Exergy and Energy Analysis of Plasma Waste-to-power Generation Model

Ransford R. Baidoo, Department of Energy and Environmental Systems
Frederick F. Ferguson, Ph.D.,
Department of Mechanical and Chemical Engineering
Frank E. Yeboah, School of Technology
North Carolina A&T State University

ABSTRACT

This research addresses three major problems currently affecting our globe. These problems are the pending energy crisis, the environmental degradation caused by an ever increasing growth of waste and the environmental degradation resulting from the continuous generation of greenhouse gas emissions.

In light of these problems, efforts are geared towards the development of a 'one-stop' solution. A preliminary survey of available technical data indicates that the three problems could be solved through the use of an efficient plasma gasification technology. The use of this plasma technology can simultaneously disintegrate waste while electrical power is generated and greenhouse gas emissions eliminated. The other two methods of converting biomass (waste) to heat energy, namely combustion and conventional gasification are also presented with the chemical composition of the three methods analyzed using thermochemical data to determine which of the three has the best optimum option for heat energy conversion and hence power generation.

An innovative aspect of this work is the analysis of the temperature effect on the chemical composition of the synthesis gas obtained from the plasma system (exergy analysis) and how its output affects the electrical energy generated.

Results show that when the plasma system is fed at about 1000 tons/day, maximum syngas and power is obtained. However, when more or less waste is fed to the plasma system, less syngas and power is obtained in both cases. It was also observed that more syngas and

power were obtained at higher temperatures. This result suggests a standard capacity for building plasma systems because at the moment, there is none.

INTRODUCTION

The world population growth, at the rate of about 1.16% per annum, is having an adverse effect on the world energy demand [1]. The United Nations also projects increasing world energy consumption at the rate of 2% per annum [2]. At the same time, the contribution from the supply of energy from fossil fuels, hydropower and non-breeder fission is decreasing [3]. Also, according to Global Footprints, a US monthly magazine, household waste continues to grow at the rate of 3% per annum [4]. In addition, according the U.S. Department of Energy (DOE), Energy Information Agency (EIA), greenhouse gas emissions persist to grow at the rate of 1% carbon-dioxide (CO_2) equivalent per annum [5]. If these trends continue, the effect would be catastrophic. It is therefore the aim of this research to address these problems using the appropriate technology.

Through photosynthesis, the sun has stored enormous chemical energy in organic materials. According to Tammemagi, this ever growing waste constitutes about 80% of organic materials [6]. This chemical energy, however, must be converted into a form that is versatile, and can be readily applied to supplement the shortfall in the world energy demand. The most versatile form, which is electrical energy, could be reached through intermediary conversions which are, chemical to heat, heat to mechanical, and eventually from mechanical to electrical in that order.

According to Mountouris et al., unlike energy, which can neither be created nor destroyed, exergy (useful available energy) holds the idea that, it is useful in the design and analysis of thermal systems that something can be destroyed. Hence, if waste is destroyed in a thermal system to produce heat energy, it has become useful. Accordingly, the chemical exergy of the produced gas mixture is determined by the composition and concentration of the components in the mixture [7]. Chemical to heat energy conversion could be achieved through three methods, namely combustion, conventional gasification (gasification) and plasma gasification ('plasmafication'). Chemical equations for each has been presented and using thermochemical data proved that, of the three, the last has the best option and is discussed in detail and considered for the power generation process. This research analyzes the exergy (energy resulting from chemical composition) and the electrical energy produced from the syngas caused by the thermal process.

THE PROBLEMS ENUMERATED

Problem # 1 The Pending Energy Crisis

Figure 1 depicts the projected energy consumption from the year 1900 to 2300 [3]. Further, Figure 1 illustrates the following problems, based on the assumptions that the world population stabilizes at 10 billion when consuming at 2/3 of US 1985 rate. While energy consumption is increasing, the supply from fossil fuels, hydropower and non-breeder fission is decreasing, and an ever growing shortfall is predicted. Consequently, there is the need for the shortfall to be supplemented through alternative energy sources.

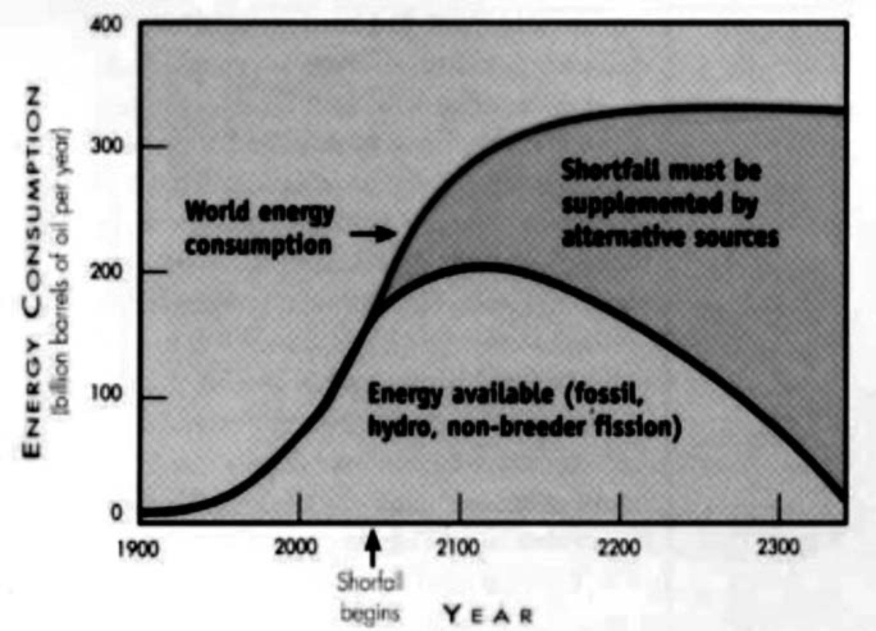


Figure 1. World Energy Consumption

One of the major objectives of this research is the exploitation of an alternative energy source that can potentially provide a viable solution to this problem by converting waste (trash) into syngas and eventually to electrical energy.

Problem #2 Environmental Degradation (Accumulation of Waste)

Research shows that the four main sources of waste are residential (50%), industrial (20%), commercial (15%), and agricultural (15%) [8]. They are, however, managed by recycling, landfill, mass burn, composting and waste-to-energy [9], which is the main focus of this research.

According to the U.S. Environmental Protection Agency (EPA), municipal solid waste (MSW) produced in the U.S. grew from 88.1 million tons in 1960 to 251.3 million tons in 2006, and the per capita waste generation is about 4.6 lb (2.08 kg) [10]. In fact, it is predicted that household waste continues to grow at a rate of 3% per annum [4].

Problem #3 Environmental Degradation (Greenhouse Gas Emissions)

Once again, according to the EIA, greenhouse gas emissions are growing at the rate of 1.0% CO_2 equivalent per annum [5].

The solution to these three problems lies with a technology that would disintegrate the waste and convert it to electrical energy, without the emission of greenhouse gases.

THE POTENTIAL SOLUTION

Available technical data developed by National Aeronautics and Space Administration (NASA) indicate that the three problems could be solved through the use of an efficient plasma gasification system. The use of this technology can simultaneously disintegrate the waste, generate power and at the same time eliminate greenhouse gas emissions.

Through photosynthesis, the sun has stored enormous chemical energy in organic materials, which happens to be the largest constituents of trash. Extracting this form of energy through the use of a plasma converter (plasmafier) can potentially harness this vast energy reserve.

Forms of Energy Conversion

Waste is an endless source and increasing source of stored chemical energy. The energy conversion methods necessary for this consideration are: chemical to heat, heat to mechanical and then to electrical.

The three methods of converting chemical energy to heat energy, as explained earlier, are combustion, gasification and plasmafication with their chemical equations shown below.

Combustion $C_mH_n + (m + n/4)O_2 \rightarrow mCO_2 + (n/2)H_2O + Q(heat)$ (Eq 1)

Gasification $C_mH_n + (m/2)O_2 \rightarrow mCO + (n/2)H_2 + Q(heat)$ (Eq 2)

Plasmafication $C_mH_n + k\ O_2 \rightarrow mC^{\pm} + 2kO^{\pm} + nH^{+} + ne^{-} + Q(heat)$ (Eq 3)

From the equations, it could be deduced that, combustion (incineration) contains more carbon dioxide CO_2 and because it is a greenhouse gas, it would promote global warming and therefore not desirable.

To make informed choices between gasification and plasmafication, relevant extracts from thermochemical data [11] were made, as shown in Table 1 and applying the Hess's law [12] to determine which type would produce more heat energy (exothermic).

Hess's law, ΔH° (Q heat) = Products – Reactants

Using methane as an example and applying the relevant thermochemical data to Hess's law we have:

Combustion $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + Q(heat)$
$= -74.6 + 2*(0.0) \rightarrow -393.5 + 2*(-241.8) = -877.1 + 74.6$
$= -802.5$ kJ/mol

Gasification $CH_4 + (1/2)O_2 \rightarrow CO + 2H_2 + Q(heat)$
$= -74.6 + (1/2)*0.0 \rightarrow -110.5 + 2*(0.0) = -110.5 + 74.6$
$= -35.9$ kJ/mol

Plasmafication $CH_4 + (1/2)O_2 \rightarrow C^{\pm} + O^{\pm} + 4H^{+} + 4e^{-} + Q(heat)$
$= -74.6 + (1/2)*0.0 \rightarrow 716.68 + 249.18 +$
$4*(0.0) + 4*(-802.4)$
$= -2169.14$ kJ/mol

Table 1. Relevant Thermochemical Data

No.	*Symbol*	*ΔfH°*
1	O	249.18
2	O_2	0.00
3	CO	–110.5
4	CO_2 (g)	–393.5
5	H	217.18
6	H^+	0.00
7	H_2 (g)	0.00
8	H_2O (l)	–285.83
9	H_2O (g)	–241.8
10	CH_4	–74.6
11	C	0.00
12	C_2	830.47
13	H_2 (l)	0.00
14	$C_6H_{10}O4$	–805.5
15	C^+	716.68
16	E^+	–802.4
17	CH_2O	–108.6
18	O^+	249.18

Plasmafication to combustion ratio = 2,169.14/802.5 = 2.7

This clearly shows that the heat energy produced from the plasmafier is higher than that extracted from both combustion and gasification processes.

Plasmafication

Plasma is described as the fourth state of matter. In the plasma state, the gas is ionized and the temperature is above 100,000°C [13].

Figure 2 shows plasma as the fourth state of matter at a very high temperature.

To reach this plasma state, a direct current (dc) supply of 650 volts is applied to the terminals of the electrodes.

This creates an arc at a temperature of over 13,800°C within the globe but about 3,000°C in the vicinity of the globe, as shown in Figure 2. When waste is fed into this environment, the radiant energy of the plasma arc disintegrates the trash into its constituent elements by tearing apart molecular bonds. The only exception is nuclear waste, whose isotopes are indestructible [14]. A fractional part of the energy converted to electricity is fed back to the plasmafier for continuous operation.

The net energy contributing to heating and melting a particle in contact with plasma is given by:

$$Q_n = h\ a\ (T_\infty - T_s) - \sigma\ \varepsilon\ a\ (T_s^4 - T_a^4) \qquad \text{(Eq 4)}$$

where

Q_n is the net energy contributing to heating and melting
h is the plasma particle heat transfer coefficient

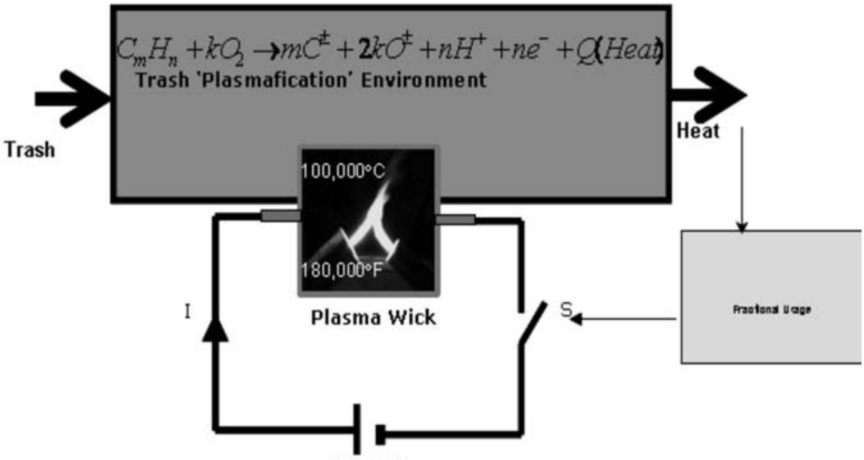


Figure 2. Plasma Generation

a is the surface area of the particle
T_∞ is the plasma temperature
T_s is the particle surface temperature
T_a is the reactor wall temperature
σ is the Stephan-Boltzmann constant
ε is the particle emissivity [15].

After the plasmafication process, synthetic gas (syngas) is produced at about 2,000°C. This syngas has two major uses, namely conversion of it to other inflammable liquids after cooling or utilizing the high temperature to run gas turbines.

Heat to Mechanical and to Electrical Energy

Now that chemical energy has been converted to heat energy in the form of syngas, the next step is to convert this heat energy to mechanical energy and eventually to electrical energy. Figure 3 depicts the schematic diagram to serve this purpose. For electrical energy to be generated, the alternator needs a prime mover. This prime mover could be a diesel engine, gas engine, gas turbine, steam turbine or water turbine. Figure 3 depicts the application of any of the turbines mentioned here. In this case hot gas, hot steam or raw water is made to impinge on the impellers of the turbine, which causes a rotational motion of the impeller to which the conductors or armature windings of the alternator are attached.

According to Faraday's law [16], any time a conductor cuts or is cut by a magnetic field, an emf is induced in that conductor. The magnitude of the induced emf is given by

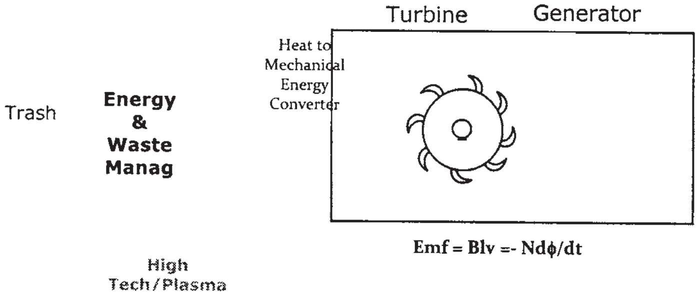


Figure 3. Heat to Electrical Through Mechanical Conversion

$$e = BLV \qquad \text{(Eq 5)}$$

where

B is the flux density
L is the length of the conductor
V is the velocity at which the conductor cuts or is cut by the magnetic field.

According to Lenz's law, the induced emf is also given as

$$E = -N \frac{d\varphi}{dt} \qquad \text{(Eq 6)}$$

where

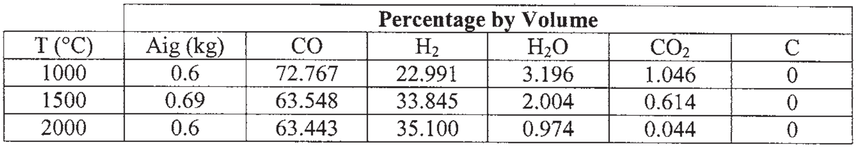
N is the number of turns of wire on the armature
$d\varphi$ is the rate of change of flux
dt is the rate of change of time [17].

This means that a magnetic field is necessary for an emf or electricity to be generated, as shown in Figure 3. After the generation, electrical load R could then be connected to the supply.

PLASMA FURNACE MODELING

To model the plasma power generation system, data obtained from the Technical University of Lodz, Poland [18], and re-produced in Table 2 were used for the modeling and analysis.

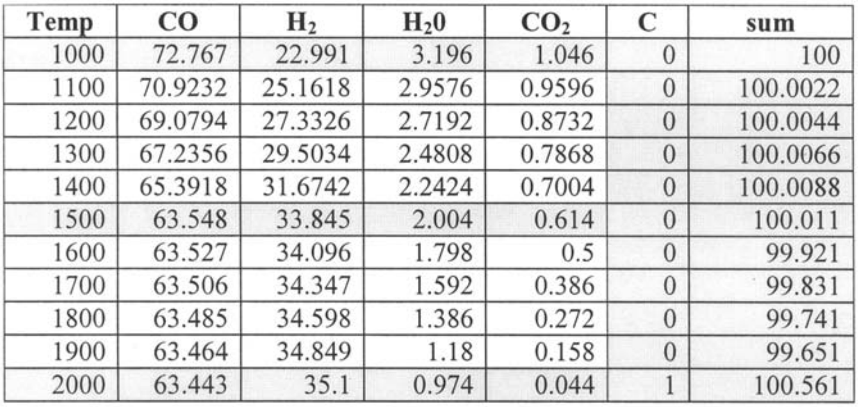
Table 2. Products of Plasma Limited Oxidation Percentage by Volume



	Percentage by Volume					
T (°C)	Aig (kg)	CO	H_2	H_2O	CO_2	C
1000	0.6	72.767	22.991	3.196	1.046	0
1500	0.69	63.548	33.845	2.004	0.614	0
2000	0.6	63.443	35.100	0.974	0.044	0

To have increments of 100°C instead of 500°C, as well as their corresponding data for the chemical elements and compounds of the syngas produced, interpolation was carried out on the data, first between 1000

Table 3. Interpolated Values Between 1000 and 2000°C



Temp	CO	H_2	H_20	CO_2	C	sum
1000	72.767	22.991	3.196	1.046	0	100
1100	70.9232	25.1618	2.9576	0.9596	0	100.0022
1200	69.0794	27.3326	2.7192	0.8732	0	100.0044
1300	67.2356	29.5034	2.4808	0.7868	0	100.0066
1400	65.3918	31.6742	2.2424	0.7004	0	100.0088
1500	63.548	33.845	2.004	0.614	0	100.011
1600	63.527	34.096	1.798	0.5	0	99.921
1700	63.506	34.347	1.592	0.386	0	99.831
1800	63.485	34.598	1.386	0.272	0	99.741
1900	63.464	34.849	1.18	0.158	0	99.651
2000	63.443	35.1	0.974	0.044	1	100.561

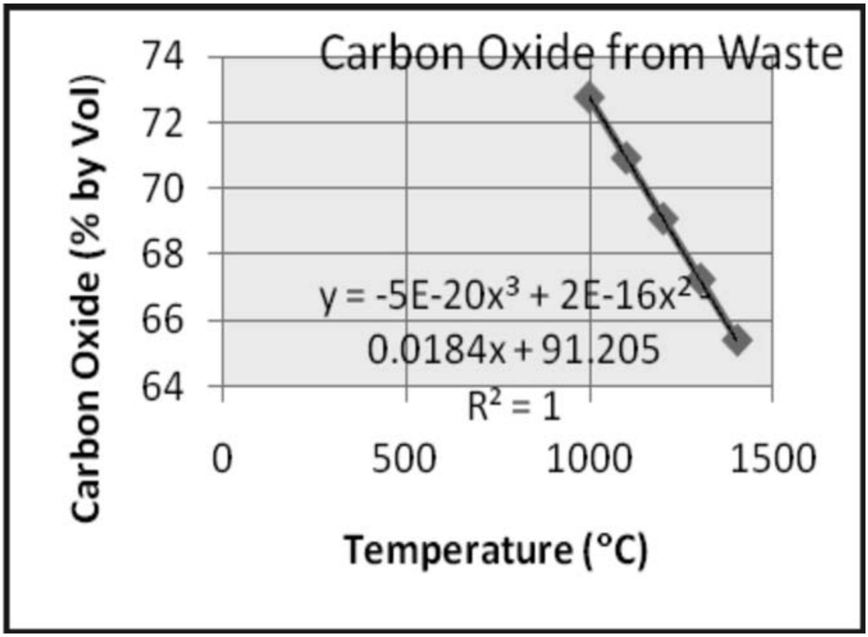


Figure 4. Chart and Equation of CO Extrapolated from Table 3

and 1500°C and then between 1500 and 2000°C using the linear interpolation formula. The results are shown in Table 3.

To have a numerical model for the plasma furnace, a chart was drawn for the various elements and compounds against temperature using Table 3 to extrapolate an equation for the model. Figure 4 depicts, for example, the chart and equation for CO, where x is temperature and y is CO.

The same procedure was carried out to draw charts and extrapolated equations for H_2O, CO_2, and H_2. The resulting equations (7 through 14) are shown below.

The charts and figures show that CO and CO_2 decreased with increases in temperature while for H_2 the value increased with increases in temperature. An if statement greater than 1000°C was written in an Excel© spreadsheet in conjunction with the above equations, and an expression written to simulate the compounds H_2O, and CO, and the elements H_2, and C in incremental temperature of 50°C.

Determination of Quantity of Syngas

From the results obtained for a set temperature, the quantity of synthetic gas emanating from the plasma converter was given as H_2 + CO and the environmental efficiency given as $(CO)/(CO + CO_2)$.

For H_2O, From 1000–1450,
$y = 1E{-}21x3 - 2E{-}18x2 - 0.0024x + 5.58$ (Eq 7)
For H_2O, From 1500–2200,
$y = 2E{-}21x3 - 9E{-}18x2 - 0.0021x + 5.094$ (Eq 8)

For CO_2, From 1000–1450,
$y = 7E{-}22x3 - 2E{-}18x2 - 0.0009x + 1.91$ (Eq 9)
For CO_2, From 1500–2200,
$y = 3E{-}22x3 - 2E{-}18x2 - 0.0011x + 2.324$ (Eq 10)

For CO, From 1000–1450,
$y = 1E{-}19x3 - 4E{-}16x2 - 0.0184x + 91.205$ (Eq 11)
For CO, From 1500–2200,
$y = 3E{-}20x3 - 2E{-}16x2 - 0.0002x + 63.863$ (Eq 12)

For H_2, From 1000–1450,
$y = 5E{-}20x3 - 1E{-}16x2 + 0.0217x + 1.283$ (Eq 13)
For H_2, From 1500–2200,
$y = 8E{-}20x3 - 4E{-}16x2 + 0.0025x + 30.08$ (Eq 14)

Quantity of Municipal Solid Waste (MSW) Generated by the Whole Community

To determine the quantity of municipal solid waste generated by the community, one has to find the average quantity of waste per capita in that community and also the number of persons constituting a household in that community. The total quantity is the product of the per capita waste generated and the number that constitute a household in that community. Data from the EPA indicate that per capita generation of MSW in the US is 4.6 lb or 2.08 kg [10]. Data from Economist Blog, also indicate that the US household is made of about 2.56 persons on average [19]. From these data, a household in the US would produce about 5.32 kg per day, (2.56*2.08) of trash.

It is estimated that about 25-30% of MSW is recycled in the US [20], which should be subtracted from the total quantity generated before applying the rest to the plasma converter.

Let W_h = quantity of waste produced by a household and W_r = percentage of waste recycled, then waste to be applied to plasma converter per household equals:

$$W_p = \left(1 - \frac{W_r}{100}\right) * W_h \qquad \text{(Eq 15)}$$

Quantity of Waste-to-power Households

Research indicates that the quantity of waste fed into Plasma systems can generate electricity to power the corresponding homes as shown in Table 4, with their references.

Table 4. Data for Tons/day to Power Households

kg/hr	*Ton/day*	*Household*	*Reference*
3,125	75	3,600	21
3,541.667	85	4,000	22
9,375	225	13,500	23
50,000	1,200	26,000	24
83,333.33	2,000	60,000	25
125,000	3,000	98,000	26

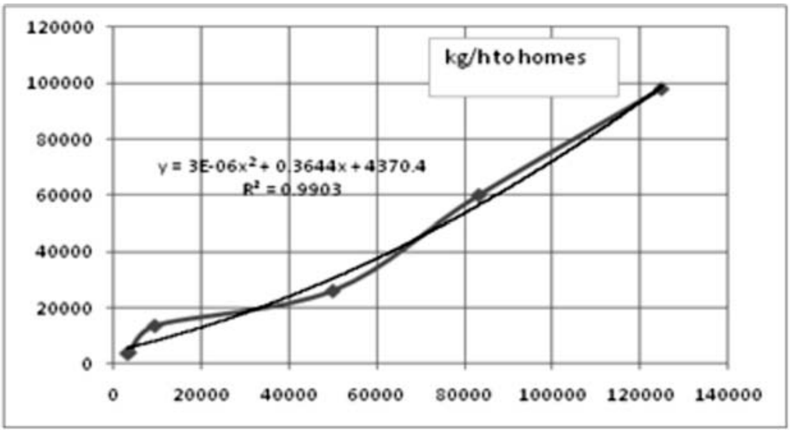


Figure 5. Data for kg/day to Power Households

To extrapolate an equation from the data for analytical purposes, another chart was drawn in excel using Table 4 between kg/day and households, as shown in Figure 5. Note that 1 ton/day = 1000/24-kg/hr.

The equation obtained was y = 3E-06x2 + 0.3644x + 4370.4 where y represents homes and x represents the weight of trash in kg/day. Using the above equation, the quantity of waste to power households was calculated in steps of 100 tons/day (kg/day).

These equations were connected in excel in such a way that if you know the quantity of waste being processed (demanded) say W_d in kg/hr, you could determine the number of homes (N_h) it could power. Having found the quantity of waste generated per household to supply the plasma W_p, you could also determine the actual quantity of waste generated W_g to produce that power, i.e., $W_g = (W_p * N_h)$. The percentage of waste generated to the actual waste being used by the plasma system (demanded) could then be found.

The percentage waste generated to demand would thus be

$$= \frac{W_g}{W_d} * 100\% \qquad \text{(Eq 16)}$$

Community Energy Demand

The electrical energy demand of the community E_d could be determined by knowing the quantity of power each household consumes a day. This could however be determined by finding the quantity of power each person consumes a day and the number of people that constitute a household. Research shows that each person in the US consumes about 10 kWh a day [27] and as stated earlier, the average household in the US is about 2.56. This means that in the US a household consumes about 25.6 kWh a day (2.56*10).

Quantity of Electricity from Syngas

Research shows that the quantity of electricity that could be generated from the syngas ranges between 1 kWh/m^3-hr and 2 kWh/m^3-hr depending upon the temperature between 1000°C and 2000°C, as shown in Table 5.

Table 5. Syngas Temperature to Power Relationship

Temperature °C	*Power* kWh/m^3-hr	*Reference*
1000	1	28
1600	1.6	29
2000	2	28

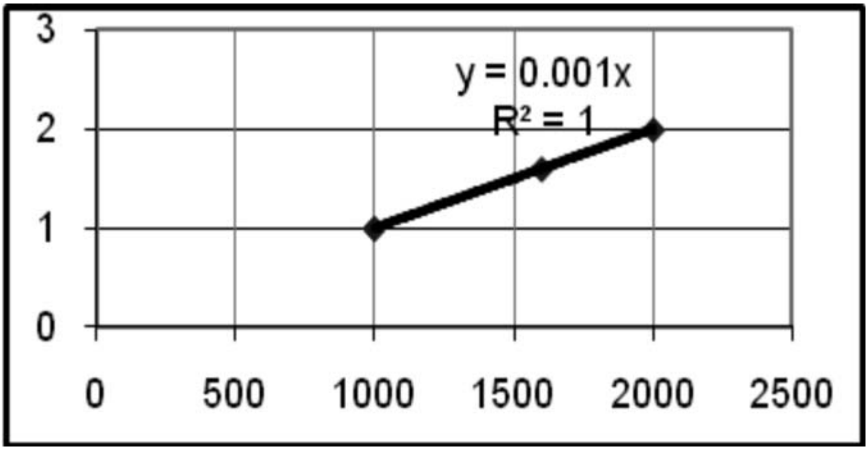


Figure 6. Syngas Temperature to Power Relationship

A chart was thus drawn to extrapolate the mathematical equation between the syngas and electric energy generated with respect to temperature as shown in Figure 6. This yielded:

$$y = 0.001 * x - 2 * 10^{-15} \qquad \text{(Eq 17)}$$

where

y is the electric energy value.
x is the temperature value.

Depending upon the temperature chosen, the actual electric energy could be calculated by multiplying this factor by the quantity of syngas produced.

The quantity of syngas obtained is the sum of hydrogen and carbon-dioxide. Therefore $E_g = (H_2+CO)*(0.001* x - 2*10^{-15})$, where E_g is the electric energy generated (kWh) and x is the operating temperature.

The percentage energy generated to demand could thus be calculated as

$$\frac{E_g}{E_d} * 100\% \qquad \text{(Eq 18)}$$

PROCEDURE

Choosing a fixed temperature of 1000°C, the waste input to the plasma system was varied from 100 tons/day to 4000 tons/day (in this case W_d), and the corresponding quantity of homes it could power (N_h), as well as the syngas it produced were determined. From these results, $W_g = W_p*N_h$ was found and hence $\frac{W_g}{W_d}*100$ could also be determined. The electrical energy generated, E_g, was also calculated from the results where $E_g = (H_2+CO) * (0.001 * x - 2*10^{-15})$, and $\frac{E_g}{E_d}*100\%$ also found.

This procedure was repeated for temperatures of 1500°C and 2000°C and the corresponding percentages of generated waste to demand as well as generated electrical energy to demand were calculated. From these results, charts were drawn for waste against electric energy,

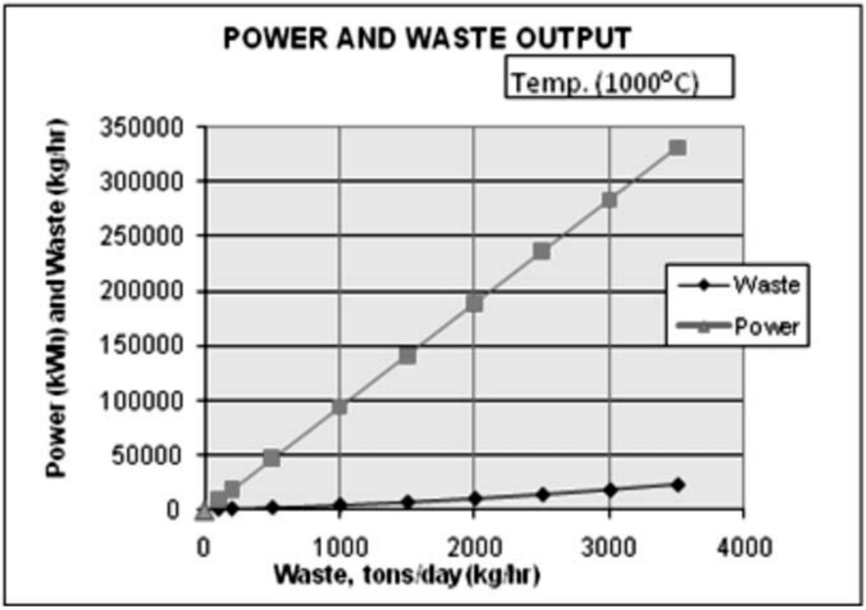


Figure 7. Waste to Generate Electrical Energy at 1000°C

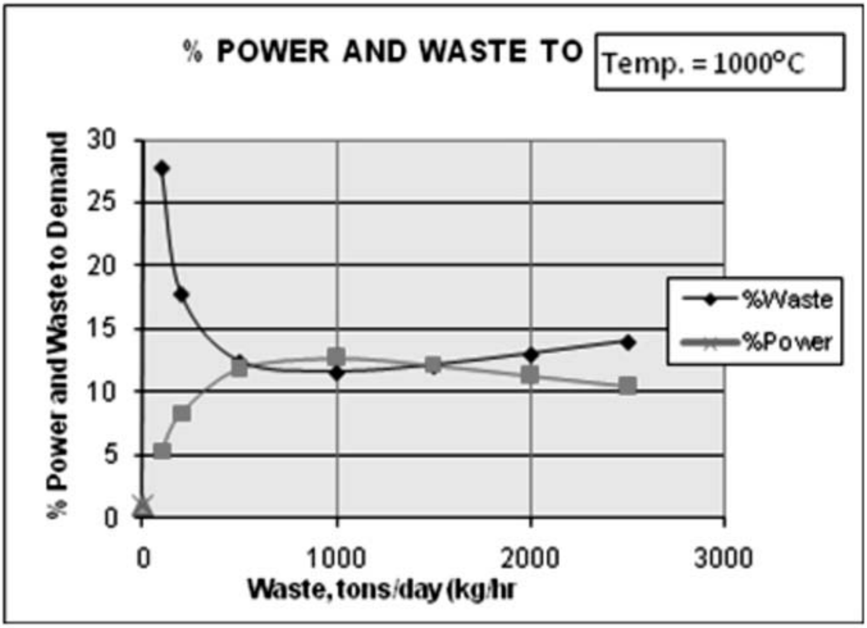


Figure 8. Percentage and Power and Waste at 1000°C

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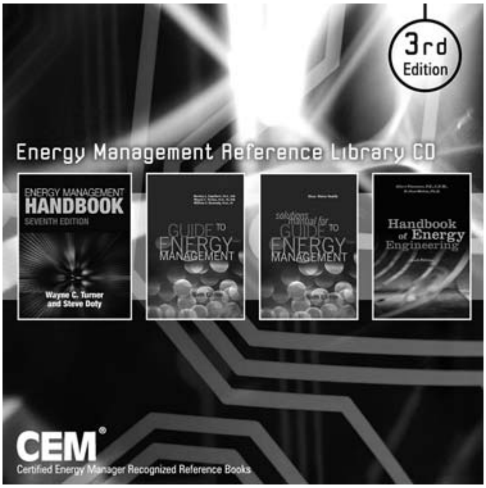

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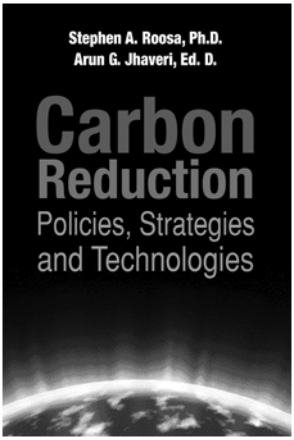

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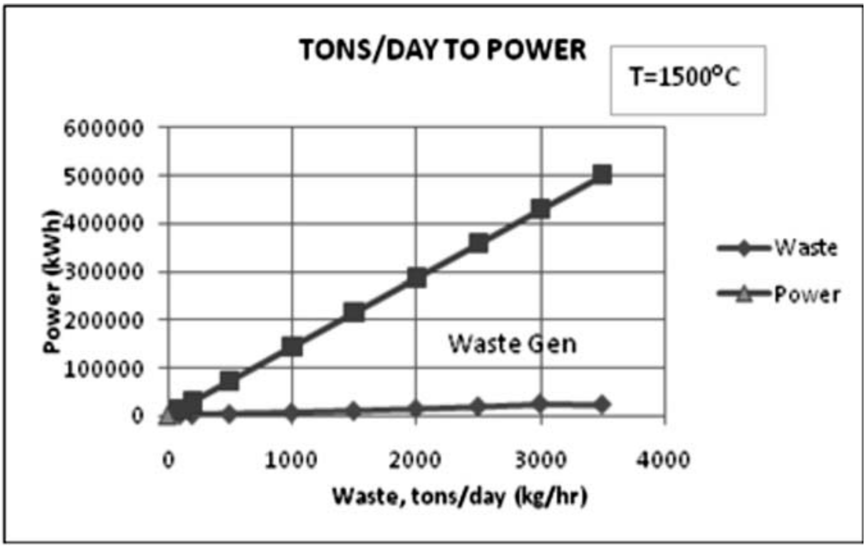

Figure 9. Waste to Generate Electrical Energy at 1500°C

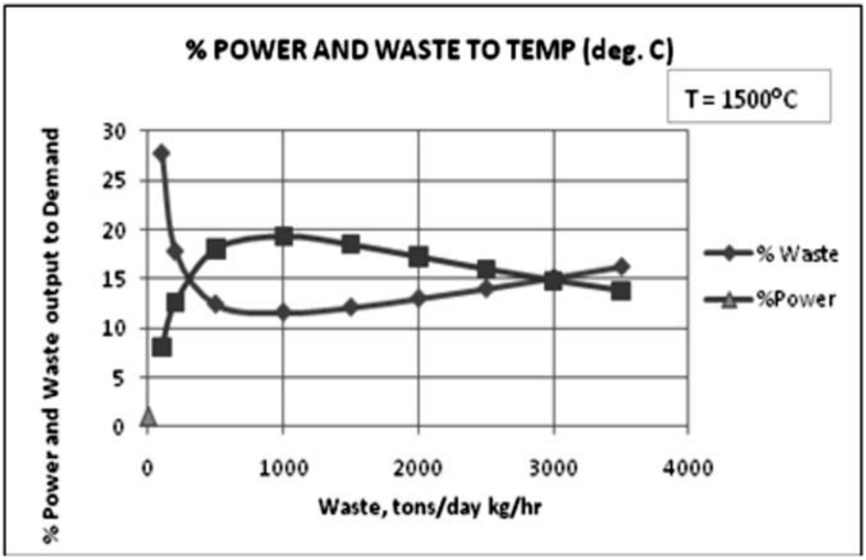

Figure 10. Percentage and Power and Waste at 1500°C

as shown in Figures 7 and 9. Charts were also drawn for % waste and percentage electrical energy, against temperature (Figures 8 and 10).

A careful study of the results from Figures 8 and 10, show that supplying the plasma system at a rate of about 1000 tons/day, gives a maximum electrical energy output, irrespective of the plasma temperature. However, at lower rates of supplying waste to the plasma system (below 1000 tons/day), lower electrical energy output is obtained. Similarly, at higher rates of supplying waste to the plasma system (above 1000 tons/day), lower electrical energy output is also obtained. It could be observed from Figures 7 and 9 that an increase in waste supply to the plasma system receives a corresponding increase in electrical energy generation.

Figure 11 depicts the chart obtained from the environmental efficiency $\frac{CO}{(CO + CO_2}$ between 1000°C and 2000°C. It could be observed that the environmental efficiency increases with increasing temperature.

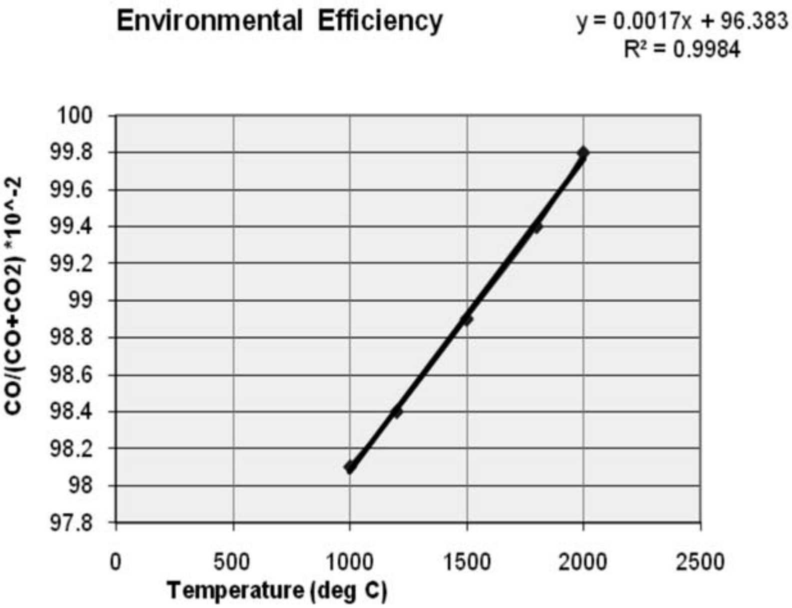

Figure 11. Environmental Efficiency Between 1000°C and 2000°C

CONCLUSION

Energy consumption, waste generation and greenhouse gas emissions will continue to grow as long as population and economic growth persists. These are serious challenges to the global community. The one-stop solution is the application of plasma technology using waste to generate electrical power to supplement the ever growing energy demand. This will as well clean the environment of filth and greenhouse gasses.

This research has shown that for the fact that plasmafication produces higher temperature than incineration and gasification, it invariably gives a higher output in power generation and less environmental effects. The results show that the plasma system must be fed at a rate that is optimum (1000 tons/day) and not below or above this rate. This also suggests that standardization of plasma systems should be based on this rate because it lacks one.

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ABOUT THE AUTHORS

Ransford R. Baidoo is a Ph.D. candidate in Energy and Environmental Systems at the North Carolina A&T State University. He received his first degree in electrical engineering from the University of Science and Technology located in Kumasi, Ghana. He worked with Tarkwa Goldfields Ltd. in Ghana where he rose to the position of senior electrical engineer. He later received a Master of Science Degree in electrical and electromagnetic engineering from the University of Wales located in Cardiff, UK. He served as a lecturer (assistant professor) at the University of Mines and Technology in Tarkwa, Ghana, and later rose to the position of senior lecturer (associate professor) before relocating to North Carolina A&T State University. He may be contacted at rkbaidoo@yahoo.co.uk.

Frederick F. Ferguson, Ph.D., is a professor in the Department of Mechanical and Chemical Engineering at North Carolina A&T State University. Dr. Ferguson also serves as the director for the Center for Aerospace Research.

Frank E. Yeboah is an adjunct assistant professor in the School of Technology, Construction Management and Occupational Safety and Health, at North Carolina A&T State University.