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Generating Electricity from a 10 MW MSW combustion plant in the area of Athens, Greece: A Feasibility Study

By

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Declaration of author's rights

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This work is dedicated to my father, Panagiotis Papagiannakis.

Abstract

The aim of this Thesis is to perform a feasibility assessment on the development of a 10 MW MSW combustion plant for the area of Athens, Greece. The 10 MW MSW combustion plant is planned to be built in the Industrial Zone of Athens (OINOFYTA area), which is situated in a distance of 60 km from the city's centre. This particular site will utilise local MSW producing electricity for the city. Apart from power production benefit, its operation would provide an effective means of dealing successfully with the industrial and municipal waste-handling problem, which has escalated to enormous proportions in the last five years in Athens threatening the prosperity of the area. The feasibility study covers the areas of Plant Set-up Analysis, Thermodynamic Cycle Assessment, Economic Assessment and Environmental Impact Assessment. The student is undertaking the role of the engineer called to assess the potential venture.

Contents

CHAPTER 1- Introduction

Biomass

Biomass accounts for all the living matter, which exists in the thin layer of Earth called the Biosphere. Based on the cyclic process, which involves energy supplied from the sun, through storage in plants and eventual natural recycling via a series of chemical and physical processes in plants, the atmosphere, the living matter and eventually radiation from the Earth as low-temperature heat, biomass is thus potentially an enormous store of energy, which is restored continuously.

Biomass comprises a potential source of energy utilisation for humans. Today, efforts are focused in capturing biomass at the stage of stored chemical energy, which in turn is providing a fuel. Biomass is considered by many as a ‘green’ process for fuel production; providing the restraint that the human consumption doesn’t exceed the natural level of recycling, in bio-fuels there is no additional generation of heat as well as carbon dioxide, which could have both been emitted during any conventional fuel production process. If consumed ay this rate, no detrimental environmental effects will occur and thus a new sustainable system of energy production is available for further utilisation and exploitation.

Biofuels

According to the UK Energy Technology Support Unit, ‘bio-fuels are any solid, liquid or gaseous fuels produced from organic materials, either directly from plants or indirectly from industrial, commercial, domestic or agricultural wastes. They can be derived from a wide range of raw materials and produced in a variety of ways. These include the energy derived from waste residues’ utilisation, either of organic origin (e.g. plants, animal by-products) or of urban and industrial wastes and the majority of the content of each household’s dustbin’ (ETSU, 1991).

Energy from waste

The generation of energy from waste burning is a concept that has received a huge wave of interest and in the main, broad acceptance from various countries including both members of the European Union and the rest of the world in the last fifteen years. Its practical deployment, which features the development of MSW combustion units, is in various stages of progress for the majority of these countries. At the current time, Austria leads in the generation of energy from waste field in Europe, currently having several units in operation, which utilise the local waste efficiently. Other countries such as Germany, Denmark and the United Kingdom follow at a steady and methodical pace.

What is MSW?

According to the US Environmental Protection Agency the term MSW accounts for Municipal Solid Wastes, which describes 'the stream of garbage generated by households, commercial establishments, industries and institutions. MSW consists of everyday items from product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, plastics to paint and batteries. It does not include medical, commercial and industrial hazardous or radioactive wastes, which must be treated separately' (US Environmental Protection Agency).

Waste to Energy plants

There are two discrete configurations of waste to energy plants, which are designated separately according to their characteristics and codes of operation: the refuse-derived fuel plant and the mass-burning plant. Their operation is differentiated by one characteristic element, which takes place before MSW is combusted: in an RDF plant separation of non-combustible particles is undertaken by MSW shredding. By comparison, in a Mass-Burning plant the MSW is not separated, but is combusted directly in much the same way as fossil fuels are used in other combustion technologies. Apart from this fundamental difference, both plants combust MSW by following an identical set-up, converting water into steam to drive a turbine connected to an electricity generator/gearbox formation.

The refuse-derived fuel plant employs mechanical processes to shred incoming MSW separating the non-combustibles in order to produce a high-energy fuel fraction and thus improved efficiency. One of the most appealing aspects of RDF is that it can be employed as a supplementary fuel in conventional boilers. Furthermore, RDF's energy content is around half that of UK's industrial coals and nearly two thirds that of low grade US coal.

By contrast, the Mass Burning Plant is designed to burn unprocessed MSW directly in boilers. The combustion takes place in furnaces under specified conditions of excess air. Removal of bulky objects in some cases is suggested as a minimal stage of pre-processing for mass-burn units. Nevertheless, the efficiency of the fuel flow is satisfactory whether or not this practice is followed.

Biomass in Greece

Although Greece is well regarded as one of the few countries that has developed and supported implementation of a range of renewable technologies for energy generation, based on solar trends (photovoltaics) and wind turbines, unfortunately it remains reluctant to embrace the prospects offered by the utilisation of Biomass. The reasons for this view can be largely attributed to a lack of financial incentives as well as technological drawbacks both of which have rendered Greece inactive in this area of renewable technologies: Priority has been given to the utilisation of wind turbines technology and solar systems due to the huge wind and sunlight potential of the country and this potential has translated into financial benefits for individual investors and the Government alike. From a technological point of view, until recently, the primary focus of the local industry was targeted on the technological development of the wind turbines and solar systems technologies because it was felt that there was a market niche to be exploited, leaving no space for the research and development of other options such as Biomass.

However, over the last five years there has been a dramatic shift of policy and interest: although the wind turbines and the solar systems technologies are still profitable, Biomass and especially Energy from Waste has risen on the agenda and has gone through intense debate in respect of whether or not it can make a useful energy contribution and be financially viable to be introduced in Greece. The reason for such a change in the country's official position has been the exponentially escalating problem of wastes dumping, which is taking place in designated and non-designated disposal sites around Athens and other major cities in Greece and threatens to destroy an already pollution damaged ecological system as well as result detrimental effects in public health.

Although strong legislation put into force in the recent years has successfully dealt with the various emissions problems from local industry, the Government has remained intransigent in terms of predicting the inception of the waste problem in the past. Greece is already facing a court case and a legal suit from the European Union due to its incapability to deal effectively and permanently with the issue of waste disposal. At this point it should be highlighted that each individual Greek citizen creates only one third of the quantity of waste generated by any other citizen in the European Union. That percentage translates to 0.74 kg daily, which isn't high by any means. The problem focuses more on where this waste is stored due to the shortage of suitable sites.

Nevertheless, these dumped quantities of waste can provide an excellent source of MSW for energy production. The development of Energy to Waste plants in the major cities could provide an effective and permanent solution to the waste problem Greece is facing at the current time. Energy to Waste plants could combust large quantities of MSW and generate power solving the waste problem, complying with the energy legislation and satisfying the local power need simultaneously. However, as yet, no positive moves by the local Government have been taken place in this direction.

The current study will undertake a feasibility assessment for a 10 MW Municipal Solid Waste plant for the area of Athens, Greece. The plant is anticipated to be built in the Industrial Zone of Athens (OINOFYTA area), which is situated in a distance of 60 km from the city's centre. This particular site possesses a number of interesting features - the most distinctive one being the proximity to the designated

MSW dumping sites of East Athens (17 out of a sum of 27 areas that exist in Athens).

Reasons for performing the feasibility study

The study is undertaken from the viewpoint of a real feasibility study in order to attempt to emulate the constraints that would be imposed by a commercial investor. This consultancy allocation accounts as an issue of particular engineering interest because it exposes the student to a rapidly developing technology, which he is called to investigate in depth before deciding about its degree of suitability for further development in his native country. Moreover, it acts as a vehicle to study and comment on an existing problem in Athens, which has social, environmental and health implications.

Throughout the assessment of the study, a strong effort is made to retain the level of objectivity in terms of presenting the case objectively and commenting on the suitability of the potential venture for further development according to the sources and data available during the time the investigation took place. It was also intended from the outset to assess the project independently and without bias in order to maintain integrity and objectivity in the recommendations presented at the end of the study.

Why a Mass-Burning plant and not an RDF plant?

From the outset, one of the fundamental aspects to be assessed was which Waste to Energy plant configuration would be the most suitable to apply in the current situation.

The advantages of the mass-burn plant type are numerous: negligible front-end processing of the MSW is demanded before the combustion takes place eliminating a significant source of expense. Furthermore, mass-burn facilities are considered easy to maintain and operate. On the other hand, because of the heterogeneous nature of the pre-combusted MSW, high quantities of excess air are needed for proper combustion, employing a larger boiler and flue gas cleaning system when compared with a facility using RDF technology for the equivalent quantity of MSW.

The advantages of the refuse-derived fuel plant type are focused mainly on the relatively higher energy content of the RDF fuel, which originates from the pre-combustion separation processing. In monetary terms however, the financial evaluation of already operational refuse-derived fuel plants indicates a different issue: The RDF set-up demands an increased up-front capital investment (Steam Plant Operation, sixth edition, 1992).

After careful and detailed examination of all aspects presented above as well as taking into account the financial intensiveness of the project for the external investor, the decision was made to explore the option of the Mass Burning type of Waste to Energy plant for the area of Athens, Greece.

CHAPTER 2- Plant Set-up Analysis

Introduction:

This chapter provides a detailed breakdown of the 10 MW MSW combustion plant apparatus including technical information for the most important parts of the site. The aim of this chapter is to gain familiarity with the plant's main constituent units, which is required in order to understand in depth its operation for the work that follows later on. As a necessary step towards the achievement of this goal, the unit is grouped in five sections (Systems) according to each System's designated function. A sixth section designated as Plant Engineering highlights the interconnecting mediums (pumps, connectors) that link the systems together into a unit. All systems are presented in Tables below and additional details are provided individually for each one. Furthermore, an illustration of the plant set-up is provided in Figure 2.1 at the end of the chapter.

Systems Breakdown

Table 2.1: Preparation, Fuel Handling and Ash Disposing Systems

Air Injection System in the combustion Chamber	Feeding System	Ash Disposing System
Air Filter	MSW Collection Pit	Ash Burnout Grate
Forced Draft Fan	Feed Chute	Shiftings Conveyor
Steam Air Heater	Ram Feeder	Ram Extractor
Wind Box		Bottom Ash Conveyors

MSW Collection Pit

Before mass burning takes place at the Rotary Water Walled Furnace, MSW is unloaded into the collection pit or bunker from dustcarts. The MSW collection pit is developed according to strict EU standards of safety and hygiene, which demand the elimination of odour and dust particles generated from the MSW unloading in the adjacent areas to the pit.

The pit's size will vary according to the daily consumption of MSW required to cover the plant's power generating specifications. Most notably, the quantity of MSW stored must be twice the quantity of MSW consumed daily to cover the plant's power generating specifications. This analogy is by no means accidental, in fact it is considered as one of the most important actions that must take place, so that unfortunate situations such as the risk of a fire in the premises are minimised: when MSW remains stored in collection pits for a period of more than three days, temperatures ranging from 90 °C to 100 °C can build up within the mass of waste and in combination with gases such as methane that develops from rotting waste can cause a fire to start that can lead to considerable damage to various areas of the plant. The collection pit must be well lit to allow observation and fire extinguishers must be available in adjacent areas to it and its minimum width must be 8 m.

Air Filter, Forced Draft Fan, Steam Air Heater, Wind Box

In order to achieve the most efficient combustion of the MSW in the Rotary Water walled Furnace, excess air is injected in a percentage of no more than 45% (Steam Plant Operation, Sixth Edition, McGraw-Hill Inc., 1992). Incoming air from the external environment passes through an air filter. Next, it is heated by a steam air heater and introduced by a forced draft fan to the wind box configuration. The wind box is an array of insulated tubes supplying hot combustion air to the Rotary Water walled Furnace in the pre-combustion phase.

Feed Chute, Ram Feeder

MSW enters the feed chute by a conveyor of crane. The feed chute directs the MSW to a ram feeder, which carries it to the Rotary Water Walled Furnace for combustion. There are several types of Ram Feeders; the most widely used being the Worm type, the Propulsive type and the Cylindrical type. For the current case of the MSW combustion plant, the Propulsive type is employed.

The Propulsive ram feeder passes through the Rotary Water Walled Furnace and features four zones of treatment for the MSW; during the first two stages the

MSW is dried and an initial burning is manifested. The third and fourth stages are where the primary burning occurs. The hot combustion air is provided via the wind box and is directed from the bottom of the feeder upwards under pressure. The ram feeder is constructed by chromium cast-iron and the inclination given to the structure is considered a factor of pivotal importance for its effective operation.

Ash Burnout Grate, Shiftings Conveyor, Ram Extractor, Bottom Ash Conveyors

The combustion's by-products, which include inert ash at their majority as well as a small quantity of metal particles, are lead to the ash disposing areas via the shiftings conveyor. Just before their final disposal, the collection of the metal particles is taking place employing magnets at the Ram Extractor. The inert ash left is stored at bottom ash conveyors.

Table 2.2: Rotary water walled furnace

Rotary Water walled Furnace

Rotary Water Walled Furnace

One of the most recent improvements in boiler design and the configuration chosen for this MSW plant due to its highly efficient energy recovery, is the water walled furnace, which offers several advantages compared with other configurations such as refractory lined furnaces. Compared with the latter, the rotary water walled furnace features a leak proof enclosure, which eliminates phenomena such as gas leakage and corrosion of casing. Refractory maintenance concerns are also eliminated. Moreover, the furnace expands and contracts uniformly as a unit. This results in the elimination of relative expansion problems that occur between water-cooled walls and refractory lined casings.

For a designated volume, the rotary water walled design features lower heat release rates on area basis due to the larger effective projected area occupied during combustion, which lower effectively the heat fluxes. Depending on the furnace's dimensions, the improvement in performance ranges between 5% and 15%. The furnace exit gas temperatures are also lower. A cool environment at the flame front area due to the design also results in a reduction in the NO_x emissions produced during combustion.

The combustor is constructed of boiler water tubes connected by perforated steel webs, which allow pre-heated air to enter the combustor. A steel casing surrounds the rotary barrel. The combustor's rotating mode is set at 7 revolutions per hour. The rotation enables the MSW to tumble down the axis of the combustor allowing an excellent means of drying the material before combustion. Burning occurs in four stages in the combustor: During the first two stages the MSW is dried and an initial burning is manifested. The third and fourth stages are where the primary burning occurs and temperatures reach the 600 °C for the specified unit. Highly turbulent airflow is created due to the rotating action of the combustor that leads to an effective burnout in a little excess of air scheme. After about 50-55 minutes in the combustor, the remaining MSW and ash fall onto an after burning grate where any combustibles still present are burned before the ash is directed into the ash collection area.

Table 2.3: Boiler and Feed Heating Systems

Boiler	**Feed Heating System**
Super Heaters	Closed Feed water Heaters (5)
Condenser	Open Feed water Heater (1)
Economiser	

Superheaters

Steam that is heated above the temperature corresponding to its saturated vapour pressure is termed superheated. This steam contains more heat compared with saturated steam at the same temperature. This added portion of heat provides a surplus of energy to a turbine for conversion to electric power. Superheated steam can be transmitted over long distances with only an infinitesimal heat loss. The process also reduces condensation effectively and problems such as erosion of turbine blades are reduced to a minimum due to the absence of moisture in the steam.

The superheater surface is the surface, which concentrates steam on one side and hot gases on the other. Hence, the tubes are dry except for the steam that circulates them. A uniform distribution of the steam enables the prevention of steam tubes overheating.

The superheaters used in this design are designated as convection and radiant types. The convection super heater is placed in the gas stream, where most of its heat is received by convection. The conventional convection superheater employs two headers into which two seamless tubes are welded or rolled. For the steam to make a pass back and forth through the connecting tubes, the headers are baffled. The headers are small and removing caps similar to those for boiler-tube access provide access to the tubes. Radiant super heaters are placed near the furnace and receive the bulk of its heat by radiation.

Employing either a convection-type or a radiant-type superheater does not guarantee that uniform steam-outlet temperature is achieved. Hence, a combination superheater is installed to achieve this goal. Steam leaving the boiler drum makes a first pass through the convection section, then to the radiant section and finally to the steam header. However, this arrangement will not guarantee the desired results, so a bypass damper is used aiming to bypass the gas or a portion of the gas around the convection section controlling the final steam-outlet temperature for various boiler ratings.

A reheater is also employed in the unit for steam reheating after the steam leaves the high-pressure area of the turbine. The incorporation of the superheater and the reheater aims to boost the overall thermodynamic plant efficiency.

Condenser

Steam condensers are vessels in which exhaust steam is condensed by contact with cooling water. The steam condensation creates a vacuum that reduces the back - pressure of the engine or turbine leading to an increase in horsepower and efficiency of the unit. The heat contained in the steam is absorbed by the cooling water, thus reducing the volume of steam as the condensation takes place. When a space filled with steam is cooled until the condensation point is reached, the resulting water occupies only a small portion of the original steam volume and a vacuum is created.

The continuous condensation of the exhaust steam reduces the pressure below the level of the atmospheric pressure.

The configuration employed for the current scenario is designated as a surface condenser. This is a closed vessel filled with tubes of small diameter. The condenser features:

- The shell, including tube support plates, hot well and connecting piece, which is fabricated by heavy steel plate welded into one uniform unit.
- Water tube boxes, which are deep and its design features large nozzles to keep water velocities down.
- The hot well, which is employed for storage requirements.
- Tubes, made of aluminium alloys and various stainless-steel compositions, rolled and expanded into the tube sheets at both ends forming a strong and resistant tube-sheet joint.
- A diaphragm-type shell expansion element, which enables the thermal expansion and contraction of the tube bundle under operating conditions.
- An air cooler, which provides full-length scavenging of the non-condensables.
- An impingement plate, placed below the steam inlet to protect the tube bundle against moisture impingement.

The water flowing through the condenser is supplied from a natural water source and may undergo a single-pass or a reverse path before being discharged. Exhaust steam enters at the top of the condenser from the turbine and passes down, around and between the tube bank tubes. Cold water is flowing through the tubes in quantities able to condense the steam. Non-condensable gases and air that find their way into the condenser must be removed in order to reduce the backpressure and prevent the re-entering of air and oxygen into the system, thus minimizing the possibilities of corrosion in the piping and the boiler.

Economiser

The economiser is a heat exchanger located in the passage between the boiler and the stack, designed to recover some of the heat from the products of combustion.

It is comprised of a series of tubes through which water flows on its way to the boiler.

There are two categories of economisers: the parallel-flow and the counter - flow. In the parallel-flow economiser, the flue gas and the water flow in the same direction. The hottest flue gases come into contact with the coldest feed water. In the counter-flow economisers, the flue gas and the water flow in opposite directions. The latter type, which applies to the unit under examination, is considered to be more efficient resulting an increased heat absorption scheme. During operation, feed water enters at the one end of the economiser and is directed to the steam drum through a complicated system of tubes and headers. The inlet temperature of feed water at the steam drum is higher than at the inlet temperature to the economiser.

An alternative construction of economisers using flanged joints is generally preferred to the traditional header construction, due to the advantages of the latter to use a minimum number of return-bend fittings as well as not to require hand-hole fittings and gaskets and to be free from expansion difficulties. The modern economiser is comprised of a continuous coil of tubes rolled or welded into headers at each end. The advantage of this structure is based on the fact that now acid cleaning of tubes is possible and gaskets and hand-holes are eliminated.

Closed feed water heaters

A closed feed water heater is a device in which the heat in the steam is transferred through tubes, which separate the water form the steam. It is comprised by a steel or cast iron outer shell that holds the steam for heating and also houses the copper or brass tubes that supply the heat transfer surface.

Closed feed water heaters can be classified by the number of times the water transverses the length of the unit before being discharged: these types are one-, two-, three- or four-pass. In the current case, the closed feed water heaters employed are classified as two-pass. The rates of expansion of the shell and tubes parts of the closed feed water heaters vary due to the dissimilar nature of the metals from which they are constructed. Several methods have been developed over the years to compensate for this difference in expansion rates with the most widely used one being the packing of each tube so that it can independently expand from the shell.

Other methods include the building of heaters without using packed joints between the tubes and the tube sheet, where the tubes are bent into the form of the letter U as well as building floating-head-type heaters, which are comprised of separate tubes, sheets and cover parts that are free to expand inside the shell.

In the closed feed water set-up, no mixing of steam and water takes place. The application of a pump to force water through several heaters is a common practice allows utilisation of the steam from several extraction points in the steam turbine. Closed feed water heaters are unsuitable for heating hard water as the formation of deposits that occur in the tubes' surfaces restrict the flow and retard heat transfer.

Open feed water heater

The open feed water heater or de-aerator is a device in which the steam and water come into direct contact and the effluent is the combination of the inlet water and the supply steam. Design characteristics encourage the temperature of the outlet water to approach the saturation temperature of the supply steam in contrast to the closed feed water heaters where the steam and water are separated by tubes through which the heat is transferred.

Open heaters are used for feed water heating that also provides some additional functions: The combined make-up water and condensate is introduced into the heater through a spray system and provides a satisfactory mixing of the water and steam. This process path leads to the rapid heating of water and the removal of oxygen and other non-condensable gases, which are vented by the heater. The heated and de-aerated water is stored in a section of the heater or in an additional tank. The level of water existing in this tank controls the flow of the make-up water to the heater. When the level in the storage tank drops, the supply of make-up water to the heater takes place via valves.

Table 2.4: Steam Turbine Generator

Steam Turbine System
High-Pressure Turbine
Medium-Pressure Turbine
Low-Pressure Turbine
Generator/Gearbox

Extraction Turbine

Alternatively known as a high-pressure to intermediate to low pressure configuration, this type of steam turbine used in the current study features openings in its casing for the extraction of a portion of the steam at some intermediate pressure before the remaining steam condenses, establishing a superheated-reheated steam pattern that aims to optimise the thermodynamic efficiency of the plant. The steam extraction pressure may or may not be automatically regulated. This regulated extraction enables additional steam flow through the turbine to generate additional electricity during periods of low thermal demand.

Numerous mechanical designs are now available that feature various limits of thermodynamic and electrical generating efficiencies. The steam turbine thermodynamic efficiency defines how efficiently the turbine extracts power from the steam itself. The electrical generating efficiency for a steam turbine is defined as the ratio of net power generated to the total fuel input into cycle. During operation, the steam expands through a high-pressure ratio and the steam begins to condense in the turbine when the temperature of the steam drops below the saturation temperature at that pressure. Blade erosion occurs from the drops' impact on the blades if water drops are formed in the turbine. At this particular point of the expansion, the steam is returned to the boiler for re-heating to high temperature and then returned to the turbine for further expansion.

Design Characteristics of Extraction Turbine used in 10 MW MSW combustion plant

The turbine casing is horizontally split. Two materials have been specified for the high-pressure section: low-alloy steel for intermediate steam pressure and temperature applications and a medium-alloy steel for high steam pressure and temperature applications. The shaft is made of forged steel. Two types of shaft material have been specified: low-alloy steel for low-pressure applications and high-alloy steel (13% chromium steel) for high-pressure applications.

The front and rear sections of the turbine are identical. The intermediate section has been designed to accommodate intermediate pressure valves. Cylindrical moving blades of reaction stage(s) have 'T' roots and integral shrouds. Two materials are employed for the construction of the moving blades: 13% chromium steel with molybdenum and vanadium is applied for temperatures over 350 °C and 13% chromium steel is used for lower temperatures. The reaction stage fixed blades are cantilevered in the blade carriers and held together by a riveted shroud or inserted in the blade carriers as complete diaphragms. They are made of 13% chromium steel.

There is an emergency stop valve (Push-to-Close type), which protects the turbo-unit against the un-wanted effects of over-speed. The valve's response time is set at 50 milliseconds and possesses a high reliability factor. It is installed on each live steam inlet flange and is mounted directly on the casing, thus minimising the steam volume that continues to expand through the turbine after valve closure. The steam extraction can be performed by bleeding or controlled by one or more intermediate pressure controls. Tilting-pad journal bearings are used in general. Double acting, tilting-pad thrust bearings are installed with a thrust equalising device. Both journal and thrust bearings are fitted with thermo-elements for temperature detection and monitoring. Labyrinth-type end seals are applied. Lubrication and control oil systems have a common reservoir, pumps, filters and coolers.

(Source: Nuovo Pignone)

Generator/Gearbox

The Gearbox is positioned between the slow motor shaft and the fast generator shaft. This device, the generator allows shaft to run at approximately

70 times faster than the rotor shaft. This is necessary, as the generator has to rotate at a much higher speed than the rotor. The gearbox transports the entire power output from the rotor to the generator.

Table 2.5: Stack Gas Clean Up and Pollution Controls

Dry Scrubber System
Dry Scrubber
Baghouse
Ash Recycle System
Induced Draft Fan
Stack

Dry Scrubber System

Dry scrubbing is currently the most rapidly developing technology in the area of sulphur dioxide removal from the flue gas of MSW fired boilers. As a process, it results in the production of a dry product e.g. fly ash and the maintenance of the flue gas above the moisture dew point. Other acid gases are also removed in addition to sulphur dioxide such as hydrogen chloride and particulate matter. During dry scrubbing, the heat in the flue gas at the air heater outlet is used to dry and condition the atomised slurry of alkaline reactants. The majority of the sulphur dioxide present is collected from the flue gases. The remaining material with the normal fly ash in the flue gas is then collected in the baghouse. Effective ash handling is undertaken in an ash recycle system.

Dry scrubbers are defined in two categories by virtue of their design: the Rotary Atomizer formation, which is incorporated at the particular site in research, and the Dual Fluid Nozzles formation, which utilises nozzles with fluid atomisation, quite to these used in liquid fuels combustion. In the rotary atomiser set-up, gas and reagent flow pattern symmetry is achieved and the flue gas dispenser system that is additionally provided mixes the large gas volumes involved. The rotary atomiser is placed on the vertical centre line of the spray dryer absorber and the flue gas runs around the atomiser from above and below. The atomiser is equipped with a vertically mounted motor, of which the spindle speed can vary according to the design of the gear drive.

The liquid slurry enters the rotating wheel and is accelerated and atomised at the wheel's multiple nozzles forming a spray of droplets. This spray leaves the nozzles in a horizontal direction at a 180° spray angle. To assure complete drying, a high volume of flue gas, entering at a temperature of 175 °C must be treated with a relatively small amount of reactant slurry. This implies that as the plant size increases, the dry absorber's dimensions increase faster than the dimensions of the atomiser itself, and gas contact with the cloud of reagent droplets occurs further away from the atomiser wheel. This results the inlet flue gas' division into two streams in order to balance the cloud of droplets. As the flue gas comes in contact to the fine lime slurry droplets cloud, it dries them as they react with the sulphur dioxide in the flue gas to form dry calcium sulphate and calcium sulphite powders.

The flue gas exits the spray dryer absorbers carrying a quantity of dry reacted chemicals to the baghouse. Baghouse formations are characterised according to the method they employ for fly ash removal from the filter medium. An additional reaction takes place between the dry chemicals and flue gas during the removal of the particulates. Baghouse formations remove more than 99.9% of the fly ash from the flue gas. From the baghouse, flue gas is directed to an induced-draft fan and then exits to the atmosphere through the stack. The waste-product material and fly ash quantities received from the spray dryer absorbers and the baghouse are totally dry. These products are transported pneumatically or mechanically to collection areas and stored.

Table 2.6: Plant Engineering

Pump System
Condensate pump
Boiler Feed water pump
Forced circulation Pump
Spray Attemperator
Rotary connector

Spray Attemperator (De-Superheater)

A factor of pivotal importance in achieving the optimal plant efficiency demands that a constant superheat temperature is required over a load range. This requires that a sufficient surface is installed to make sure that the temperature is obtained at the minimum load condition. If higher loads are needed, the super heat temperature will exceed limits because of the amount of its installed surface, unless the temperature is controlled. A de-superheater (or attemperator) will be used to control the superheat temperature. This is achieved by mixing water with the steam at an intermediate stage of the superheater (spray-type attemperator) and will ensure the maximum steam temperature is not exceeded.

Boiler Feed water pump

The closed feed waters tube sections must withstand the water pressure and the shell must withstand the pressure of the steam. The water is forced through one or more heaters by a single pump, the Boiler Feed water pump. This would be constructed of copper or brass to supply heat transfer insulation.

Condensate Pump

A pump employed to raise pressure from the vacuum levels to 350 pounds per square inch.

Forced circulation Pump

A pump incorporating a small cooler in the seal configuration. The cooler is charged by the plant's closed-loop cooling system. Its operation is utilised mainly during start-up.

The plant apparatus breakdown took place so familiarity is gained with the plant's main constituent units. The resulted understanding of its operation is considered of pivotal importance for the evaluation the assessments following later on.

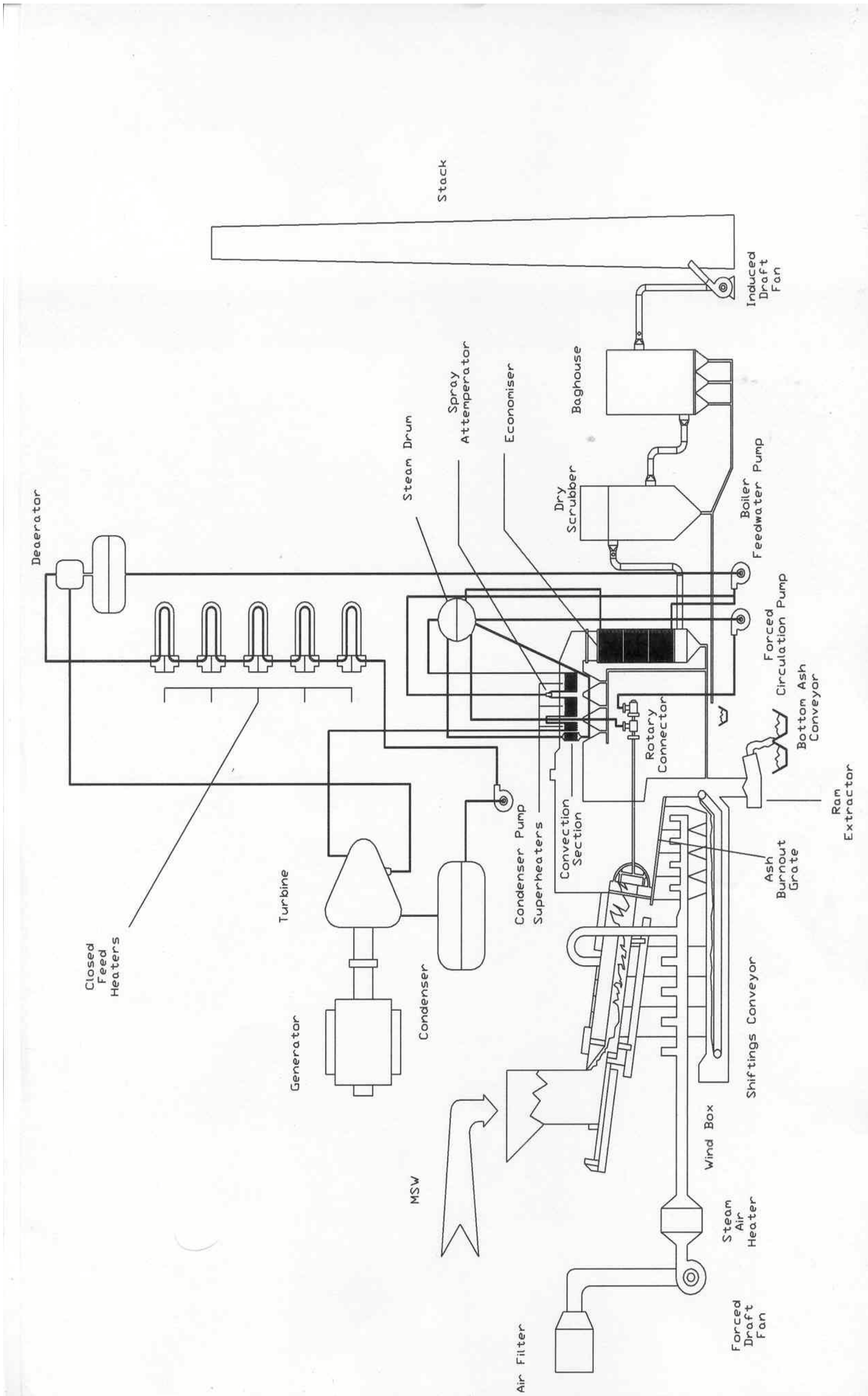


Figure 2.1: 10 MW MSW Combustion Plant Set-up

CHAPTER 3- Production Assessment:

Introduction:

The Production Assessment process aims to identify and satisfy three areas of research. Initially, the Power Potential sourcing from the MSW mass burning utilisation for the area of Athens, Greece is forecasted. At a second stage, the evaluation of the daily and annual combustible quantity of MSW is calculated in relation to the MSW combustion plants' load ranging factor. Finally, the evaluation of annual kWh production is performed taking into account the examined plant's actual load factor parameter. The concurrent evaluation of the heat flow rate (Btu/kWh) acts as a verification method to the calculations certifying their validity.

Load Factor:

The plant load factor is defined as the ratio of Actual Operational Capacity to the Optimal Operating Capacity. In the particular MSW plant the Optimal Operating Capacity is 10 MW and the Actual Operational Capacity is accounted in the range between 6.5 to 8.5 MW. According to ETSU, 'a variation of load factor in the range of 65% to 85% is considered feasible due to the plants' developed set-up complexity and capacity levels as well as the safety measures and precautions standards established by local laws and authorities' (ETSU, 1991). For the particular combustion plant in research the current load factor is defined at 75% due to the plants' developed set-up complexity and capacity levels.

Load Factor = Actual Operational Capacity / Optimal Operating Capacity (eq. 3.1)

Heat Rate:

The Heat Rate is the method of evaluating the Energy Efficiency of a plant. Energy Efficiency, in general, measures the amount of primary energy from the raw fuel needed to produce a specified amount of delivered energy. The Heat Rate is the amount of energy (Btu) in the fuel needed to produce one kilowatt-hour (kWh) of electricity. The lower the heat rate the more energy efficient the plant is. Heat rate is not applicable for wind and solar plants, since they don't use fuel in the traditional sense of the word. In case of the current study, the Heat Rate for electricity production of one kilowatt-hour is given with a value of 3412 Btu/kWh. Other average fuel conversion factors are listed below:

Source	Average Fuel Conversion Factors
Electricity	3,412 Btu/kWh
Fuel Oil	138,700 Btu/gallon
Natural Gas	1,030 Btu/cubic foot
LPG/Propane	95,500 Btu/gallon
Coal	24,580,000 Btu/ton
Purchased Steam	1,000 Btu/pound

Table 3.1

Methodology:

The method of Production assessment commences by establishing the total quantity of MSW in Athens (Tonnes/Year) and its designation in Domestic, Commercial, Street Sweeping and Industrial parties. A breakdown of the MSW in terms of the nature of the constituents follows accompanied by a % per kg estimate in three designated categories: Domestic, Commercial and Industrial. The final Average % per kg estimation aims to provide a succinct view of the Average Quantity of generated MSW (Tonnes/ Day) in relation to the MSW synthesis.

The Calorific values of the MSW synthesis components (MJ/kg) are specified values (Energy Recovery from municipal Solid Waste in Dhaka City, Bangladesh, Md. Alam Jahangir, 2002) used in order to calculate the Calorific values of Domestic, Commercial and Industrial Waste. The % percentage of Domestic, Commercial and Industrial waste is also calculated excluding the small portion of Street Sweeping. The summed product of the % percentage of Domestic, Commercial and Industrial waste times the Calorific values of Domestic, Commercial and Industrial Waste provides the Average Calorific Value of waste generated in Athens (MJ/kg). The Calorific Value of waste generated in Athens is converted in kWh/Tonne in order to evaluate the Specific Energy output per tonne of waste at a conventional thermal efficiency 35% (kWh/Tonne). Finally, the Power Potential (MW) for a plant sourcing from the MSW mass burning utilisation is estimated.

In order to estimate the daily and annual combustible quantity of MSW in relation to a load factor range from 65% to 85% the standardised values of Btu/kg of MSW according to their synthesis are introduced and an average value (Btu/kg) is calculated (Estimated average gross calorific values fuels in 2001). The selection of the average Btu/kg value designates the random collection of MSW that takes place in the feeding area before the combustor after which burning occurs.

The burning process that leads to utilisation of the MSW is completed in 60 minutes. At this stage the values of Btu/hr of a water-walled combustor for a load factor ranging between 65% and 85% are introduced. Dividing these to the Average Btu/kg value of MSW leads to the establishment of the daily and annual quantity of MSW utilised in the combustor. Ishikawajima-Harima Heavy Industries Co Ltd., who is leading manufacturers of water-walled rotary combustors, provided the Btu/hr values. The annual production of kWh follows, estimating levels of energy generated from the MSW plant for the ranging load factor parameter, which includes the actual load factor for the examined site. Finally the Heat Rate is calculated and acts as a verification tool for the validity of calculations.

Process:

MSW potential in Athens, Greece:

<table>
<tr><th colspan="2">Source-Commodity</th><th>Quantity (Tonnes/Year)</th></tr>
<tr><td colspan="2">Domestic</td><td>635000</td></tr>
<tr><td colspan="2">Commercial (including building material)</td><td>754000</td></tr>
<tr><td colspan="2">Street Sweeping (Branches, leaves etc.)</td><td>3200</td></tr>
<tr><td>Slush (biological cleaning)</td><td rowspan="4">Industrial</td><td>2700</td></tr>
<tr><td>Petroleum based substances</td><td>20000</td></tr>
<tr><td>Marble dust, sand spraying</td><td>86000</td></tr>
<tr><td>Combustor’s ashes</td><td>35</td></tr>
<tr><td colspan="2">TOTAL</td><td>1482935</td></tr>
</table>

Table 3.2

MSW Synthesis:

MSW type	**Domestic (% per kg)**	**Commercial (% per kg)**	**Industrial (% per kg)**
Organics	59.8	62	30
Paper-Carton	20.4	8.6	17.5
Glass	2.7	4.7	1.6
Plastics	7	8	13.8
Metals	2.8	1.3	4
Textiles, Wood, Leather, Elastics	3.45	11.7	25.95
Inert Matter	0.7	0.3	0.5
Miscellaneous	3.15	3.4	6.65
TOTAL	100	100	100

Table 3.3

An Average % per kg is essential to be established:

Component	**Average % per kg**	**Average MSW (Tonnes/Year)**	**Average MSW (Tonnes/Day)**
Organics	50.6	750365.11	2055.79
Paper-Carton	15.5	229854.925	629.73
Glass	3	44488.05	121.88
Plastics	9.6	142361.76	390.03
Iron and Metal Packaging	2.7	40039.245	109.69
Textiles, Wood, Leather, Elastics	13.7	203162.095	556.60
Inert Matter	0.5	7414.675	20.31
Miscellaneous	4.4	65249.14	178.76
TOTAL	100	1482935	4062.83

Table 3.4

The Calorific Value of each Waste Fraction is provided as standardised data below:

Component	Calorific Value (MJ/kg) Dry Matter
Organics	18
Paper-Carton	17
Glass	0
Plastics	40
Iron and Metal Packaging	0
Textiles, Wood, Leather, Elastics	32
Inert Matter	0
Miscellaneous	18

Table 3.5

The summed product of the Calorific Value (MJ/kg) of Dry Matter multiplied by the Domestic Waste (% per kg) and divided by the number of the Components that possess a calorific value provides the Calorific Value (MJ/kg) of Domestic Waste. The Calorific Values of Commercial and Industrial Waste occur in the same pace:

Calorific Value of Domestic Waste (MJ/kg)	3.7406
Calorific Value of Commercial Waste (MJ/kg)	4.0356
Calorific Value of Industrial Waste (MJ/kg)	4.6792

Table 3.6

The percentages of waste in individual sectors excluding street sweeping is:

MSW Waste	%
Domestic	42.400
Commercial	50.341
Industrial	7.258

Table 3.7

The Average Calorific Value of MSW waste generated in Athens is calculated by the equation:

Average Calorific Value of MSW (MJ/kg) = (3.7406 + 4.0356 + 4.6792)/3 = 3.9781 (eq. 3.2)

This value is multiplied by 1000 in order to have the MJ/Tonne analogy and is transformed to kWh/ton:

Average Calorific Value of waste generated in Athens (kWh/Tonne) = [Average Calorific Value of MSW (MJ/Tonne)/3600]*1000 (eq. 3.3)

Average Calorific Value of waste generated in Athens (kWh/Tonne)	1099.104

Table 3.8

The Specific Power output per ton of waste (kWh/Tonne) at a conventional thermal efficiency of 35% occurs by multiplying the Average Calorific Value by 0.35:

Specific Energy output per tonne of waste (kWh/Tonne)	384.686

Table 3.9

Finally the Power Potential for a plant sourcing from the MSW mass burning utilisation is calculated:

Power Potential (MW) = [(Waste Generation* Specific Energy output per tonne of waste) / Average Calorific Value of waste] / 1000 (eq. 3.4)

Power Potential (MW)	144.174

Table 3.10

This figure gives an indication of the maximum capacity level, at which an MSW plant could be developed taking under consideration a 100% mass burning utilisation of the MSW waste produced in Athens.

The values of Btu/kg of MSW are introduced below:

Component	**Btu/kg of MSW**
Organics	295.8
Paper-Carton	5381.89
Glass	0
Plastics	2565.12
Iron and Metal Packaging	0
Textiles, Wood, Leather, Elastics	613.68
Inert Matter	0
Miscellaneous	99.33

Table 3.11

The Average value of MSW: 1791.164 Btu/kg

The following Table presents the variation in values of Btu/hr of a water-walled combustor for a load factor ranging between 65% and 85%.

Maximum Operating Capacity (kW)	**Load Factor**	**Btu/hr**	**Average Btu/kg of MSW**
10000	65	22178000	1791.164
10000	66	22519200	1791.164
10000	67	22860400	1791.164
10000	68	23201600	1791.164
10000	69	23542800	1791.164
10000	70	23884000	1791.164
10000	71	24225200	1791.164
10000	72	24566400	1791.164
10000	73	24907600	1791.164
10000	74	25248800	1791.164
10000	75	25590000	1791.164
10000	76	25931200	1791.164
10000	77	26272400	1791.164
10000	78	26613600	1791.164
10000	79	26954800	1791.164
10000	80	27296000	1791.164
10000	81	27637200	1791.164
10000	82	27978400	1791.164
10000	83	28319600	1791.164
10000	84	28660800	1791.164
10000	85	29002000	1791.164

Table 3.12

The calculations presented below are executed and their results are tabulated:

Quantity of MSW in combustor (kg/hr) = (Btu/hr) / Average Btu/kg of MSW (eq.3.5)

Quantity of MSW in combustor (Tonnes/day) = (Quantity of MSW/ 1000)* 24 (eq.3.6)

Quantity of MSW in combustor (Tonnes/Year) = MSW (Tonnes/day)*365 (eq. 3.7)

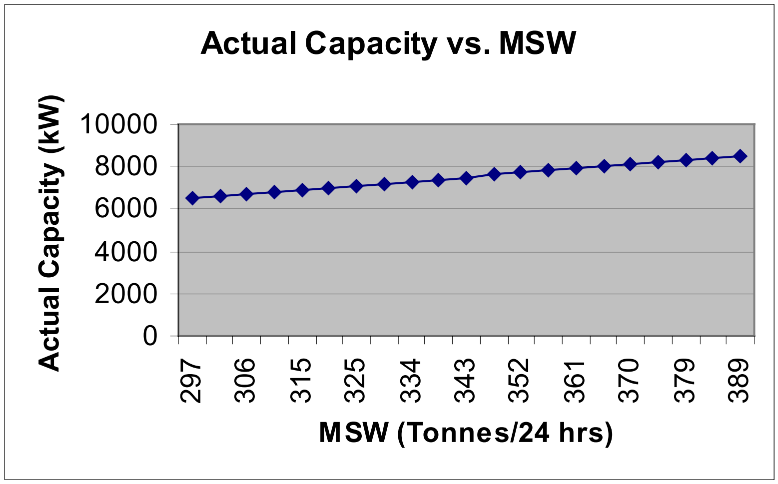
kWh Annual Production = Maximum Capacity *Load Factor * 24 * 365 (eq. 3.8)

Heat Rate = [(Btu/hr) * 24 * 365] / kWh Annual Production (eq. 3.9)

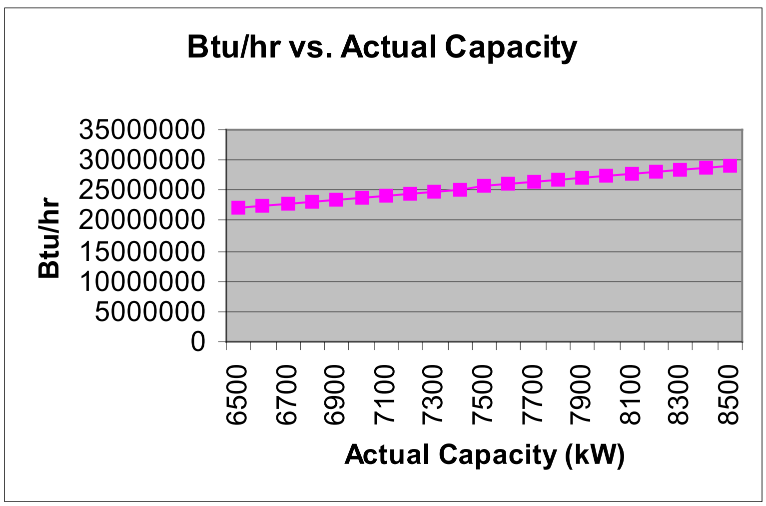
Quantity of MSW in combustor (kg/hr)	**Quantity of MSW in combustor (Tonnes/day)**	**Quantity of MSW in combustor (Tonnes/Year)**	**kWh Annual Production**	**Heat Rate (Btu/kWh)**
12381.89245	297.165	108465.377	56940000	3412
12572.3831	301.737	110134.075	57816000	3412
12762.87375	306.308	111802.774	58692000	3412
12953.3644	310.880	113471.472	59568000	3412
13143.85506	315.452	115140.170	60444000	3412
13334.34571	320.024	116808.868	61320000	3412
13524.83636	324.596	118477.566	62196000	3412
13715.32702	329.167	120146.264	63072000	3412
13905.81767	333.739	121814.962	63948000	3412
14096.30832	338.311	123483.660	64824000	3412
14286.79898	342.883	125152.359	65700000	3412
14477.28963	347.454	126821.057	66576000	3412
14667.78028	352.026	128489.755	67452000	3412
14858.27093	356.598	130158.453	68328000	3412
15048.76159	361.170	131827.151	69204000	3412
15239.25224	365.742	133495.849	70080000	3412
15429.74289	370.313	135164.547	70956000	3412
15620.23355	374.885	136833.245	71832000	3412
15810.7242	379.457	138501.944	72708000	3412
16001.21485	384.029	140170.642	73584000	3412
16191.70551	388.600	141839.340	74460000	3412

Table 3.13

The comparison of the calculated value of the Heat rate with the one depicted at Table 3.1 as a standard value (3412 Btu/kWh) verifies the calculations and indicates that the energy production rates in relation to the plant's load factor are rational and functional. The graphs of Actual Capacity vs. MSW and Btu/hr vs. Actual Capacity are provided to indicate the ever-growing quantity of combustible material as well as the rising of the Btu/hr limit when the load factor increases.



Graph 3.1: Actual Capacity vs. MSW



Graph 3.2: Btu/hr vs. Actual Capacity

In summary, a Table featuring the performance characteristics in terms of energy production for the actual 75 % Load Factor MSW combustion plant in research is presented below:

Load Factor (%)	**Btu/hr**	**Average Btu/kg for MSW**	**MSW (Tonnes/24 hrs)**	**MSW (Tonnes/year)**	**kWh (Annual)**	**Heat Rate (Btu/kWh)**
75	25590000	1791.164	342.88	125152.35	65700000	3412

Table 3.14

CHAPTER 4- Thermodynamic Plant Efficiency Assessment:

Introduction

The aim in this chapter is to perform the Thermodynamic Efficiency Assessment of the MSW combustion plant in study. The process features the evaluation of the power output per unit mass flow rate from the boiler; the specific steam consumption and the heat supplied in the boiler per unit mass flow rate. The cycle's thermodynamic efficiency and the cycle's thermodynamic efficiency for the case of no bleed steam for the feed heating values, which are evaluated at the end of this step-by-step calculating process, are anticipating to detect whether the application of feed heating boosts the operating cycle's thermodynamic efficiency. Moreover, taking into account the Generator/Gearbox thermodynamic efficiency loss accounted at 10%, the calculation of the overall plant efficiency is also taking place for both cases.

As additional research, all of the above points will be re-evaluated and compared as if for all the closed feed heaters the temperature of the feed water leaving the heater is 3K and 7K below the saturation pressure of the bleed steam. The aim of such a process is to detect alternating patterns in the cycles' thermodynamic as well as the overall plant efficiencies and to comment on the reasons these occur.

Operating Conditions:

For the 10 MW MSW plant under research, the steam supply conditions to the turbine are 150 bar and 600 °C. The steam leaving the high-pressure turbine at 25 bar and 300 °C is reheated to 600 °C before expanding in the intermediate pressure turbine to 2 bar and 280 °C and then through the low-pressure turbine to the condenser pressure of 0.030 bar when the dryness fraction is 0.98.

There are six stages of feed heating to pressures 85, 45, 25, 10, 2, and 0.30 bar. The feed water leaves the open heater at the saturation temperature corresponding to the saturation temperature of the bleed steam. For all the closed feed heaters the temperature of the feed water leaving the heater is 5K below the saturation pressure of the bleed steam. The condensate leaving each heater is saturated at the saturation pressure of the bleed steam and is flashed through a reducing valve into the preceding water. A number of assumptions are made in order to guarantee the optimal operation of the introduced plant set-up as well as to perform the assessment with the highest degree of accuracy:

- One of the feed heaters is OPEN at approximately atmospheric pressure, which acts as a de-aerator removing the dissolved gases in the feed water.
- The condition line for each turbine is a straight line in the h-s chart.
- Pump work is neglected.
- The Generator/Gearbox thermodynamic efficiency loss is accounted at 10% and must be taken under consideration in the calculation of the overall plant efficiency.

Thermodynamic Efficiency of cycle:

The thermodynamic efficiency of the cycle is defined as the ratio of Power Output per unit mass flow rate from the boiler to the heat supplied in the boiler per unit mass flow rate.

Overall Plant Efficiency:

The overall plant efficiency is defined as an indicator of how efficiently power is extracted from the steam generated from the MSW mass burning in a predefined cyclic process.

Methodology:

In order to perform the thermodynamic efficiency assessment of the cycle, the values of enthalpies of the steam at the various points indicated throughout the cycle's operating conditions must be found. The h-s chart provided in the Appendix illustrates the thermodynamic path. Points 1 and 4 are marked and joined by a straight line. Where this line cuts the pressure lines of 85 bar and 45 bar indicates the location of points 2 and 3. In a similar practice, for the re-heating scheme, a same straight line joins points 5 and 7 and where this cuts the 10 bar line point 6 is established. Point 7 is joined to point 9 (0.030 bar) and where the line cuts the 0.3 bar line point 8 is fixed.

The enthalpy of water is considered to be approximately equal to the saturation value h_f at the same temperature. The enthalpies of the feed water leaving the closed feed heaters are calculated as follows:

For Point 11

$h_{11}=h_f$ at (69.1-5) °C = 64.1 °C = 268 kJ/kg (eq. 4.1)

Similar work is performed for the Points 13, 14, 15 and 16 in order to establish the enthalpy values. The enthalpy leaving the open heater is saturated at the pressure of 2 bar, hence: h_{12} = 505 kJ/kg.

The cycle path is illustrated in Fig. 4.1 at the end of this chapter. Assuming the bleed steam flow rates per unit mass flow rate from the boiler to be y_1, y_2, y_3, y_4, y_5 and y_6 the application of the energy balance for each feed heater leads to the following equations:

First Heater: (for p= 85 bar h_f=1341 kJ/kg)

$y_1*h_2+h_{15}-h_{16}-y_1*(1341)=0$ (eq. 4.2)

Second Heater: (for p=45 bar h_f=1122 kJ/kg)

$y_2*h_3+h_{14}+(1341*y_1)-h_{15}-1122*(y_1+y_2)=0$ (eq. 4.3)

Third Heater: (for p=25 bar h_f=962 kJ/kg)

$h_5*y_3+h_{13}+1122*(y_1+y_2)-h_{14}-962*(y_1+y_2+y_3)=0$ (eq. 4.4)

Fourth Heater: (for p=10 bar h_f= 763 kJ/kg)

$h_6*y_4+h_{12}+962*(y_1+y_2+y_3)-h_{13}-763*(y_1+y_2+y_3+y_4)=0$ (eq. 4.5)

Open Heater: $h_7*y_5+h_{11}*(1-y_1-y_2-y_3-y_4-y_5)+763*(y_1+y_2+y_3+y_4)-h_{12}=0$ (eq. 4.6)

Sixth Heater: (for p=0.30 bar h_f=289 kJ/kg, for p=0.030 bar h_f=101 kJ/kg)

$h_8+y_6-289*y_6=(h_{11}-101)*(1-y_1-y_2-y_3-y_4-y_5)$ (eq. 4.7)

A visualisation of the energy balance for each feed heater is provided in Figures 4.2 and 4.3 at the end of this chapter. The resulted values of y_1, y_2, y_3, y_4, y_5

and y_6 are imported to evaluate the thermodynamic efficiency of the operating cycle. This estimation though cannot be performed directly as it is comprised by a series of intermediate calculations that must be executed, following a step-by-step pattern, which will eventually deliver the anticipated results. The step-by-step approach is initiated by calculating the Power Output per unit mass flow rate from the boiler:

Power Output per unit mass flow rate from the boiler (kW per kg/s steam flow) = $(h_1-h_2) + (h_2-h_3) * (1-y_1) + (h_3-h_4) * (1-y_1-y_2) + (h_5-h_6) * (1-y_1-y_2-y_3) + (h_6-h_7) * (1-y_1-y_2-y_3-y_4) + (h_7-h_8) * (1-y_1-y_2-y_3-y_4-y_5) + (h_8-h_9) * (1-y_1-y_2-y_3-y_4-y_5-y_6)$ (eq. 4.8)

The required steam flow from the boiler to give a power output of 10 MW:

Boiler Steam Flow Rate (kg/s) = 10000/ Power Output per unit mass flow rate from the boiler (eq. 4.9)

The Specific Steam Consumption is also calculated:

Specific Steam Consumption (kg/kWh) = 3600/ Power Output per unit mass flow rate from the boiler (eq. 4.10)

The heat supplied in the boiler per unit mass flow rate (kW per kg/s) is:
$(h_1-h_{16}) + (h_5-h_4) * (1-y_1-y_2)$ (eq. 4.11)

The cycle efficiency is provided by the equation:

Cycle Efficiency = Power Output per unit mass flow rate from the boiler / Heat supplied in the boiler per unit mass flow rate (eq. 4.12)

For the case of no bleed steam for feed heating, the power output per unit mass flow rate (kW per kg/s) is alternated to:

$(h_1-h_4) + (h_5-h_9)$ (eq. 4.13)

The Specific Steam Consumption and the Cycle Efficiency can then be re-evaluated.

For the cases where for all the closed feed heaters the temperature of the feed water leaving the heater is 3K and 7K below the saturation pressure of the bleed steam the same methodology is taking place to calculate the Cycle Efficiency.

The Generator/Gearbox thermodynamic efficiency loss is accounted at 10% and must be taken under consideration in the calculation of the overall plant efficiency:

Overall Plant Efficiency (%) = Cycle Efficiency * 0.9   (eq. 4.14)

Process:

The steam leaves the high-pressure turbine from 600 °C to 300 °C. The enthalpies of points 1 to 10 are marked at the h-s chart and presented below:

Points	Pressure (bar)	Enthalpies (kJ/kg)
1	150	3581
2	85	3370
3	45	3150
4	25	3010
5	25	3686
6	10	3425
7	2	3025
8	0.3	2755
9	0.03	2490
10	0.3 (saturated)	101

Table 4.1

The enthalpies of points 11 to h16 are also calculated and presented:

Points	$h_{11} = h_f$ at 5K less than the saturation temperature at 0.30 bar Enthalpies (kJ/kg)
11	268
12	505
13	740.88
14	938.28
15	1096.11
16	1313.42

Table 4.2

The resulted values of y_1, y_2, y_3, y_4, y_5 and y_6 from the application of the energy balance for each heater are:

y_1	0.107102021
y_2	0.066259693
y_3	0.062284187
y_4	0.070994164
y_5	0.030907932
y_6	0.044861916

Table 4.3

For these particular rates the following results occur:

Power Output per unit mass flow rate from the boiler (kW per kg/s steam flow)	1342.530723
Boiler Steam Flow Rate (kg/s)	7.44861911
Specific Steam Consumption (kg/kWh)	2.68150288
Heat supplied in the boiler per unit mass flow rate (kW per kg/s)	2826.387482
Cycle efficiency (%)	47.49

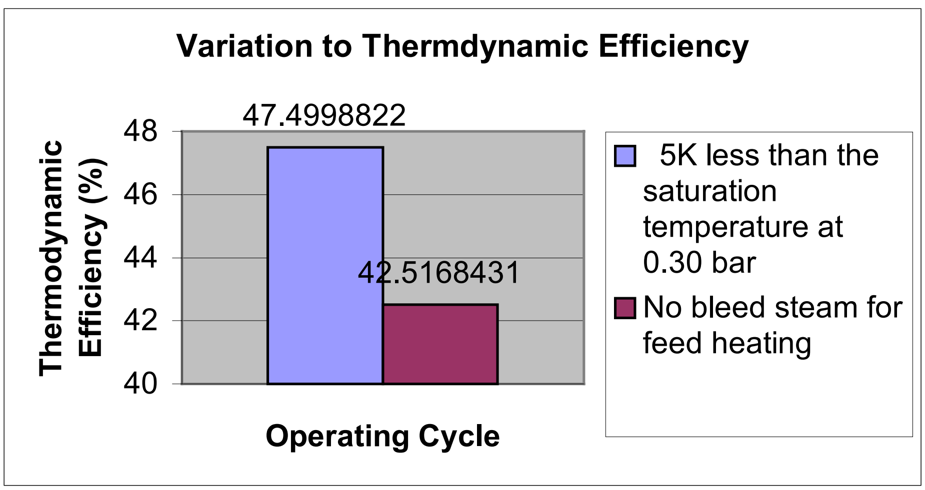
Table 4.4

As for the alternative option of no bleed steam for feed heating the calculation of the Power Output per unit mass flow rate from the boiler, the Specific Steam Consumption and the thermodynamic efficiency of the cycle is taking place in order to clarify whether the application of feed heating boosts the operating cycle's thermodynamic efficiency:

Power Output per unit mass flow rate from the boiler (kW per kg/s steam flow)	1767
Specific Steam Consumption (kg/kWh)	2.037351443
Cycle efficiency (%)	42.51

Table 4.5

Graph 1 indicates the thermodynamic efficiency variation in relation to the bleed steam for feed heating is provided:



Graph 4.1

For all the closed feed heaters the temperature of the feed water leaving the heater is 3K below the saturation pressure of the bleed steam:

The enthalpies of points 11 to h16 are calculated and presented:

Points	**h_{11} = h_f at 3K less than the saturation temperature at 0.30 bar Enthalpies (kJ/kg)**
11	276.83
12	505
13	749.35
14	948.13
15	1107.22
16	1322.35

Table 4.6:

The new values of y_1, y_2, y_3, y_4, y_5 and y_6 from the application of the energy balance for each heater are:

y_1	0.1060276
y_2	0.06699702
y_3	0.062810595
y_4	0.07416183
y_5	0.02818557
y_6	0.047188707

Table 4.7

For these particular rates the following results occur:

Power Output per unit mass flow rate from the boiler (kW per kg/s steam flow)	1340.465967
Boiler Steam Flow Rate (kg/s)	7.460092423
Specific Steam Consumption (kg/kWh)	2.685633272
Heat supplied in the boiler per unit mass flow rate (kW per kg/s)	2817.685357
Cycle efficiency (%)	47.57

Table 4.8

For all the closed feed heaters the temperature of the feed water leaving the heater is 7K below the saturation pressure of the bleed steam:

The enthalpies of points 11 to h16 are calculated and presented:

Points	**h_{11} = h_f at 7K less than the saturation temperature at 0.30 bar Enthalpies (kJ/kg)**
11	259.58
12	505
13	731.57
14	929.71
15	1087.43
16	1300.56

Table 4.9

The values of y_1, y_2, y_3, y_4, y_5 and y_6 from the application of the energy balance for each heater are:

y_1	0.105041893
y_2	0.066427922
y_3	0.062666971
y_4	0.067609609
y_5	0.033815778
y_6	0.042727717

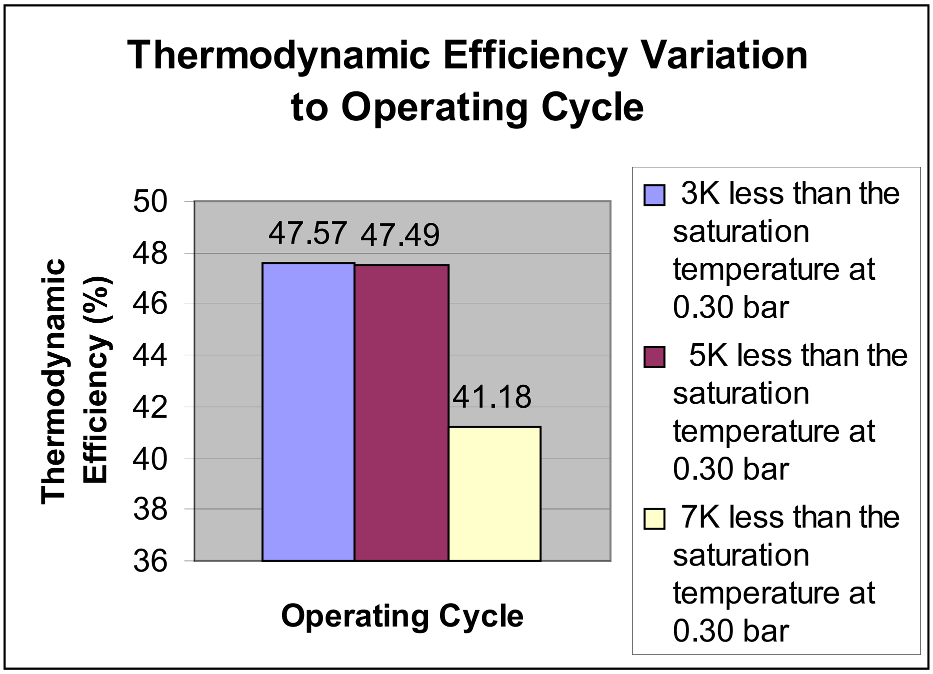
Table 4.10

For these particular rates the following results occur:

Power Output per unit mass flow rate from the boiler (kW per kg/s steam flow)	1347.228143
Boiler Steam Flow Rate (kg/s)	7.422647792
Specific Steam Consumption (kg/kWh)	2.672153205
Heat supplied in the boiler per unit mass flow rate (kW per kg/s)	3271.362102
Cycle efficiency (%)	41.18

Table 4.11

Graph 4.2 depicts the variation of the thermodynamic efficiency of the 5K less than the saturation temperature at 0.30 bar cycle in relation to the two alternative operating cycles (3K and 7K less):

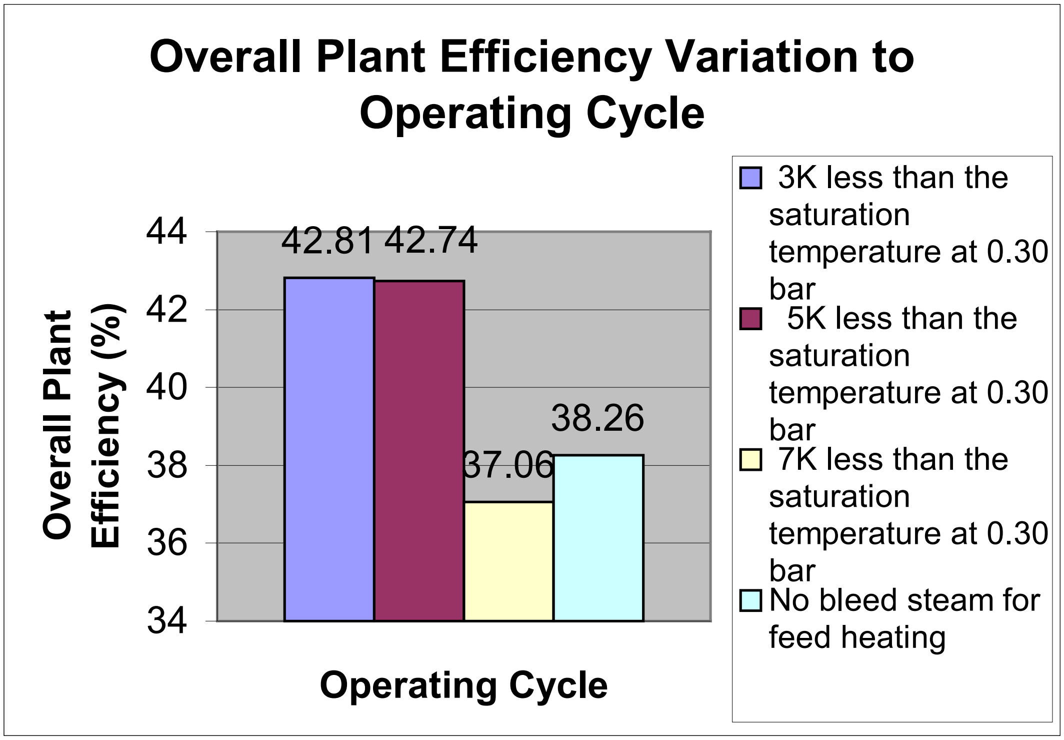


Graph 4.2

Based on a Generator/Gearbox thermodynamic efficiency loss of 10%, the overall plant efficiency for all operating cycles is presented in Table 4.12 and depicted in Graph 4.3:

$h_{11} = h_f$	Overall Plant Efficiency (%)
3K less than the saturation temperature at 0.30 bar	42.81
5K less than the saturation temperature at 0.30 bar	42.74
7K less than the saturation temperature at 0.30 bar	37.06
No bleed steam for feed heating	38.26

Table 4.12



Graph 4.3

The execution of the Thermodynamic Efficiency assessment for the introduced operating cycles detected a reduction pattern in the cycles' thermodynamic as well as the overall plant efficiencies in relation to the application of feed heating as well as to the temperature difference of the feed water leaving the heater below the saturation pressure of the bleed steam. Comments on the reasons this reduction occurs are provided in the Discussion chapter later on.

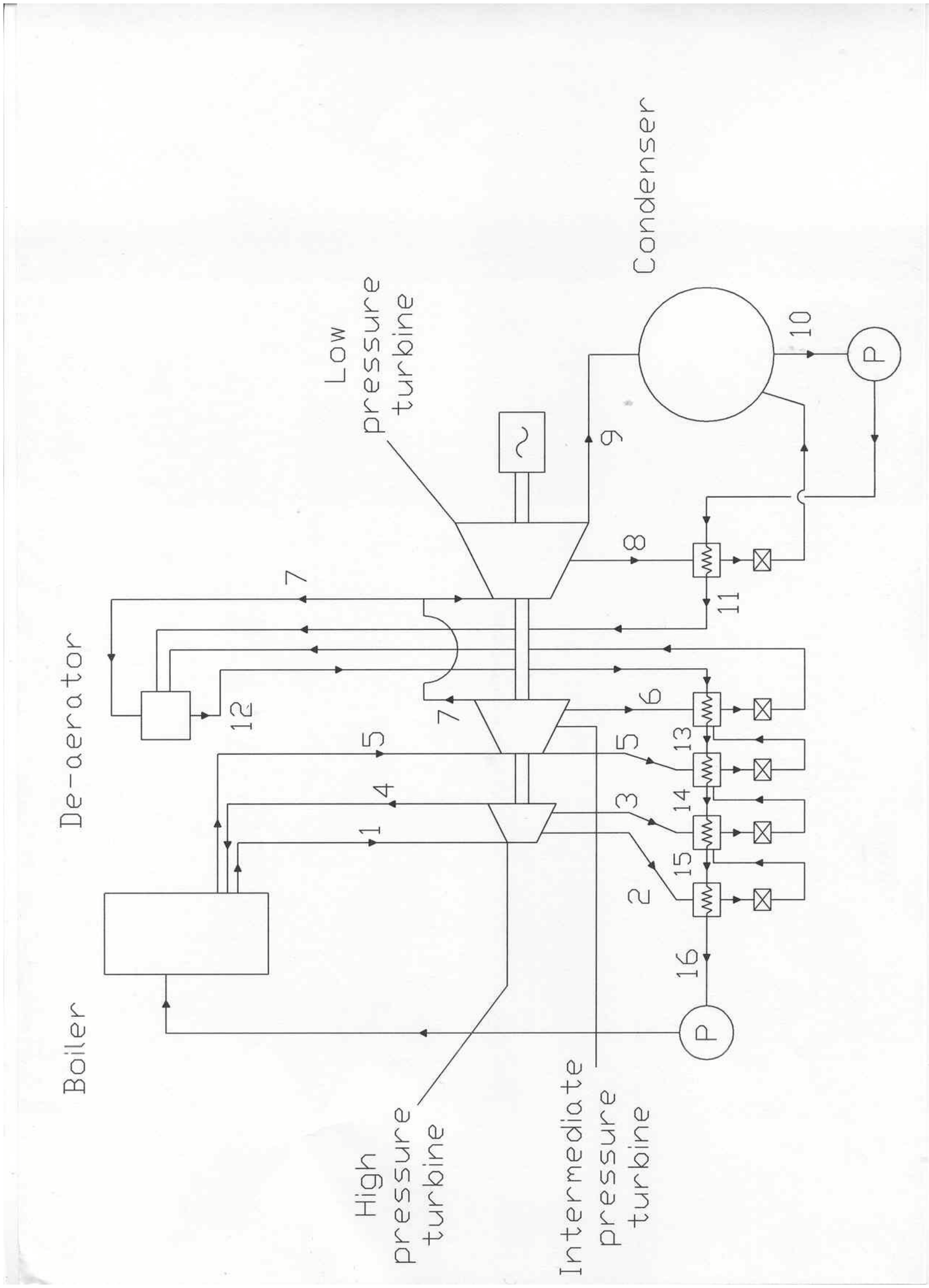


Figure 4.1: Thermodynamic Cycle Path

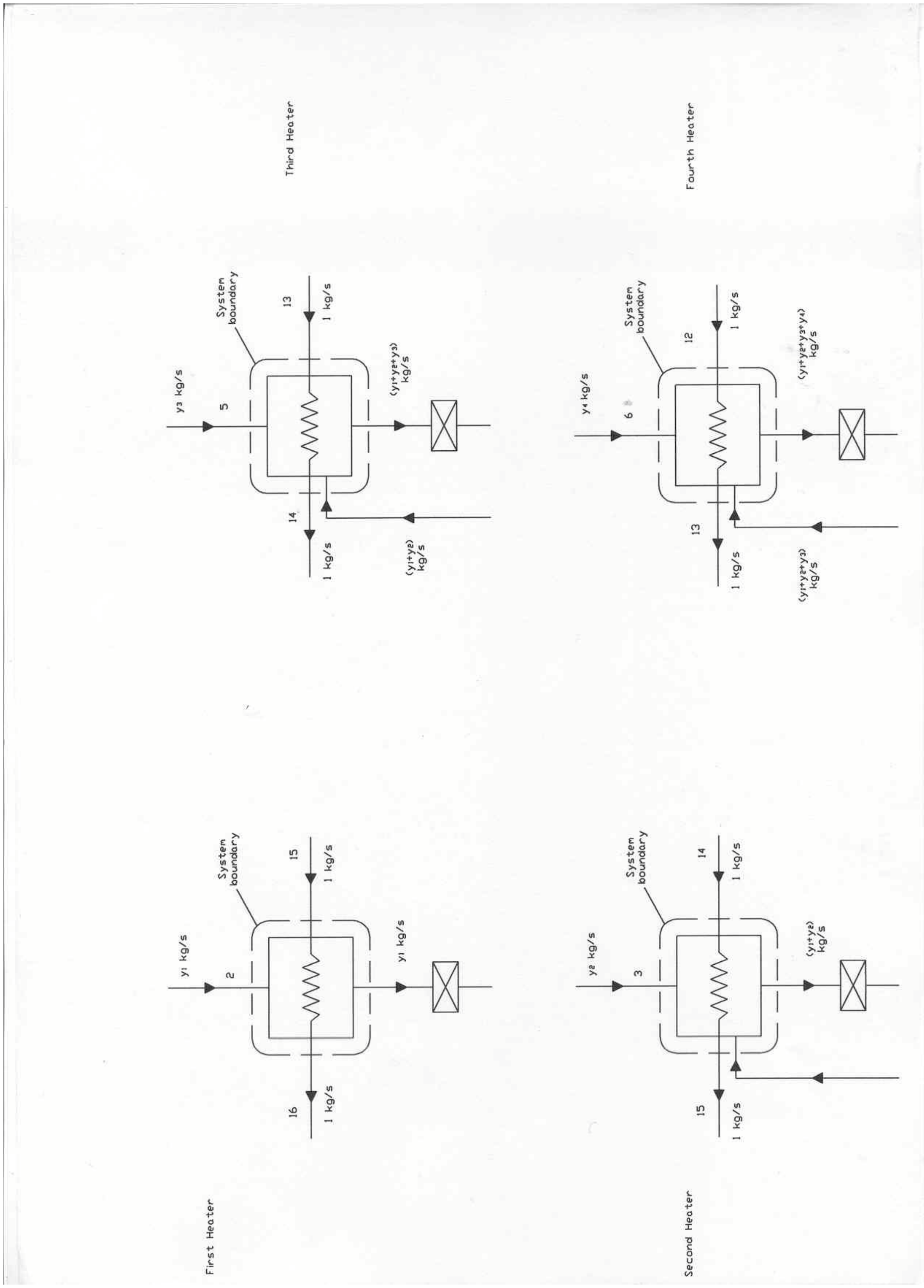


Figure 4.2: Closed Feed Water Heaters

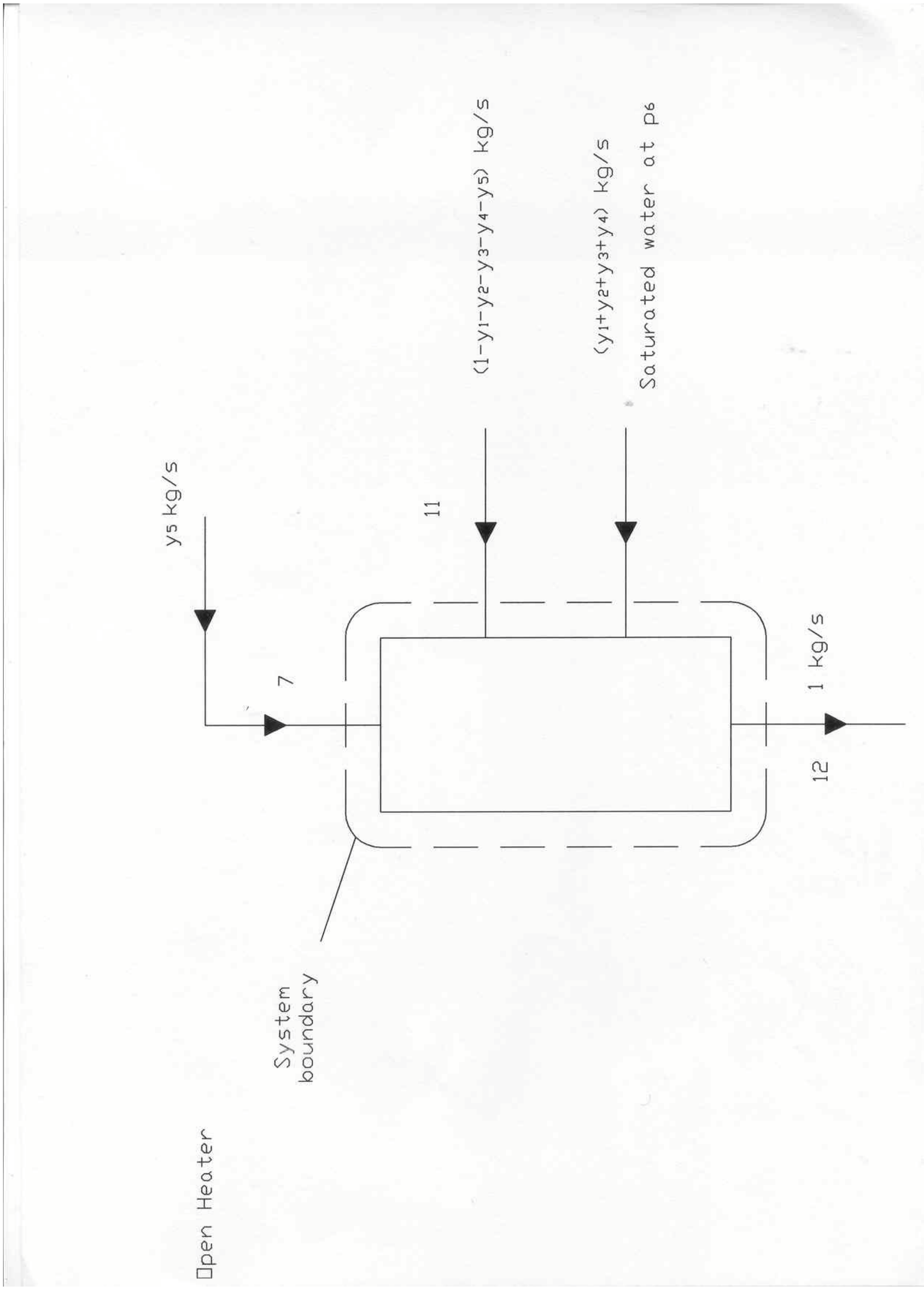


Figure 4.3: Open Feed Water Heater

CHAPTER 5- Economics

Introduction

The aim of the economic assessment is to establish whether or not the development of a 10 MW MSW combustion plant for the area of Athens, Greece would be a profitable investment under the current Energy Law and financial trends and barriers that are in force. The key feature of the analysis is the quantification of the Capital and Operational Costs for the combustion plant. A detailed breakdown of all financial factors, relating to the development and operation of the plant, is taking place in order to ensure the highest level of accuracy in the resultant figures.

The employment of a cash flow chart enables the creation of channels through which detailed forecasting can be made regarding the financial performance of the potential project in relation to its operations and adaptability within the standards established by the local Energy Law. The Net Present Value and Internal Rate of Return are the standardised financial tools used by engineers to perform such feasibility assessments. In this case, they are employed in order to clarify whether or not this potential project would have financial benefits for the investors.

Net Present Value (NPV):

NPV is an approach used in capital budgeting where the present value of cash inflow is subtracted from the present value of the cash outflows. NPV compares the value of a currency today with the value of that same currency in the future, after taking into account inflation and return. If the NPV of a prospective project is positive, then it should be economically viable. However, if it is negative, then the project should probably be rejected, as cash flows may be negative.

Internal Rate of Return (IRR):

For an investment that requires and produces a number of cash flows over time, the internal rate of return is defined to be the discount rate that makes the net present value of those cash flows equal to zero. Given that definition, IRR is defined by the equation:

NPV (C, t, IRR) =0   (eq. 5.1)

There is no closed-form solution for IRR, in general, it is calculated iteratively, employing a trial-and-error process. Selecting a value for IRR and inserting it into the NPV calculation generates a value for NPV relatively close to zero. Based on this method, picking different IRR values and repeating the process until the NPV is as close to zero as possible focuses the IRR range to a singular value.

Public Power Corporation (PPC):

The Public Power Corporation of Greece was established in 1950 with the aim of mapping out and implementing a national energy policy, which through the intense exploitation of domestic resources would make electrical power the property and right of all Greek citizens. Since January 2001, PPC operates as an S.A company, listed on the Athens and London Stock Exchanges on December 2001. Today PPC S.A. is Greece's largest power generation company and the country's sole producer supply company, providing electricity to approximately 6.7 million customers from a total population of 10 million in Greece. PPC is also the sole company with a fully owned power transportation system in Greece. PPC owns the 97% of the installed power capacity in Greece, generated by lignite, oil and hydroelectric stations, natural gas stations as well as wind and solar energy parks. Today, PPC alone covers the country's rapidly increasing power needs and is now expanding its activities to other markets, such as telecommunications.

The deregulation of Greece's energy market (February 2001) saw the granting of power generation licenses to other companies and private bodies. Thus, responsibility for power transportation was taken over by an independent company, which was set up for that purpose, DESMHE S.A. (Manager of Greek Electric Power Transportation System). Similarly, the overall control of the Greek Power System

(Power Generation, Transportation and Distribution) has now been taken up by RAE (Regulating Authority for Energy).

PPC is the largest business in Greece in terms of assets. In 2002 the Company recorded revenues increased by 11.2% to Euro 3.437 million and net income increased by 157.9% to Euro 216 million. Total electrical power is generated in 98 privately-owned power stations, and is transported 10.330 km high voltage lines and distributed to consumers via 200.989 km-long network.

(COMPANY REGISTERED OFFICE
PUBLIC POWER CORPORATION S.A.
30 CHALKOKONDYLI St.
10432 ATHENS, GREECE)

The Energy Law in Greece:

The current Energy Law came into force under the designation No. 2244 in October of 1994. It's content takes into account the energy production regulation potential from sustainable sources and from conventional fuels and further dispositions. Under this regulation, the energy production from any external party outside of the state is obliged to fall in either one of the two following categories:

- As a self-producer connected or disconnected to the power grid, who generates the energy in order to cover its operational needs and sells the entire rest of the energy produced to PPC S.A.
- As an independent producer connected or disconnected to the power grid, who buys energy from PPC to cover its operational needs and sells its entire produced power to PPC S.A.

Both categories abide by a number of legislative barriers, which forbid any deviations from these two established entities. Producers are obliged to sell the produced energy to PPC S.A., which buys it in exclusive. A contract with a lifespan of 10 years, which defines the charging of energy for self-producers or independent producers, is signed with PPC S.A. and can be only re-negotiated after the passing of the agreement's duration. For a self-producer the selling of energy from sustainable sources is established at 70% of the general invoice and monthly charge in low voltage or in medium voltage and in high voltage. For co-production, 60% of the general invoice and monthly charge in low voltage or in medium voltage and in high voltage is applied. For independent producers, the energy selling price is established at 90% of the general invoice and monthly charge in the medium voltage or in the high voltage concerning production of energy from renewable sources and in 70% of the general invoice and monthly charge for independent producers from co-production of natural gas combustion. The power selling price is established at 50% of the general invoice and monthly charge in the medium voltage or in the high voltage (Energy Law of Greece, no.2244).

The general invoice is designated under the code name Γ 22 (Gamma 22) and a detailed breakdown of its contents with the tabulation of the actual energy and power selling prices for both categories of producers is presented below in Tables 5.1 and 5.2:

Self-Producer	**Γ 22 Invoice Selling Prices (£/kWh)**	**Actual Selling Prices (£/kWh)**	
Non-connected to the Grid		**Self-Production (70% of Invoice Selling Price)**	**Co-Production (60% of Invoice Selling Price)**
From Renewable Sources	0.0424	0.0296	0.0254
From Conventional Plants	0.0364	0.0254	0.0218
Connected to the Grid			
Low Voltage	0.0424	0.0296	0.0254
Medium Voltage	0.0343	0.0240	0.0205
High Voltage: Peak-Time	0.0224	0.0156	0.0134
Intermediate Load	0.0155	0.01085	0.0093
Minimum Load	0.0115	0.00805	0.0069

Table 5.1: Energy and power selling prices for Self-Producers and Co-Producers

Independent Producer	Γ 22 Invoice Selling Prices (£/kWh)	Actual Selling Prices (£/kWh)	
Non-connected to the Grid		**Independent Production (90% for Energy and 50% for Power of Invoice Selling Price)**	**Co-Production (70% for Energy and 50% for Power of Invoice Selling Price)**
From Renewable Sources	0.0546	0.0491	0.0382
Connected to the Grid			
Medium Voltage: Energy	0.0441	0.0396	0.0308
Medium Voltage: Power	1.134 £/ kW	0.567 £/ kW	0.567 £/ kW
High Voltage: Energy	0.0441	0.0396	0.0308
High Voltage: Power	1.134 £/ kW	0.567 £/ kW	0.567 £/ kW

Table 5.2: Energy and power selling prices for Independent Producers and Co-Producers

For this particular study, it is considered that the potential investor is an independent producer, for whom the selling ratings of Medium Voltage for Energy (0.0396 £/KWh) and Power (0.567 £/kW) apply. The 10 MW MSW combustion plant is designed so that it buys energy from PPC S.A. to cover its operational needs and sells its entire produced energy to PPC S.A as defined previously, thus avoiding additional expenses, which would apply in case energy generation was taking place onsite.

Methodology:

Initially, a detailed assessment of the capital and operational costs of the 10 MW MSW combustion plant over its 30 years of designed lifespan will be presented. To complete the task, a designated breakdown of the plant components and categorisation in terms of the apparatus tasks is attempted. The plant is divided into six categories, which are presented below in Tables, including the constituent parts from which they are comprised. This grouping enables evaluating the capital and operational costs effectively and accurately:

Table 5.3: Fuel Handling, Storage and Preparation System

Air Injection System in the combustion Chamber	**Feeding System**	**Ash Disposing System**
Air Filter	Feed Chute	Ash Burnout Grate
Forced Draft Fan	Ram Feeder	Shiftings Conveyor
Steam Air Heater		Ram Extractor
Wind Box		Bottom Ash Conveyors

Table 5.4: Water walled Furnace

Water walled Furnace

Table 5.5: Boiler and Feed Heating Systems

Boiler	**Feed Heating System**
Super Heaters	Closed Feed water Heaters (5)
Condenser	Open Feed water Heater (1)
Economiser	

Table 5.6: Steam Turbine Generator

Steam Turbine System
High-Pressure Turbine
Medium-Pressure Turbine
Low-Pressure Turbine
Generator/Gearbox

Table 5.7: Stack Gas Clean Up and Pollution Controls

Dry Scrubber System
Dry Scrubber
Baghouse
Ash Recycle System
Induced Draft Fan
Stack

Table 5.8: Plant Engineering

Pump System
Condensate pump
Boiler Feed water pump
Forced circulation Pump
Spray Attemperator
Rotary connector

The Licence of Development of the MSW combustion plant is included in the Capital Costs evaluation as an expense because it is considered a significant and recurring factor. The Operating Costs are established by taking into consideration the factors of Total Annual Labour Wages, Operation and Maintenance costs including the expenditure (£) in energy to operate the plant, Plant Insurance and Licence of Operation, the latter being paid in equal sums every year until the end of the plant's life time. A 40% allowance scheme is provided by the EU for the development of the plant. Hence, the investor is obliged to provide the 60% of the overall investment in cash for the development of the plant. This expense is designated in the Operating Costs as the Capital Charge Rate, which is split into equal portions and is paid every year as stated above.

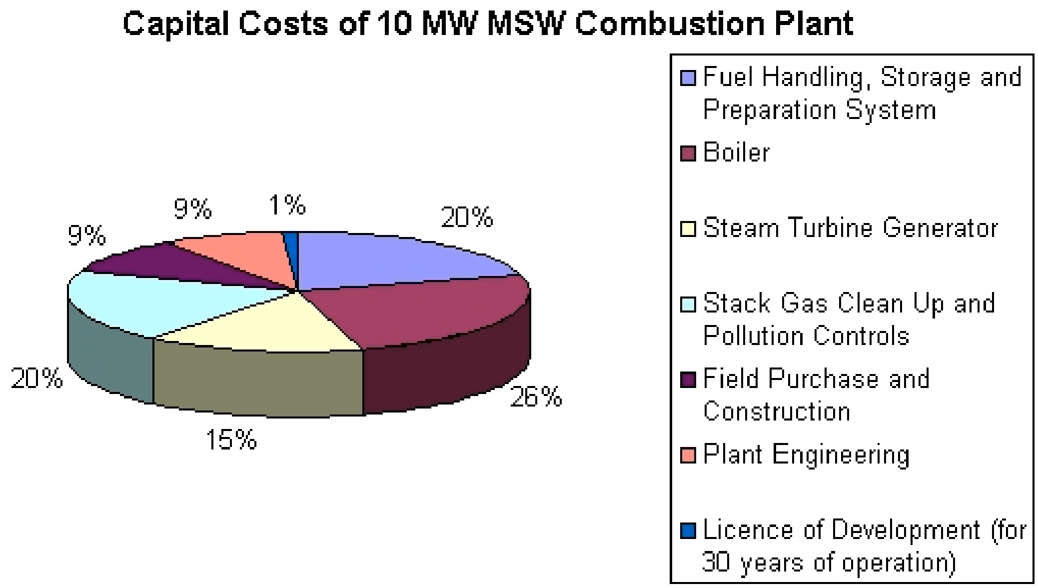
At this stage, a cash flow analysis of the potential venture is considered of pivotal importance in order to clarify whether or not this potential project has financial benefits for the investor. The selling rating of High Voltage for Energy (0.0396 £/KWh) is applied for the potential investor as an independent producer selling to PPC S.A. in relation to the Annual Power Production of the plant for the specified Load Factor of 75%. If the NPV of the prospective projection is positive, then the venture should be considered financially feasible.

Process:

A detailed Capital Costs assessment is presented in Table 5.9. A percentage analogy (%) of the total expenses is included as well as a graph that illustrates the breakdown:

Capital Costs	£	%
Fuel Handling, Storage and Preparation System	8,724,716	20.255
Water walled Furnace, Boiler and Feed Heating Systems	10,905,895	25.318
Steam Gas Turbine Generator	6,543,537	15.191
Stack Gas Clean Up and Pollution Controls	8,700,000	20.197
Field Purchase and Construction	4,000,000	9.286
Plant Engineering	3,700,000	8.589
Licence of Development (accounting for 30 years of operation)	500,000	1.160
TOTAL	43,074,148	100

Table 5.9: Capital Costs of 10 MW MSW combustion plant



Graph 5.1: Capital Costs of 10 MW MSW Combustion Plant

The plant would operate on a 24-hour basis, 7 days a week employing three 8-hour shifts of 24 people per shift. The personnel's breakdown in relation to their occupation and wage level is presented in Table 5.10. The accurate establishment of the Labour Wages is considered of pivotal importance and is considered as one of the major factors that affect the fluctuation of the Annual Operating Costs.

Occupation	**Number of Employees per shift**	**Labour Wages (£/year)**
Workers	15	120,758
Engineers	5	104,289
Staff	3	30,547
General Manager	1	16,196
TOTAL	24	271,790

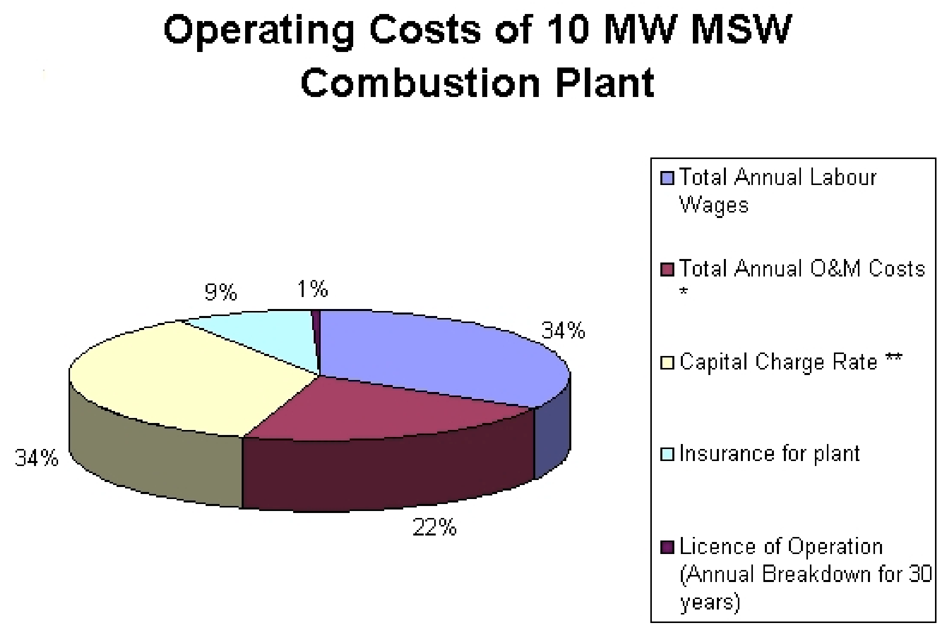
Table 5.10: Labour Wages

Annual Operating Costs are assessed and presented in Table 5.11. A percentage (%) analogy to the total expenses is also included as well as graph 5.2, depicting their breakdown:

Annual Operating Costs	£	%
Total Annual Labour Wages	815,370	33.44
Total Annual O&M costs*	524,208	21.50
Capital Charge Rate**	861,483	35.40
Plant Insurance	215,371	8.83
Licence of operation (Annual Breakdown for 30 years)	16,670	0.68
TOTAL	2,433,102	100

Table 5.11: Annual Operating Costs of 10 MW MSW combustion plant

The designation * in the Total Annual O&M factor signifies the inclusion of the expenses for energy required to operate the plant. The designation ** is accounted as the 60% of the investment's Capital Costs the individual investor must cover, paid into equal portions every year until the end of the plant's lifetime due to a 40% allowance provided by the EU for the development of the project. An additional grant of £500,000 will be provided to the plant owner from the Government on an annual basis for the effective handling of MSW, which results in the permanent wastes reduction in the designated storing areas around the vicinity of Athens. This allowance reduces the Operational Costs to £1,933,102 annually.



Graph 5.2: Operating Costs of 10 MW MSW Combustion Plant

The cash flow analysis of the potential venture is undertaken in order to clarify whether or not this potential project has financial benefits for the investor. Its development takes place in an Excel working sheet. Initially, the working years of the plant are introduced (30) in addition to the Load Factor (75%), the energy production (kWh/year) and the selling price (£/kWh) to the supplier, which is set by the general invoice Γ22 (Gamma 22). The annual income from selling the produced energy is given by the equation:

Incomes from energy (As) = Selling price * energy production (£/year)
(eq.5.2)

The total operating costs (Ate) are introduced in the spreadsheet taking into account the 40% allowance provided by the EU as well as the £500,000 grant that will be provided to the plant owner from the Government on an annual basis for the effective handling of MSW. The Annual cash income (Aci) is calculated from the equation:

Aci = As – Ate (£) (eq. 5.3)

The Tax charging (Ait) of 35 % applies in the annual cash income under the current legislative instrument in force, assuming the company has issued shares in the Stock Exchange market. In any other case the Tax charging would be accounted at the 40% mark. The Net Annual cash income (Anci) is estimated as the value occurring from the subtraction of the tax charged annual cash income from the annual cash income:

$$Anci = Aci - Ait \quad (£) \quad \text{(eq. 5.4)}$$

At this point, the total capital costs (Atc) are introduced in the equation and the annual net cash after tax (Acf) occurs as the resulted value of the subtraction of the capital costs from the net annual cash income:

$$Acf = Anci - Atc \quad (£) \quad \text{(eq. 5.5)}$$

The discount rate (fd) is accounted at 10% for the investment and is calculated for the number of operating years according to the equation:

$$fd = 1/(1+i)^n \text{, where } i = 0.1 \text{ and } n = 0,1,2,3....,30 \quad \text{(eq. 5.6)}$$

The net annual discounted cash flow (Adcf) occurs as the product of the discount rate times the annual net cash after tax for each year:

$$Adcf = fd * Acf \quad (£) \quad \text{(eq. 5.7)}$$

For this particular calculation, the value of the operating costs with a negative sign convention is inserted at the year 0 slot in the spreadsheet.

The value of NPV is anticipated to be positive in the end of year 30, a fact, which automatically signals the profitability of the investment. Furthermore, the sooner the transition from a negative to a positive NPV rate occurs the better for the investor. This alternation in NPV rates establishes that the break-even point is reached, the investment costs are covered and hence profit is generated from that particular moment until the end of the factory's predicted lifespan. The detailed breakdown of the cash flows in relation to the Annual Energy Production of the plant for the specified Load Factor of 75% is presented in Table 5.12 on the next page:

Year	Load Factor %	Energy Production kWhr/year	Selling Price kWhr €/kWhr	Ar Incomes from Power €	Atc Total Oper. Cost €	Aci - Ar-Atc Annual cash Income €	Ait Tax 35%	Anci - Aci-Ait Net Annual Cash Income	Atc Total Capital Cost €	Acf - Anci-Atc Annual net cash flow after tax	fd 1/(1+I)^n	Adcf Net Annual discounted cash flow	NPV Net Present Value (€)	IRR
0	0	0	0	0	0	0	0	0	25844488	-25844488	1	-25844488	-25844488	####
1	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.90909091	395092.4545	-25449395.55	
2	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.826446	359174.8366	-25090220.71	
3	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.751314	326522.3416	-24763698.37	
4	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.683013	296838.6109	-24466859.76	
5	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.620921	269853.3222	-24197006.43	
6	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.564473	245320.9254	-23951685.51	
7	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.513158	223019.3392	-23728666.17	
8	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.466507	202744.7353	-23525921.43	
9	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.424097	184313.2772	-23341608.16	
10	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.385543	167557.6432	-23174050.51	
11	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.350493	152324.8536	-23021725.66	
12	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.31863	138477.1397	-22883248.52	
13	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.289664	125888.4668	-22757360.05	
14	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.263331	114444.1003	-22642915.95	
15	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.239392	104040.1702	-22538875.78	
16	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.217629	94581.93337	-22444293.85	
17	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.197844	85983.33873	-22358310.51	
18	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.179858	78166.59256	-22280143.92	
19	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.163507	71060.42016	-22209083.5	
20	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.148643	64600.50049	-22144483	
21	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.13513	58727.72772	-22085755.27	
22	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.122845	53388.64584	-22032366.62	
23	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.111678	48535.44865	-21983831.18	
24	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.101525	44122.93759	-21939708.24	
25	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.092295	40111.5639	-21899596.67	
26	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.083905	36465.25564	-21863131.42	
27	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.076277	33150.11387	-21829981.3	
28	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.069343	30136.58568	-21799844.72	
29	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.063039	27396.85657	-21772447.86	
30	75	65700000	0.0396	2601720	1933102	668618	234016.3	434601.7	0	434601.7	0.057308	24906.15422	-21747541.71	

Table 5.12: Combustion Plant Cash Flow

CHAPTER 6- Environmental Impact

Introduction

A detailed analysis regarding emissions associated with the operation of the MSW combustion plant is presented in this chapter focusing attention particularly at the type of emissions (Nitrogen Oxides, Sulphur Compounds, Particulate Matter, Carbon Monoxide, Carbon Dioxide) as well as the source from where they are exhausted (boiler, steam turbine). Applicability of alleviation options like combustion process emissions control, flue gas re-circulation and the dry scrubber and bag house system's performance are examined in depth in order to establish the most efficient and environmentally-friendly operation of the MSW combustion plant.

Environmental Profile

The environmental friendliness of the 10 MW MSW combustion plant's operation is considered a factor of pivotal importance for the establishment of the venture in the area of Athens. The Capital city of Greece hosts nearly 50% of the total population of the country and a 60% of the country's total industrial activity. It becomes evident that in this fragile environmental system, although strong legislation put into force in the recent years has successfully dealt with the various emissions problems from local industry, a newly operating industrial site is obliged to uphold the environmental standards in order to gain support from the government, other political parties, local environmental groups and citizens alike. The last group especially, has regarded the development of an MSW combustion plant in the area of Athens with extreme hostility in the past insisting on the health dangers of the emissions particulates as well as the quantities in which they are released in the atmosphere by the MSW mass burning process.

Post-combustion derivatives of the 10 MW MSW combustion plant

The post-combustion derivatives of the MSW plant are a subject of particular interest due to their character: it is considered that the mass burning combustion reduces the MSW's total weight by a rate of 75% and volume by a rate of 90% leading to the formation of inert ash material (60% of the burnout weight distribution) as well as fly ash material in a percentage rate of 40% of the burnout weight distribution. Table 6.1 on the next page presents a detailed breakdown of post-combustion products in relation to Plant Load Factor focusing particularly on the 75% Load Factor scheme that is currently under investigation as the potential investment. Ferrous materials comprise the 3% of the inert ash quantity and are removed by a system employing magnets before the inert ash is deposited in a specified collection area. This portion of inert ash can be collected regularly and sold as a first class fertiliser to interested industries later on.

The portion of the fly ash that is generated from the mass burning combustion has a code of handling and storing that is more complicated because of its constituent products: Nitrogen Oxides (NO_x), Sulphur Oxides (SO_x), Particulate Matter (PM), Carbon Monoxide (CO), Carbon Dioxide (CO_2) as well as HCL, dioxins/furans, heavy metals and organic constituents create a mixture that is hazardous for the environment as well as for public health if released into the atmosphere unprocessed.

It is of pivotal importance to develop a system that processes and neutralises these derivatives to the strict legislative standards that are in force in the current time, in order to ensure the preservation of public health as well as the environmental sustainability of the industrial site. To bring the project to fruition, a strategy involving the detailed forecasting of the main sources of emissions exerted from an MSW combustion plant as well as an investigation of emissions control codes and practices currently employed into force is described in the following pages. A discussion of the advantages of dry absorption on the path to the exhaust stack through the operation of a dry scrubber system is undertaken with the aim to certify the unit's essential role in neutralising the hazardous derivatives.

Load Factor (%)	MSW (tonnes/24 hrs)	Material after burnout (tonnes/24 hrs)	Inert Ash (tonnes/24 hrs)	Ferrous Metals [3% of Inert Ash] (tonnes/24 hrs)	Fly Ash (tonnes/24 hrs)
65	297.1654187	74.29135468	44.57481281	1.337244384	29.71654187
66	301.7371944	75.4342986	45.26057916	1.357817375	30.17371944
67	306.30897	76.5772425	45.9463455	1.378390365	30.630897
68	310.8807457	77.72018643	46.63211186	1.398963356	31.08807457
69	315.4525214	78.86313035	47.31787821	1.419536346	31.54525214
70	320.024297	80.00607425	48.00364455	1.440109337	32.0024297
71	324.5960727	81.14901818	48.68941091	1.460682327	32.45960727
72	329.1678484	82.2919621	49.37517726	1.481255318	32.91678484
73	333.7396241	83.43490603	50.06094362	1.501828308	33.37396241
74	338.3113997	84.57784993	50.74670996	1.522401299	33.83113997
75	342.8831754	85.72079385	51.43247631	1.542974289	34.28831754
76	347.4549511	86.86373778	52.11824267	1.56354728	34.74549511
77	352.0267268	88.0066817	52.80400902	1.584120271	35.20267268
78	356.5985024	89.1496256	53.48977536	1.604693261	35.65985024
79	361.1702781	90.29256953	54.17554172	1.625266251	36.11702781
80	365.7420538	91.43551345	54.86130807	1.645839242	36.57420538
81	370.3138294	92.57845735	55.54707441	1.666412232	37.03138294
82	374.8856051	93.72140128	56.23284077	1.686985223	37.48856051
83	379.4573808	94.8643452	56.91860712	1.707558214	37.94573808
84	384.0291565	96.00728913	57.60437348	1.728131204	38.40291565
85	388.6009321	97.15023303	58.29013982	1.748704194	38.86009321

Table 6.1: Breakdown of post-combustion derivatives in relation to Plant Load Factor

Boiler and Steam Turbine Emissions

The main sources of emissions exerted from an MSW combustion plant focus on the steam turbine and the boiler operating at the plant. Steam turbine emissions vary according to the source of the steam (MSW waste). Boiler emissions vary depending on the synthesis of the fuel type (mostly organic waste combusted) as well as local environmental conditions. Boiler emissions include Nitrogen Oxides (NO_x), Sulphur Oxides (SO_x), Particulate Matter (PM), Carbon Monoxide (CO), Carbon Dioxide (CO_2).

Nitrogen Oxides (NO_x):

The pollutant referred to as NO_x , is a composite of nitric oxide (NO) mainly and nitrogen dioxide (NO_2) in variable composition. NO_x is formed by three mechanisms: thermal NO_x, prompt NO_x and fuel-bound NO_x. Thermal and fuel-bound formations are the predominant mechanisms encountered in industrial boilers. Thermal NO_x, formed when nitrogen and oxygen in the combustion combine in the flame, comprises the majority of NO_x, formed during the combustion of gases and light oils. Fuel-bound NO_x is associated with oil fuels and forms when nitrogen in the fuel and oxygen in the combustion air react. The most significant factors establishing the levels of NO_x emissions from a boiler are the flame temperature and the amount of nitrogen in the fuel. Equally influential factors are the air excess level during combustion (at a maximum of 45%) and the combustion air temperature.

Sulphur Compounds (SO_x):

Emissions of sulphur relate directly to the fuel's sulphur content, and are not dependent on the boiler size or the burner's design. Sulphur dioxide (SO_2) comprises nearly 95% of the total quantity of sulphur emitted with the remaining 5% emitted being sulphur trioxide (SO_3). SO_x are generally considered dangerous pollutants due to their reaction with water vapour, which leads to the formation of sulphuric and acid mist, which is extremely corrosive in its air-, water-, and soil borne forms. Some types of MSW contain quantities of sulphur released during combustion.

Particulate Matter (PM):

PM emissions are dependent on the boiler's grade and consist of many different compounds such as nitrides, sulphates, carbons, oxides and other incombustible fuel elements. For industrial boilers the most effective method of PM control lies in the use of high-grade fuel and the ensuring of a proper burner set-up, adjustment and maintenance.

Carbon Monoxide (CO_x):

CO forms during combustion when carbon in the fuel oxidizes incompletely, ending up as CO instead of the expected CO_2. Older boilers possess higher levels of CO in general than newer equipment because of the fact that older designs do not have CO control schemes. Poor burner designing and firing conditions are primarily responsible for the high levels of CO boiler emissions. Proper burner maintenance maintenance and regular equipment upgrading as well as using an oxygen control package can control CO emissions successfully.

Carbon Dioxide (CO_2):

Although CO_2 is not generally considered a pollutant in the sense of affecting public health, its emissions are considered here due to its contribution to global warming. Atmospheric warming occurs due to the penetration of solar radiation to the surface of the Earth. Infrared radiation is absorbed from the CO_2 in the atmosphere, which as a result in creases the atmosphere's temperature. The amount of CO_2 emitted is in direct relation to the fuel synthesis and the system efficiency.

Boiler Emissions Control Options – NO_x

NO_x control has been the primary focus of extensive research on emission control and development in boilers. The following methods comprise the most prominent strategies for emission control approaches employed currently or anticipated to be employed successfully in the future.

- **Combustion Process Emissions Control:**

Combustion control techniques feature a more satisfactory financial incentive than post-combustion control methods and are used on industrial boilers for NO_x control. Combustion temperature controlling has been the principal focus of combustion process control in boilers. Combustion control requires tradeoffs- high temperatures favour complete burn up of the fuel and low residual hydrocarbons and CO, but end up forming NO_x particulates. A lean combustion dilutes the combustion process and reduces combustion temperatures and consecutively NO_x formation, allowing a higher compression ratio or peak firing pressures, which result a higher overall efficiency. There is a danger though, if the mixture is too lean, of misfiring and occurrence of an incomplete combustion that produces increasing rates of CO and VOC emissions.

- **Flue Gas Re-circulation (FGR):**

FGR is considered one of the most effective methods in reducing NO_x emissions from industrial boilers to date. With FGR, a portion of the relatively cool boiler exhausts gases re-enters the combustion process, reducing the flame temperatures and the associated and inevitable NO_x formation process. It is the most popular and effective NO_x reduction method for fire-tube and water-tube boilers, the second configuration specifically applying to the case of the particular 10 MW plant under research.

External FGR employs a fan to re-circulate the flue gases into the flame, with external pipe work carrying the gases from the stack to the burner. A valve responding to boiler input controls the re-circulation rate. Induced FGR relies on the combustion air fan for flue gas re-circulation. Via ducts or via internal flow, a proportion of the gases is taken to the air fan, where they are pre-mixed with combustion air and are introduced into the flame in the burner. Induced FGR employs a relatively uncomplicated and reliable integral design in newer boiler configurations. The physical limit to NO_x reduction via FGR is calculated at 80% in natural gas-fired and MSW-fired boilers.

- **Low Excess Air Firing (LAE):**

Excess air is a means of ensuring complete combustion in the interior of the water walled combustor. Greater excess air levels than 45% can lead to the formation of thermal NO_x due to the combination of the excess nitrogen and oxygen in the combustion air entering the flame. Low excess firing results the limiting of the excess air that enters the combustion process, reducing the amounts of nitrogen and oxygen that eventually enters the flame. Burner design modification accomplishes this and optimisation employs oxygen trim controls. LAE aids to reduce the overall NO_x emissions at a range of 5% to 10%.

- **Burner Modifications:**

Modifying the standard burner design in order to create a larger flame achieves lower flame temperatures and results in a lower thermal NO_x formation. While most boiler types and sizes can accommodate modifications in their burners, it is more effective for boilers firing natural gas, air and distillate fuel oils, with little effectiveness in heavy oil-fired boilers. Burner modifications should be complemented with other NO_x reduction methods (e.g. flue gas re-circulation) in order to comply with the demanding environmental regulations. Positive impact on boiler operating parameters such capacity, turndown, CO levels and efficiency can materialize by achieving low NO_x levels through burner modifications.

- **Water/Steam Injection:**

Lowering of thermal NO_x formation in conjunction with overall NO_x emission rates is achieved if water or steam is injected into the flame, thus reducing the flame temperature. However, the drawback of this method is that it can lower the boiler efficiency by a fraction of 3% to 10%. There is also a practical limit concerning the amount of water or steam that can be injected without causing condensation-related problems. This particular method is used regularly in conjunction with the burner modification technique and its application can result NO_x reduction of up to 80%.

Post-Combustion Emissions Control

There are a number of techniques for exhaust gas treatment that can be applied to industrial boilers.

- **Selective Catalytic Reduction (SCR):**

This particular technology involves the injection of a reducing agent into the boiler exhaust gas in the presence of a catalyst. The reducing agent is allowed to operate by the catalyst at lower exhaust temperatures than SNCR, in the range of 260 °C to 650 °C depending of the type of the catalyst. NOx reductions up to a limit of 90% are achievable by adopting this process. The two most-commercially-used agents are ammonia and aqueous urea. Urea decomposes in the hot exhaust and SCR reactor, releasing ammonia. An approximation of 0.9 to 1.0 moles of ammonia is required per mole of NO_x at the SCR reactor's inject inlet in order to achieve 80 to 90% NO_x reduction. The drawbacks of SCR are focused on the fact that on-site storage of ammonia is required, which is a hazardous chemical and can slip through the process unreacted.

- **Selective Non-Catalytic Reduction (SNCR):**

In boiler SNCR, ammonia or urea are inserted as reducing agents in the boiler exhaust gases at a temperature ranging from 760 to 870 °C. The aim is to break down the NOx in the exhaust gases to water and atmospheric nitrogen. However one problem of SNCR is that in order to reduce the industrial boilers' NO_x emissions at a rate of 70% the agent must be introduced at a specific flue gas temperature. Furthermore, the location of the exhaust gases at the necessary temperature is constantly changing in a cycling boiler, which makes this method inappropriate for some types of boilers.

Boiler Emissions Control Options – SO_x

The most commonly applied method for controlling SO_x emissions is dispersion via a tall stack in order to limit ground level emissions. However, the demanding SO_x emissions legislative requirements in force now imply the use of reduction methods. These include the use of low in sulphur apportionment fuel, desuphurising fuel and flue gas desulphurisation (FGD). The application of low in sulphur apportionment fuels is the most cost effective SO_x control method for industrial boilers, mainly because it does not require installation and maintenance of specialised equipment.

FGD systems are divided in two categories: regenerable and non-regenerable. The most common non-regenerable result in a waste product that requires proper disposal. Regenerable FGD converts the waste product into a sellable product such as sulphuric acid. SO_x emissions are reduced by 95% by the application of the FGD method.

The advantages of dry absorption on the path to the exhaust stack

Dry processing of gaseous effluents features the injection of reagents in dry powder form aiming to neutralise acid gases such as HF, SO_2, HCL or to captivate volatile heavy metals such as Hg, Cd, Se, As or organic components such as dioxins/furans, PCB's and PAH's. A ceramic barrier filter is employed as the medium through which the separation of salts and contaminated absorbents as well as the dust takes place. In order to create a broad-spectrum absorbent, the dry powder is selectively blended. Calcium chloride $Ca(OH_2)$ is commonly used for acid gas removal. Active carbon is also used for the adsorption of volatile matter and heavy metals.

Calcium chloride $Ca(OH_2)$ is used for some time in removing acid pollutants from post-incineration flue gases. The following reactions explain its application:

$$Ca(OH_2) + 2HF \longrightarrow CaF_2 + 2H_2O$$

$$Ca(OH_2) + 2HCL \longrightarrow CaCl_2 + 2H_2O$$

$$Ca(OH_2) + 2SO_2 + \tfrac{1}{2}\, O_2 \longrightarrow CaSO_4 + 2H_2O$$

The production of sulphate, calcium chloride and calcium fluoride are the direct derivatives (calcium based salts) from the neutralisation of the acid gases. The of Calcium chloride performance is dependant on the temperature, moisture content, the excess dosing rate and the specific surface area of the reagent. Applying the latest reagents in a dosing rate of three times the stoichiometric ratio, the removal efficiencies can reach up to 99% for HF and HCL and 95% for SO_2. The stoichiometric ratio accounts as the theoretically necessary quantity of reagent for neutralisation.

Activated carbon can also be employed in order to remove environmentally toxic pollutants such as heavy metals and organic constituents. During the process, activated carbon is mixed with a 'carrier' inert material, most commonly $Ca(OH_2)$, in order to raise the smouldering point of pure activated carbon and to facilitate the handling of the mixed reagent. The excess dosing rate for carbon is dependant on the waste input as well as the emissions standards that require to be met.

CHAPTER 7- Discussion

Determining the viability of the potential development of the 10 MW MSW combustion plant for the area of Athens, Greece is a difficult task to accomplish. Extensive research on the data collected and evaluated in previous sections needs to be performed in order to reach a cohesive and objective verdict.

From the outset is established that the 10 MW MSW combustion plant load factor limit of 75% would be achieved by the combustion of 125,152 tonnes of MSW on a yearly basis. This accounts for almost 8.5% of the quantity of MSW dumped in designated areas around Athens per year. Although this percentage creates a positive momentum regarding the potential of the full utilisation of the MSW source for Athens, the rate of Annual kWh production for the current scheme cannot be considered satisfactory in relation to the quantity of raw material combusted. It was expected that a rather higher Annual kWh production rate could be achieved and this realisation leads to the question why is that not the case.

A review of the Btu/kg rates for the MSW components (Table 3.11) in terms of the Average % per kg (Table 3.4) provides an answer on why this implication exists for the current case: The MSW source used for energy generation comprises 50% of Organic material, which, as an element, does not posses a high thermal content (295.8 Btu/kg) compared with paper and plastics. Particularly for the last two components their thermal content is established at 5381.89 Btu/kg and 2565.12 Btu/kg equivalent, their low Average % per kg rates though reduce the Average thermal content rate of the combusted MSW in its total, providing a raw material that is not very efficient, unless it is used in bulk quantities during combustion.

The evaluation of the thermodynamic cycle efficiency was a task of pivotal importance to the study, involving an extensive quantitative analysis that is due to the plant's complex set-up. At this particular industrial site, an array of feed heaters (open and closed), an extraction turbine as well as other devices are employed, aiming to boost the overall thermodynamic efficiency. The operation of the unit is established in a high-pressure cycle involving six stages of feed heating, the feed water leaving the open heater at the saturation temperature corresponding to the saturation temperature of the bleed steam. For the closed feed heaters, the temperature of the feed water leaving the heater is 5K below the saturation pressure of the bleed steam. The introduction of the high-pressure cycle scheme yields to a better cycle efficiency and lower fuel costs over the lifespan of the plant, it is anticipated however that this will imply a greater capital cost for the boiler system.

The thermodynamic efficiency of the cycle calculated based on the above-mentioned parameters, yields a percentage of 47.49% before utilisation through the Generator/Gear box apparatus, which is considered satisfactory taking into consideration the plant's operational constraints and level of complexity. For the case where no feed heating applies, it was shown that the thermodynamic efficiency of the cycle is reduced considerably (42.51%) although the power output per unit mass flow rate from the boiler was shown to have increased. The steam mass flow rate for this case is 5.659 kg/s, this stresses the point that for a no feed heating scheme a smaller boiler could be used. Alternatively, the thermodynamic efficiency increase yields a reduction in fuel burned that results cash saving. On the assumption that this is great enough to offset the boiler expenditure, feed heating is proved to be an economic and ergonomically attractive proposition.

The secondary cycles featuring a temperature difference of 3Kand 7K for the feed water leaving the heater below the saturation pressure of the bleed steam are examined in order to identify potential variations in the thermodynamic efficiency of the cycle. The execution of calculations deducts a thermodynamic efficiency of 47.57% for the 3K-temperature difference scheme and a thermodynamic efficiency of 41.18% for the 7K-temperature difference scheme. This indicates that a decreasing stream in the thermodynamic efficiencies is manifested as the temperature of the feed water (in Kelvin) leaving the heater the saturation pressure of the bleed steam increases. This information can be used as a general code of practice in improving the thermodynamic efficiency of an MSW plant, although in the current case couldn't boost dramatically the thermodynamic efficiency rate of the primary cycle.

Taking into account the small thermodynamic efficiency loss in the Generator/Gearbox, the overall plant efficiencies for all cycles examined are found to follow a pattern, which remains faithful to the principles for the thermodynamic efficiencies introduced above. The decreasing stream in the overall plant efficiencies as the temperature of the feed water (in Kelvin) leaving the heater the saturation pressure of the bleed steam increases, still applies when the overall plant efficiency of the no bleed steam for feed heating scheme is considerably lower compared with the equivalent value of the 5K-temperature difference cycle. This analysis certifies the positive attributes of the primary thermodynamic cycle (5K-temperature difference cycle) employed in the plant and validates its effective operating code.

Environmentally, the MSW combustion plant complies under the current Emissions Law in that its force focuses primarily on the effective reduction of emissions from industrial sites (Nitrogen Oxides, Sulphur Compounds, Particulate Matter, Carbon Monoxide, Carbon Dioxide) as well as on the efficient operation of the sources from which they are emitted (boiler, steam turbine). The effective practice of combustion process emissions control and flue gases re-circulation together with the operation of the dry scrubber and bag house system, are expected to deliver the optimal environmentally friendly operation of the MSW combustion plant.

The Economic analysis performed for the particular venture however, highlights some points of particular interest that raise doubts about the profitability of the investment. Beginning with the estimation of the plant's Capital Costs, the inclusion of all comprising factors leads to a figure of £43,074,148. A 40% allowance provided by the European Union for the development of the project reduces the investor's capital requirements to £25,844,488 , which are paid into equal portions every year until the end of the plant's lifetime. This factor affects the Operational Costs of the investment, raising the total number to £2,433,102 annually. However, an additional grant of £500,000 may be provided to the plant owner from the Government on an annual basis for the effective handling of MSW, which reduces the Operational Costs to £1,933,102. From the forecasting of the Capital Costs and the Operational Costs presented above it is realised that the potential investment is extremely financially intensive.

The verification of the Government grant assumption presented above is included in the execution of the cash flow analysis for the investment. Performing the analysis by taking into account the Annual Energy Production (kWh) in relation to the Selling Price (£0.0396) established by the general invoice Γ 22 (Gamma 22) factors, the estimation of NPV is deducted as negative. The application of the IRR tool also does not lead to a tangible outcome either, verifying the NPV' s outcomes. It has been mentioned before that the Annual Energy Production (kWh) was not considered satisfactory because of a low Average thermal content of the waste due to the highly organic nature of the MSW fuel. This now becomes an issue, affecting the viability of the investment. A higher Annual Energy Production rate could possibly have improved the NPV findings, but in the current case this probability does not apply.

Employing a trial-and-error process by alternating the Selling Price factor under the assumption the current Annual Energy Production rate remains constant; a Selling Price of 0.17 (£/kWh) has to be established in order to consider the investment financially profitable. That is almost 5 times the current selling price of the kWh to the supplier specified by the Energy Law in Greece, which is considered too expensive by any standards.

CHAPTER 8- Conclusions

The detailed examination of the Production Assessment, Thermodynamic Plant Efficiency, Environmental Impact and Economics factors for the potential 10 MW MSW combustion plant for the area of Athens, Greece leads to the conclusion that although a plant of this size possesses a satisfactory thermodynamic as well as environmental operation, it is not considered a financially profitable venture for any external investor under the current regulatory standards. Although the MSW potential for the 10 MW energy production is tangible in the area, the development of a mass burning plant utilising it, for the pre-defined rates provided, would not result in a profitable business.

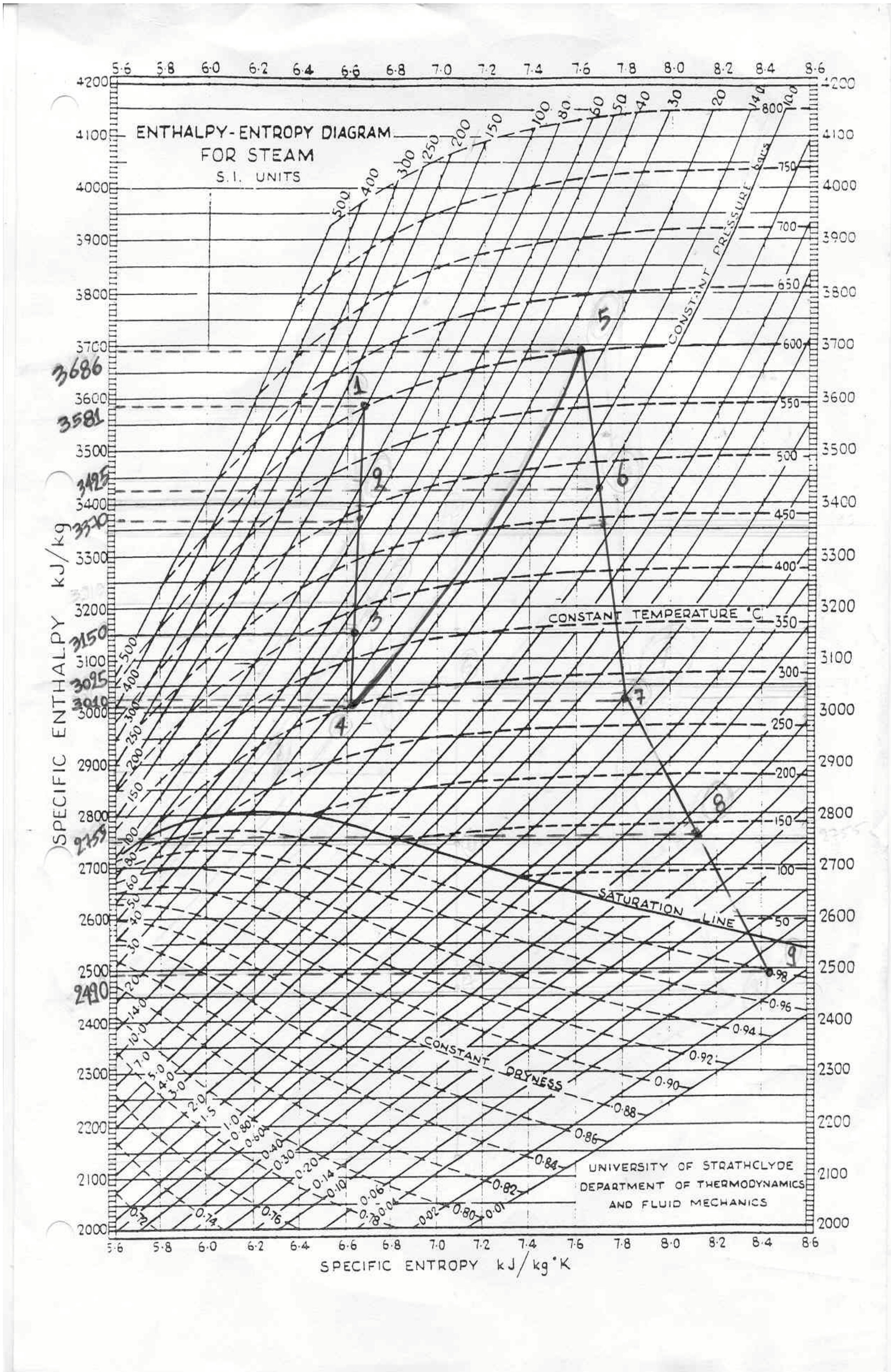
An alternative approach to the investment, which might yield a more positive outcome, would be if a higher power capacity were achieved from the combustion plant. The 10 MW set-up is not adequate to offset the extensive financial implications of the plant. In order to address this, a new set-up would have to be introduced from the start and additional research would have to be performed in order to define what power capacity level would be profitable in relation to the equivalent capital and operational costs of the venture.

However, it is not solely the issue of financial intensiveness for the external investor that marks this potential investment as a failure. It is also the fact that such an investment does not have adequate legislative or financial support from the local Government in order to allow it to progress because of the fact that other renewable technologies are under the Government focus for expansion and development for the time being. Unfortunately, this leads to the conclusion the only conditions under which the Waste to Energy plant concept could come into fruition would be if the Government made the breakthrough initially in order to establish a new market, thus enabling and encouraging external interest and investing to follow later on.

A Selling Price diversification in the general invoice Γ 22 (Gamma 22) implied from the restructuring of the current Energy Law would also be a step to the right direction. An effective pricing of the energy generated from other renewable sources apart from those already established could be achieved by taking into account the degree of difficulty in which this energy is extracted. In this case, the new invoice would include a breakdown of the kWh pricing, indicating the source from which it has been extracted. In this situation, energy extracted by a state Waste to Energy plant could be used as a secondary source of energy consumption from the customer base initially, and as the Biomass market opens up could progress to becoming a primary energy providing source next to other well established renewable technologies.

In summation, by taking into account the infancy stage, in which the concept of Waste to Energy is placed in Greece at the current time, it would be very difficult for an external investor to make a breakthrough in this field in the next five years. Moreover, even if this technology is proved successful in dealing with the problem of waste handling for Athens, unless considerable legislative and financial incentives are provided by the Government in addition to creating a momentum by taking the initiative in opening the market, the Waste to Energy plant concept will not come to fruition.

Appendix A


ENTHALPY-ENTROPY DIAGRAM
FOR STEAM
S.I. UNITS
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SPECIFIC ENTROPY kJ/kg°K
CONSTANT PRESSURE bars
CONSTANT TEMPERATURE °C
SATURATION LINE
CONSTANT DRYNESS
UNIVERSITY OF STRATHCLYDE
DEPARTMENT OF THERMODYNAMICS AND FLUID MECHANICS
3686
3581
3425
3370
3150
3025
3010
2755
2490

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