	0.183	0.02	-0.38	0.04
Aggregate	39.41		6.67	35.59	12.52

The high proportion of food wastes by weight in solid wastes may affect the effort of recycling. This mixed, heterogeneous character of solid waste is a major factor in the failure of recycling efforts aimed at recovering valuable materials from the solid waste refuse (Pavoni, 1975). In addition to the expenditure of labor and money involved in separating desirable material from the remainder of the waste stream, other factors such as higher transportation of costs for recycled waste materials (relative to virgin materials composed of the same substances), a general lack of acceptance of recycled materials and the consequent lack of markets for those materials are also of the causes of recycling efforts failure. Recyclable materials such as metals (0.66 %), glasses (0.6 %), paper (5.0 %), cardboard (1.79 %), plastics (5.75 %), textiles (1.6 %) and rubber (0.02 %) take 36.5 % of the total solid wastes, Yitayalbeyene (2005).

The test result in Table 8 and Table 9 therefore further compared with data in Table 10 and the following base data for this Thesis consumption is estimated.

Table 11 : Estimated Waste Character Data

	C	H	O	N	S	FC	VM	A	H₂O	LHV (MJ/Kg)
RWCD	18.93	3.61	24.69	0.76	0.07	12.48	35.59	12.52	39.41	6.67

3.3.1 ESTIMATION OF PROXIMATE ANALYSIS

Thermo-chemical behavior of above discussed waste such as moisture content, ash content, volatile matter and fixed carbon were determined by standard procedures. The moisture content is determined by the loss in weight that occurs when a sample is dried in a laboratory oven at 105 °C for 1 hour. The volatile matter has been determined by involving measurement of weight loss following combustion of about 1g waste in a furnace at 950°C for 6 min. To determine the ash content, the char samples were further heated in a laboratory ash furnace at 750 °C for at least 3 hours. The results of the estimated proximate analyses of the waste are shown in Table 11.

3.3.2 ESTIMATION OF ULTIMATE ANALYSIS

Estimated elemental or ultimate analysis of the waste sample is shown in Table 11. The chemical elements, such as carbon, hydrogen, oxygen, nitrogen and Sulfur, that constitute the waste is determined by using ultimate analyzer. However, for this study, the result of ultimate analyzer is further compared with literatures and adjusted to acceptable values.

3.3.3 ESTIMATION OF LOWER HEATING VALUE

The sample is weighted and placed in a digital Bomb calorimeter for lower heating value determination. The digital Bomb calorimeter is then sealed and the waste sample is ignited electrically. The complete combustion of the waste releases heat and it is measured through the temperature change, which is measured by using a digital sensor, of the water bath surrounding the bomb calorimeter. The heat of combustion can be calculated from the resulting rise in temperature. The same step is re-repeated for accurately determining heating value. The adjusted test result shows that the lower heating value is 6.67 MJ/kg as indicated in Table 11.

3.4 THERMODYNAMIC MODELLING OF A WASTE TO ENERGY PLANT

The thermodynamic model of WTE plant considered in this thesis aim to discuss major plant components working principle and mathematical model used for the analysis. The major plant components include heat exchangers, evaporator, super heater, economizer, turbine, and pumps.

3.4.1 PLANT LAYOUT

Mass burn WTE plants that consume solid waste less than 100,000 ton/year are grouped as Small Scale Waste to Energy Plants [61]. The plant layout in this study is for a mass-burn incinerator with energy recovery at small scale for the sole production of electricity consuming 6.12 ton/hr or 32, 313 ton/year of waste, which corresponds to approximately 11.33 MW of thermal input, is combusted over combustion line with a Rankine cycle. The steam turbine expected to generate approximately 2 - 3 MW of net electric power. In order to preheat the primary and secondary combustion air, steam is extracted from the steam cycle at a pressure of 1.3 and 0.8 bar. Part of steam extracted at 1.3bar and 0.8bar is used for de-aerator and to preheat the feed water heater respectively. The superheated steam, which enters into the steam cycle, is assumed to enter at a pressure of 40 bar/ 400°C. The exhaust steam from the Rankine cycle is condensed by using water cooled condenser with a nominal condensation pressure of 0.07 bar. The flue gases leaving the boiler shouldnot to exceed exit temperature of 180°C and enter in to a flue gas treatment system that includes Electrostatic Precipitator (ESP), Selective Catalytic Reactor (SCR),and Fabric Filter. In order to control the NO_x, Selective Catalytic Reduction (SCR) system is used with the injection of Ammonia in the flue gas. The reducing reagent, ammonia or urea, selectively reacts with nitrogen oxides that exist in the flue gas at high temperature and converts into harmless molecular nitrogen and water vapour without using a catalyst. Part of flue gas exiting EPS is recirculated to Furnace for reduction of excess air at secondary port. Water cooled grate is used for reduction of excess air at primary port. In the last part of the flue gas treatment system line, a small portion of heat is recovered for condensate and feed-water preheating. This final heat exchanger is also used to maintain the stack temperature at 135 °C. The plant process flow is indicated in Figure 24.

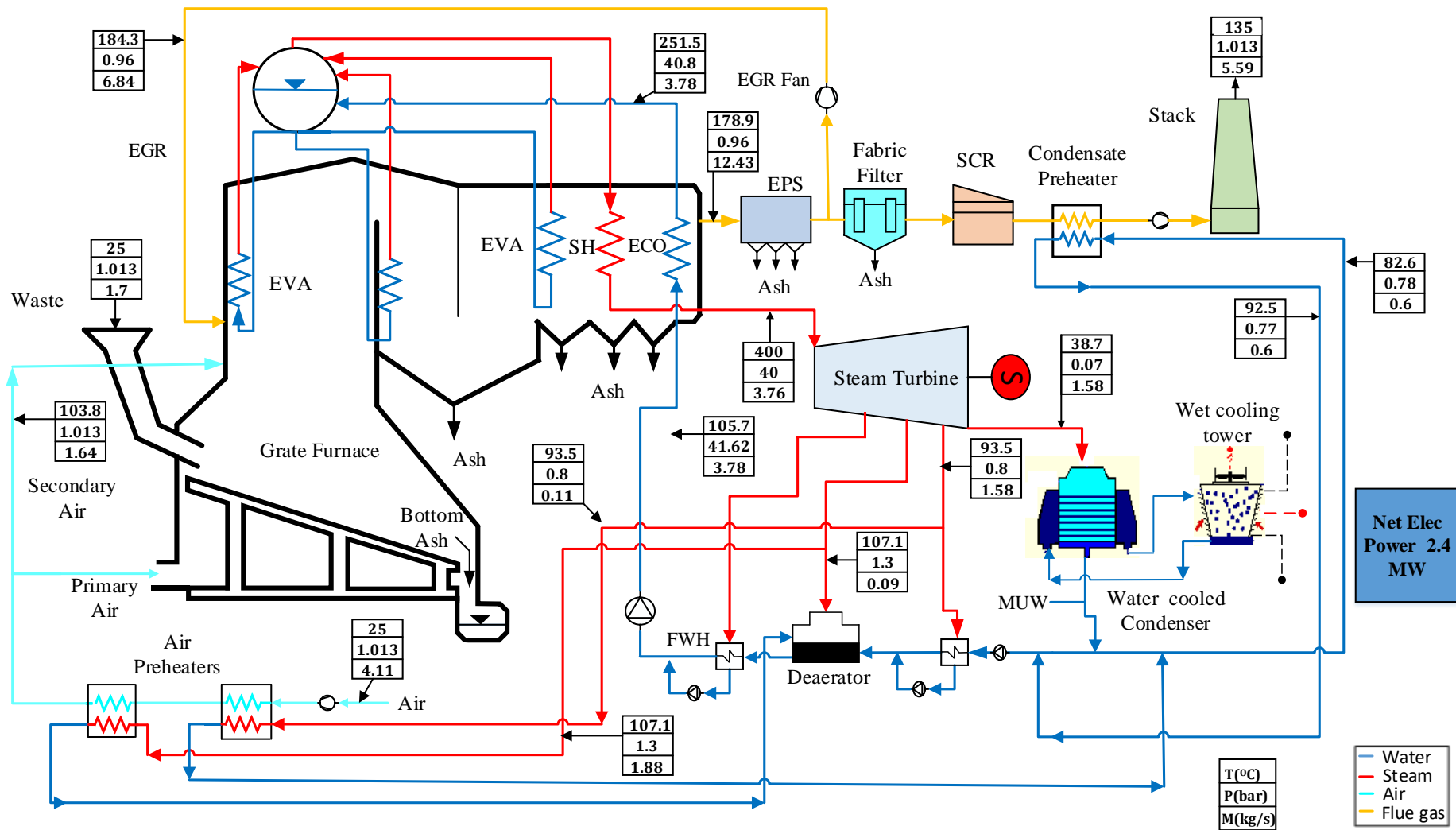


Figure 24 : Schematic representation of SSWTE plant modeled in Visio

3.4.2 ASSUMPTIONS FOR MODEL PLANT SIMULATION

All SSWTE plants in this study will operate for 330 days per annum, two shifts per day (16hr).

Table 12 : Main assumptions adopted for plant simulations

Reference conditions for model plant	
Ambient temperature (°C)	15
Ambient pressure (bar)	1.01325
Relative humidity (%)	60
Plant	
Treated waste (t/y)	32, 313.60
Equivalent working hour (h/y)	5,280
Waste flow rate (kg/s)	1.7
Rated thermal input, MW _{LHV}	11.33
Combustor	
Primary air preheating temperature(°C)	60
Secondary air preheating temperature(°C)	150
Thermal losses, % LHV	1
O ₂ at boiler exit, % Vol. dry	6.0
Losses of unburnt carbon, % LHV	1.65
Ratio of supplied excess air	1.45
Boiler	
Flue gas temp. at boiler exit (°C)	180
Steam production (kg/s)	--

Thermal losses, % of exchanged power	1.0
Steam cycle	
Steam Temperature (°C) at the turbine inlet	400
Steam pressure (bar) at the turbine inlet	40
De-aerator pressure (bar)	1.3
Steam bleeding for primary and secondary air preheating (bar)	1.3 and 0.8
Condensation pressure (bar)	0.07
O ₂ at Stack, % vd	6.0
Flue gas re-circulated (% mass)	20
Stack temperature (°C)	135

3.4.3 THERMODYNAMIC MODELS

Here mathematical model of particular elements of the model plant: heat exchanger, steam turbine, condenser and a circulation pump is discussed. Assumed is internal irreversibility in the turbine and pump.

Heat exchangers

It is assumed that the heat exchangers are well-insulated so that all the heat transfer is between the flue gas and the water. In keeping with overall assumptions, it is also assumed that the flow is steady, and that the differences in entering and leaving potential energy and kinetic energy are negligible. The balance of rates of heat transferred in the heat exchanger (including the de-aerator) can be written in the form

$$\dot{Q}_{in} - \dot{Q}_{out} = \dot{Q}_{loss} \quad (1)$$

Where \dot{Q}_{in} - rate of heat supplied to a fluid. \dot{Q}_{out} -rate of heat received from a fluid. \dot{Q}_{loss} - rate of heat lost to surroundings. For the case of the open-feedwater heat exchanger the following equation can be applied.

$$\dot{m}_s h_s + \dot{m}_{con} h_{con} + \dot{m}_w h_i = \dot{Q}_{loss} + (\dot{m}_{con} + \dot{m}_s) h_m + \dot{m}_w h_o \quad (2)$$

Where: \dot{m}_{con} – mass flow rate of condensate, h_s – steam enthalpy, h_{con} – condensate enthalpy, h_m – enthalpy of the condensate-steam mixture, h_i – water enthalpy at inlet to heat exchanger, h_o – water enthalpy at outlet from heat exchanger. Therefore the efficiency of the feedwater heat exchanger can be expressed by,

$$\eta_{HE} = \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = \frac{\dot{m}_w (h_o - h_i)}{\dot{m}_s (h_s - h_m) + \dot{m}_{con} (h_{con} - h_m)} \quad (3)$$

The heat transfer \dot{Q} is expressed as

$$\dot{Q} = U \times A \times LMTD = \frac{LMTD}{\frac{1}{U \times A}} = \frac{\frac{\Delta T_{hot} - \Delta T_{cold}}{\ln\left(\frac{\Delta T_{hot}}{\Delta T_{cold}}\right)}}{R_t} \quad (4)$$

$$= \frac{\frac{\Delta T_{hot} - \Delta T_{cold}}{\ln\left(\frac{\Delta T_{hot}}{\Delta T_{cold}}\right)}}{\frac{1}{h_{con,in} \times A_{in}} + \frac{R_{fou,in}}{A_{in}} + \frac{\ln\left(\frac{D_{out}}{D_{in}}\right)}{A_{out}} + \frac{R_{fou,out}}{A_{out}} + \frac{1}{h_{con,out} \times A_{out}}}$$

Where U is the overall heat transfer coefficient, A is the heat transfer area that is constant, it is determined during on-design conditions and LMTD is the log mean temperature difference between hot and cold stream.

There are several ways to estimate the pressure drop (ΔP) for the flow of fluid in a heat exchanger. A reasonable estimate can be obtained by the relatively simple approach described below [58].

$$\Delta P_{shell} = \frac{2fG_s^2 D_s (N_B + 1)}{\rho D_e \left(\frac{\mu}{\mu_s}\right)^{0.14}} \quad (5)$$

In this equation, f is a Fanning friction factor for flow on the shell side, G_s is the mass velocity on the shell side, D_s is the inside diameter of the shell, N_B is the number of baffles, ρ is the density of the shell-side fluid, μ_s is the shell side viscosity, D_e and is an equivalent diameter.

The mass velocity $G_s = \frac{\dot{m}}{S_m}$, where \dot{m} is the mass flow rate of the fluid, and S_m is the crossflow area measured close to the central symmetry plane of the shell containing its axis. This area is defined as

$$Cross\ flow\ area = D_s L_B \frac{clearance}{pitch} \quad (6)$$

Where L_B is the baffle spacing

Calculation of the tube-side pressure drop is made by first estimating the (Darcy) friction factor $f_{corrected}$ for flow through the tubes from the value of the Reynolds number and the relative roughness, and applying the viscosity correction. Then, this friction factor is used to evaluate the pressure drop for flow through the tubes by

$$\Delta P_{tube} = f_{corrected} \frac{L}{D} \left(\frac{1}{2} \rho V^2\right) \cdot Number\ of\ tube\ passes \quad (7)$$

Where L , is the length of the tubes, D is the inside diameter of the tubes, ρ is the density of the tube-side fluid, and V is the average flow velocity through a single tube.

Steam turbine

Maximum generator output is directly affected by changes in the efficiencies of the various turbine sections and changes in the flow capacity of the first three or four stages of a turbine[73]. Changes in the flow capacity of following stages may indicate a physical change in the steam path and consequential effects on local steam path efficiency. A change in the flow capacity of the turbine or the flow capacity of a particular turbine stage is reflected in the stage pressure, temperature, and flow relationship. For all turbine stages except the first and last stage, the stage pressure ratios are essentially constant and the basic flow equation simplifies to[73]:

$$\dot{m} = K A C_q \sqrt{\frac{P}{v}} \quad (8)$$

Where: \dot{m} —mass flow rate, K - a constant, A —flow passage area of a stage, C_q - coefficient of discharge, P - inlet stage pressure, v -specific volume at stage inlet. Equation (8), can be written as

$$FF = K A C_q = \frac{\dot{m}}{\sqrt{\frac{P}{v}}} \quad (9)$$

Where FF , is the flow function. This equation states that the flow function ($\dot{m} / \sqrt{P/v}$) is related to the flow passage area of the stage A and the design and condition of the stage passage C_q . In more general terms, the flow function relates to the steam path condition. If a particular stage flow function has changed, then the downstream condition of the turbine steam path must have changed. This is a powerful diagnostic tool in identifying damage, deposits, erosion or other problems

which have affected a group of stages within the turbine steam path. When the effective flow area of a stage changes, the stage pressure ratio also changes.

The expansion process from state 1 to 2 in Figure 25, for the steam turbine stage can be characterized by the definition of internal turbine efficiency according to relation [74].

$$\eta_{i_T} = \frac{h_1 - h_2}{h_1 - h_{2s}} \quad (10)$$

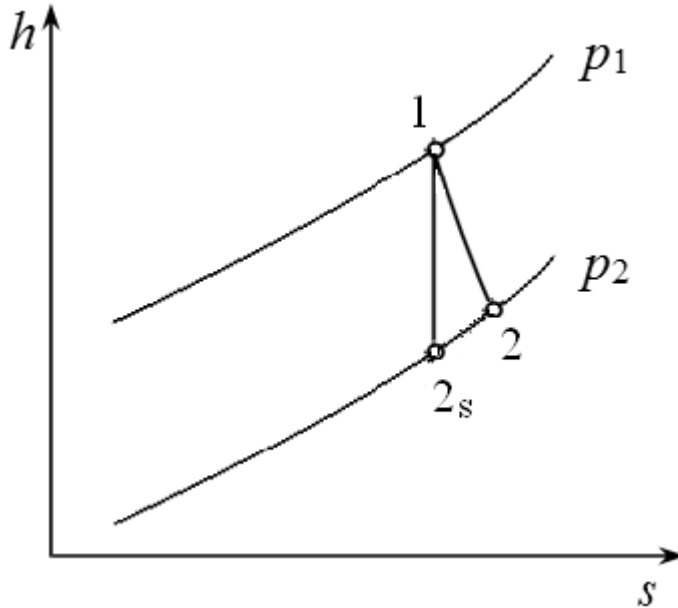


Figure 25 : steam expansion on enthalpy - entropy diagram

Where: h_1, h_2, h_{2s} - fluid enthalpy in states 1, 2, and 2s, The electric power, generated by a stage, N_{el_T} , is determined from the following relation

$$N_{el_T} = \eta_g \eta_{mT} \dot{m} (h_1 - h_2) \quad (11)$$

Gross electric power of the power unit has been determined on the basis of electric power produced by successive turbine stages, N_{el_T} which can be written as,

$$N_{el_gross} = \sum N_{el_T} \quad (12)$$

Efficiency for gross production of electricity has been defined as a ratio of electric power generated by the turbine, N_{el_gross} , to the rate of heat of chemical energy in the fuel which is described as [74],

$$\eta_{N_{el_gross}} = \frac{N_{el_gross}}{\dot{m}_{fuel} LHV} \quad (13)$$

Feed pump

The electric power consumed by the pump, N_{el_pump} , for increasing the working fluid pressure is determined using the pump internal efficiency η_{i_pump} , mechanical efficiency, η_{m_pump} , efficiency of conversion of electric energy into mechanical, η_{el_me} and pressure P_2 , which must be ensured by the pump. The liquid at the inlet to the pump has a given temperature, T_1 , pressure P_1 and mass flow rate \dot{m}_w . The process of pressure increase, referring enthalpy - entropy relations, in a real pumping from P_1 to P_2 , as compared to isentropic pumping, characterized by the pump internal efficiency defined as [74],

$$\eta_{i_pump} = \frac{h_{2s} - h_1}{h_2 - h_1} \quad (14)$$

Where: h_1 , h_2 , h_{2s} - enthalpy of fluid in real process (1 - 2) and isentropic process (1 - 2s).

The consumed electric power by the pump, N_{el_pump} , is determined from relation [74].

$$N_{el_pump} = \frac{\dot{m}_w(h_2 - h_1)}{\eta_{el_me} \eta_{m_pump}} \quad (15)$$

3.5 THERMOFLOW SOFTWARE

THERMOFLEX is a Thermoflow's fully flexible heat balance and engineering calculation program that allows to run both design calculation and off design simulation of a given model. It allows multi-run macros to explore trends and can also be used in conjunction with one of Thermoflow's application specific programs (GT PRO, GT MASTER, STEAM PRO, and STEAM MASTER), either by linking the THERMOFLEX model to the application specific model, or by directly loading the generated plant design in to THERMOFLEX for further editing (www.thermoflow.com). It is a modular program that is used to model and simulate all types of power plants such as gasifiers, Waste-to-Energy plants, Conventional steam cycles, Gas turbine, coal fired plants, repowering and other power plants both at design and off design conditions [75]. Thermoflow has also integrated a feature called PEACE[®] (Preliminary Engineering and Cost Estimation) which is a module integrated with a fully flexible mass/heat balance tool called Thermoflex[®]. PEACE[®] automatically generates a preliminary engineering specification, including dimensions, weights and materials as well as estimates for foundations and labor hours for installation and erection for all plant equipment based on the mass/heat balance simulation result. It is worthwhile to mention that PEACE[®] instructs to size the components and calculates the cost of thermal power plants. It can also dictate component sizes and allow the program to find the influence of the new sizes on the mass/heat balance and recalculates the costs of the overall plant. The main inputs to perform on design analysis comprises of the overall Waste-to-Energy plant configuration, the specific details about the equipment layout (number of feed water heaters, de-aerator, type of condenser and cooling tower etc.), thermodynamic constraints (maximum flue gas temperature at the inlet of super-heater, re-heater pressure etc.), equipment constraints (material choice, tubing details, etc.) and losses (pressure drop, heat losses, losses due to unburnt carbon in the ash etc.). Then, Thermoflex calculates compressively the mass/energy balance of each component and the overall energy performance of the system as well as it establishes the equipment size [75]. The following block diagrams shows the design mode steps employed by Thermoflex modeling, Figure 26 and Figure 27.

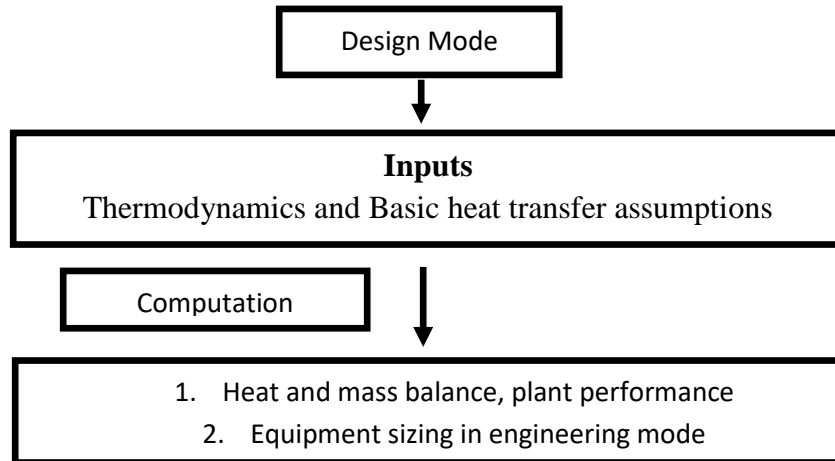
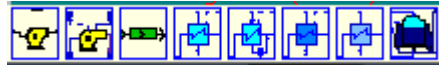


Figure 26 : Design mode steps employed by Thermoflex

Draw Small Scale Waste to Energy Plant Model



Check Model Drawing



Define/ Edit Inputs

- Edit Fuel source: Insert all waste character data (Table 11)
- Edit Turbine inputs: inlet steam pressure to 40bar, mechanical and isentropic efficiency 99.8% and 85% respectively
- Edit super heater inputs: super-heated steam temp 400°C
- Edit steam condensation pressure to 0.07bar
- Edit primary and secondary air heating temperature to 60°C and 150°C
- Set economizer exit flue gas temperature to 180°C
- Set flue gas to stack 135°C
- Edit Furnace inputs: set waste feed rate 1.7Kg/s, excess air ratio to 1.45, minor heat loss 1%, oxygen in flue gas 6%...
- Set recirculated flue gas to Furnace to 20%
- Set air and Fuel source temp and pressure to 25°C and 1.013bar
- Set steam extraction pressure for primary air heating at 1.3bar and 0.8bar
- Set steam extraction pressure for feed water heater at 10bar

Check Inputs



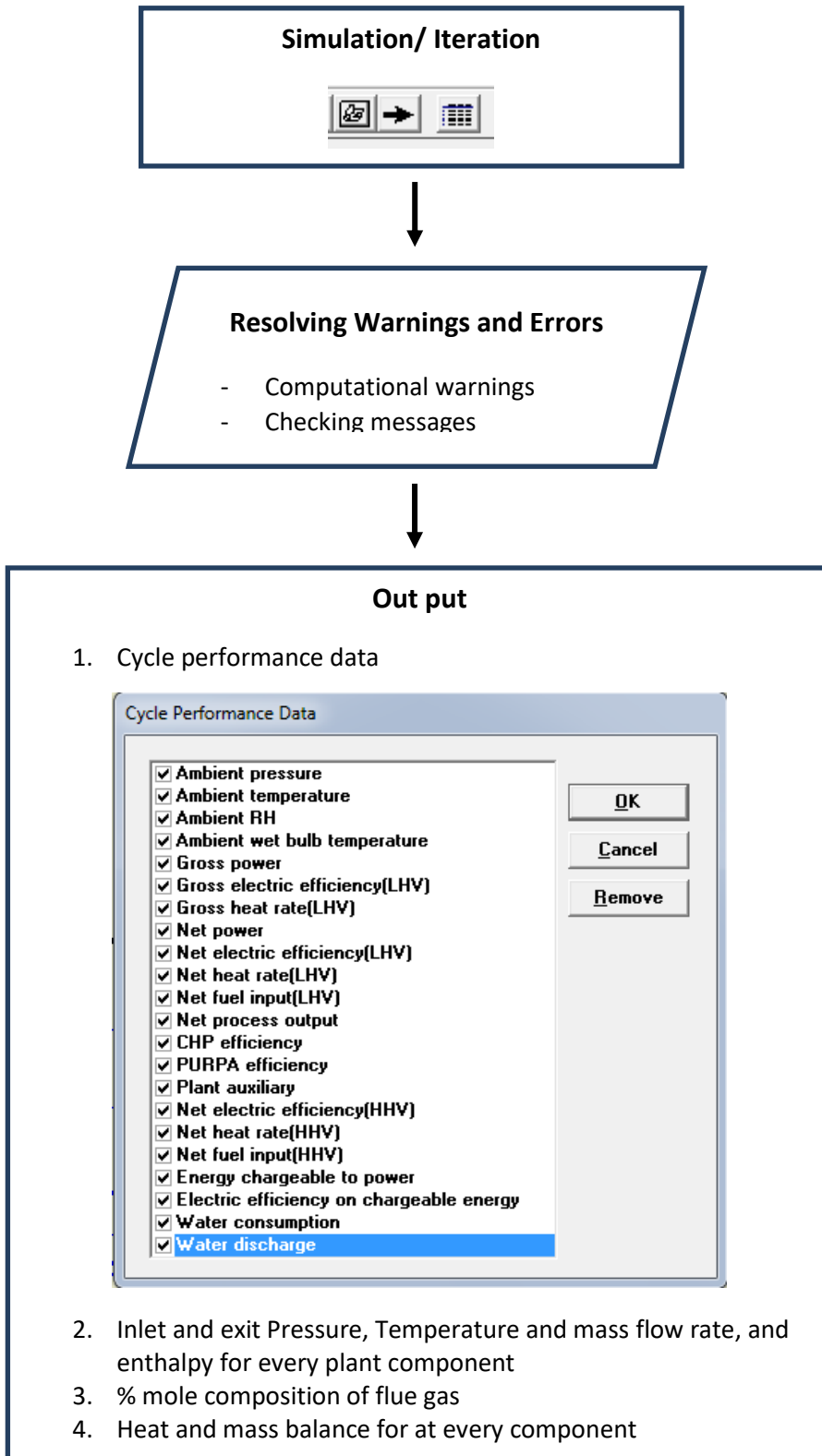


Figure 27 : Thermoflex model development and simulation steps

3.6 PLANT MODELING AND SIMULATION

For assessing the energy performance of the assumed small scale waste to energy plant, a detailed model of the plant has been performed by using a Thermoflex[®] (please see Figure 29 which is a screen print of model or a more elaborated same model under Figure 24). The waste character data in Table 11 is inserted in to the model, Figure 28. Assumption data from Table 12, were inserted in to the model. For example, excess air ratio, fuel flow rate, O₂ at boiler exit, etc inserted as shown in Figure 29. Emission is defined with Figure 30. In this way all assumption were inserted to the model.

The mass flow, temperature, and pressure at the inlet and exit of each component or subsystem have been calculated iteratively until boiler exit temperature and flue gas temperature to the stack becomes around 180⁰C and 135⁰C. Thus, the software calculated also the overall cycle performance indicators: gross and net electric power generated and efficiency, thermal input, electric power used for auxiliary, etc. It is important to note that while modeling in the software, all the factors that affects the energy performance of the WTE plant, such as heat transfer, heat losses, pressure drop in each component, emission reduction efficiency, and auxiliary power consumptions, etc has been considered. The model has been calibrated to account the entire physical processes that take place in the real waste to energy plant using operational data of actual existing small scale WTE plants. Even though some of the data that are available are usually not complete or scarce, the developed model reasonably predicts the performances of each components and the overall system by using few input parameters.

A lot of sensitivity analysis has been performed on the main operating parameters to understand their effects on performance of the whole plant. Thus, based on these few parameters the model is calibrated to reproduce the energy performance of the real plant performance of the plant. It is important to note that before modifying the system, the model is checked and validated with data from existing actual similar plants and the capability of the software has been thoroughly validated. Thus, combining the mass/energy balance results, the performance of the plant has been studied thoroughly.

Thermoflex[®] calculates auxiliary power consumptions of the components (Electrostatic Precipitator, Fans, pumps, Grate furnace, auxiliaries for flue gas treatment systems, etc.) and

other miscellaneous auxiliary consumptions for handling various solid streams, since it affect the net Electric power and net electric efficiency of the plant. Simulation System summary is indicated in Appendix II.

Sensitivity analysis is made for the production of net electric power, gross and net electric efficiency. The analysis is against fuel moisture content, ambient temperature, condenser pressure, fuel lower heating value, percent of excess air, and ash content. Figure 27 shows the model small waste to energy plant as per assumptions set under Table 12 and Figure 28 shows calculated pressure, temperature, mass flow rate and enthalpy at every stream number according to this model.

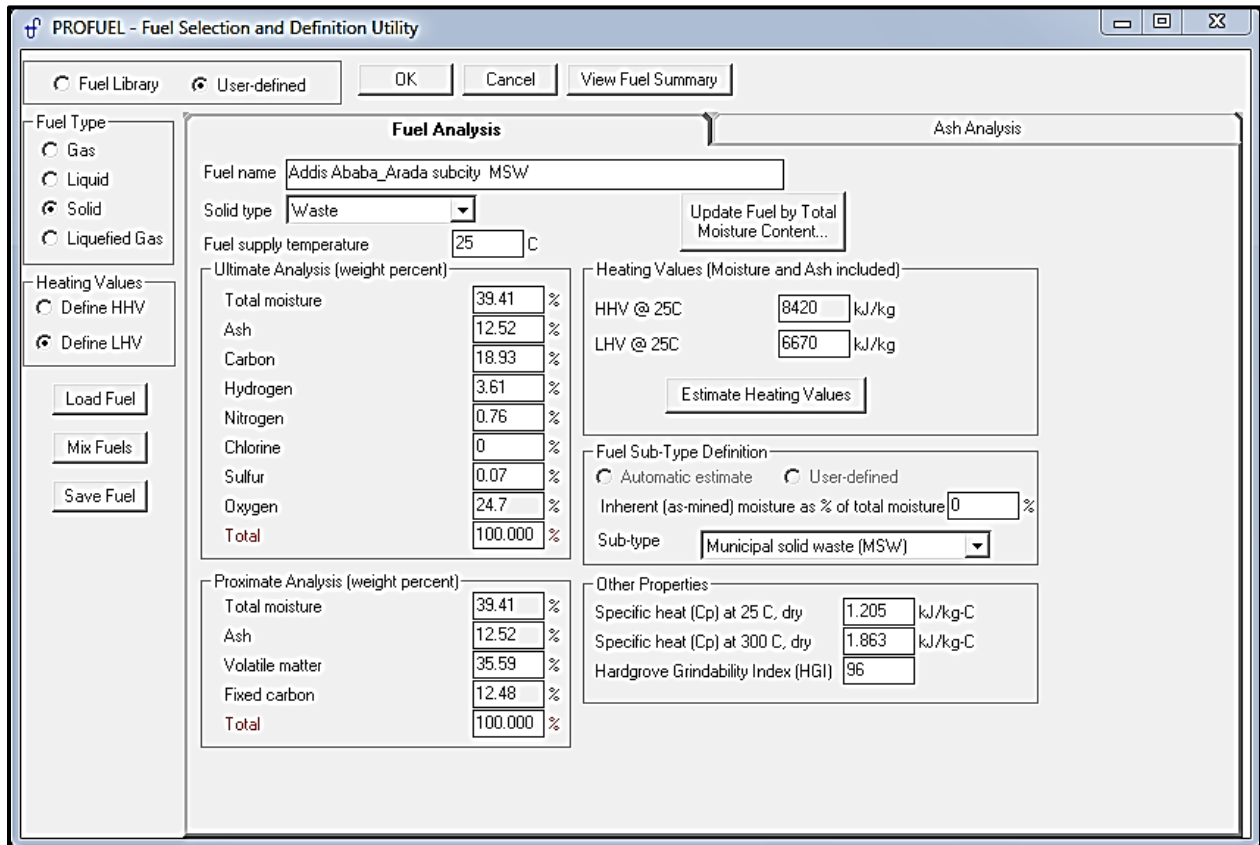


Figure 28 : Fuel Selection and Definition menu

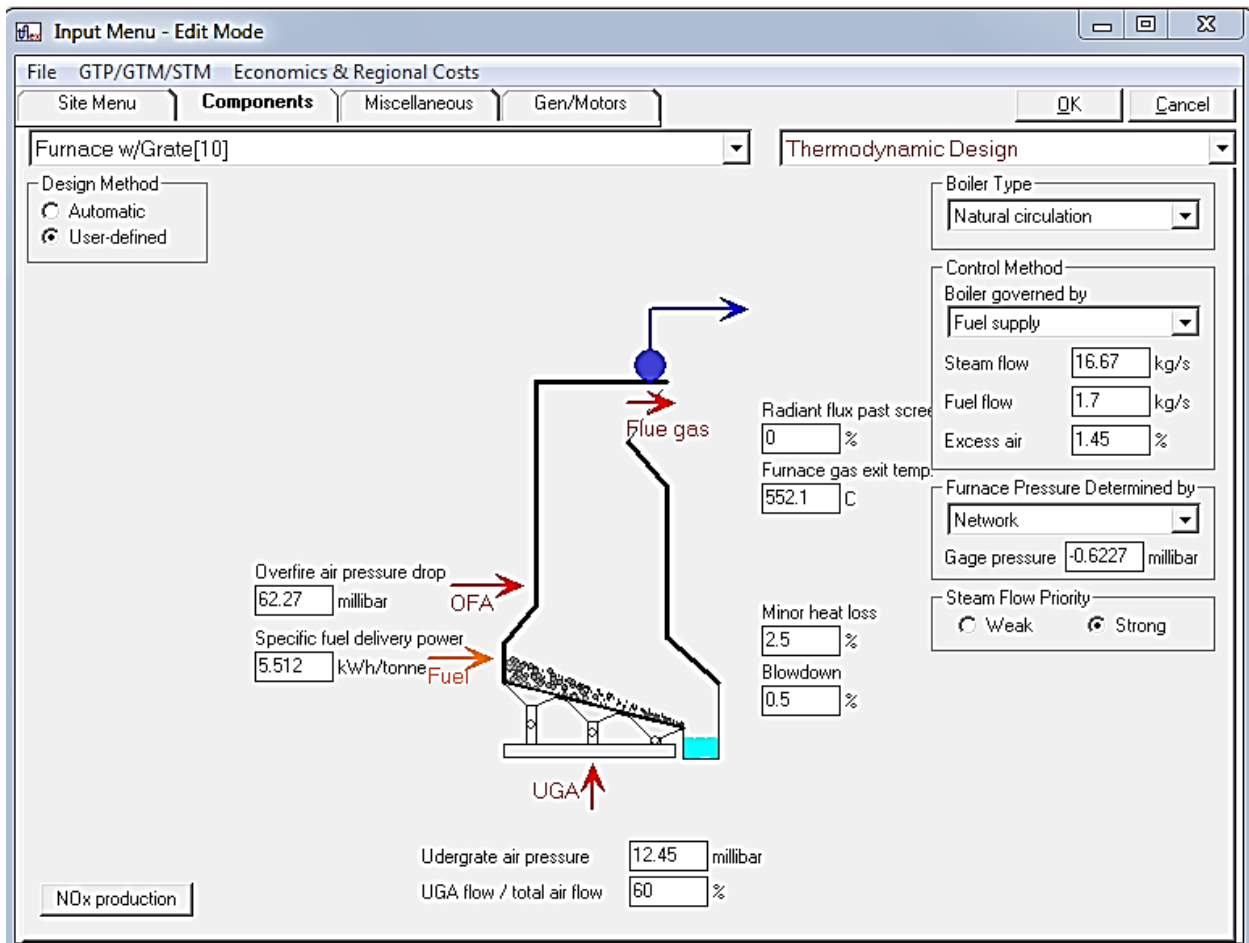


Figure 29 : Input menu for Furnace with grate

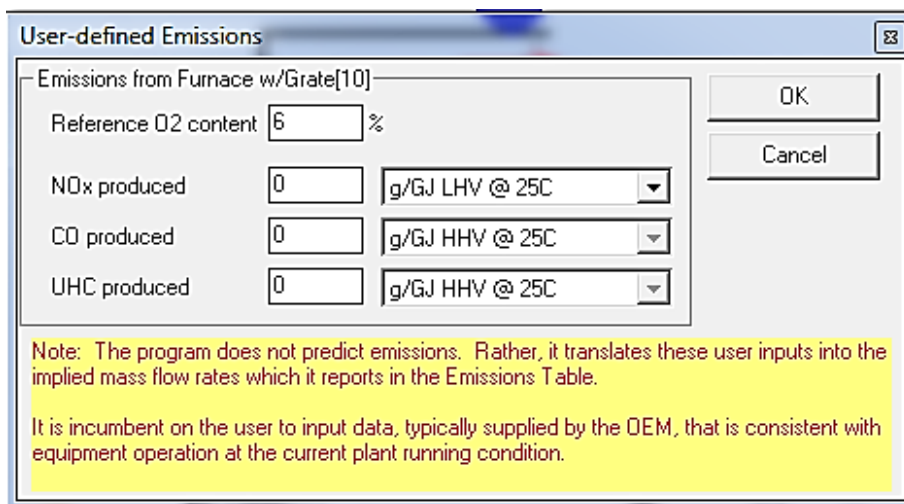


Figure 30 : Emission defining menu

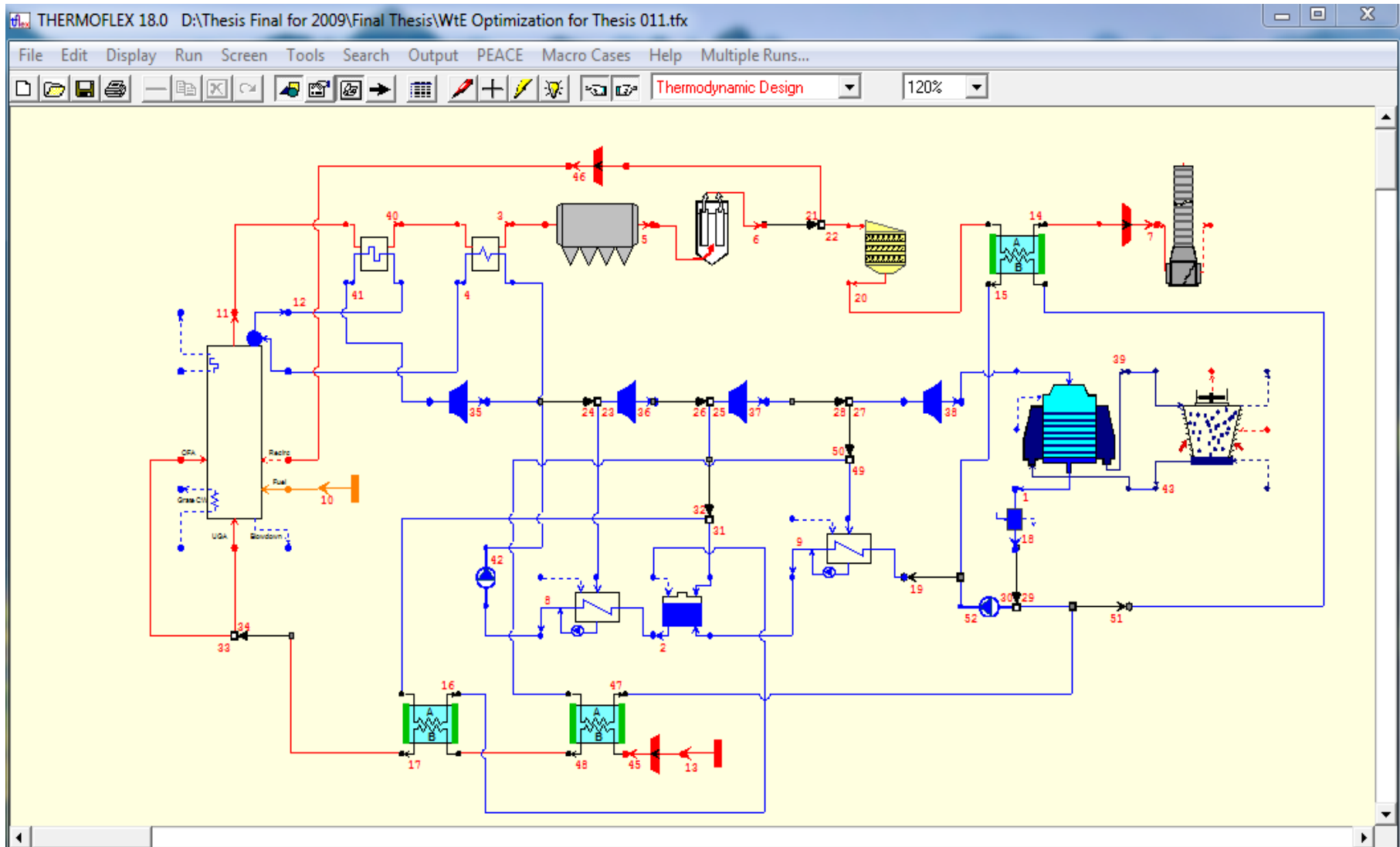


Figure 31 : WtE plant model developed in Thermoflex®

No.	Fluid	P [bar]	T [C]	M [kg/s]	H [kJ/kg]
1	Water	0.78	38.7	1.58	162.18
2	Water	1.69	104.8	3.78	439.42
3	Air/gas	0.96	178.9	12.43	
4	Water	40.80	251.5	3.78	1619.19
5	Air/gas	0.95	178.9	12.43	
6	Air/gas	0.93	178.9	12.43	
7	Air/gas	1.01	150.3	5.59	
8	Water	1.66	104.8	3.78	439.42
9	Water	0.75	88.3	3.51	369.94
10	Fuel	1.03	25.0	1.70	
11	Air/gas	0.96	552.1	12.43	
12	Water	40.80	251.5	3.76	2799.82
13	Air/gas	1.01	25.0	4.11	
14	Air/gas	0.90	135.0	5.59	
15	Water	0.77	92.5	0.60	838.41
16	Water	1.27	106.6	1.88	2499.43
17	Air/gas	1.03	103.8	4.11	
18	Water	0.78	26.6	3.21	111.69
19	Water	0.77	58.2	3.32	243.82
20	Air/gas	0.92	178.9	5.59	
21	Air/gas	0.93	178.9	6.84	
22	Air/gas	0.93	178.9	5.59	
23	Water	10.00	243.1	3.76	2927.28
24	Water	10.00	243.1	0.00	2927.28
25	Water	1.30	107.1	1.88	2598.06
26	Water	1.30	107.1	1.88	2598.06
27	Water	0.80	93.5	1.58	2534.40
28	Water	0.80	93.5	0.30	2534.40
29	Water	0.78	26.6	0.49	111.69
30	Water	0.78	26.6	2.72	111.69
31	Water	1.30	107.1	0.00	2598.06
32	Water	1.30	107.1	1.88	2598.06
33	Air/gas	1.03	103.8	1.64	
34	Air/gas	1.03	103.8	2.46	
35	Water	10.00	243.1	3.76	2927.28
36	Water	1.30	107.1	3.76	2598.06
37	Water	0.80	93.5	1.88	2534.40
38	Water	0.07	38.7	1.58	2266.31
39	Water	0.67	30.8	79.26	129.33
40	Air/gas	0.96	458.6	12.43	
41	Water	40.00	400.0	3.76	3215.51
42	Water	41.62	105.7	3.78	446.07
43	Water	1.01	20.8	79.26	87.49
45	Air/gas	1.07	30.5	4.11	
46	Air/gas	0.96	184.3	6.84	
47	Water	0.78	93.0	0.11	1400.08
48	Air/gas	1.05	60.0	4.11	
49	Water	0.80	93.5	0.19	2534.40
50	Water	0.80	93.5	0.11	2534.40
51	Water	0.78	82.6	0.60	345.95
52	Water	0.77	26.6	2.72	111.69

Figure 32 : Simulated stream data at every stream no.

4. RESULT AND DISCUSSION

In this section, the main results and discussions of the Master thesis is presented in a logical order. First, the simulation result has been validated using literature data, Table 7. After model validation, detail sensitivity analysis has been performed to see the effects of some of the main operating parameters on the performance of the plant. Finally different ways to improve the efficiency of Small Scale Waste-to-Energy plants has been suggested.

4.1 MODEL VALIDATION

Before simulating a SSWTE plant model, we must ask a simple question: is the model valid? If a model is not valid, then any results based on the model will be unreliable. Validation is concerned with determining whether the model is an accurate representation of the system under study. The conceptual model of a process is a formal definition of the system under consideration in logical or mathematical form, typically comprising the underlying theoretical equations. In this section, we will only focus on the validation of our models.

All the data set as assumptions under Table 12 and those actual small scale operational data in Table 7, were consolidated to be used as validation data, Table 13.

Table 13 : Model Validation data

	Case 1	Case 2	Case 3
Expected MW of electric power	4.2	2.5	2
Ambient temperature (°C)	15	15	15
Ambient pressure (bar)	1.01325	1.01325	1.01325
Relative humidity (%)	60	60	60
Plant			
Treated waste (t/y)	60, 000.00	43, 000.00	60, 000.00
Equivalent working hour (h/y)	5,280	5,280	5,280
Waste flow rate (kg/s)	3.16	2.26	3.16

Rated thermal input, MW_{LHV}	31.22	19.23	37.88
Combustor			
Primary air preheating temperature	60	60	60
Secondary air preheating temperature	150	150	150
Thermal losses, % LHV	1	1	1
O ₂ at boiler exit, % Vol. dry	6.0	6.0	6.0
Losses of unburnt carbon, % LHV	1.65	1.65	1.65
Ratio of supplied excess air	1.45	1.45	1.45
Boiler			
Flue gas temp. at boiler exit (°C)	180	180	180
Steam production (kg/s)	--	--	--
Thermal losses, % of exchanged power	1.0	1.0	1.0
Steam cycle			
Steam Temperature (°C) at the turbine inlet	390	355	215
Steam pressure (bar) at the turbine inlet	40	34	16
De-aerator pressure (bar)	1.3	1.3	1.3
Steam bleeding for primary and secondary air preheating (bar)	1.3 and 0.8	1.3 and 0.8	1.3 and 0.8
Condensation pressure (bar)	0.07	0.07	0.07
O ₂ at Stack, % vd	6.0	6.0	6.0
Flue gas re-circulated (% mass)	20	20	20
Stack temperature (°C)	135	135	135

When the model validation data inserted in to the Thermoflex model and simulated for each three cases, it is observed that the electric power generated slightly increased from 4.2MW to 4.25MW, 2.5MW to 2.52, and 2MW to 2.04MW which is a 0.05MW, 0.02MW, and 0.04MW increment respectively. The net electric efficiency is 21.21%, 21.20%, and 21.25% respectively. The boiler exit temperature were 178.9°C, 179°C, and 180.2°C respectively which are valid as the boiler exit temperature should not exceed 180°C [59]. Flue gas temperature to the Stack is 133.21°C, 134.2°C, and 134.8°C respectively which are valid as the flue gas temperature to stack should not exceed 135°C [59]. This shows the formulated model can be used as a small scale waste to energy plant model.

4.2 RESULT OF MODEL SIMULATION

After the model is validated, then it further simulated with desired assumed operating parameters listed under Table 12. The result of simulation is listed in Table 14. All parameters not listed in this table are constant parameters that do not change after simulation.

Table 14 : Result of Simulation

Assumed conditions for model plant (Table 12)		Simulation Result
Primary air preheating temperature	60	60
Secondary air preheating temperature	150	103.8
Flue gas temp. at boiler exit (°C)	180	178.9
Steam production (kg/s)	--	3.76
Stack temperature (°C)	135	135
Net electric power generated (MW)	--	2.4
Gross electric efficiency (%)	--	24.2
Net electric efficiency (%)	--	21.27

As can be observed from the result the generated electric power which is 2.4 MW is close to actual small scale waste to plants capacity as indicated in Table 7 or Table 13 Case 2, and the

gross electric efficiency 24.2% is also acceptable as compared with practical operational WTE plants. Practical gross electric efficiency and steam parameters are shown in Table 15. This indicates that the model and assumed operational parameters indicated in Table 12, resulted in desired small scale electric power with acceptable gross electric efficiency.

Table 15 : Practical steam parameters with gross electric efficiency [59]

Live steam Temperature (°C)	Live steam Pressure (bar)	Gross electric Efficiency (%)
400	40	25.2
400	40	26.3
400	40	26.6
500	90	29.4
500	90	30.4
500	90	31.4

4.3 RESULT OF FLUE GAS TREATMENT

In actual large scale WTE plants, a CEMS, monitors the flue gases as they exit the bag-house filters, to determine the gas composition on a continuous basis. The CEMS is regularly calibrated and have an independent power supply in the event of a power failure to the facility. The CEMS monitor the following substances

- Oxides of Nitrogen (NO_x);
- Carbon Monoxide (CO);
- Total Dust;
- Total Organic Compounds (TOC);
- Hydrogen Chloride (HCL);
- Hydrogen Fluoride (HF); and
- Sulfur Dioxide (SO₂).

The validated small scale waste to energy plant simulated model flue gas composition exiting the stack is as indicated in Table 16.

Table 16 : Stack flue gas composition of model SSWTE plant

Flue gas component	% mole	mg/l
N ₂	52.618	657.73
O ₂	0.201	2.87
CO ₂	12.855	254.14
H ₂ O	33.677	270.76
Ar	0.631	10.48
SO ₂	0.018	0.53

As per EU Waste Incineration DIRECTIVE 2000/76/EC, some emission limits are stated in below table.

Table 17 : Emission limit as per DIRECTIVE 2000/76/EC

Component	Unit	Limit	
Total dust	mg/l	0.01	Daily average
Total organic carbon	mg/l	0.01	Daily average
HCL	mg/l	0.01	Daily average
HF	mg/l	0.01	Daily average
SO ₂	mg/l	0.05	Daily average
NO _x	mg/l	0.2	Daily average
Dioxins and furans	ng/l	0.0001	6 - 8 hour average

As can be seen from the above two tables the flue gas composition at stack comply with emission limits as all of gases except sulfur dioxide, are environmentally friendly gases that can exist naturally in air. However, as it can be observed from Table 16, the flue gas contains significant moisture content which is 33.68%. This moisture results from evaporation of waste during combustion process. From waste character data indicated in Table 11, the moisture content of feed waste is 39.41%. It is obvious that the water vapor in the flue gas can be condensed and the latent heat can be recovered using Flue Gas Condensation System [59]. But

there should be a suitable infrastructure preferably a district heating grid operated year-round to use the heat. Details of this method is discussed in Literature Review section 2.8.6.

4.4 SENSITIVITY ANALYSIS

The sensitivity analysis aim is for the purpose of understanding how the plant behaves with respect to electric power generation and gross electric efficiency when a specific operational parameter change. The selected operational parameters for such analysis are: moisture content of fuel, ambient temperature, condenser pressure, lower heating value of fuel, excess air, ash content of fuel, and fuel flow rate. The analysis is carried out by defining macro cases for the model developed in Thermoflex®. For all analysis many iteration were tested until temperatures of flue gas leaving economizer and to stack reach less or equal to 180⁰C and 135⁰C respectively with all other parameters stated under Table 12 constant.

For the purpose of analyzing the effect of specific operational parameter on net electric power generation and gross electric efficiency, all other operational parameters were kept constant and only that parameter is varied.

4.4.1 Effect of Moisture Content on plant performance

MSW drying process is where the moisture content is evaporated by heat energy. Wastes with low moisture content will evaporate more quickly, resulting in a higher temperature in the combustion bed. But higher moisture content takes a longer drying period and cause lower bed temperature. This necessitates utilization of auxiliary fuel to raise the temperature so as to reach adiabatic flame temperature thereby maintaining normal bed combustion. Higher moisture content of a waste lengthen the evaporation process time of the fuel, weakening the combustion process and taking up most of combustion time. This time can be up to 2/3 of the whole combustion process [76].

Flue gas compositions were also influenced by moisture content of waste. The average concentration of CO and CO₂ above the grate is inversely proportional to moisture content in the waste fuel. When moisture content is low, a great amount of CO was produced in a short time;

therefore, the combustion process is short and intense. Insufficient air supply with a low O₂ concentration surrounding fuel particles is also a reason for high CO concentration in theregion towards the end of whole combustion process. NO concentration decreases as the moisture level in the fuel increased. Drier fuels had a higher NO due to high burning rates [76].

In this thesis the effect of fuel moisture content on small scale waste to energy plant performance is demonstrated by net electric generation potential and gross electric efficiency of the plant. Hence, when moisture content of the fuel increase by 10%, the net electric power production decrease by 27.92%. This is due to the fact that during combustion, significant amount of heat is used for evaporating the moisture in the waste and this heat if not recovered goes with water vapor in a flue gas. This over all reduce the energy recovery potential of the WTE plant. As discussed in Literature Review section 2.8.6, Flue gas Condensation System can be used to recover heat from water vapor in a flue gas if there is a demand for district heating. This implies that moisture content of the waste fuel plays a significant role in plant performance. Figure 33 assure that Combustion of waste fuel with moisture content of above 46% is not recommendable in conventional fixed bed grate fired waste to energy plant as electric power production potential significantly drops.

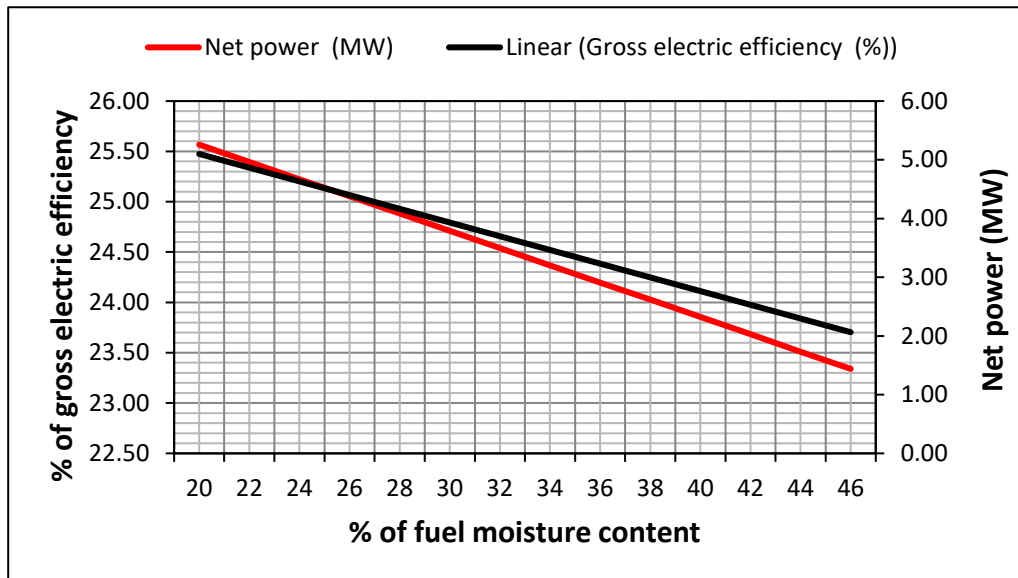


Figure 33 : Effect of moisture content on electric power and efficiency

4.4.2 Effect of ambient temperature on plant performance

The condenser temperature which is the ambient air temperature has a strong influence on the plant efficiency, the lower the condenser temperature, the greater the pressure drop across the turbine which resulted in greater enthalpy drop which increases power generation. Even though lower ambient temperatures result in higher enthalpy drop due to high pressure drop, lowest condensation pressures due to low ambient temperatures are not advisable as last stage turbine blades damaged by the water droplets formed at low pressure and temperature. For understanding how the temperature affect electricity generation and efficiency, simulation result of model small scale plant were shown in Figure 34. As can be seen from the figure, as the temperature lower toward the optimum ambient temperature of 19°C, the electric power generated will increase, after this optimum temperature further reduction in temperature reduce the amount of generated electricity. The gross electric efficiency however is constant.

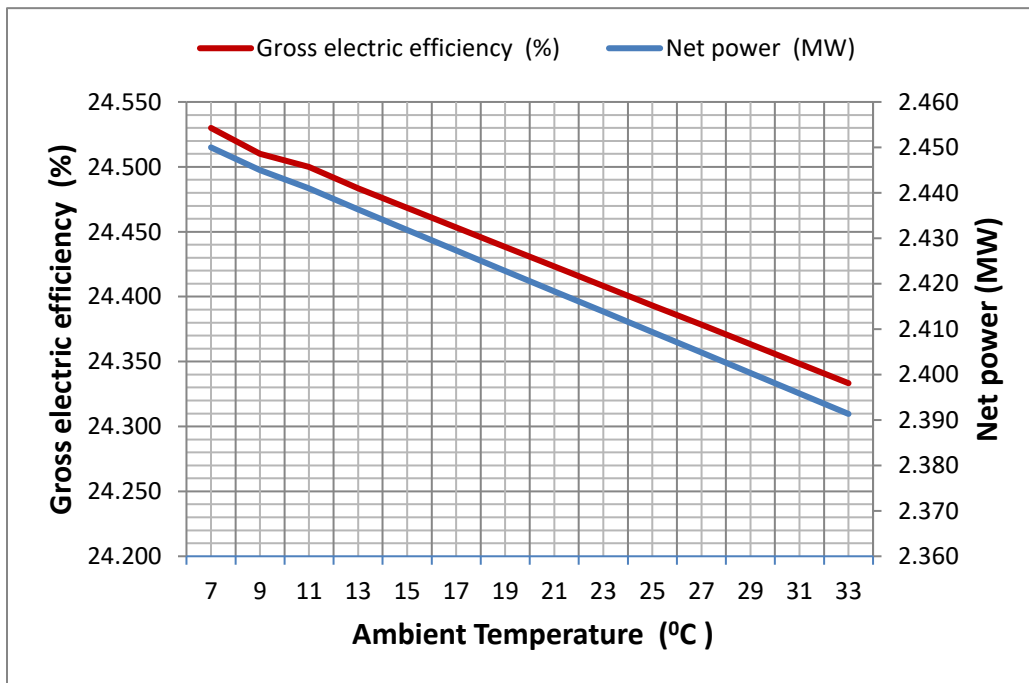


Figure 34 : Effect of temperature on electric power and efficiency

The effect of ambient temperature on power production is shown on enthalpy – entropy diagram shown in appendix I.

4.4.3 Effect of steam condensation pressure on plant performance

Air cooled condensers can reasonably achieve pressure level of 0.08bar in regions of a moderate climate resulting in a generator output increase of about 1.9% compared to a technically more modest solution with 0.1bar. Further optimization may be reached by cooling towers about 0.06bars or water-cooled condensers about 0.03bars [77]. As discussed, lower enthalpy at the outlet of the turbine means the amount of heat to be transferred to the atmosphere for complete condensation decreases. The enthalpy at the outlet of the turbine can be lowered by:

- Expanding the steam to a lower outlet pressure, i.e. a lower condenser pressure/temperature. But this increases the moisture content in the outlet steam.
- Increasing the inner efficiency of the turbine. The limiting moisture content of the steam at the turbine outlet depends on the particular design and the maximum acceptable values may vary between 10 up to 14% [77]. The higher the limiting moisture content the higher the demand on design and material quality of the low pressure stages at the outlet of the turbine. A possible increase in the inner turbine efficiency targets for reduction of the frictional heat produced by the turbine. The inner efficiency resulting from the turbine manufacturer's design is in the range between 70 and 90%. Differences in the turbine design may have an important impact on the plant efficiency and may justify additional expenses for improved systems.

In this thesis, water cooled condensers with wet cooling tower, which operate with condensation pressure of 0.07bar, were used for simulation of proposed model. The result of simulation shows, as depicted in Figure 31, that lower condensation pressures have a fairly reasonable influence on the generator output such that the condensation of the steam should be generally done as close as possible to the low pressure. But this lower pressure has to be limited for different types of cooling methods. The following figure clearly show that a decrease of condenser pressure by 0.01bar resulted in electric power generation increment of 0.67%.

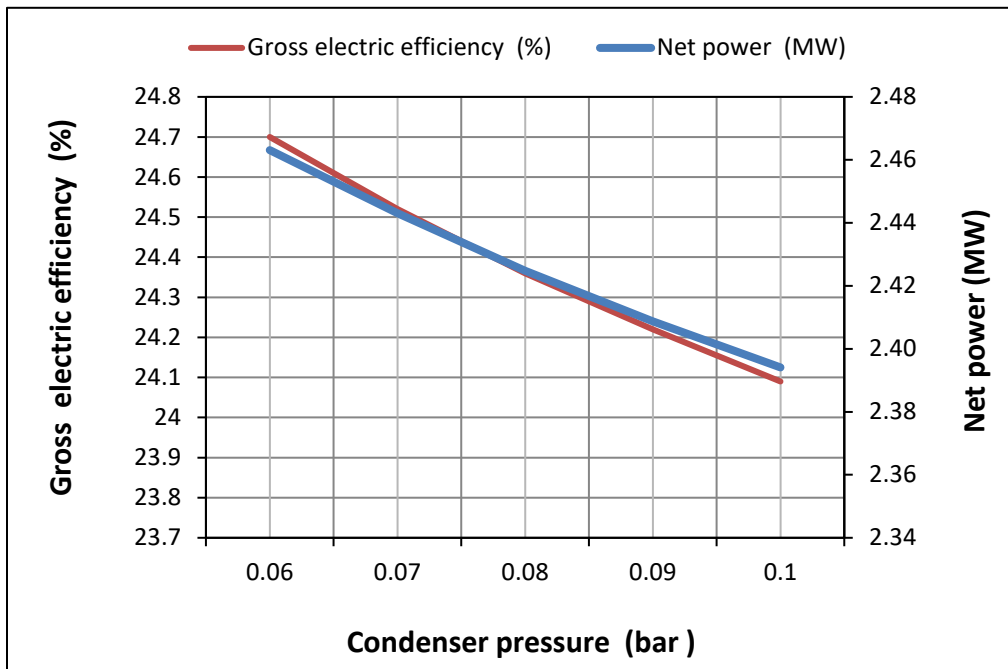


Figure 35 : Effect of condenser pressure on electric power and efficiency

4.4.4 Effect of lower heating value of fuel on plant performance

The heating value of the waste is one of the key parameter affecting waste to energy plants. Variations in heating value in general and specifically lower heating value obviously impact the performance of combustion process, the boiler, and overall plant efficiency which also impacts the feed rate of waste to the grate. To maintain constant lower heating value during combustion of waste, feed waste is usually continuously mixed by overhead crane to provide homogenous mix of waste to combustion grate. In modern WTE plants, a system called “Automatic Combustion Control” is used to maintain a uniform flue gas temperature profile– thus reducing the size and number of hightemperature regions and to control the primarycombustion air distribution and ratio of primaryto secondary combustion air flow. Furthermore, the system controls and adjusts the position of the main combustion zone to meet variations in the waste heating value [6]. The lower heating value increment by 9.17% result in megawatt electric generation increment of 9.85%. This shows that lower heating value has great influence on electric power generation performance. LHV increases in dry seasons as moisture content of

wastes lower relatively. But in rainy season, stand by diesel fuel source usually used which will be fired in case of times when the waste burning process results in lower heat rate.

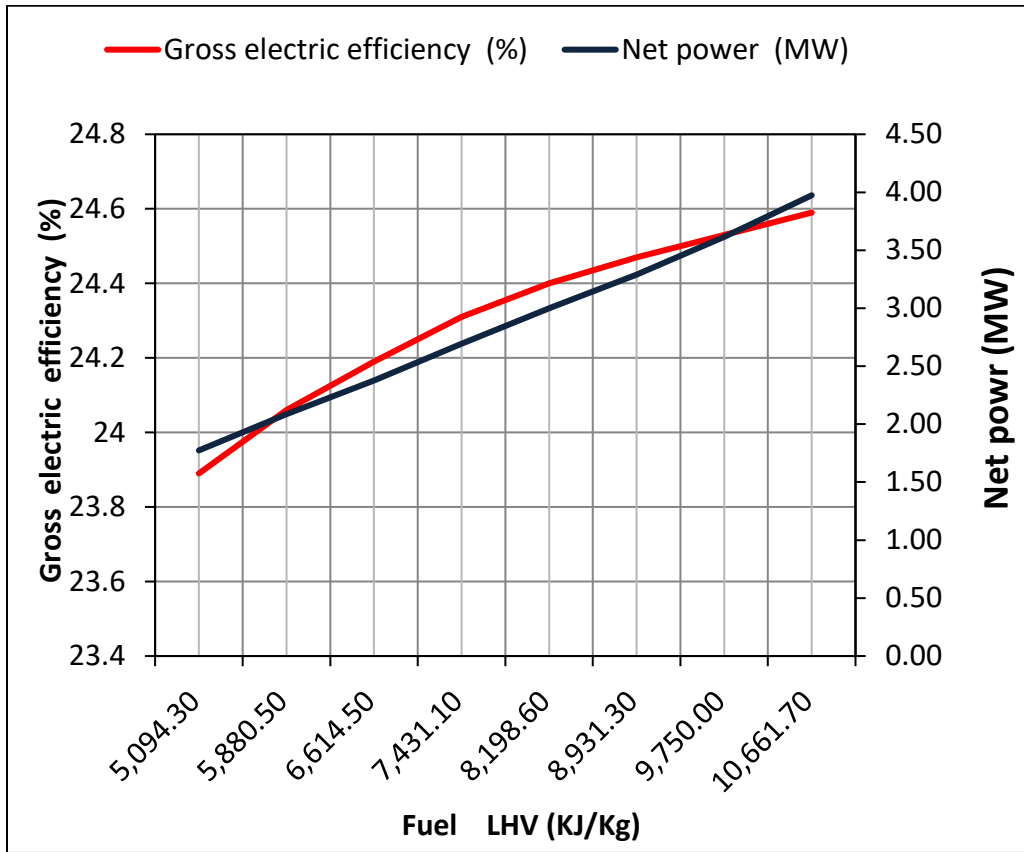


Figure 36 : Effect of fuel lower heating value on electric power and efficiency

4.4.5 Effect of excess air on plant performance

The total air supply to the combustion process is the sum of the primary and secondary air. To secure complete burn out it is necessary to operate at a certain surplus of air which is excess air. The excess air passes all the way through the boiler and the flue gas treatment system to the chimney and depending on the flue gas temperature in the chimney it represents a loss of energy and hence a loss of thermal efficiency. Achieving maximum efficiency means having as little excess air as possible. Flue gas recirculation is a good method to lower the excess air rate, which increases thermal efficiency and reduces the size of the downstream gas clean-up equipment. A further advantage is that lower excess air rate results in less O₂ level in flue gas

and less nitrogen passing through the combustion chamber, and therefore lower formation of thermal NO_x [9]. The excess air ratio can be reduced on the primary air supply side by using a water-cooled grate and on the secondary air supply side by re-circulating a part of the treated flue gas [57].

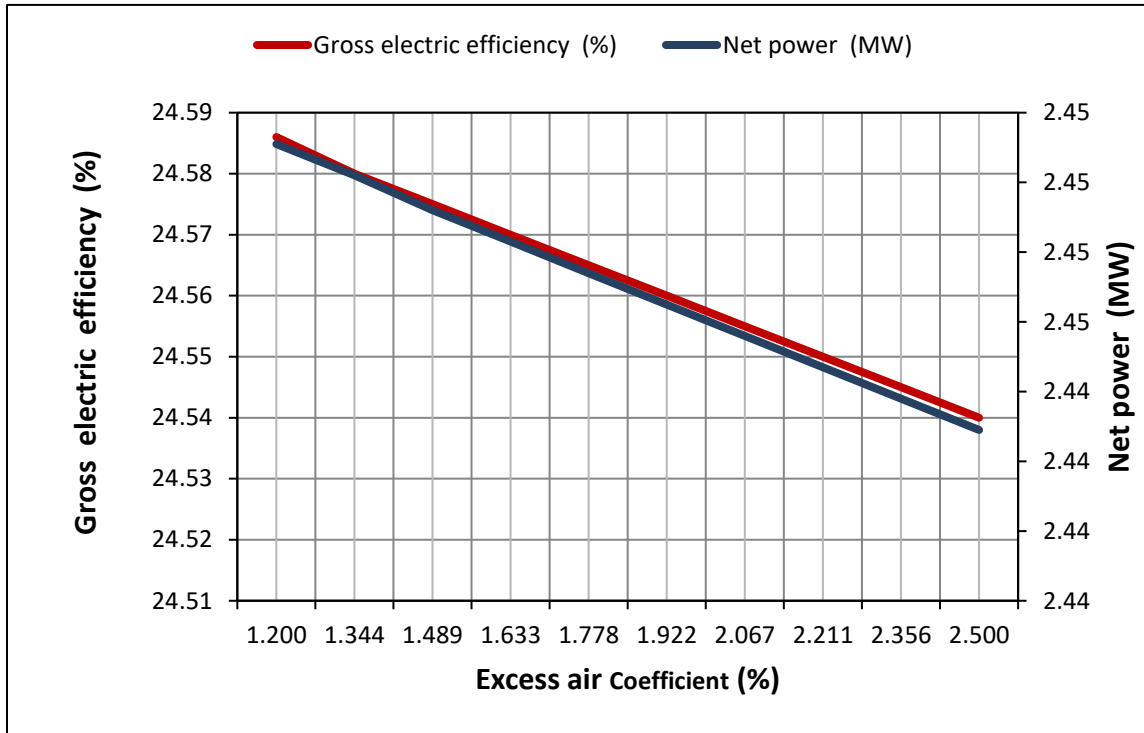


Figure 37 : Effect of excess air on electric power and efficiency

4.4.6 Effect of fuel ash content on plant performance

The solid residues produced by the combustion process, bed ash and filter ash (fly ash) and the quantities will depend on the ash content of the waste feed material. High ash content waste usually has a low calorific value. As the ash content in waste feed increase, enough amount of heat cannot be available for the boiler for steam production which reduce steam flow rate or steam parameters which intern reduce the amount of electric power generated. The simulation result depicted in Figure 34, shows that an increase in waste feed ash content by 2.5%, resulted in decrease in net megawatt electric power of 10.9%.

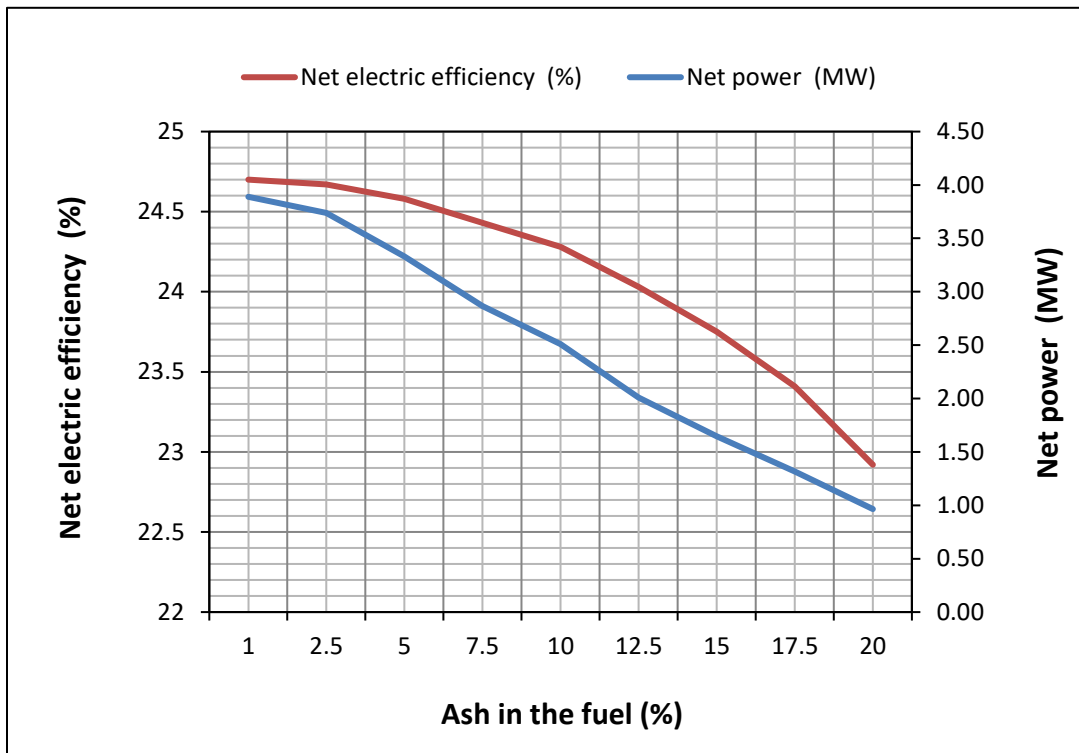


Figure 38 : Effect of fuel ash content on electric power and efficiency

4.4.7 Effect of fuel flow rate on plant performance

Lastly the effect of fuel flow rate on megawatt power production capacity of the plant was carried out with similar procedure. The fuel flow rates were selected on the bases of daily waste generation rate of selected towns of Ethiopia as indicated in Figure 2. It can be seen from this figure that Mekelle, Dire Dawa, and Jimma generates waste in the order of 47 – 87 ton/day, whereas Bahir Dar, Harar, and Awasa generate waste in the order of 27 – 46 ton/day. The effect of waste flow rate is shown in Figure 35 based on Table 18.

Table 18 : Effect of fuel flow rate data

Fuel flow rate (ton/day)	23.04	41.76	60.48	79.2	97.92
Net power (MW)	0.57	1.03	1.50	1.97	2.45
Flue gas leaving Economizer (°C)	179.8	179.8	179.8	179.8	179.8
Flue gas to Stack (°C)	135	135	135	135	135

Temperature leaving the Economizer should not greater than 180⁰C and to the Stack should not greater than 135⁰C [59]

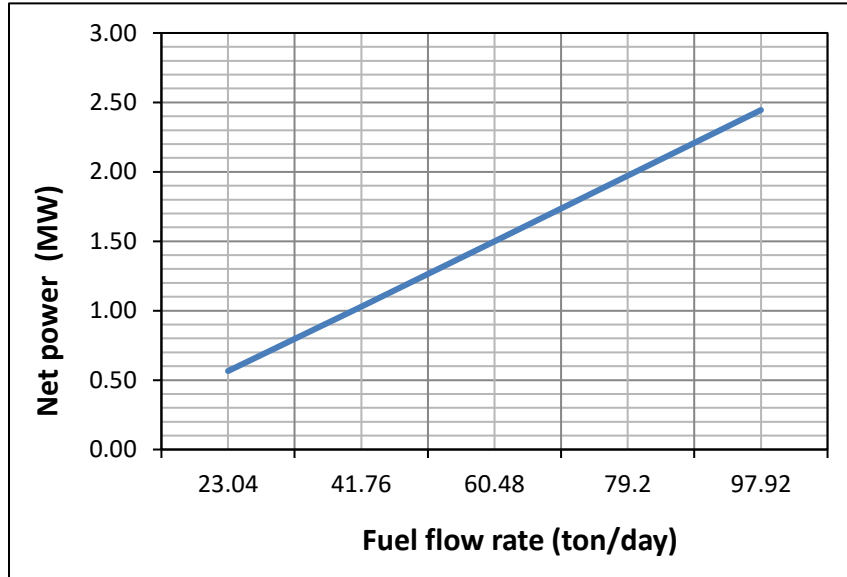


Figure 39 : Effect of fuel flow rate on electric power and efficiency

Accordingly, the model WTE plant studied in this thesis can easily be implemented in sub cities of Addis Ababa or other regional towns of Ethiopia. For instance due considering daily waste generation potential of above selected towns and assuming proximate and elemental composition nature of all Ethiopian solid waste nearly same, Figure 36 shows attainable megawatt electric power through implementation of the model. From Figure 36, it can be observed that fuel flow rate has almost linear impact on net electric generation rate. A 1% increment in fuel flow rate resulted in 1% increment of net MW electric power.

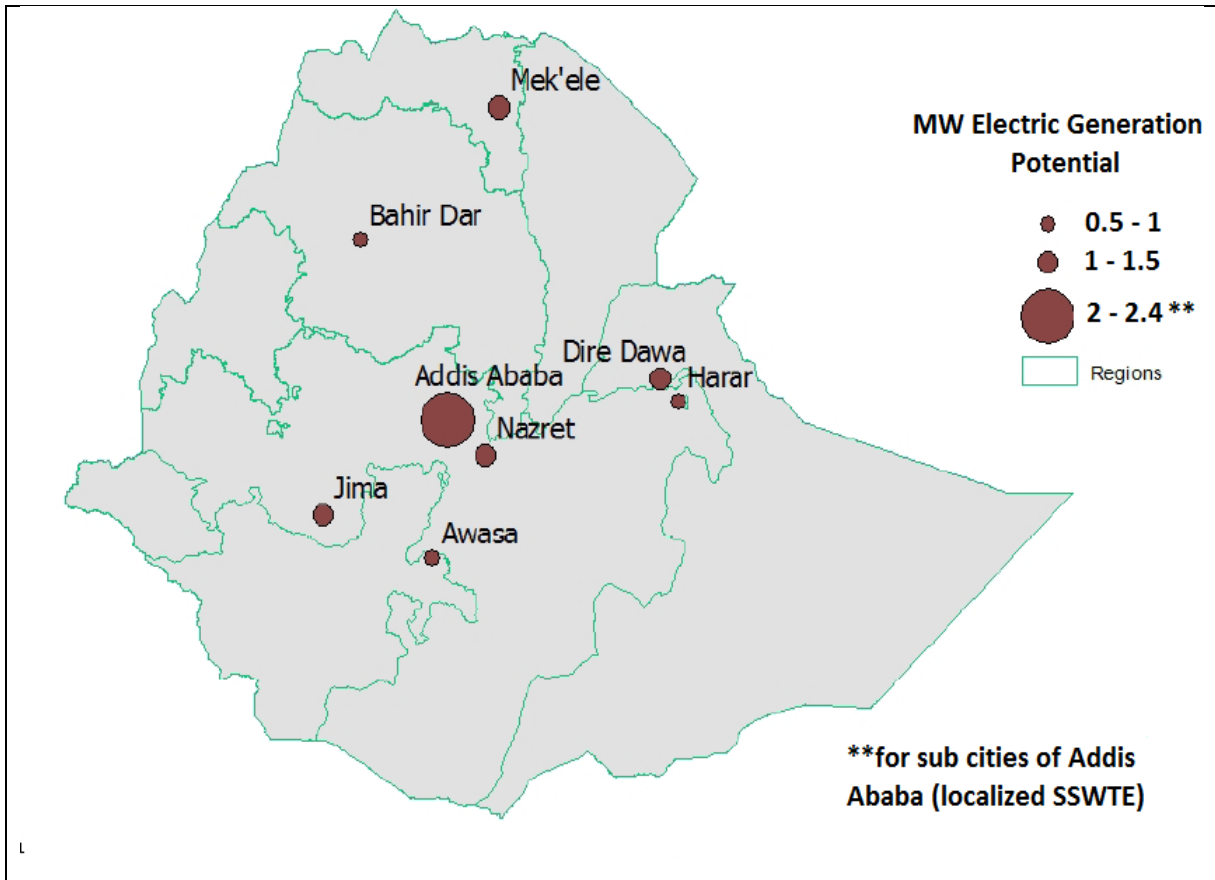


Figure 40 : Electric generation potential of Ethiopian towns from MSW

4.5 WAYS TO IMPROVE EFFICIENCY of Small scale Waste-to-Energy plants

4.5.1 Boiler Exit Temperature

Boiler exit temperature is the temperature of flue gas leaving the economizer. Decreasing this temperature increases both net electric power and net electric efficiency of Waste-to-Energy plants. It has to be noted that decreasing boiler exit temperature below limited value also has a negative impact due to the fact that it will bring low temperature corrosion (Dew point corrosion) of final heat recovery heat exchanger [59]. When temperature of flue gas falls beneath the acid dew point, wet chemical corrosions appear on cold surfaces. Nowadays, to avoid low temperature corrosion problems, Teflon can be coated. Thus, in this way, efficiency of small scale waste-to-energy plants can be increased and low temperature problems of boiler tube can be avoided. Figure 37 show effect of boiler exit temperature.

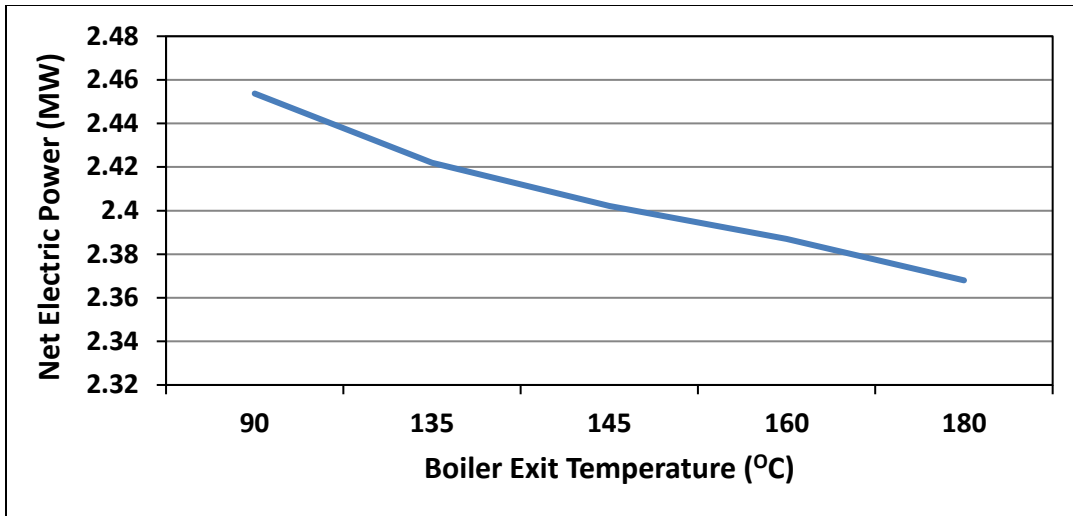


Figure 41 : Effect of boiler exit temp on net power

4.5.2 Condenser Pressure

Figure 38. shows the effects of condenser pressure on the net electric efficiency of Small Scale Waste-to-Energy plant. Decreasing the condenser pressure plays a significant role. It has to be noted that using water cooled condenser increases the efficiency of any power plants. However, we need to have a nearby sufficient water source to a SSWTE plant. If that is not the case, we have to use air cooled condenser. However, the efficiency of power plant using air cooled condenser is lower [59].

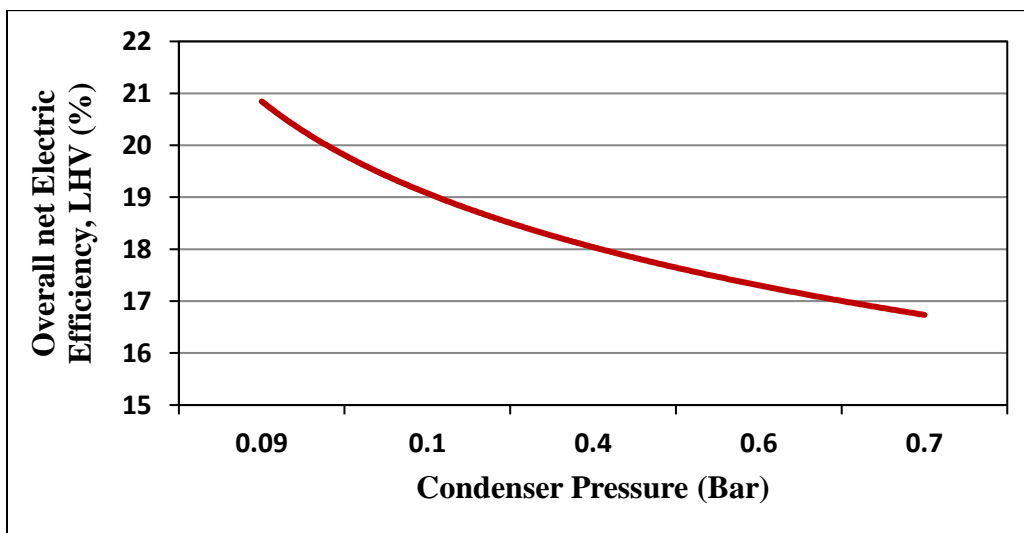


Figure 42 : Effect of condenser pressure on net power

4.5.3 Steam Inlet Temperature

Increasing steam inlet temperature from 320°C to 450°C, increase the net electric efficiency from 19.46 % to 22.3 %. However, increasing steam inlet temperature leads to corrosion of boiler and super heater tubes. This is due to the fact that at high temperature chlorine tends to separate from HCl gas and react with Fe from metal tubes and forms FeCl₂ as flue gas pass the boiler and super heater tubes. During combustion nearly all chlorine from various components of MSW volatilized and converted to HCl gas. This acid gas component is the reason for high temperature corrosion [54] [59].

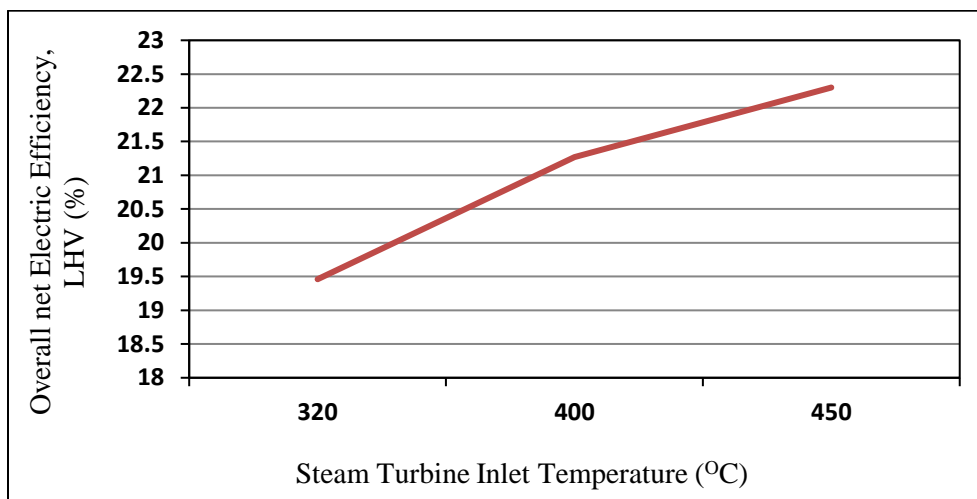


Figure 43 : Effect of turbine inlet temperature on net power

In general, reducing excess air, increasing steam inlet temperature, reducing condenser pressure, reducing boiler exit temperature, reducing moisture and ash contents, increases efficiency of Waste-to-Energy plants. However, there is a technical limitation for each of the above mentioned input and operational parameters. For example, reducing excess air increases the efficiency but also it increases the possibility of having un-burnt carbon in the bottom ash, thus, further decreases the efficiency of the plant. Thus, there is no linear relationship in the real situation.

5. CONCLUSION

Waste presents a source of energy. The energy utilization is possible with the appropriate integrated waste management system and utilization of appropriate technologies within the legally permissible environmental impact. Such system can create power, which can be distributed to the citizens or industry. Future waste management is going to depend on WTE technologies for the high calorific part of the waste stream, not suitable for recycling. Despite its abundance, due to heterogeneous nature of waste, some differences with respect to conventional fossil fuel have to be considered in the chemical-to-electrical energy conversion process.

In this Thesis, the nature of Addis Ababa municipal solid waste is studied with preparation of mixed municipal waste samples. The samples were characterized by laboratory analysis and Proximate analysis, Ultimate or Elemental analysis, and Lower Heating Value of mixed waste were determined and the data is further compared with previous studies and adjusted for the Thesis input. A small scale mass burn waste to energy plant thermodynamic model is synthesized in Thermoflex® software. Assumptions were set for the model plant after studying similar small scale actually operational plants. The model is validated with actual similar plant's operational parameters. Then after, the developed assumptions with waste character data were inserted in to the model and the model was simulated to generate basic plant operation parameters. The result shows that the model is valid and it was seen that 2.4MW electric power can be generated with waste input of 1.7Kg/s, and with gross electric efficiency of 24.24% (net 21.27). Emission levels of flue gas to Stack were compared with relevant European emission directive, which shows all components of flue gas except SO₂, are environmentally friendly gases.

Considering the regional Ethiopian towns waste generation capacity of 23.04 ton/day to 97.92 ton/day, the model was further simulated with this waste input range, and resulted in that regional towns of Ethiopia can generate a net electric power of 0.57MW to 2.45MW. The result further show that, assuming a per capita electric consumption of Ethiopian towns household to be 1.2KW, the generated electric power of 2.4MW can electrify 2,000 town houses.

Sensitivity analysis were also done for the validated model with respect to basic operational parameters: fuel moisture content, ambient temperature, condenser pressure, lower heating value

of fuel, excess air, fuel ash content, and fuel flow rate. The result shows that decreasing fuel moisture and ash content, increasing ambient temperature up to 22⁰C, decreasing condenser pressure, increasing lower heating value of fuel, decreasing amount of excess air, and increasing fuel flow rate will boost generated net electric power and efficiency of the model Small scale Waste to Energy plant. Other means to enhance efficiency of Small scale Waste to Energy plant are decreasing boiler exist temperature and increasing turbine steam inlet temperature. However, these last two measures, should be applied with limitation: turbine steam inlet temperatures should not exceed preferably above 400⁰C to avoid high temperature corrosion in super heater tubes, and lowering boiler exit temperature result in low temperature corrosion.

This Thesis shows that, mass burn Small scale Waste to Energy plant for thermal treatment of municipal solid waste can be unquestionable means to get dual benefit from waste fuels, one is generated electric power and the other is avoidance of waste landfills as waste landfills are source of polluting emissions.

6. FUTURE DEVELOPMNET

Further work should aim at collecting as much as many experimental samples at various places in a specific city or town and thereafter use them for improved waste characterization. As this study not includes industrial wastes, it is recommended to include industrial wastes in waste characterization. The aim should also extend to analyzing the Hybrid Combined Cycle concept that uses dual fuels: one is municipal solid waste another may be a low grade fossil fuels. One method of applying Hybrid combined cycle is integration of a Gas turbine with conventional WTE plant with high efficiency thermodynamic energy cycle, designed to minimize corrosion problems which are normal in conventional plants. Financial models for analyzing net present value investment appraisal of capital costs, revenues operation costs, and maintenance costs are necessary and helpful for implementing the process model developed in this study.

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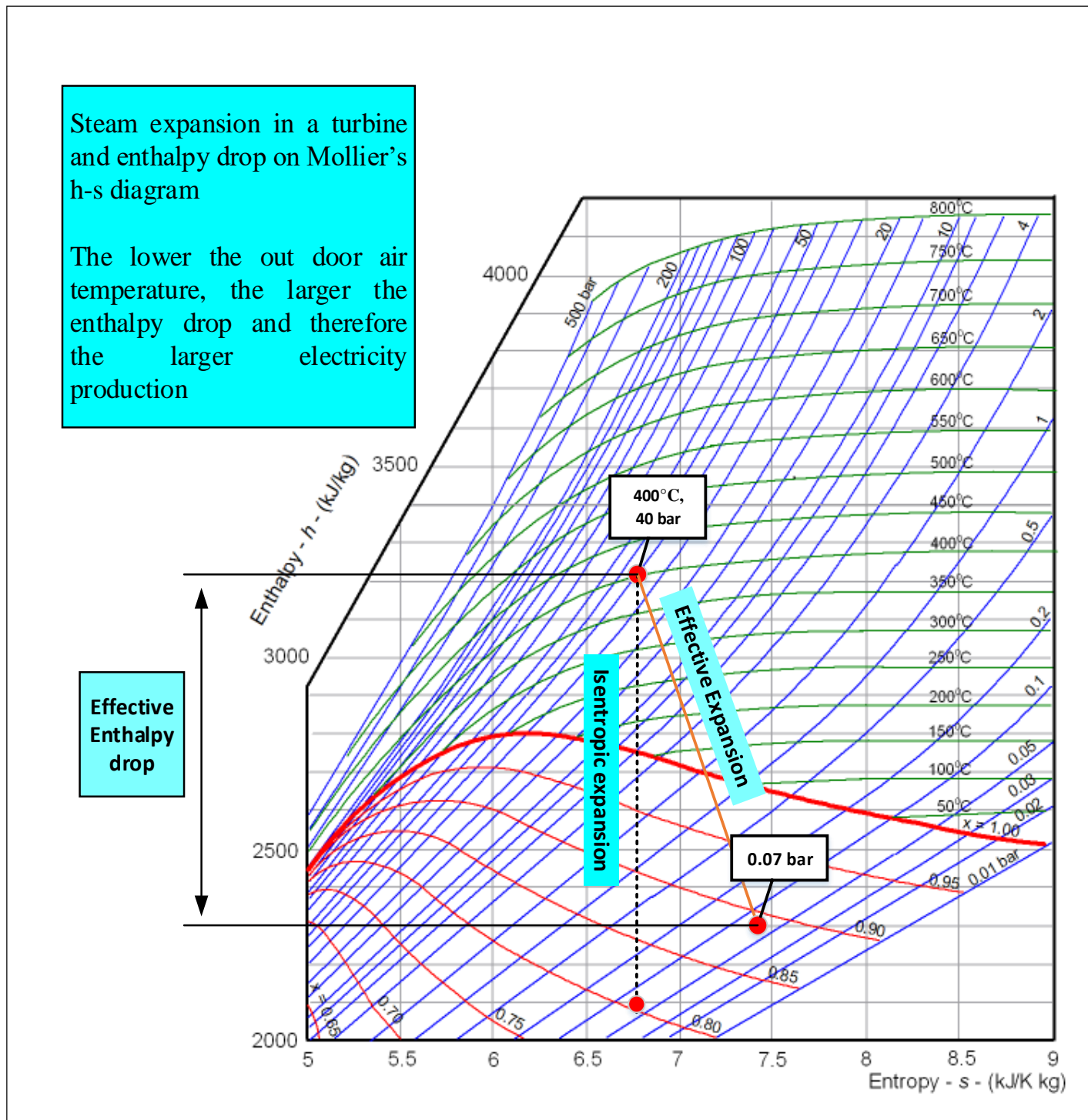
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8. APPENDIX

1. Steam expansion on turbine stage shown in h-s diagram.



II. Thermoflex model output system summary

*** SYSTEM SUMMARY ***

Steam Property Formulation - Thermoflow STQUIK

Ambient pressure = 1.013 bar Temperature = 15 C RH = 60 %

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		LHV	HHV
Net fuel input	[kW]	11339	14315
Gross heat rate	[kJ/kWh]	14851	
Net heat rate	[kJ/kWh]	16925	21367
Gross electric efficiency	[%]	24.24	
Net electric efficiency	[%]	21.27	16.85
CHP efficiency	[%]	21.27	
PURPA efficiency	[%]	21.27	

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Power Device (s)

Generator/Component Output [kW]	Shaft [kW]	Eff [%]
Steam Turbine[25]	1081.2	
Steam Turbine[26]	1235.0	
Steam Turbine[27]	119.4	
Steam Turbine[28]	421.7	
Generator[1] 2748.7	2857.3	96.20
Total Generator (s) 2748.7		

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Auxiliary Device (s)

Component	Shaft [kW]	Motor	Eff [%]	[kW]
Electrostatic Precipitator[4]				31.6
Fabric Filter[5]				15.2
Fan[33]	23.3	Motor No.3	91.95	25.4
Fan[34]	45.7	Motor No.4	93.21	49.1
Fan[6]	105.2	Motor No.1	94.42	111.5
Feedwater Heater w/Pump[7] pump				0.0
Feedwater Heater w/Pump[8] pump				0.0
Furnace w/Grate[10] aux				33.7
SCR(Conventional boiler) [16]				0.1
Water Pump[31]	25.9	Motor No.2	92.16	28.1
Water Pump[38]	0.0	Motor No.5	99.90	0.0
Wet Cooling Tower(PCE) [29] fan				14.7
Total components auxiliaries				309.3
Total miscellaneous auxiliary				27.5
Total plant auxiliary				336.8

Component	Heat Device(s)	[kW]
Fuel Source[9]	Chargeable as Fuel (LHV)	11339
Gas/Air Source[11]	Not Considered	41.76
Makeup/Blowdown[14]	Not Considered	103.1

Heat Balance [kW]		
Deaerator[2]		
Heat removed/lost		219.30
Economiser[3]		
Heat input	12.91	
Heat removed/lost		33.49
Fan[6]		
Compression power	104.20	
Fan[33]		
Compression power	23.10	

Fan[34]			
Compression power	45.27		
Feedwater Heater w/Pump[7]			
Pumping power	0.00		
Feedwater Heater w/Pump[8]			
Pumping power	0.00		
Fuel Source[9]			
Heat input	11339.00		
Furnace w/Grate[10]			
Heat removed/lost		199.80	
Gas/Air Source[11]			
Heat input	0.00		
General HX[12]			
Heat removed/lost		3.00	
General HX[13]			
Heat removed/lost		1.85	
General HX[35]			
Heat removed/lost		1.25	
Makeup/Blowdown[14]			
Heat input	-4063.00		
SCR(Conventional boiler)[16]			
Heat removed/lost		0.00	
Stack[24]			
Heat removed/lost		841.60	
Steam Turbine[25]			
Expansion power		1083.40	
Steam Turbine[26]			
Expansion power		1237.50	
Steam Turbine[27]			
Expansion power		119.70	
Steam Turbine[28]			
Expansion power		422.50	
Superheater[30]			
Heat input	4.82		
Heat removed/lost		11.81	
Water Pump[31]			
Pumping power	25.11		
Water Pump[38]			
Pumping power	0.00		
Wet Cooling Tower(PCE)[29]			
Heat removed/lost		3311.00	

Total Energy Input	7491.00		
Total Energy Output		7487.00	
Cycle Heat Balance Error		-4.88	-0.0430 %
=====			

Zero enthalpy @ 77F (25C) & vapor H2O.

Mass Flow Balance [kg/s]

=====		
Deaerator[2]		
Mass flow out		1.62

Fuel Source[9]			
Mass flow in	1.70		
Furnace w/Grate[10]			
Mass flow out		0.23	
Gas/Air Source[11]			
Mass flow in	4.11		
Makeup/Blowdown[14]			
Mass flow in	1.64		
Mass flow out		0.00	
Stack[24]			
Mass flow out		5.59	
Wet Cooling Tower(PCE) [29]			
Mass flow out		0.00	

Total Mass Flow In	7.44		
Total Mass Flow Out		7.44	
Cycle Mass Balance Error		0.00	-0.0004 %
=====			

*** COMPONENT RESULTS (37 components) ***
 Steam Property Formulation - Thermoflow STQUIK

H* is the program enthalpy based on 77F (25C) & vapor H2O.

Deaerator(s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]
[kJ/kg]					
=====					
=====					
Deaerator[2]:					

Water in	9	0.7539	88.32	3.515	-2177.55
369.94					
Heating H2O	31	1.300	107.13	0.000	50.57
2598.06					
Flash in	16	1.275	106.56	1.879	-48.06
2499.43					
Water out	2	1.691	104.80	3.778	-2108.06
439.42					
Vented steam flow =			1.617		

Mode: Thermodynamic Design
 Deaerator type: Horizontal Heater (HH)
 Operating pressure = 1.2 bar, saturation temperature = 104.8 C
 Additional water head at inlet = 5 m H2O = 0.4906 bar
 Additional water head at outlet = 5 m H2O = 0.4906 bar

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 =====
 Economiser(s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]

[kJ/kg]

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 =====

Economiser[3]:

Water in	42	41.62	105.67	3.778	-2101.42
446.07					
Water out	4	40.80	251.51	3.778	-928.30
1619.19					
Gas in	40	0.9609	458.65	12.431	543.66
Gas out	3	0.9584	178.95	12.431	185.52

Mode: Design

Heat transfer to water-side = 4432 kW, Heat loss = 33.49 kW

UA = 46.28 kW/C, DTlgm = 128.8 C

Gas flow = 12.43 kg/s, outlet temperature = 178.9 C, outlet enthalpy = 185.5 kJ/kg

Flyash flow = 0.0426 kg/s, Heat transfer rate = 12.91 kW

Gas-side pressure drop = 2.491 millibar, water-side pressure drop = 0.816 bar

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Electrostatic Precipitator(s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]

[kJ/kg]

=====
 =====

Electrostatic Precipitator[4]:

Gas in	3	0.9584	178.95	12.431	185.52
Gas out	5	0.9503	178.95	12.431	185.52

Mode: Thermodynamic Design

Particulate removal efficiency = 99.44 %, particulate (dust) removed = 0.0423 kg/s

Pressure drop = 8.095 millibar, power consumption = 31.61 kW

Inlet dust load = 1338.2 ng/J; = 4465 mg/Nm³ @ 6% O₂, dry

Outlet dust load = 7.493 ng/J; = 25 mg/Nm³ @ 6% O₂, dry

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=====

Fabric Filter(s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]

[kJ/kg]

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=====

Fabric Filter[5]:

Gas in	5	0.9503	178.95	12.431	185.52
Gas out	6	0.9279	178.95	12.431	185.52

Mode: Thermodynamic Design, Type: Pulse Jet

Particulate removal efficiency = 99.9 %, particulate (dust) removed = 0.0002 kg/s

Pressure drop = 22.42 millibar, power consumption = 15.19 kW

Inlet dust load = 7.493 ng/J; = 25 mg/Nm³ @ 6% O₂, dry

Outlet dust load = 0.0075 ng/J; = 0.025 mg/Nm³ @ 6% O₂, dry

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=====

Fan(s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]

[kJ/kg]

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Fan[6]:

Gas in	14	0.9023	135.00	5.594	131.82
Gas out	7	1.013	150.30	5.594	150.44

Compression power = 104.2 kW Shaft power required = 105.2 kW

Mech. loss = 1.052 kW Mech. eff. = 99 %

Overall apparent isentropic eff. = 80 % Polytropic eff. = 80.29 %

Overall pressure rise = 110.9 millibar

Pressure rise (before control damper) = 110.9 millibar

Design point RPM = 3600

Design mode

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Fan[33]:

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Gas in           13      1.013      25.00      4.107      0.00
Gas out          45      1.067      30.53      4.107      5.63
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Compression power = 23.1 kW   Shaft power required = 23.34 kW
Mech. loss = 0.2334 kW   Mech. eff. = 99 %
Overall apparent isentropic eff. = 80 %   Polytropic eff. = 80.13 %
Overall pressure rise =                53.9   millibar
Pressure rise (before control damper) = 53.9   millibar
Design point RPM = 3600
Design mode
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Fan[34]:

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Gas in           21      0.9279      178.95      6.837      185.52
Gas out          46      0.9634      184.33      6.837      192.14
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Compression power = 45.27 kW   Shaft power required = 45.73 kW
Mech. loss = 0.4573 kW   Mech. eff. = 99 %
Overall apparent isentropic eff. = 80 %   Polytropic eff. = 80.07 %
Overall pressure rise =                35.52   millibar
Pressure rise (before control damper) = 35.52   millibar
Design point RPM = 3600
Design mode
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Feedwater Heater w/Pump(s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]
[kJ/kg]					

Feedwater Heater w/Pump[7]:

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Water in           2      1.691      104.80      3.778      -2108.06
439.42
Water out          8      1.658      104.80      3.778      -2108.06
439.42
Steam in           24      10.00      243.08      0.000      379.80
2927.28
-----

```

Heat Xfer = 0 kW

UA of condensing section = 0 kW/C
 UA of drain cooler section = 0 kW/C
 UA of desuperheating section = 0 kW/C
 Pumping power = 0 kW Electrical power required = 0 kW
 Mech/motor loss = 0 kW Mech/motor eff. = 92 %
 Shell pressure = 1.031 bar Saturation temperature = 100.5 C
 Terminal difference = -4.30 C
 Design mode

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Feedwater Heater w/Pump[8]:

Water in	19	0.7689	58.25	3.321	-2303.66
243.82					
Water out	9	0.7539	88.32	3.515	-2177.55
369.94					
Steam in	49	0.8000	93.51	0.194	-13.09
2534.40					

Heat Xfer = 414.6 kW
 UA of condensing section = 25.88 kW/C
 UA of drain cooler section = 0 kW/C
 UA of desuperheating section = 0 kW/C
 Pumping power = 0 kW Electrical power required = 0 kW
 Mech/motor loss = 0 kW Mech/motor eff. = 92 %
 Shell pressure = 0.8 bar Saturation temperature = 93.51 C
 Terminal difference = 5.50 C
 Design mode

=====

Stream	Fuel Source(s)				
	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]
[kJ/kg]					

=====

Fuel Source[9]:

Fuel	10	1.026	25.00	1.700	6670.00
------	----	-------	-------	-------	---------

Fuel type = Solid Fuel name = Addis Ababa_Aradasubcity MSW
 Source specified pressure = 1.08 bar delivery pressure = 1.03 bar

=====

Furnace w/Grate(s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]
=====					
Furnace w/Grate[10]:					

Air in	33	1.026	103.78	1.643	80.33
Primary Air	34	1.026	103.78	2.464	80.33
Recirculation	34	1.026	103.78	2.464	80.33
Fuel in	10	1.026	25.00	1.700	6670.00
Gas out	11	0.9634	552.10	12.431	669.91
H2O in	4	40.80	251.51	3.778	-928.30
1619.19					
Blowdown	0.019	-1453.74	1093.75		
Sat. Steam out	12	40.80	251.51	3.759	252.33
2799.82					

Mode: Thermodynamic Design

Furnace gage pressure = -49.81 millibar, excess air = 1.45 %
 Adiabatic = 810.4 C, effective radiating = 682.6 C, waterwall surface = 462.7 C
 Heat transfer to waterwall = 4428 kW
 Heat losses = 110.7 kW
 Fuel input (LHV) = 11.34 MW, (HHV) = 14.32 MW
 Fuel delivery power = 33.73 kW
 Bottom ash mass flow = 0.1703 kg/s, fly ash mass flow = 0.0426 kg/s
 Flue gas composition [Mole %]
 O2 = 0.201% CO2 = 12.855% H2O = 33.677% N2 = 52.618% Ar = 0.631% SO2 = 0.018%

Gas/Air Source(s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]
=====					
Gas/Air Source[11]:					

Gas	13	1.013	25.00	4.107	0.00

Gas composition [Mole %]
 O2 = 20.557% CO2 = 0.030% H2O = 1.875% N2 = 76.616% Ar = 0.923% SO2 = 0.000%

=====
 =====

General HX(s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]

[kJ/kg]

=====
 =====

General HX[12]:

A path Gas in	20	0.9204	178.95	5.594	185.52
A path Gas out	14	0.9023	135.00	5.594	131.82
B path H2O in	51	0.7843	82.60	0.604	-2201.54
345.95					
B path H2O out	15	0.7689	92.45	0.604	-1709.07
838.41					

Mode: Design

Heat transfer = 297.4 kW, Heat loss = 3.004 kW

UA = 4.763 kW/C, Pinch = 46.08 C

A path pressure drop = 0.018 bar, B path pressure drop = 0.0154 bar

=====
 =====

General HX[13]:

A path H2O in	32	1.300	107.13	1.879	50.57
2598.06					
A path H2O out	16	1.275	106.56	1.879	-48.06
2499.43					
B path Gas in	48	1.046	60.00	4.107	35.65
B path Gas out	17	1.026	103.78	4.107	80.33

Mode: Design

Heat transfer = 183.5 kW, Heat loss = 1.854 kW

UA = 11.82 kW/C, Pinch = 2.778 C

A path pressure drop = 0.0255 bar, B path pressure drop = 0.0205 bar

=====
 =====

General HX[35]:

A path H2O in	50	0.8000	93.51	0.110	-13.09
2534.40					
A path H2O out	47	0.7843	92.98	0.110	-1147.41
1400.08					
B path Gas in	45	1.067	30.53	4.107	5.63
B path Gas out	48	1.046	60.00	4.107	35.65

Mode: Design

Heat transfer = 123.3 kW, Heat loss = 1.245 kW

UA = 2.671 kW/C, Pinch = 32.98 C

A path pressure drop = 0.0157 bar, B path pressure drop = 0.0209 bar

Makeup/Blowdown (s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]

Makeup/Blowdown[14]:

H2O in	1	0.7843	38.73	1.576	-2385.31
162.18					
H2O out	18	0.7843	26.61	3.211	-2435.79
111.69					

Makeup flow = 1.635 kg/s Temp = 15 C Enthalpy = 63.04 kJ/kg

Mixer (s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]

Mixer[15]:

H2O 1 in	15	0.7689	92.45	0.604	-1709.07
838.41					
H2O 3 in	52	0.7689	26.61	2.717	-2435.79
111.69					

```

H2O out          19    0.7689    58.25    3.321  -2303.66
243.82
-----
-----

```

None clockwise inlet flow(s) throttled

Mixer[37]:

```

-----
H2O 1 in         47    0.7843    92.98    0.110  -1147.41
1400.08
H2O 2 in         29    0.7843    26.61    0.494  -2435.79
111.69
H2O out          51    0.7843    82.60    0.604  -2201.54
345.95
-----
-----

```

None clockwise inlet flow(s) throttled

SCR(Conventional boiler) (s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]

SCR(Conventional boiler) [16]:

```

-----
Gas in           22    0.9279    178.95    5.594   185.52
Gas out          20    0.9204    178.95    5.594   185.52
-----
-----

```

Mode: Thermodynamic Design

Catalyst Type: dirty fuel new SCR

NOx reduction effectiveness = 80 %; NOx removed = 0.0002 tonne/hr

Pressure drop = 7.472 millibar

Inlet NOx = 6 ng/J; = 20.02 mg/Nm³ @ 6% O₂, dry; = 9.752 ppmv @ 6% O₂, dry

Outlet NOx = 1.2 ng/J; = 4.004 mg/Nm³ @ 6% O₂, dry; = 1.95 ppmv @ 6% O₂, dry

NOx removed = 0 kg/s; NH₃ consumed = 0 kg/s

SCR power consumption = 0.0573 kW

Splitter(s)

Stream H	No	P [bar]	T [C]	M [kg/s]	H* [kJ/kg]
=====					
=====					
Splitter[17]:					

Gas in	6	0.9279	178.95	12.431	185.52
Gas 1 out	21	0.9279	178.95	6.837	185.52
Gas 2 out	22	0.9279	178.95	5.594	185.52

None clockwise outlet flow(s) throttled					
=====					
=====					
Splitter[18]:					

H2O in 2927.28	35	10.00	243.08	3.759	379.80
H2O 2 out 2927.28	23	10.00	243.08	3.759	379.80
H2O 3 out 2927.28	24	10.00	243.08	0.000	379.80

None clockwise outlet flow(s) throttled					
=====					
=====					
Splitter[19]:					

H2O in 2598.06	36	1.300	107.13	3.759	50.57
H2O 2 out 2598.06	25	1.300	107.13	1.879	50.57
H2O 3 out 2598.06	26	1.300	107.13	1.879	50.57

None clockwise outlet flow(s) throttled					
=====					
=====					
Splitter[20]:					

H2O in 2534.40	37	0.8000	93.51	1.879	-13.09
H2O 2 out 2534.40	27	0.8000	93.51	1.576	-13.09

H2O 3 out	28	0.8000	93.51	0.303	-13.09
2534.40					

None clockwise outlet flow(s) throttled

Splitter[21]:

H2O in	18	0.7843	26.61	3.211	-2435.79
111.69					
H2O 1 out	29	0.7843	26.61	0.494	-2435.79
111.69					
H2O 3 out	30	0.7843	26.61	2.717	-2435.79
111.69					

None clockwise outlet flow(s) throttled

Splitter[23]:

Gas in	17	1.026	103.78	4.107	80.33
Gas 2 out	33	1.026	103.78	1.643	80.33
Gas 3 out	34	1.026	103.78	2.464	80.33

None clockwise outlet flow(s) throttled

Splitter[36]:

H2O in	28	0.8000	93.51	0.303	-13.09
2534.40					
H2O 2 out	49	0.8000	93.51	0.194	-13.09
2534.40					
H2O 3 out	50	0.8000	93.51	0.110	-13.09
2534.40					

None clockwise outlet flow(s) throttled

Splitter[22]:

H2O in	26	1.300	107.13	1.879	50.57
2598.06					
H2O 2 out	31	1.300	107.13	0.000	50.57
2598.06					

```

H2O 3 out          32      1.300    107.13    1.879    50.57
2598.06
-----
-----

```

```

None clockwise outlet flow(s) throttled
=====
=====

```

Stack(s)

```

Stream              No      P      T      M      H*
H
                   [bar]   [C]   [kg/s]  [kJ/kg]
[kJ/kg]
=====
=====

```

```

Stack[24]:
-----
-----

```

```

Gas in              7      1.013    150.30    5.594    150.44
-----
-----

```

```

Type: Main stack
Mode: Thermodynamic Design
Pressure drop (inlet to ambient) = 0 millibar
Outlet dust load = 0.0075 ng/J; = 0.0243 mg/Nm^3 @ 6% O2, dry
Outlet SO2 = 171.2 ng/J; = 554.2 mg/Nm^3 @ 6% O2, dry; = 193.9 ppmv @ 6%
O2, dry
Plume visibility index = 0.25, Plume visible
Water dew point = 72.11 C, Sulfur dew point = 130.1 C
Gas composition [Mole %]
O2 = 0.201% CO2 = 12.855% H2O = 33.677% N2 = 52.618% Ar = 0.631% SO2 =
0.018%
SO3 ppm = 1.008 CO2 mass flow = 1.181 kg/s
=====
=====

```

Steam Turbine(s)

```

Stream              No      P      T      M      H*
H
                   [bar]   [C]   [kg/s]  [kJ/kg]
[kJ/kg]
=====
=====

```

```

Steam Turbine[25]:
-----
-----

```

```

H2O in              41      40.00    400.00    3.759    668.02
3215.51

```

H2O out	35	10.00	243.08	3.759	379.80
2927.28					

Mode: Thermodynamic Design; Type of inlet control: Sliding
Type of Performance: Normal
Shaft power = 1081.2 kW Mechanical loss = 2.167 kW Current RPM = 3600
Dry step efficiency = 85 % Overall apparent isentropic eff. = 82.04 %
Actual nozzle area = 0.0009 m^2 Number of steps = 6
Inlet pressure = 40 bar Pressure after inlet loss = 36.8 bar
Exit pressure = 10 bar enthalpy = 2927.3 kJ/kg steam superheat = 63.2 C
=====

Steam Turbine[26]:

H2O in	23	10.00	243.08	3.759	379.80
2927.28					
H2O out	36	1.300	107.13	3.759	50.57
2598.06					

Mode: Thermodynamic Design; Type of inlet control: Sliding
Type of Performance: Normal
Shaft power = 1235 kW Mechanical loss = 2.475 kW Current RPM = 3600
Dry step efficiency = 85 % Overall apparent isentropic eff. = 85.92 %
Actual nozzle area = 0.0027 m^2 Number of steps = 5
Inlet pressure = 10 bar
Exit pressure = 1.3 bar enthalpy = 2598.1 kJ/kg steam quality = 0.9604
=====

Steam Turbine[27]:

H2O in	25	1.300	107.13	1.879	50.57
2598.06					
H2O out	37	0.8000	93.51	1.879	-13.09
2534.40					

Mode: Thermodynamic Design; Type of inlet control: Sliding
Type of Performance: Normal
Shaft power = 119.4 kW Mechanical loss = 0.2393 kW Current RPM = 3600
Dry step efficiency = 85 % Overall apparent isentropic eff. = 81.5 %
Actual nozzle area = 0.0109 m^2 Number of steps = 1
Inlet pressure = 1.3 bar
Exit pressure = 0.8 bar enthalpy = 2534.4 kJ/kg steam quality = 0.9424
=====

Steam Turbine[28]:

H2O in	27	0.8000	93.51	1.576	-13.09
2534.40					
H2O out	38	0.0689	38.74	1.576	-281.18
2266.31					

Mode: Thermodynamic Design; Type of inlet control: Sliding
Type of Performance: Normal
Shaft power = 421.7 kW Mechanical loss = 0.8451 kW Current RPM = 3600
Dry step efficiency = 85 % Overall apparent isentropic eff. = 79.24 %
Actual nozzle area = 0.0114 m^2 Number of steps = 4
Inlet pressure = 0.8 bar
Exit pressure = 0.0689 bar enthalpy = 2266.3 kJ/kg steam quality = 0.8731
=====

Superheater(s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]

Superheater[30]:

Steam in	12	40.80	251.51	3.759	252.33
2799.82					
Steam out	41	40.00	400.00	3.759	668.02
3215.51					
Gas in	11	0.9634	552.10	12.431	669.91
Gas out	40	0.9609	458.65	12.431	543.66

Mode: Design
Heat transfer to water-side = 1562.5 kW, Heat loss = 11.81 kW
UA = 8.768 kW/C, DTlgm = 178.2 C
Gas flow = 12.43 kg/s, outlet temperature = 458.6 C, outlet enthalpy = 543.7 kJ/kg
Flyash flow = 0.0426 kg/s, Heat transfer rate = 4.821 kW
Gas-side pressure drop = 2.491 millibar, water-side pressure drop = 0.8 bar
=====

Water Pump(s)

Stream	No	P	T	M	H*
H					

[kJ/kg] [bar] [C] [kg/s] [kJ/kg]

=====

Water Pump[31]:

H2O in	8	1.658	104.80	3.778	-2108.06
439.42					
H2O out	42	41.62	105.67	3.778	-2101.42
446.07					

Pumping power = 25.11 kW Shaft power required = 25.89 kW
 Mech. loss = 0.7767 kW Mech. eff. = 97 %
 Overall apparent isentropic eff. = 62.96 % Isentropic eff. = 85 %
 Overall pressure rise = 39.96 bar
 Pressure rise (before control valve) = 53.94 bar
 Design point RPM = 3600
 Design mode

=====

Water Pump[38]:

H2O in	30	0.7843	26.61	2.717	-2435.79
111.69					
H2O out	52	0.7689	26.61	2.717	-2435.79
111.69					

Hydraulic power = 0 kW Shaft power produced = 0 kW
 Mech. loss = 0 kW Mech. eff. = 97 %
 Overall apparent isentropic eff. = 100 % Isentropic eff. = 100 %
 Overall pressure rise = 0 bar
 Pressure rise (before control valve) = 0 bar
 Design point RPM = 3600
 Design mode

=====

Water-cooled Condenser (PCE) (s)

Stream	No	P	T	M	H*
H					
		[bar]	[C]	[kg/s]	[kJ/kg]

=====

Water-cooled Condenser (PCE) [1]:

Steam in	38	0.0689	38.74	1.576	-281.18
2266.31					
Cnd. @ hot well	1	0.7843	38.73	1.576	-2385.31
162.18					
CW in	43	1.013	20.83	79.263	-2460.00
87.49					
CW out	39	0.6685	30.83	79.263	-2418.16
129.33					

 Mode: Thermodynamic Design
 Condenser pressure = 0.0689 bar, Saturation temperature = 38.74 C
 Condenser heat rejection (per unit) = 3316 kW
 Steam mass flow (per unit) = 1.576 kg/s
 Cooling water flow (per unit) = 79.26 kg/s, Inlet = 20.83 C, Exit = 30.83 C
 Cooling water pressure drop = 0.3447 bar
 Water head to condensate outlet = 3.658 m
 =====
 =====

Wet Cooling Tower (PCE) (s)

Stream	No	P	T	M	H*
H		[bar]	[C]	[kg/s]	[kJ/kg]
[kJ/kg]					

=====

Wet Cooling Tower (PCE) [29]:

Water in	39	0.6685	30.83	79.263	-2418.16
129.33					
Water out	43	1.013	20.83	79.263	-2460.00
87.49					

Mode: Thermodynamic Design
 Cooling tower total heat rejection = 3316 kW
 Water temperature range = 10 C, Approach to wet bulb = 10 C
 Cycles of concentration = 5, Basin temperature = 20.83 C
 Water evaporated = 1.029 kg/s, Blowdown = 0.2573 kg/s, Makeup = 1.287 kg/s
 Blowdown temperature = 20.85 C, Makeup water temperature = 20 C
 Exit air flow = 65.35 kg/s Inlet wet bulb = 10.83 C Exit wet bulb = 26.83 C
 Plume visibility index = 0, Plume invisible
 Fan electricity consumption (total) = 14.72 kW
 Water flow into tower / Air flow into wet tower, L/G = 1.232
 =====
 =====