MUNICIPAL SOLID WASTES INCINERATION WITH COMBINED CYCLE: A CASE-STUDY FROM SÃO PAULO

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Abstract. *Large urban centers have a huge demand for electricity, for the needs of its residents, and a growing problem of management of solid waste generated by it, that becomes an public administrative and great social problem. The correct disposal of solid waste generated by large urban centers is now one of the most complex engineering problems involving logistics, safety, environment, energy spent among other tools for sound management of municipal solid waste (MSW). This study was carried out a study of the use of incinerators and residue derived fuel (RDF) and MSW with combined cycles, with the aim of producing thermal and mechanical energy (this later becomes electrical energy) and solid waste treatment in São Paulo. We used existing models and real plants in the European Union in this case, with the aim of making it the most viable and compatible with the current context of energy planning and resource today. A technical and economic feasibility study for a plant of this nature, using the scheme, is presented. It is expected a good attractiveness of using incinerators combined-cycle, due to its high efficiency and its ability to thermoelectric generation.*

Keywords*: cogeneration, combined cycle, incineration, municipal solid waste*

1. INTRODUCTION

In recent decades the urban centers are facing problem of public order and private sectors in transportation; logistics; processing of wastes of different composition, varying in its presentation, size and composition; liquid wastes, such as sewage sludge; flue gas and heat in the exhaust gas; water supply for cooling tower, among others (CARVALHO JR.; LACAVA, 2004). The origin of such waste is mostly residential, industrial and hospital, which is the most delicate for the final disposition, due to its high toxicity.

In the Sao Paulo state, about 15,000 tons of solid waste is produced per day and a considerable percentage of this waste is processed and landfilled, a small percentage is recycled and a minimum part is incinerated, and the priority for use of waste incinerators is for health services. For Holanda (2003), the percentages of waste quantities and types of processing are: 76% for disposition without technical care, 10% for sanitary landfills; 13% for controlled landfills (with sealing, leachate treatment system and gas control), 0.9% for composting plants and 0.1% for incineration plants.

When control and adequate treatment for the final disposal of waste is not provided, damages to the environment, such as soil and water contamination (reaching rivers, oceans, groundwater among others), air pollution (gases greenhouse effect, acid rain, particulate matter among others) are present. In this case, population is harmed with the proliferation of animal disease vectors (such as Aedes aegypti, rats, cockroaches, dogs, fleas, among others) and it is open to the access of unassisted people. Due to various problems caused by the final destination of the waste, this question becomes a challenge of engineering, logistics and environmental issues for various sectors of society. Due to these reasons, the proper management of waste has become an opportunity, not only in processing but the possibility of power generation, both electrically and thermally, and the sale of certified emission reduction, the so-called carbon credits.

The first alternative is the recycling of waste, bringing interesting economic and environmental advantages because it is used as raw material for various industries, reducing the production cost and reducing the gross volume of waste to landfills and incinerators. The most classic examples are recycling paper, glass, aluminum, steel, plastic and others.

Beyond recycling there is the use of landfills with biogas production, that feeds internal combustion engines for generating electricity to meet most the needs of the landfill (and even export surplus electricity). But due to increased production of waste, landfills in São Paulo are on their capacity limit and one possible alternative would be to use incinerators for the destruction of solid wastes, associated to the electricity and thermal energy production on waste-to-energy incineration systems. With this alternative, the ashes of the incineration could be landfilled with a 90% reduction in volume and 75% by weight of waste (Menezes et al., 2000).

2. STATE OF THE ART

Municipal solid wastes are composed of several elements of organic waste such as food scraps and toilet paper; electronic waste, such as batteries and cellular batteries; solid waste, such as paper, glass bottles, plastics and metals in general. In São Paulo, due to its characteristics of a metropolis with high population density, production and heterogeneity of waste is very high.

The waste from a site depends on several factors such as the characteristics of its population, income level, habits, the time of year in which wastes are collected, among other factors. Table 1 presents typical data of São Paulo wastes.

Table 1 - Typical garbage from the city of São Paulo, and divided by elements in mass fraction.

Components	Content Sao Paulo (Wt%)	moisture (Wt%)	Ash (Wt%)	Analysis of Composition (% dry basis)				
				C	H	N	S	O
Organic waste	49,50	70,00	5,00	48,00	6,40	2,60	0,40	37,60
Paper	12,00	10,20	6,00	43,50	6,00	0,30	0,20	44,00
Paperboard	6,80	5,20	5,00	44,00	5,90	0,30	0,20	44,60
Plastic	22,90	0,20	10,00	60,00	7,20	0,00	0,00	22,80
Fabrics	2,40	10,00	2,50	55,00	6,60	4,60	0,20	31,20
Rubber	0,30	10,00	10,00	78,00	10,00	2,00	0,00	0,00
Leather	0,30	10,00	10,00	60,00	8,00	10,00	0,40	11,60
Wood	1,30	1,50	1,50	49,50	6,00	0,20	0,10	42,70
Glasses [a]	1,50	2,00	98,90	0,50	0,10	0,10	0,00	0,40
Ferrous metals [a]	1,90	2,00	90,50	4,50	0,60	0,10	0,00	4,30
Aluminum [a]	0,90	2,00	90,50	4,50	0,60	0,10	0,00	4,30
Other	0,20	3,20	68,00	26,30	3,00	0,50	0,20	2,00

a - the organic materials are contained in labels, coating and other materials attached
Source: (MENDES, Aramaki, Hanak, 2003) and (Tchobanoglous et al., 1993)

The typical solid waste composition of São Paulo shows that people eliminates a significant proportion of organic material with a considerable percentage of moisture in its composition, and this makes it difficult to destine it to the industry recycling specially because it is generally mixed with materials easy reuse.

2.1. The lower calorific value of municipal solid waste

The solid waste presents a particular calorific value, and it is necessary to know its chemical composition for determining it; based on the data presented in Table 1, the calorific value of solid waste can be calculated. If the specific heat at constant pressure (c_p) of each substance is admitted constant, the lower heating value (LHV) can be calculated by Equation (1).

$$LHV = c_p\left(T_f - T_i\right) \tag{1}$$

However, as c_p varies with temperature, it must be integrate over the initial and final temperatures, as shown in Equation (2).

$$LHV = \int_{T_i}^{T_f} c_p dT \tag{2}$$

The specific heat of every substance that is part of solid waste must be considered, with the weighted values corresponding to the number of moles n_i, on a dry basis, according to Equation (3).

$$LHV = \int_{T_i}^{T_f} \sum_i n_i c_{p,i} dT \tag{3}$$

However, the residue contains moisture, so it is necessary to make a change in Equation (3) on the right side, adding the energy of water evaporation contained in the amount of waste, according to Equation (4).

$$LHV = \int_{T_i}^{T_f} \left[\sum_i n_i c_{p,i} \right] dT + \Delta H_1 \tag{4}$$

in which ΔH_1 is the latent heat of vaporization of water at 25 ° C, whose value is 584.4 [cal / g].

According to the available data, the molecular composition of solid waste can be approximated by $C_{25.55}H_{39.3}N_1S_{0.033}O_{10,27}$ $(H_2O)_{4,56}$. The equations presented at Table 2 are of interest for the calculation of the calorific value of solid waste.

Table 2: Equations for calculating the specific heat of the combustion products

Substance	c_p [cal/mol.K]	Interval [K]
CO_2	$10{,}34 + 0{,}00274T - 195500/T^2$	273 – 1200
H_2O	$8{,}22 + 0{,}00015T + 0{,}00000134T^2$	300 – 2500
N_2	$6{,}5 + 0{,}0010T$	300 - 3000
SO_2	$7{,}7 + 0{,}0053T + 0{,}00000083T^2$	300 - 2500

(Source: Carvalho Jr; McQuay, 2007)

2.2. The combined cycle adopted

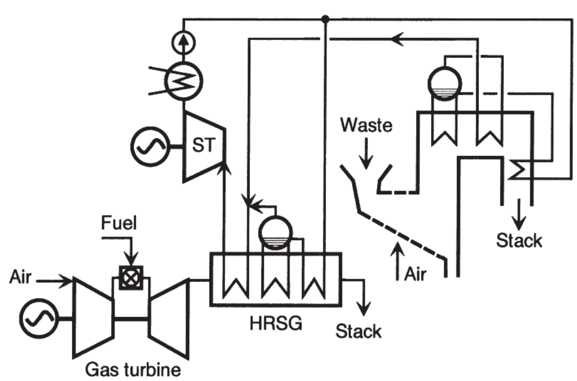
A combined cycle is proposed as the configuration to be used in this study, with an incinerator associated to a boiler attached to the outlet of the incinerator exhaust gas, a gas turbine, a steam generator recovery boiler, a condenser and a steam turbine.

For Consonni and Silva (2007), the elements which constitute the solid wastes generate a very aggressive exhaust gas that imposes damages to the incineration plant, even to the filters among other components. This equipment must be designed and constructed to withstand all kinds of aggressive nature of the incinerator exhaust gas and at the same time to produce steam at a given pressure and temperature.

One of the primary care is the recovery of the elements. According to Consonni and Silva (2007), the exhaust gas from each process must be disposed separately, with no mixture of exhaust gases of gas turbine system and the output of the incineration boiler due to two problems associated to this procedure. The first problem is the pressure drop of exhaust gas in the gas turbine components that will impose the use of induction fans to maintain the pressure in the combustion process, and also will cause an additional consumption of electricity in the process.

The second problem noted by Consonni and Silva (2007) is the significant drop in the incinerator efficiency, as it requires an amount of air for the burning and destruction of waste, and no air can get from another combustion process, even if this has high excess air.

Considering these facts, the cycle to be adopted in the present study is the one of Figure 1, in which the discharge of exhaust gases is separated and at the same time there is a steam recovery process, from heat recovery steam generator and incineration boiler, for being directed to steam turbine.



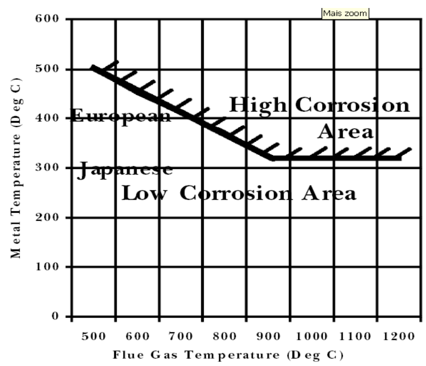
(Source: Korobitsyn; Jellema and Hirs, 1999)

Figure 1. Scheme of an incineration plant with heat recovery boiler in parallel with a gas range and the recovery boiler

Even according to Consonni and Silva (2007), the aggressive nature of the gases from incineration processes do not allow the elevation of the production parameters of process steam, causing generation processes with low thermal efficiency of 1st and 2nd law of Thermodynamics.

One of the problems presented in the incineration process is the corrosion rate in certain areas of thermal equipment, as can be seen in Figure 2, which shows the areas of low and high corrosion as a function of operating temperature of the incinerated waste. It presents the operating temperatures of incineration furnaces used by Europe and Japan and their sensitivity to the types of corrosion found in the gas temperature of the incineration process (SWITHENBANK, 2000).

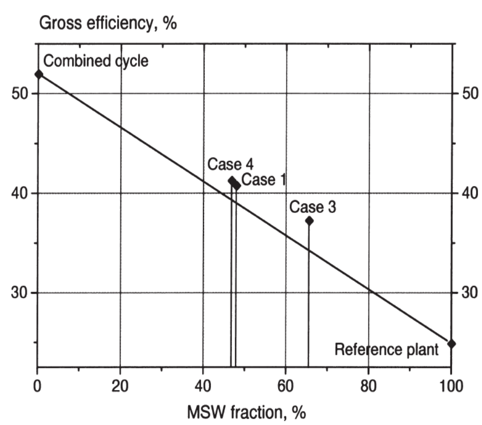
This parameter is interesting for a broader analysis of the operating time of equipment with an incineration process for the production of superheated steam. When using gases from incinerators, it is necessary to evaluate the safety, reliability and cost benefits of the equipment to be attractive to the thermoelectric generation sector.



Source Swithenbank (2000)

Figure 2. Typical corrosion in incinerators diagram

For Korobitsyn, Jellema and Hirs (1999), it is interesting the use of combined cycle in incinerators because the efficiency of the incineration plant can be raised with the gas turbine. A conventional combined cycle has a thermal efficiency in the range 45-55%. In Figure 3, the average is around 52% for a conventional combined cycle and 41% for a combined cycle integrating incineration process. The scheme proposed in Figure 1 is the one presented in Figure 3 as Case 1.



(Source: Korobitsyn; Jellema and Hirs, 1999)

Figure 3. Diagram of the total efficiency by the amount of solid waste incinerated in different settings

3. MATERIALS AND METHODS

3.1. The incineration plant

The incineration plant is based on a combined cycle, which has some attractive features such as the amount of electricity produced, the thermal potential, the solid waste disposal for a wide diversity, and that make it financially, environmentally and energetically attractive.

3.2. Basic parameters of an incineration plant

According to Korobitsyn, Jellema and Hirs (1999), the pressure and temperature recommended for an incineration plant is 40 bar and 400°C to generate process steam boiler in the incinerator. According to the CEWEP (2004a), these values may be augmented; some incineration plants of European Union countries operate at 500°C and 120 bar, as a plant located in Germany, or at 520°C and 65 bar, as described in CEWEP (2004b).

For the present analysis, it will be adopted as operating parameters 65 bar and 450°C, which results in an enthalpy of 3294 kJ/kg; at the entrance of the combustor boiler it will be considered a pressure of 67 bar due to the pressure drop and a temperature of 80°C, the latter being adopted by Korobitsyn, Jellema and Hirs (1999), with an enthalpy of 340 kJ/kg.

The processing of solid waste considers a production of 84,000 ton per year. For Mendes et al. (2004), it is considered 95% of that waste as non-recyclable, i.e., only 5% are interesting for recycling because it will present metals. Thus, considering 8000 hours per year of operation for the incineration plant, an average rate of processing residue of 9.90 ton/hour, or 2.75 kg/s of solid waste to be incinerated is considered in the calculation.

The lower calorific value was evaluated and presents an approximate value of 11 MJ/kg; for an efficiency of 85% for the boiler associated to the incinerator and a volume control over there, the production of process steam is modeled according to equation (5).

$$\left(\dot{m}_{MWS} \times PCI_{MWS}\right) \times \eta_{HRSG} = \dot{m}_{Steam} \times \left(h_{output} - h_{entry}\right) \qquad (5)$$

With Equation (5), 8.73 kg/s of process steam is estimated. The ratio of the mass flow of process steam generated by mass flow of solid waste incinerated is approximately 3.2 kg (steam)/kg (MSW). Compared with values and Søren Kleis (2004), whose values are 3.6 kg (steam)/kg (MSW), a certain consistency of results can be observed.

A control volume is applied to the gas turbine; the needed care in the selection of the gas turbine is to avoid the temperature exhaust gas to be quite high compared with the critical parameters of steam production, that pinch point temperature is in the range of 10 to 30°C and that temperature of chimney is in the range of 100 to 200°C for the sake of thermal energy efficiency. Table 3 sets are some gas turbines that have the characteristics to be used in parallel with the cycle of incineration.

Table 3. Models set the gas to be analyzed to make an appropriate choice.

Manufacturer	Model	Potency [kW]	HR [kJ/kWh]	Efficiency	RP	$\dot{m}_{gas}$ [kg/s]	T_{output} [°C]	Rotation [RPM]
Asltom	GT8C2	56200	10651	33.80%	17,6	197	508	6204
Bharat	PG6591(C)	42300	9915	36.30%	19	117	575	7100
Bharat	PG6581(B)	42100	11225	32.10%	12,2	145	544	5163
GE Energy Heavy Duty	PG6581(B)	45400	9825	36.60%	19,6	122	581	7100

(Source: GAS TURBINE WORLD HANDBOOK GTW 2009, 2009)

With the parameters of the boiler steam conditions of the incinerator it is possible to perform the calculation of heat transfer with equation (6), with $c_{p,\ gas}$ = 1.014 kJ / kg.K and of the recovery boiler efficiency of 75%. By calculating the mass flow of process steam will be made to the calculations of temperature chimney taking 150°C as the first estimate. Equation 7 expresses the expression for calculating the temperature of the chimney, considering the saturation temperature of the process steam as 281°C.

$$\dot{m}_{Gas} \times c_{p,gas} \times \left(T_{output,\ gas} - T_{ch1}\right) \times \eta_{HRSG} = \dot{m}_{steam} \times \left(h_{output} - h_{entry}\right) \qquad (6)$$

$$Tch = T_{output,\ gas} + (T_{steam\ sat} + \Delta PP - T_{output,\ gas}) \times \left(\frac{\dot{m}_{GN} \times \left(T_{output,\ gas} - T_{ch1}\right)}{\dot{m}_{steam} \times \left(h_{output} - h_{entry}\right)}\right) \qquad (7)$$

The respective values of the mass flow of steam generated by the recovery boiler, a chimney with pinch point temperature ΔPP = 30°C and for ΔPP = 10°C are shown in Table 4.

Table 4. Calculated values of mass flow of steam, temperature of a chimney for ΔPP of 30°C and 10°C of their joint gas produced

Manufacturer	Model	$\dot{m}_{Steam}$	$T_{CH,\ \Delta PP\ 30°C}$	$T_{CH,\ \Delta PP\ 10°C}$
Asltom	GT8C2	18,33	245,33	218,67
Bharat	PG6591(C)	12,93	223,00	196,33
Bharat	PG6581(B)	14,92	233,33	206,67
GE Energy Heavy Duty	PG6581(B)	13,68	221,00	194,33

With the values shown in Table 4, the more attractive gas turbine for the proposed scheme is GE Energy Heavy Duty model PG6581(B), for which the temperature chimney is in a proper range of operation, so that no formation of condensation on pipes in the vicinity of the chimney temperature is 100°C and so there is no waste of heat energy to the recommended temperature should be below 200°C for a pinch point temperature between 10 and 30°C. In Table 5 it is presented the main points of operation of the incineration plant in the combined cycle.

Table 5. Values of design for the combined cycle integrated with a combustor.

thermodynamic state / equipment	T [°C]	P [MPa]	h [kJ/kg]	steam quality
Turbine steam inlet	450	6,5	3294	-
Turbine steam exit	33	0,005	2319	0,9
Check the condenser	33	0,005	2319	0,9
Condenser outlet	33	0,005	138	0
Check in deaerated	33	0,005	138	0
Output deaerated	80	0,101	335	-
Pump inlet	80	0,101	335	-
Pump output	82	6,7	348,5	-
Check the boiler	82	6,7	348,5	-
Check out the boiler	450	6,6	3293	-

With a control volume in the deaerator, the following equations can be presented:

$$\dot{m}_{deaer} \times h_{Steam} + \dot{m}_{inlet,Steam} \times h_{exit,cond} = \dot{m}_{Total} \times h_{tank} \tag{8}$$

$$\dot{m}_{deaer} + \dot{m}_{inlet,\ Steam} = \dot{m}_{Total} \tag{9}$$

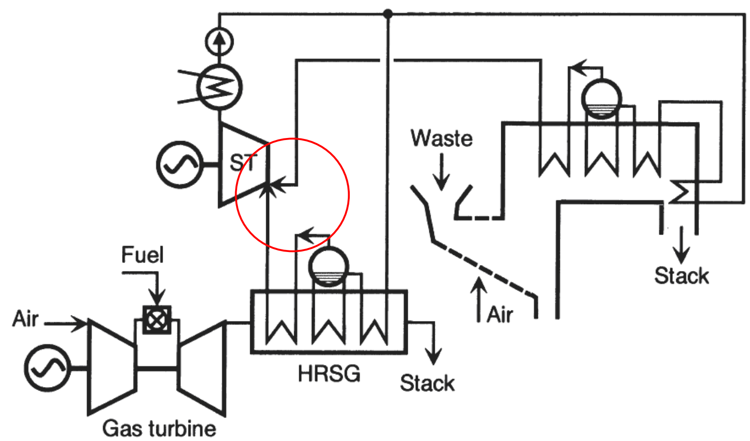
$$\dot{W}_{ST} = \dot{m}_{inlet,Steam} \times (h_{Steam} - h_{exit,st}) \tag{10}$$

$$\eta_{Global} = \left(\frac{W_{ele,GT} + W_{ele,ST}}{\left(HR \times W_{ele,GT} + PCI_{MWS} \times m_{MWS}\right)} \right) \tag{11}$$

Isolating the mass flow rate of deaerator, the necessary terms to the equalization of income and thermoelectric generation plant are available. The following results are then presented: the total mass will be 22.41 kg/s of process steam, the flow of mass to be deaerated is 1.4 kg/s steam, so 21 kg/s is available for a production in thermal steam turbine of 19,460 kW. The thermal efficiency is approximately 42.07% for a plant configuration shown in Figure 4, in which the detail expresses the main difference relative to the scheme presented in Figure 1.

3.3. Parameters for calculating the expected revenue

Investors have many methodologies for the analysis of a particular investment, each of these with a specific focus and differential. The payback is turned to the time variable of the initial investment, while the Net Present Value (NPV) turns to the value of capital flows obtained from a given base date.



(Adapted from: Korobitsyn; Jellema and Hirs, 1999)

Figure 4. Scheme of an incineration plant with heat recovery boiler along with a set and gas recovery boiler and can operate off point of the project.

The idea of the Internal Rate of Return (IRR) has emerged as another model for investment analysis, focused on a variable rate. The use of IRR attempts to bring together in one single number the power to decide on a specific investment; this number is not necessarily linked to the market interest rate. The IRR is a number intrinsic to the project, i.e., it does not depend on any parameter other than the expected cash flows from that investment.

The IRR is an interest rate that makes the present value of cash inflows equal to the value of this cash outflows of investment; it may be total or partial. This means that the IRR is the rate that tends to cancel the investment. It is a rate that if used will cause the project profit to be zero (INTERNAL RATE OF RETURN, 2010).

It was considered three different scenarios, as shown in Table 6. The optimistic scenario has a minimum tax of attractiveness (TMA) of 8% and increased costs of electricity, 150 U.S.$/MWh. The pessimistic scenario presents the larger TMA, 9%, and lowest cost of electricity, 80 U.S.$/MWh. The intermediate scenario considers the average values. The tax rate for income tax and social contribution will be considered 34%.

Table 6. Values of MAC and electricity costs for three hypothetical scenarios of the market.

Scenarios	TMA	Electricity costUS$/MWh
Optimistic	8 %	100
Intermediate	9 %	85
Pessimistic	10 %	65

4. RESULTS

The results for a financial analysis of an incineration plant in combined cycle are shown in Figures 5 and 6. They present the results of the analysis of NPV and IRR scenarios considering the optimistic, pessimistic and intermediate shown in Table 6.

5. CONCLUSIONS

The excessive generation of municipal solid waste is a problem for society. It is therefore important to evaluate and implement management alternatives that may offer economic and energy benefits. The alternative of municipal solid waste incineration in a combined cycle is more advantageous from the energy point of view that incineration of municipal solid waste in a simple Rankine cycle. As Mendes et al. (2004) pointed out, municipal solid waste incineration systems has a low global warming potential GWP (Global Warming Potential), despite its high cost. The results obtained in the present paper indicate a significant increase of the overall efficiency of the plant due to the use of two different fuels. In the case of incineration cycle, the overall efficiency is estimated to be 42%, a value that is considered adequate considering the results of Korobitsyn; Jellema and Hirs (1999) in their studies for a comparative analysis with combined cycles and cycle combustor combined simple.

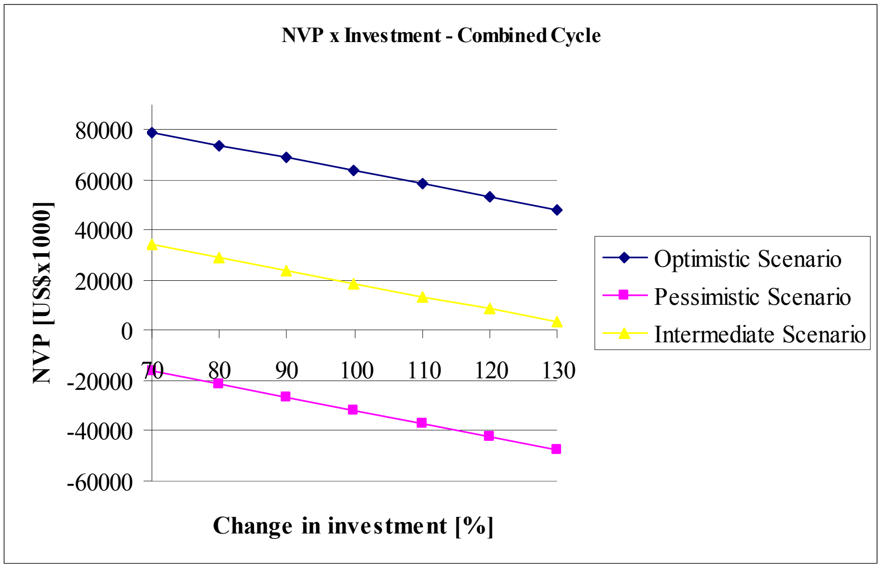


Figure 5. Graph of the financial analysis using the methodology and the variation of the NPV of the investment for three different scenarios.

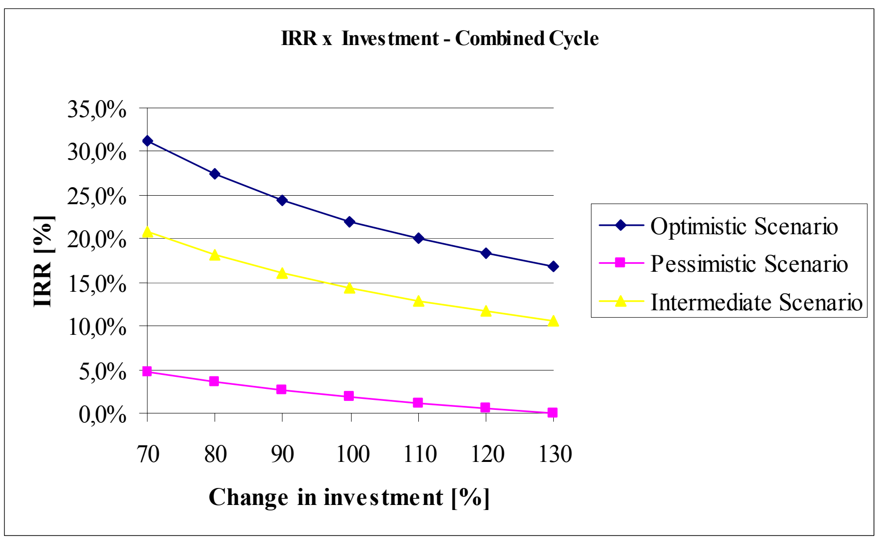


Figure 6. Scheme of an incineration plant with heat recovery boiler along with a set and gas recovery boiler and can operate off point of the project.

Incineration is shown as a technological alternative suitable for the disposal of municipal solid waste, solid waste for processing in order to compress it and its high efficiency. Thus, the combined cycle contributes to a higher generation of electricity, due to the use of natural gas throughout the gas. An enterpreune such this one have interesting economic return, with IRR above 30%, but it is important to remember that in the case of combined cycle there is a risk for the use of natural gas, whose price has risen significantly in recent years. The investment cost of this technology is high compared to internal combustion engines associated to landfills biogas, which should hinder investment decisions on them. Its main advantage is the capacity of reducing the mass and volume of municipal solid waste, which increases the availability and useful life of existing landfill sites.

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