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Investigating the Energy Potential from Co-firing Coal with Municipal Solid Waste

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Abstract

With the increasing population and economic development of Mauritius, the demand of electricity increases each year. This has brought a significant rise in the consumption level of fossil fuels to meet these demands. Currently, the increasing prices of fossil fuels on the international market are having severe repercussion on the economy of the country.

There are around 444, 570 tons of municipal solid waste (MSW) generated per year in Mauritius and this amount is giving rise to disposal problem. One of the disposal options could be the generation of electricity through combustion of the waste. At the same time, there are several coal power plant in the country that generate both heat and power. This study was, therefore, initiated to investigate the effect of co-firing MSW and coal. Proximate and ultimate analyses were conducted on both MSW and coal. The optimum blending ratio of MSW and coal was found to be 80 % MSW and 20 % coal by mass that is 1119 tons per day of MSW. The electrical output from the mixture of MSW and coal was 51 MW out of which 29.7 MW was generated from MSW only which represent around 58 % of the total produced power of the plant.

Total cost saving from this co-firing project is estimated at 456 million Mauritian Rupees (MUR). The MSW has a lower heating value, however, it was seen that pollutant emission was reduced in the co-firing process. Gaseous pollutant emissions like CO2 was reduced significantly at this blending ratio compared to firing coal solely. Greenhouse gases (GHG) emissions were reduced on two counts: firstly reducing combustion of coal and secondly avoiding methane emission at the landfill site, which is equivalent to around 1.92 million Metric tonnes of CO2 equivalent annually.

The findings from this study showed that MSW could be a good renewable fuel for co-firing with coal combustion. It reduces both the amount of land allocated annually for landfilling and the dependence on fossil fuels.

Keywords: co-firing, municipal solid waste, coal, GHG reduction

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1. INTRODUCTION

Satisfying the world's insatiable appetite for fuel without destroying the environment is the biggest challenge facing the energy industry. There is a growing awareness that current energy systems are not sustainable. In recent years, demand for energy has surged mainly due to increasing human population, urbanization and modernization. The world relies heavily on fossil fuels to meet its energy requirements. World energy consumption is rising at average annual growth rate of 1.6 % with the developing world demanding an ever-increasing share. Fossil fuels such as coal, oil and gas are providing almost 80 % of global energy demands and the balance shared between renewable and nuclear energy at about 13.5 % and 6.5 % respectively (Muneer *et al*., 2007). Due to competitive pressures to cut costs and reduce emissions of air pollutants and greenhouse gasses (GHG) from fossil fuels, owners and operators of industrial and commercial facilities are actively looking for proper energy sources and ways to use energy more efficiently.

2. ENERGY FROM CO-FIRING COAL AND WASTE

Mauritius is a small island developing state situated in the Indian Ocean with a population estimated around 1.3 million inhabitants in 2005 (CSO, 2005). The economic prosperity of the last 20 years has resulted in an improved standard of living and has brought drastic changes in consumption pattern. Consequently, the amount and nature of solid waste generated has changed considerably. The amount of solid waste generated in Mauritius is around 1218 tons per day in 2007. At present, Mauritius has a waste infrastructure which is based on landfill. The composition of the different components of the municipal solid waste (MSW) is shown in Table 1.

Table 1: Composition of MSW

	Percentage, %
Garden waste	43
Kitchen waste	25
Paper	12
Plastic	13
Textile	3
Metal	1
Glass	1
Others	2

Source: MOLG, 2007

The concept of waste to energy (WTE) is strengthening in many countries. MSW can be directly fired or co-fired with coal (Suksankraisorn *et al*, 2004). Co-firing, partial substitution of coal as a main fuel in a utility boiler with 'carbon lean' renewable alternative for generating electricity, is probably the most compatible way to use renewable waste with the current fossil fuel dependent system. Direct co-firing is the least expensive, most straightforward, and most commonly applied approach worldwide (Fouad *et al*, 2010). The MSW and the coal are burned in the coal boiler furnace, using the same or separate mills, conveyors and burners, depending principally on the MSW fuel characteristics.

This technique allows coal utilities to have a renewable fuel source at almost no cost or very little cost instead of burning coal which is much costly and polluting. At the same time they are helping to free up landfill space for other non-combustible and non-recyclable materials and avoiding uncontrolled release of landfill gas (LFG) to atmosphere due to MSW decomposition. Additionally, burning biodegradable fraction of MSW recycles atmospheric CO_2, while coal (and other fossil fuels) releases CO_2 that are stored for millions of years and causes global warming. Therefore, direct co-firing is probably one of the most realistic ways for immediate use and a good stepping stone towards more viable and sustainable renewable energy practices. This study was therefore initiated to assess the energy potential from co-firing coal and MSW as well as the economic benefits and environmental impacts of the proposed fuel to the energy sector of Mauritius.

3. METHODOLOGY

The following tests were carried out in the laboratory:

Gross calorific value

The calorific value of the sample was carried in the Bomb Calorimeter. A small quantity of the sample usually less than 1 g was placed in a crucible. The crucible and sample were then placed in bomb cylinder and oxygen at a pressure of 25 atm was admitted. The cylinder was lowered into a calorimeter water bucket where it was connected to two ignition wires. The initial temperature of the water was noted before switching on the power and the final temperature was also recorded. The standard formula for a sample burnt becomes:

$$\text{Calorific Value (Cal/grams)} = \frac{\text{Standardisation factor (1311) x Temperature Rise}}{\text{Mass of sample}}$$

Moisture content

Samples were taken in triplicate and weighed, and dried to constant weight in an oven at 105 ^{0}C for 24 hours. The samples were then cooled in a desiccator and the difference in weight was recorded. The moisture content was calculated as follows:

$$\text{Moisture content (\%)} = \frac{\text{Loss in weight X 100}}{\text{Net wet weight}}$$

Carbon, Hydrogen, Nitrogen, Sulphur (CHNS)

5 g of dried sample was turned into powder using a grinder of which 2mg of powder was weighed in an aluminium capsule and was injected into the apparatus called CHNS 932 for combustion. This apparatus gave the percentage of total carbon, nitrogen, hydrogen and sulphur on a dry basis by analyzing the products of combustion.

4. FUEL INVESTIGATION

The different characteristics of MSW in Mauritius and coal were determined and are shown in Table 2. The Higher Heating Value (HHV), moisture content and chemical composition of MSW were computed from the results of the different components. The water content of the raw MSW was found to be 44.1. This high contribution of water comes mainly from the large percentage of organic waste (food and garden wastes) in MSW, representing around 68 %.

From the ultimate analysis, the amount of sulphur, nitrogen and carbon by weight is very much higher for coal than for MSW. When considering on a wet basis, it is found that the Net Calorific Value (NCV) of mixed MSW is 8.55 MJ/kg while that of coal at 24.515 MJ/kg.

Table 2: Characteristics of MSW and Coal

Samples	Moisture	HHV, MJ/kg	Chemical composition (% by Weight)			
			C	H	N	S
Garden waste	57.7	16196	47.8	6.0	3.4	0.3
Food wastes (mixed)	72	15310.61	73.0	11.5	0.4	0.1
Mixed paper waste	9.8	16678.6	40.9	5.4	-	0.13
Mixed plastics waste	1.75	38127.6	73.6	7.5	-	0.01
Textile waste	7.17	20956.7	53.7	4.5	-	0.06
Mixed MSW (96 %) (excluding inert and miscellaneous)	44.1	15301.7	30.15	4.0	0.68	0.05
Bituminous Coal	6.6	26248.1	63.85	2.7	1.35	0.45

5. MASS AND ENERGY BALANCE – CASE STUDY

Against a scarce landfill area the only solution is to co-fire MSW with coal in existing Independent Power Producer (IPP) plants. Carl Bro (2005) found that co-fire of MSW with coal is very good in the Mauritian context. The mixture of MSW and coal as boiler fuel was studied in a spreader stoker boiler at a local IPP plant (coal-fired). The plant operates on the Rankine cycle and has Condensing Extraction Steam Turbine (CEST). The plant operates 24 hours continuously for about 333 days in a year between shutdowns for maintenance and inspections. Using the moisture for mixed MSW at 44.1 % and of coal at 6.6 %, the $HHV_{as\ fired}$ is tabulated in Table 3.

Table 3: $HHV_{AS\text{-}FIRED}$ of mixed MSW, coal and different mixtures of mixed MSW and coal.

FUEL	$HHV_{AS\text{-}FIRED}$ (MJ/kg)
Mixed MSW	**8.55**
Coal	**24.515**
90 %MSW 10% coal	**10.469**
80 %MSW 20% coal	**11.8826**
70 %MSW 30% coal	**13.394**
60 %MSW 40% coal	**14.768**
50 %MSW 50% coal	**16.204**

The parameters that are used to determine the mass of fuel and amount of energy are shown in Table 4. Because of the uneven demand of electricity during a whole day, it is assumed that the hourly production capacity of the plant is 51 MW.

Table 4: Operating parameters at coal fired plant

		Unit
Superheated steam to CEST	525	°C
	82	bars
Exhaust steam from the CEST	45	°C
	0.1	bar
	0.95 (dryness fraction)	
Boiler efficiency, η_{boiler}	80 - 90	%
Boiler feed water	125	°C
Turbine efficiency (CEST), $\eta_{turbine}$	95	%
Turbo alternator efficiency, η_{turbo}	97	%

5.1 Calculation for Mass Flow Rate of Fuel for Combustion

Consider boiler feed of composition (100-X) % MSW and X % coal.

(i). Turbo Alternator

Electrical power output from turbo alternator is assumed to be = 51MW

Turbo alternator efficiency = 97 %

Hence, input to turbo alternator = (51/97) * 100 = 52.577 MW

(ii) Turbine (CEST)

Input to turbo alternator = output from turbine

Mechanical power output from turbine = 52.577 MW

Turbine efficiency (CEST) = 95 %

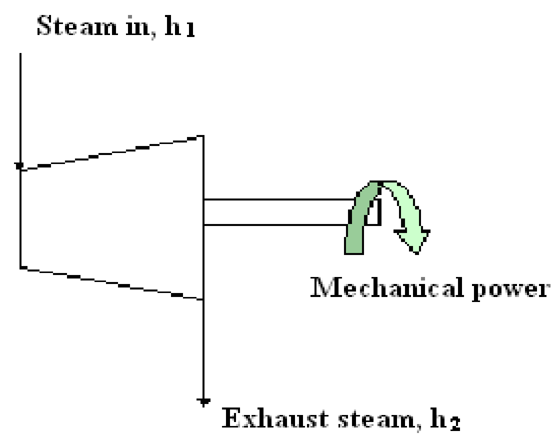

Figure 1: Steam in and exhaust from turbine

Therefore, mechanical power output from turbine = efficiency ofturbine*mass flow rate of steam * (change in enthalpy across turbine)

(iii) Steam Conditions

Exhaust steam, h_2 from turbine = 0.1 bar, 45 ^{0}C and dryness fraction 0.95

Superheated steam, h_1 fed to turbine = 82 bars and 525 ^{0}C

From steam tables; Enthalpy of superheated steam, h_1 = 3457.45 kJ/kg

Let x = 0.95 be the quality of the exhaust steam.

From saturated steam tables, at a pressure of 10 kPa and 45 ^{0}C

Enthalpy of saturated liquid, h_f = 191.83 KJ/kg

Enthalpy of saturated liquid/vapour, h_{fg} = 2392.8 KJ/kg

Thus, enthalpy of exhaust steam, h_2 or h_{av} = 2465 KJ/kg

Mechanical power output from turbine =
efficiency of turbine * mass flow rate of steam *(change in enthalpy across turbine)

52.577 MW = 0.95 * mass flow rate of steam * (3457.45 -2465)

Therefore, Mass flow rate of superheated steam $= \frac{\text{Power output}}{\text{Workdone}}$

= ***55.765 kg/s***

Thus mass flow rate of steam at 82 bars and 525 ˚C required for production of 51 MW of electricity in an hour = 55.765 kg/s

= 200.754 tons/hr

(iv) Boiler Efficiency

Boiler efficiency is dependent on heating value, but is also affected by the moisture content. Taking into consideration the $HHV_{as\ fired}$ for raw MSW at moisture of 44.1%, and assuming the moisture content in practical varies from 40 to a maximum 60 %, it would be reasonable to assume average net boiler efficiency for mixed MSW and coal at 85 %. The boiler efficiency equation is given by

$$\eta_{boiler} = \frac{m_s * (h_g - h_f)}{m_f * HHV_{as\ fired}}$$

where;

η_{boiler} = is the efficiency of the boiler

m_s = is the mass flow rate of superheated steam, kg/s

h_g = is the enthalpy of superheated steam. kJ/kg

h_f = is the enthalpy of feed water kJ/kg

m_f = is the mass flow rate fuel, kg/s

$HHV_{as\ fired}$ = is the heat value of fuel, kJ/kg

Feed water condition = 125 ˚C

From the saturated steam tables, the enthalpy is found to be 524.99 kJ/kg.

The mass flow rate of fuel (MSW or coal or any MSW mixture with coal) was calculated using the specific $HHV_{as\ fired}$ for each fuel composition in the boiler efficiency equation. The results are tabulated in Table 5.

Table 5: Amount of combustible MSW burnt and coal saved per day.

Fuel Composition (Mass basis)	**$HHV_{as\ fired}$ (MJ/kg)**	**Mass fuel required (tons/day)**	**Mass MSW burnt (tons/day)**	**Mass coal burnt (tons/day)**	**Amount of coal saved (tons/day)**
100 % coal	24.52	640.37	*0*	640.37	***0***
50 %MSW 50% coal	16.20	1025.8	*512.9*	512.9	***127.47***
60 %MSW 40% coal	14.77	1125.6	*675.36*	450.24	***190.13***
70 %MSW 30% coal	13.39	1241	*868.7*	372.3	***268.07***
80 %MSW 20% coal	11.88	1398.87	*1119*	279.87	***360.5***
90 %MSW 10% coal	10.47	1587.8	*1429*	158.8	***481.57***
100 %MSW	8.55	1944.12	*1944.12*	0	***640.37***

Combustible MSW available per day = 0.96 * 1,218 tons = 1,169 tons. 1,429 tons of daily MSW, that is 90% of MSW, is practically unavailable while 1,119 tons MSW, that is 80%, can be supplied easily. The appropriate co-firing rate for using 1,169 tons of daily combustible MSW as per Table 5 is 80 % MSW and 20 % coal on mass basis. Since the MSW has a low heat value, the auxiliary fuel that is coal is more than enough at this co-firing rate (@ 20 % mass) to maintain a sufficient furnace temperature (major problem when using wet fuels). The LHV of the mixture has now increased to 11.9 MJ/kg. About 50 tons of combustible MSW per day will be in excess at this co-firing rate which can be used in emergency cases such as peak hour electricity demand of 63 - 64 MW. 360.5 tons per day or 120,046.5 tons of coal on an annual basis is saved.

5.2 Electrical Output from Co-firing

Taking the 80 % mass share of co-fired MSW, the "green power" derived from MSW can be estimated to be as follows;

$$\text{Electricity for MSW share } E_O = \frac{0.8 * 8.55}{0.8 * 8.55 + 0.2 * 24.5} \text{ X } 51 \text{ MW}$$

$$= 29.7 \text{ MW}_{electrical}$$

The electricity from MSW represents around 58 % of the total produced electrical power. This co-firing project will not affect the amount of energy input to the boiler at the power plant, however, a significant amount of coal is being replaced by MSW that has to be disposed of at certain expense. The ratio of 80 % of MSW and 20 % of coal will result in 56 % reduction of coal to produce the same amount of steam. The total amount of power produced is 51 MW. Assuming 333 days of operation, the co-firing power plant will produce 408 GWh out of which 236.6 GWh (58%) is from MSW.

Co-firing system retrofits require relatively small capital investments per unit of capacity, in comparison to those required for most other renewable energy technologies and carbon sequestration alternatives (Fouad *et al*, 2010). The cost saving calculated is as follows:

Cost Saving from reduced coal consumption = annual cost saving from reduced coal consumption (Rs/year) = Rs 240 million

Cost Saving from reduced landfill = annual cost avoided by diverting MSW from landfill (Rs/year) = Rs 216 million

6. GHG EMISSION

6.1 Determining GHG Emissions

6.1.1Determining amount of Fossil Fuel CO_2 Avoided by Burning Carbon Neutral MSW

The amount of coal requirements without co-firing per year = 213,243 tons
Assuming all carbon in the coal is incorporated into CO_2 without any losses such as CO formation. Then amount of C that would involve in combustion with as fired coal from was calculated to be 63.85 % per kg coal as per Table 2. Total amount of C = 0.6385 * 213,243 = 136,156 tons
For, every kilogram of carbon burned, 3.7 kilograms of CO2 are emitted.
Hence, total amount of fossil fuel CO_2 emitted with 100 % coal
= 136,156 * 3.7 = 503,777 tons ………… A

<u>Co-firing 80 % MSW with 20 % coal on a mass basis</u>

Yearly coal requirements under co-firing program = 279.87 tons/day * 333 days
= 93,196 tons
Amount of C involved in combustion per kg coal = 0.6385 * 93,196 = 59,505 tons
The MSW is assumed to have a maximum of 13 % non-biological material (all plastics excluding metals, glass and miscellaneous wastes). Table 1, within the 96 % combustible materials of MSW, the amount of plastic is 13/96 = 13.54 %
Non-biogenic carbon involved in MSW = 13.54 % * 0.3015 kg C per kg as fired MSW = 0.0408 kg fossilized C per kg as fired MSW
= 0.0408 * 1119 *333(0.96) tons MSW/year
= 14,595 tons fossilized C

Total fossilized C involved in co-firing program = 14,595 + 59,505 = 74,100 tons
This yields an approximate of 74,100 * 3.7 = 274,170 tons of CO_2 emission.

The subsequent fossil fuel CO_2 reduction from co-firing MSW is 45.5 %.

6.1.2 Determining CO_2 and CH_4 emission from the landfill site

The maximum capacity of landfilled MSW to produce methane as reported by (Kumar et al, 2004)Franklin is estimated to be 62 standard m^3 of CH_4 per tonne and with 25 % biodegradable MSW landfilled, the maximum amount of natural gas generated by biodegradation is estimated to be 130 Nm^3/tonne. For Mauritian MSW, assuming a minimum of 75 % of biodegradable component (garden, food, paper and part of textile waste), the amount of natural gas generated can be proportionally estimated. It is found to be 390 Nm^3/ tonne of MSW.

Assumptions:

The following assumptions were made:

1. No methane capture program is undertaken at the landfill.
2. The landfill gas is estimated to be generated from future deposition of MSW in our landfills (i.e. from year 2009 onwards).
3. A yearly constant 444,570 tonnes of MSW for the future 10 years.

The followings were derived from the assumptions:

- Landfill gas releases = 444,570 tonnes MSW x 390 Nm^3/tonne
  = 173.4 million Nm^3 LFG.

Assuming the LFG consist of 54% of CO2 and 46% of CH4

Amount of uncontrolled methane releases = 0.46 * 173.4 million Nm^3 LFG
= 79.8 million Nm^3 of methane

79.8 million Nm3 of methane is equivalent to 57, 0000 tonnes of methane.

The carbon equivalent number is obtained by multiplying methane emissions by its GWP of 21 times that of carbon dioxide, which is = 1.20 million tonnes of carbon equivalent

Amount of CO2 released = 0.54 * 173.4 million Nm3 LFG
= 93.6 million Nm3 CO2

93.6 million Nm3 CO2 is equivalent to 183,857 tonnes of carbon equivalent

Therefore, yearly production of CO_2 equivalent GHG from the landfill site

= 1.20 million tonnes + 183,857 tonnes

= 1.38 million tonnes .... (B)

Total yearly CO_2 equivalent emissions (A + B) = 503,777 tonnes + 1.38 million tonnes = 1.89 million tonnes (C)

The amount of GHG produced from the co-firing project is 274,170 tons of CO_2 emission. Therefore, 1.61 million tonnes of CO2 will be avoided by the co-firing project.

7. CONCLUSION

With the 372, 627 tons/year of MSW, the gross yearly electricity production is 236.6 GWh representing 58 % of equivalent “green power” production by this grid-connected co-firing power plant. This avoids 29.7 MW (~ 237,360 MWhrs) of fossil fuel based emissions. With the project activity, total yearly CO_2 production is 274,170 tonnes compared to 1,920,000 tonnes without the co-firing project. This is equivalent to an annual 1.61 million CO_2 Emission Reduction. MSW is considered as a biomass. Therefore, it should be recognized that biomass can be one of the alternatives to fossil fuel for power generation and mitigating GHG emissions.

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