Techno-Enviro and Economic Analysis of MSW-Fired Power Plant: A Case Study of Hyderabad, Pakistan

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Abstract— In this paper, the thermodynamic, environmental and economic analysis is conducted on 210 MW dual fired Jamshoro Power plant unit, operating it on MSW generated in Hyderabad City. Firstly, a mathematical model has been developed for MSW operated Jamshoro Power plant and is analyzed in Engineering Equation Solver (EES) software. The thermodynamic parameters including mass flow rate of MSW required, net power output and energy efficiency are determined. The environmental effects including mass of flue gases is calculated and a comparative study is performed between parameters of existing power plant and modeled MSW plant. The economics of the plants including capital and transportation costs are also considered. According to the results, the mass flow rate of MSW required is 23.16 Kg/s or 2001 tons/day in dry state and 43.23 Kg/s or 3735 tons/day in wet/moisture state which in actual is easily generated in the Hyderabad city i.e. 4000 tons/day in wet state. The net power output and energy efficiency of the MSW plant are 23.16 Kg/s, 189 MW and 29.93% respectively, which is satisfactory to operate MSW plant. The flue gases including including CO_2, SO_2, NO are produced at a rate of 41.323, 0.08 and 1.328 Kg/s. Using MSW as fuel source, PKR.6.13 billion can be saved per year.

Keywords: MSW, Mass flow rates, energy efficiency, heat generation capacity, flue gases, costs.

I. INTRODUCTION

Pakistan has been facing severe energy crisis and suffering from various environmental issues faced due to mismanagement of MSW (municipal solid waste). Nowadays, alarming situations are seen to occur due to mishandling of waste [1]. Industrialization, rapid growth in population and lack of trainings create dramatic problems in developing solid waste management systems [2]. The major reason of generation of MSW is unforeseen increase in urbanization. Approx. six billion people will occupy urban areas by 2050 [3, 4].Out of very serious issues such as air-noise pollution and waste water generation, the proper disposal of MSW is the most challenging problem [5]. Thermal or heat treatment techniques can be applied to about 90% of MSW, thus addressing power generation and waste disposal issues [6]. The per capita MSW generation lies from 0.7 to 1.5 kg/day and 0.9 to 1.6 kg/day in Asia and European Union, respectively. Consequently, MSW is being produced in millions of tons per day, globally [7, 8]. The major cities of Pakistan generate MSW at the rate 1.9 kg per house to 4.3 kg per house per day, on average basis. [9]. More than 90% of collected solid waste is either dumped openly at low laying natural areas and road sides, put into open water [10]. Despite having enormous quantity of MSW being generated in Pakistan, no any practice been applied for generating power from it. Hyderabad being the 2nd largest city of province Sindh and the 3rd largest city of Pakistan, lies between 68°22′6″ East and 25°22′45″ North. It has about 2 million population [11]. It generates MSW at a rate ranging from 0.6 to 0.8 kg per day and hence generating about 1600 tons per day [12]. Table 1 shows the moisture content and weight (in %) of each component of solid waste generated in Hyderabad.

Table 1. Moisture content (%) and Percentage (%) by weight of MSW [12].

Waste component	Moisture content (%)	Physical composition by weight (%)
Wood	20	1.84
Cardboard	5	6.7
Yard waste	51.73	13.85
Food waste	76.44	30.82
Leather	10	1.11
Glass	2	6.08
Plastic	2	8.75
Textile	10	2.07
Rubber	2	1.1
Metals	8	3.66
Paper	6	5.89
Ash, bricks, dust	8	18.13
Cumulative for MSW		100

Hence, such amount of waste can be utilized to generate power to meet the energy shortage demands. Waste incineration thus offers a way to recover energy from MSW and has been used in a number of nations, including the USA, Sweden, and Germany [13]. The technique of incineration also offers the benefit of significantly lowering waste volume with little need for pre-processing and guaranteeing total destruction of dangerous refractory organic compounds [14].

M.S. Korai et al. [15] determined calorific (CV) value of MSW generated in Hyderabad. After collection of solid waste from different areas of the city, they found its calorific by applying quartering method and analysing it through bomb calorimeter. The higher as well as lower CV of the components of MSW is given in Figure 1. The gross and net CVs are estimated as 6749 and 6519 Kcal per Kg or 28237 and 27275 KJ/Kg or respectively.

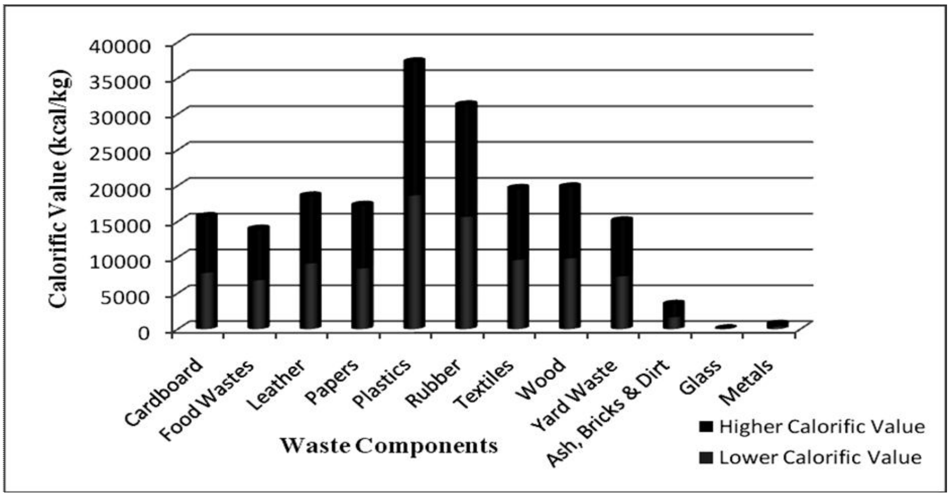

Figure 1. LCV and HCV of MSW Components [15]

S.Yazdani et al. [16] conducted comparative energy analysis of municipal solid waste incineration power plant (MSWPP) and natural gas power plant (NGPP), with capacities 3 MW and 247.5 MW and respectively, using Energy Management and Assessment tool (EMA). The outcomes of this work show that MSWPP has much higher emergy sustainability index (ESI) and percent of renewability (PR) than NGPP. The ESI and PR values for MSWPP are 1.65 and 46.81, and for NGPP are 0.05 and 5.01 respectively. Hence, as per this study, MSWPP is better than NGPP in terms of efficiency and environmental aspects.

T.A Jack et.al [17] presented the exergy and exergoeconomic analysis of a proposed steam reheat power plant powered by the municipal waste of Port Harcourt city in Nigeria. For this work, the city's expected municipal trash generation for 2020 was used to calculate the amount of power that could be obtained from a waste incinerator plant while accounting for the plant's cost effectiveness. A projected 117 MW waste-to-energy incinerator plant in Nigeria was determined to have first and second law efficiencies of 369.91% and 31.36%, respectively. The anticipated capital cost was 326 million USD with a six-year payback period and a COE of 55.7 USD/MWh.

M Ozturk et. al. [18] proposed a waste management strategy for metropolitan cities. If offers thermodynamic analysis and an emission assessment of a municipal solid waste incinerator plant using waste collected from Istanbul Turkey's 37 municipalities. According to thermodynamic analysis of the suggested system, burning municipal solid waste produces 99.4 MW of heat for district heating and 53.72 MW of electricity. The overall amount of CO_2 emissions per year, as determined by the emission assessment, is 45500 tons. By adding a carbon capture and storage unit, this amount can be decreased to 4550 tons annually. The incineration plant also releases other emissions, such as CO, NH3, N2O, CH4, and non-methane volatile organic compounds (NMVOCs), which are measured to be 0.15, 34.36, 201.03, 16.08, and 20.10 tons annually, respectively.

A study on converting three typical Russian coal-fired power plants to composite liquid fuel slurries based on waste coal processing waste with municipal solid waste components (cardboard, plastic, rubber, and wood) and spent turbine oil was proposed by G. Dimitrii et al. [19]. According to the analysis, the suggested technique will save 145 Mt of high-quality coal over the course of 25 years. The recovery of 190-260 Mt of industrial and municipal waste, including 130-260 Mt of FC, 25-38 Mt of MSW, and up to 19 Mt of used oils, will provide about 10.1 TWh of electricity and 9.7 Kcal of heat.

U.R. Zia et al. [20] assessed techno-economic energy generation potential from MSW of medium and small sized districts of Pakistan, especially Wahh cant district. The wahh cant generates 200 tons of MSW per year. The results obtained show that 21 MW of power can be generated by using this solid waste through incineration process. 19,000m^3 of biogas can be produced per day which can further generate 115 MWh of electricity by anaerobic digestion or a compost of 10000 tons, thus can decrease annual import cost by $5 million annually. The incineration process does not necessarily require any pre-treatment of MSW.

Adnan A. et al. [21] conducted research using incineration to recover energy from municipal solid waste to produce electricity in the urban areas of Dhaka and Chattogram. A detailed technical analysis involving energy, exergy, exergo economic, and emission is conducted. The power plants in these two cities show potential capacities of 169 MW and 83 MW respectively with combustion of MSW at 2.10 Million tons per year or 5753 tons per day and 1.04 Million tons per year or 2849 tons per day, respectively. The lower heating of MSW in both cities are 9.86 MJ/Kg and 9.77 MJ/Kg respectively. The energy efficiency of plants is determined of 32.3%.

This research study mainly emphasizes on utilization of solid waste Hyderabad city for power generation. The 210MW thermal Power Plant in Jamshoro [22], is considered as model power plant for undertaking thermodynamic analysis by using MSW as fuel. The fuel transportation cost and operational costs for the existing dual fired power plant are quite high and rely on the availability of fuel, which in turn can be reduced by utilizing MSW as fuel. The comprehensive thermodynamic, environmental and economic analysis of the proposed MSW is conducted in this study.

II. RESEARCH METHODOLOGY

As per previous literatures, various software and simulators have been utilized for thermodynamic analysis of power generation from MSW. However, in this study, Engineering Equation solver (EES) has been used for simulation of proposed MSW power plant. The detailed research methodology for technical, environmental and economic analysis is discussed below,

1. Technical Analysis

A mathematical model of the plant containing the equations of existing 210 MW dual fired power plant [22], have been developed. Mass burn MSW incineration method has been selected to combust MSW for generation of steam, whose mathematical equations have been substituted for the combustion chamber section in the developed mathematical model. The developed model equations have been incorporated and analysed in Engineering Equation Solver (EES) to determine the amount of MSW required, power output and energy efficiency of the power plant. The combustion and heat transfer properties taken from [22] and the calorific value of MSW generated in Hyderabad [12] have be utilized to determine the stated parameters of MSW plant. A comparative analysis have been conducted for the results obtained from the proposed plant with existing plant.

Figure 2 shows the schematic diagram of the existing power plant [22]. The same plant has been considered to undertake the study for MSW required to operate the power plant. Figure 3 shows the design of MSW power plant, in which state points are taken same as mentioned in figure 2 and Table 2 shows the assumptions taken for thermodynamic analysis of power plant. A design of power plant with MSW incineration system is shown in figure 3 [23].

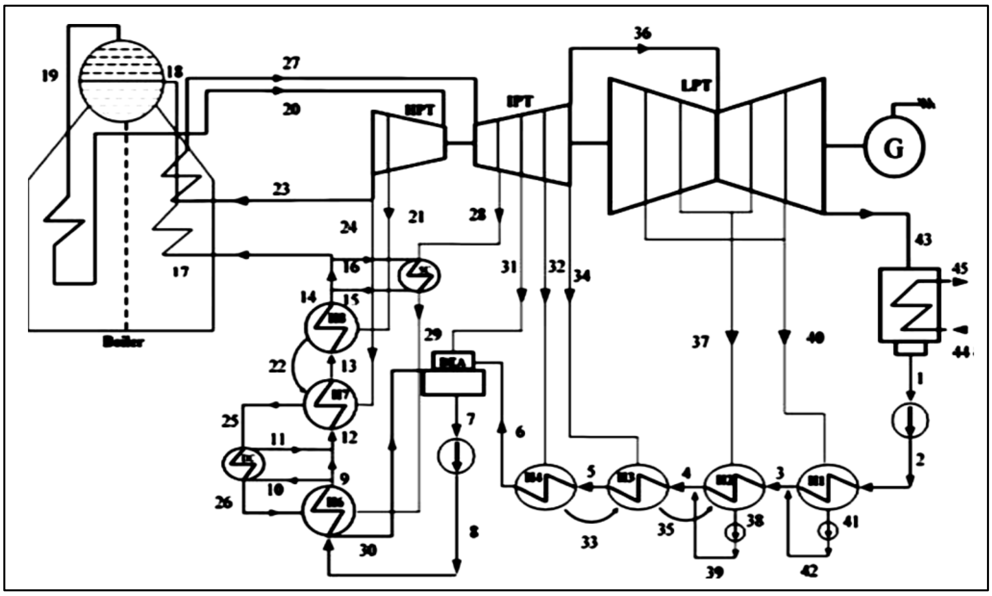

Figure 2. Schematic of power plant unit

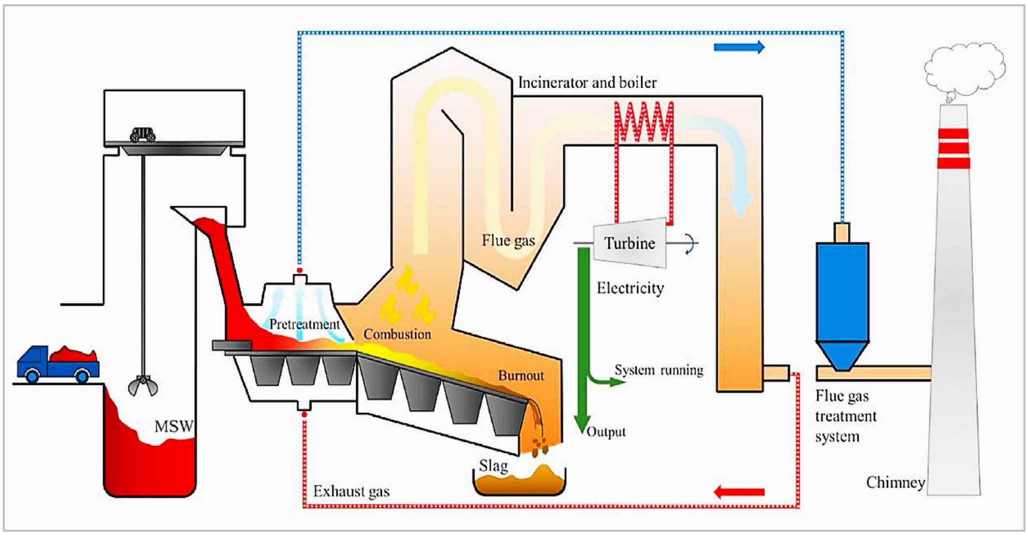

Figure 3. Design of MSW power plant unit with state points considered same as in figure 2

Table 2. Assumptions for thermodynamic evaluation of steam power plant [22]

1.	Steady-state operation of system components	
2.	Change in kinetic energy and potential energy of fluid streams neglected	
3.	Dead-state condition	101.325 kPa and 298 K
4.	Isentropic efficiency of steam turbine	90%
5.	Isentropic efficiency of pumps	85%
6.	Efficiency of Incineration boiler [24]	80%

Given below are the mathematical model equations for MSW power plant, developed by applying basic thermodynamics as given in [22],

1.1. Steam Turbine

The total power output from the steam turbines can be determined as,

$$\dot{W}_T = \dot{W}_{HPT} + \dot{W}_{IPT} + \dot{W}_{LPT} \tag{1}$$

For HPT, the power output is,

$$\dot{W}_{HPT} = \dot{m}_{20}(h_{20} - h_{21}) + (\dot{m}_{20} - \dot{m}_{21})(h_{21} - h_{23}) \tag{2}$$

For IPT and LPT, the power output is,

$$\dot{W}_{IPT} = \dot{m}_{27}(h_{27} - h_{28}) + (\dot{m}_{27} - \dot{m}_{28})(h_{28} - h_{31}) + (\dot{m}_{27} - \dot{m}_{28} - \dot{m}_{31})(h_{31} - h_{32}) + (\dot{m}_{27} - \dot{m}_{28} - \dot{m}_{31} - \dot{m}_{32})(h_{32} - h_{34}) \tag{3}$$

$$\dot{W}_{LPT} = \dot{m}_{36}(h_{36} - h_{37}) - (\dot{m}_{36} - \dot{m}_{37})(h_{37} - h_{40}) + (\dot{m}_{36} - \dot{m}_{37} - \dot{m}_{40})(h_{40} - h_{43}) \tag{4}$$

1.2. MSW Incineration combustion chamber and Boiler

An energy balance of boiler yields the following relation:

$$\dot{Q}_B = \dot{m}_{17}(h_{20} - h_{17}) + \dot{m}_{27}(h_{27} - h_{23}) \tag{5}$$

The quantity of MSW required to generate steam can be calculated through energy balance of heat supplied by MSW combustion and heat generated by steam,

$$\dot{m}_{MSW} = \frac{\dot{Q}_B}{\eta_B \times LHV_{MSW}} \tag{6}$$

The heat supplied by the combustion of MSW is calculated as,

$$\dot{Q}_{MSW} = \dot{m}_{MSW} \times LHV_{MSW} \tag{7}$$

The heat lost after combustion,

$$\dot{Q}_{lost} = \dot{Q}_{MSW} - \dot{Q}_{B} \tag{8}$$

The net calorific value / lower heating value LHV of MSW generated in Hyderabad city is taken as 6519 Kcal/Kg = 6519 x 4.184 KJ/Kg = 27275 KJ/Kg [15] and the efficiency of MSW boiler is taken as 80% [24].

1.3. Pumps

The power required associated to boiler feed water and condensate pumps are determined as follows:

$$\dot{W}_{cons,p} = \dot{W}_{cons,cp} + \dot{W}_{cons,bfp} \tag{9}$$

1.4. Condensate Pump

Energy balances of the condensate pump gives the power required as:

$$\dot{W}_{cp} = \dot{m}_1(h_2 - h_1) \tag{10}$$

1.5. Boiler Feed water pump

Similarly, for the boiler feed water pump we have:

$$\dot{W}_{bfp} = \dot{m}_6(h_8 - h_7) \tag{11}$$

1.6. Feed Water Heaters

The energy balance as applied to feed water heaters as a combined system gives the following:

$$\eta_{HPH} = \frac{\dot{m}_{17}h_{17} - \dot{m}_8h_8}{\dot{m}_{21}h_{21} - \dot{m}_{24}h_{24} + \dot{m}_{37}h_{37} + \dot{m}_{40}h_{40}} \tag{12}$$

$$\eta_{LPH} = \frac{\dot{m}_6h_6 - \dot{m}_2h_2}{\dot{m}_{32}h_{32} - \dot{m}_{34}h_{34} + \dot{m}_{37}h_{37} + \dot{m}_{40}h_{40}} \tag{13}$$

Similarly for the deaerator, energy balance yields:

$$\eta_{LPH} = \frac{\dot{m}_7h_7}{\dot{m}_{31}h_{31} + \dot{m}_{30}h_{30} + \dot{m}_6h_6} \tag{14}$$

1.7. Condenser

Energy balance of condenser are given as:

$$\dot{m}_{43}(h_{43} - h_1).\eta_C = \dot{m}_{44}(h_{45} - h_{44}) \tag{15}$$

1.8. Overall Plant

The net power output of the plant is given as:

$$\dot{W}_{T,net} = \dot{W}_T - \dot{W}_{cons,p} \tag{16}$$

The net electrical power output of the MSW plant can also be verified from the following equation [20],

$$EPP_{MSW} = \frac{277.8 \times LHV_{MSW,MJ/Kg} \times \dot{m}_{MSW,tpd} \times \eta}{24} \tag{17}$$

Where "η" is the conversion efficiency taken as 30 % [20], lies in the range of 20-40%.
As per equation, the value of lower heating value "$LHV_{MSW,MJ/Kg}$" is in MJ/Kg and mass of MSW "$\dot{m}_{MSW,tpd}$" is taken in tons per day.

The energy efficiency of the plant is given respectively as:

$$\eta_{thermal} = \frac{\dot{W}_{Tnet}}{\dot{Q}_{MSW}} \tag{18}$$

2. Environmental Analysis

In order to calculate mass flow rate of combustion products of MSW i.e. flues gases including CO_2, SO_2 and NO, it is necessary to determine the mass content of elements present in MSW components. Thus, for supplied mass of MSW, the mass of its components in dry state and wet state and then, mass content of elements and their products after combustion have been calculated. The detailed mathematical equations are as under,

2.1. Mass of MSW components

For mass of dry MSW supplied, the mass of each component of MSW in dry state and wet/moisture state is calculated using following equation,

$$\dot{m}_{C,moist} = \dot{m}_{MSW} \times \frac{PCT_{C,moist}}{PCT_{T,dry}} \quad (19)$$

$$\dot{m}_{C,dry} = \dot{m}_{T,moist} \times PCT_{C,dry} \quad (20)$$

2.2. Mass of elements

The mass of elements contained by the MSW supplied is determined as follows,

$$\dot{m}_{element} = \dot{m}_{C,dry} \times PCT_{element} \quad (21)$$

2.3. Mass of flues gases

The mass of flue gases produced by the combustion of MSW supplied is determined by,

$$\dot{m}_{flue\ gas} = \frac{M_{flue\ gas}}{M_{element}} \times \dot{m}_{element} \quad (22)$$

3. Economic Analysis

The MSW collection and transportation the MSW power plant is discussed in this work.

3.1. MSW collection and transportation cost

Assuming the collection and transportation of MSW is carried out in Nissan Trucks which are the most efficient trucks in terms of load carrying capacity i.e. 36 tons per day and fuel efficiency [25]. Thus, the collection cost of MSW in Hyderabad city can be calculated as,

$$Cost\ per\ day_{MSW\ collection} = MSW_{tons\ per\ day} \times \left(fuel_{litres\ per\ day} \times \frac{A_{Hyd}}{A_{DGBT}}\right) \times fuel\ price_{Rs\ per\ litre} \quad (24)$$

The fuel (diesel) consumed by Nissan truck for Data Ganj Bux Town (DGBT), Lahore, Pakistan is 1.8 litres per day [25], thus for Hyderabad city, ratio Area of Hyderabad city (A_{Hyd}) i.e. 292 Km^2 [26] to area of DGBT i.e. 60.12 Km^2 [25]. The fuel (diesel) price with current rate is Rs. 303.18 per litre [27].

The number of trucks needed for collection of MSW,

$$N_{trucks} = \frac{MSW_{tons\ per\ day}}{Truck\ capacity_{tons\ per\ day}} \quad (25)$$

Taking average distance of 30 km is travelled by trucks from Hyderabad city to the power plant. Then the total transportation cost will be,

$$Cost\ per\ day_{transportation} = Distance\ \times\ Cost\ per\ day_{MSW\ collection} \quad (26)$$

III. RESULTS AND DISCUSSION

The Engineering Equation solver has proven to be an effective tool in modelling and analysing the designed power plant. The results and their details are discussed below,

1. Technical Analysis

Taking the values of parameters at state points of the power plant as in [22], the mass flow rate of MSW required is calculated as 23.16 Kg/s or 2001 tons/day in dry state and 43.23 Kg/s or 3735 tons/day in wet/moisture state which in actual is easily generated in the Hyderabad city i.e. 4000 tons/day in wet state. The net power output and energy efficiency of the MSW plant are 189 MW and 29.93% respectively, which appear nearly satisfactory to operate MSW plant, as the comparison of these results with those of existing dual fired power plant [22] is illustrated in Figure 4. The plot of heat generation capacity against the mass flow rates of both the fuels i.e. furnace oil and MSW is also shown in figure 5.

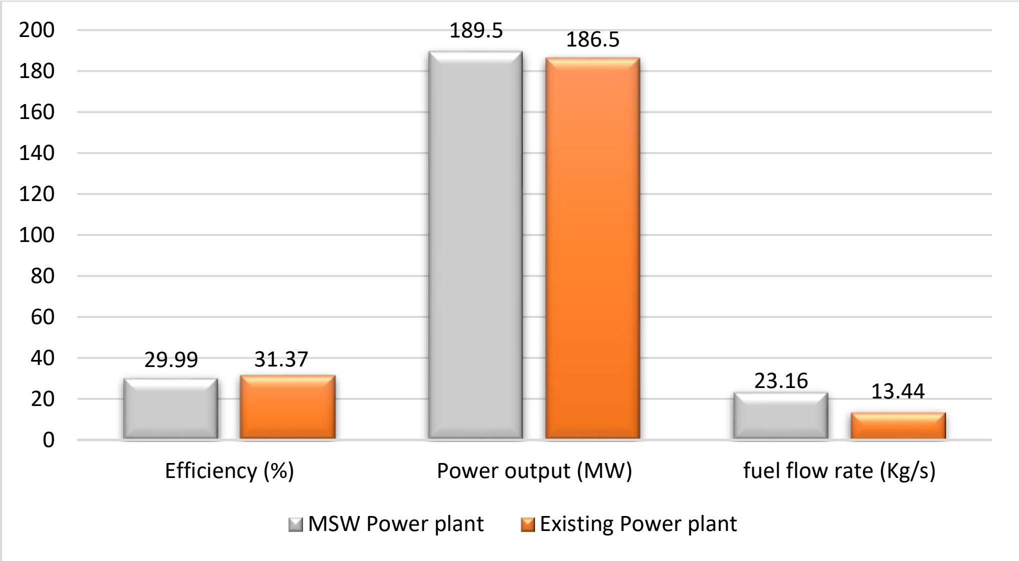

Figure 4. Comparison of power output, efficiency and mass flow rates

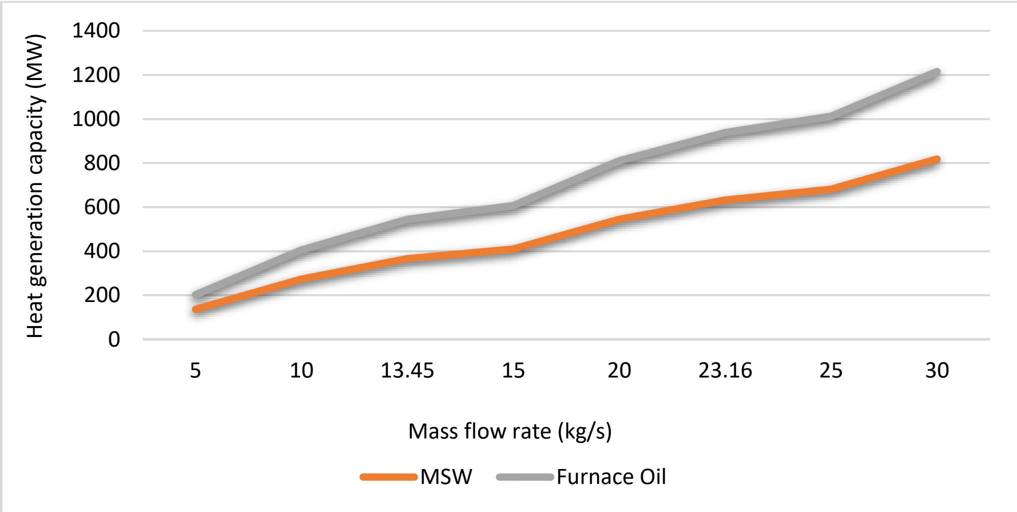

Figure 5. Comparison of Heat generation capacity

4.1 Environmental Analysis

The mass of each component present in supplied dry mass of MSW for combustion and required wet / moisture mass of MSW is calculated in table 3 taking the dry state and wet/ moisture percentage of each component of MSW generated in Hyderabad city from table 1.

Table 3. Mass of MSW components supplied in (Kg/s)

MSW component (combustible)	% in wet/ moisture state	% in dry state	Wet mass (kg/s)	Dry mass (kg/s)
Paper	8.17	5.54	3.53	2.39
Cardboard	9.29	6.37	4.02	2.75
Plastic	12.13	8.58	5.24	3.71
Organic (Food + yard waste)	61.93	27.70	26.77	11.97
Textile	2.87	1.86	1.24	0.81
Wood	2.55	1.47	1.10	0.64
Rubber and Leather	3.06	2.08	1.32	0.90
Total	**100.00**	**53.58**	**43.23**	**23.16**

The mass of elements contained by the supplied dry mass of MSW is calculated in table 4 using the percentage of elements by mass from [28]. Finally, the mass of flue gases produced from the combustion of supplied MSW can be calculated as in table 5.

Table 4. Element mass content (kg/s)

Component	Dry mass	Carbon C		Hydrogen H		Oxygen O		Nitrogen N		Sulphur S		Ash	
	(kg)	%	Mass (Kg)	%	Mass (Kg)	%	Mass (Kg)	%	Mass (Kg)	%	Mass (Kg)	%	Mass (Kg)
Paper	2.39	43.5	1.04	6	0.143	44	1.052	0.3	0.007	0.2	0.005	6	0.143
Cardboard	2.75	44	1.21	5.9	0.162	44.6	1.227	0.3	0.008	0.2	0.006	5	0.138
Plastic	3.7	60	2.22	7.2	0.266	22.8	0.844	-	-	-	-	10	0.370
Organic (Food + yard waste)	11.97	48.5	5.805	6.5	0.778	37.5	4.489	2.2	0.263	0.3	0.036	5	0.599
Textile	0.81	55	0.446	6.6	0.053	34.2	0.277	4.6	0.037	0.15	0.001	2.5	0.020
Wood	0.64	49.5	0.317	6	0.038	42.7	0.273	0.2	0.001	0.1	0.001	1.5	0.010
Rubber and leather	0.9	26.3	0.237	3	0.027	2	0.018	0.5	0.005	0.2	0.002	68	0.612
Total	**23.16**		**11.27**		**1.47**		**8.18**		**0.31**		**0.04**		**1.89**

Table 5. Flue gas mass calculation (kg/s)

Reactant Element	Reactant mass Kg/s	Reaction	Product (Flue Gas)	Mass of product Kg/s
C	11.27	$C + O_2 \rightarrow CO_2$	CO_2	41.323
S	0.04	$S + O_2 \rightarrow SO_2$	SO_2	0.08
N	0.31	$N_2 + O_2 \rightarrow 2\ NO$	NO	1.328
H	1.47	$2\ H_2 + O_2 \rightarrow 2\ H_2O$	H_2O	11.76
O	8.18	-	O_2	8.18
Total	21.27	-	-	62.671

The comparison of amount of flue gas produced by MSW power plant with existing power plant [29] is given in figure 6 and the percentage of each product of the MSW combustion is shown is figure 7.

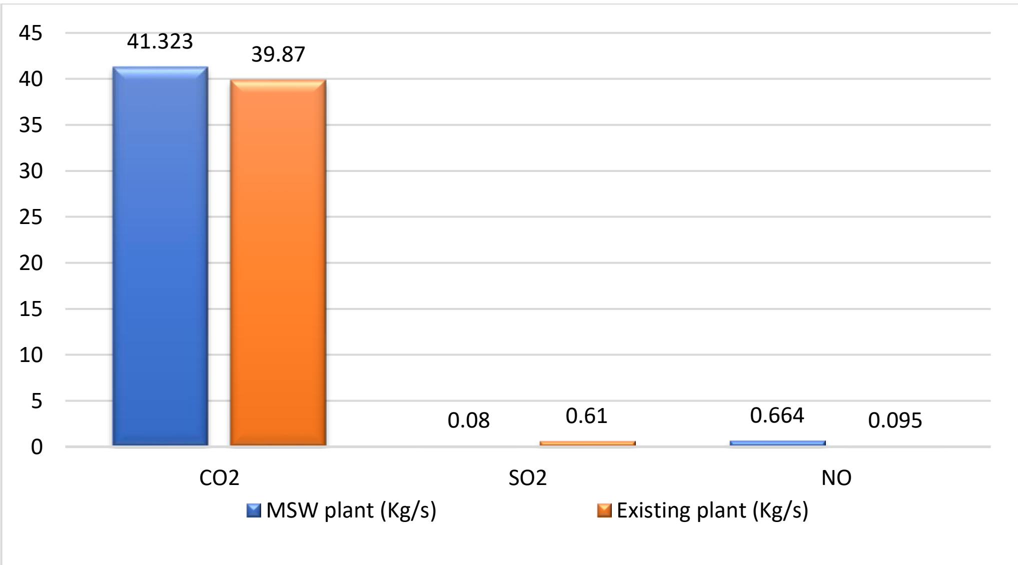

Figure 6. Comparison of flue gases

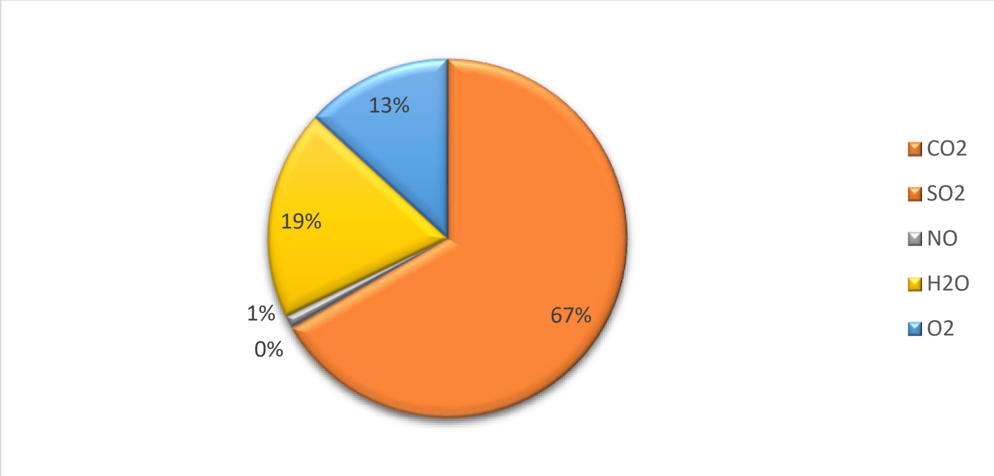

Figure 7. Percentage of flue gases produced by MSW power plant

4.2 Economic Analysis

The total cost of collection and transportation of MSW is PKR.53,011/- per ton whereas as that of furnace oil is PKR. 185,000/- per ton [30]. For continuous operation of power plant per day to generate 186 MW of power, the cost of MSW with its supply of 3735 tons per day will be PKR. 197.9 million and that of furnace oil with its supply of 1161.216 tons per day will be PKR. 214.4 million per day. Thus, the amount of PKR.16.8 million per day can be saved and with annual maintenance cost of around PKR. 1.4 million per year [25], the amount of PKR. 6.13 billion per year.

IV. CONCLUSION

This study presents thermodynamic, environmental and economic analysis of 210 MW Jamshoro Power plant unit operated using municipal solid waste (MSW) produced in Hyderabad City. The comparison reveals a good level of agreement between the parameters of both the existing and MSW fired power plant. The Engineering Equation Solver (EES) program, is a good tool to undertake the thermodynamic analysis of the stated model plant. As per results the mass flow rate of MSW needed in dry condition is 23.16 kg/s, or 2001 tons per day, and in a wet state 43.23 kg/s, or 3735 tons per day which in actual is easily generated in the Hyderabad city i.e. 4000 tons/day in wet state. The net power output and energy efficiency of the MSW plant are 189 MW and 30.01% respectively, which is satisfactory to operate MSW plant. The flue gases including CO_2, SO_2, NO are produced at a rate of 41.323, 0.08 and 1.328 Kg/s. Considering transportation cost, PKR.6.13 billion can be saved per year by utilizing MSW instead of furnace oil.

V. NOTATIONS

h	Specific enthalpy (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{Q}$	Heat flow rate (MW)
$\dot{W}$	power (MW)

Greek Letters

η	Energy efficiency

Abbreviations

LHV	Lower Heating Value
HPT	High pressure turbine
IPT	Intermediate Pressure Turbine
LPT	Low Pressure Turbine
HPH	High Pressure Heater
LPH	Low Pressure Heater
EPP	Energy Power Potential
PCT	Percentage
moist	Moisture state
dry	Dry state
MSW	Municipal solid waste

Subscripts

B	Boiler
bfp	Boiler feed pump
C	Condenser
c	MSW component
cp	Condensate pump
cons	Consumption
fw	Feed water
p	Pump
T	Turbine
t	Total

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