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Abstract: In countries such as Ghana, which are still undergoing restructuring in their economies, low-cost energy supplies are most vital for development initiatives and may not only be the main constraint to their economic growth, but a principal source of conflicts in this century. But whether a meaningful and sustainable economic growth would be achieved or not rests exclusively on the removal of these energy constraints either by way of substitution for increasingly expensive conventional energy sources or new discoveries of cheaper alternatives that would power their industries. Such alternative sources should not only be cheap with great capability of promoting viable economies of scale, but also should be eco-efficient.

Today, the traditional energy sources such as hydroelectric power, wood fuel, and oils are increasingly less attractive with a grown knowledge of their effects on the natural environment. This paper discusses research experiences gathered during a study that was undertaken in Accra, Ghana, to explore the potential for utilising municipal solid waste (MSW) for energy generation in a low-income economy and at the same time, address worsening MSW problems in the major cities. The results show that MSW in a typical low-income country is wet with low calorific values between 14 MJ/kg and 20 MJ/kg and an average energy recovery efficiency of about 40%.

Keywords: low-cost; eco-efficient; low-income economy; conventional energy sources; scale of economies; standing crop.

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1   Introduction

The twenty-first century presents many global challenges which include the following: climate change, conflicts and civil wars, malnutrition and hunger, governance and corruption, sanitation and water, communicable diseases, financial instability, education crisis, population migration, energy crisis as well as subsidies and trade barriers (Lomborg, 2004). While most regions will experience a mix of these challenges, the developing regions and regions undergoing transitions and restructuring would disproportionately receive the heaviest burden of these challenges (Kreith, 1994; WHO/EURO, 1991/1993; Renewable Energy Annual, 1996/1997). One of the dilemmas facing large cities in sub-Saharan Africa seems to be as to how to cope with the overwhelming deterioration in urban environmental health quality and how to meet urban energy and water supplies (Gourlay, 1992; Renewable Energy Annual, 1996/1997). Whereas the importance of many of the issues that were raised is appreciated, generating adequate energy to meet the demands of the ever-increasing urban population and growing industrial concerns remains the single major development constraint in many sub-Saharan African countries including Ghana (Brigwater and Boocock, 1997; Hankohl and Kristiansen, 1996; Kreith, 1994; WHO/EURO, 1991/1993).

Recent discussions on meeting regional energy demands have focused on the exploitation of sustainable non-conventional energy sources, which have already found wide application in developed countries such as Japan (Hankohl and Kristiansen, 1996; California Energy Commission, 2000). However, these discussions have not been backed

by commensurate action because of high equipment installation costs, high maintenance costs and lack of the standard of skills required for their exploitation which makes the implementation of such schemes considerably difficult in sub-Saharan Africa. This leaves the exploitation of these non-conventional energy sources in most developing countries to pilot trials, which are still yet to find large-scale application. In general, global energy security debates have found favour for low-cost and environmentally friendly energy sources, which would be available on sustainable basis.

In Ghana, non-conventional energy exploitation through useful harnessing of biomass energy locked up in urban solid waste into grid energy seems to be a more likely option that has won both political and public debates on alternative energy sources (Akuffo, 1998). This option seems to have found both public and political favour because of its potential dual ability to abate environmental pollution problems through solid waste reduction and its capability to generate substantial thermal energy through waste-to-energy conversion by incineration in mass burn or refuse-derived fuel (RDF) (The New African Initiative, 2001; Akuffo, 1998). But the application of this technology is however not yet popular in Ghana and in many other developing countries probably because of lack of knowledge and information on the suitability of urban refuse as a useful fuel resource or the skills required in the operation and management of such technologies are insufficient in these countries.

2   Aims and objectives of the study

The aim of this study was to explore the potential of urban refuse in typical developing country scenarios for energy production and as a means of minimising environmental pollution where there is overproduction of solid wastes as a consequence of rapid urbanisation. The multiple objectives were:

- boundary classification of the study area (Accra metropolis) into waste zones

- collection and characterisation of urban solid wastes

- determination of calorific and moisture contents of urban refuse

- devising of an analytical framework for the analysis of the data collected

- proposing recommendations based on the analytical framework and an approach for policy intervention.

3   Study design

3.1   Study area

The study was conducted in Accra, which is both the political and administrative capital of the Republic of Ghana. Accra is a coastal city located in the Greater Accra Region, the smallest of the ten political regions in Ghana (Stephens, 1999). It is the largest of Ghana's ten leading urban centres, with an estimated population of approximately 1.7 million in 1990 and 2.7 million in 2000 (Carboo and Fobil, 2004; Fobil and Atuguba, 2004). Accra is estimated to contain 70% of the total population of Greater

Accra Region, and harbours over 30% of the urban population of Ghana and nearly 10% of the total population of Ghana with current population growth of nearly 6% (GSS, 2002).

Accra is now widely believed to be exclusively the leading economic, commercial and industrial nerve centre of Ghana, broadly defined as Accra Metropolitan Assembly (AMA) and generally often analysed as part of a larger metropolis known as the Greater Accra Metropolitan Area (GAMA). This consists of three urban districts, viz., Accra Metropolis, Tema/Ashaiman and Ga districts (Stephens, 1999). The total annual energy demand of the GAMA is 1472.28 GHh (Power Planning Associates Ltd., 2000) and this annual figure represents both domestic and industrial units consumed annually. Nearly 70% of this annual total load is distributed over the Accra Metropolis and the Ga District.

The study area (Accra Metropolis) which is delimited on the north by latitude 08°01'N and in the west by longitude 00°21.5'W was classified into three waste zone types, namely high income low population density waste zone (HILPDWZ) called zone A, middle income medium population density waste zone (MIMPDWZ) called zone B and low income high population density waste zone (LIHPDWZ) called zone C on the assumption that there is a significant positive correlation between per capita waste generation and income levels of residents (Kreith, 1994). The proportion of the city's population in each of these zones is shown to be 3.9% in HILPDWZ, 50.4% in MIMPDWZ and 45.7% in LIHPDWZ (Fobil, 2001). The medium density population area harbours a higher percentage of the urban population than high density area because it covers a larger portion of the city's land area. The classification closely followed a previous socio-environmental zonation of the city by Songsore and Goldstein (1995). Ten houses were randomly selected from each waste zone for garbage analysis. Within each zone, refuse was pooled together from each of the ten houses to produce a huge waste composite sample. The sampling was done between November and February, a period that overlaps both rainy and dry seasons in Ghana. Subsamples, each weighing 20 kg were taken from the composite samples and oven-heated at 85°C to constant weight for determination of moisture content. The type of materials present in the waste stream of each zone was the same except that they differed in amounts and proportions present in the three different waste zones.

The component materials in the citywide waste stream were classified as:

- organic or putrescible materials

- paper and cardboard

- plastics and rubber

- glass

- metals and cans

- textile

- inert or residues

- miscellaneous or other waste.

The average percentage composition of various components in the waste stream was: 60% organic component, 8% paper and cardboard component, 8% plastics and rubber, 2% glass component, 3% metal and cans component, 2% textile component, 11% residue

or inert component and 2% miscellaneous or other components (Fobil et al., 2002). The bulk densities of solid waste in each waste zone were: 5.3×10^2 kg/m³ in zone A, 4.1×10^2 kg/m³ in zone B and 5.4×10^2 kg/m³ in zone C. The total solid waste generation in each waste district was 0.462 kg/cap/day, 0.380 kg/cap/person and 0.285 kg/cap/day in zones A, B and C, respectively. The total annual solid waste generation in each waste zone was 250,000 tons in zone A, 240,000 tons in zone B and 170, 000 tons in zone C (Fobil, 2001). These values were derived from per capita generation rates on the projected combined resident and floating urban population of 3.5 million people. The resident population in each zone on the basis of this estimation therefore translates into 136,500 in the high income area, 1,764,000 in the middle income area and 1,599,500 in the low income area (Fobil, 2001). The citywide waste disposal and management is largely collection and open dumping and some level of composting.

Figure 1   GAMA delimitations

3.2   *Sub-sample preparation for calorific determination*

Clean white polyethylene sheets were spread on the floor on which the contents of the sub samples were placed and manually separated to determine the proportions of the various waste components in the mixed waste. The procedure allowed for the determination of the amounts of combustible portions in the mixed sub-samples. All combustible materials were pulled out manually and the remaining materials were quantified as non-combustible materials. Combustible materials included the organic, plastic, paper, textile and inert materials. The different components were separately milled to pass a 200-mesh sieve, using an electrical miller (Dietz-Motoren & model # D-73265 Dettingenu Teck, GmbH & Co. KG). Simulated (or derived) samples were also prepared by remixing the various waste components (milled) so as to mimic the natural situation in the various waste stream types as they occur in reality. The samples included 'Equal percentage by wt.' prepared by remixing the milled waste components in equal proportions by weight and 'surrogate' natural samples that were made by remixing milled component in proportions similar to those found in the previous waste composition studies. Generation of these derived samples was done to find out whether variation in waste composition had any effects on such waste stream factors as calorific content of

different waste stream types as occurring in the natural environment and in each situation, only the combustible components were used to fire the bomb calorimeter.

3.3 Determination of calorific value of urban refuse

In this determination, known dry weights of MSW were moulded into pellets and fed into a bomb calorimeter (IKA®-Calorimeter: Analtfentechnik Ltd, Germany, Model # C4000 Adiabatic). The samples were then ignited in excess oxygen at 30 bars using an electric arc where the rise in temperature due to combustion of the sample was noted and the calorific values of MSW read.

4 Results and discussions

The moisture contents of the solid waste from the three zones were obtained as 62.2% in zone A, 46.9% in zone B and 39.8% in zone C, respectively, suggesting that the solid wastes in Accra are wet as shown in the Table 1. There were some differences in the mean gross energies per kilogram of waste from the three zones and also among the various sample types both within and between the three zones investigated. The calorific content of MSW was also found to vary significantly with time both within and between waste zones (Fobil, 2001; Kreith, 1994) suggesting a close association between gross energies and material composition in waste stream. The mean of the gross energies was highest in zone A, followed by that in zone B and zone C in that order (see Table 1), thereby making a strong argument for the case that the gross energy content per unit mass of mixed wastes is higher in zone A than in zones B and C and higher in zone B than in zone C. It was not clear which factors were responsible for this trend of observation, but it appeared that some socio-economic and socio-cultural parameters may have been responsible for it. Paper and cardboard and organic/putrescible components had the highest gross energies per unit mass than were in textile, although the calorific value for paper and cardboard was higher than in putrescible organic component. It should be noted that the calorific value for plastics and rubber component, which had tremendous heating value, was not determined because of equipment limitations. Therefore, the determined energy values did not include plastic wastes in the waste streams considered.

Table 1   Calorific content of MSW from urban waste zones in Accra, Ghana

	Energy content (MJ/kg)		
Sample Type	*Zone A*	*Zone B*	*Zone C*
Simulated	16.54 ± 0.0	17.02 ± 0.0	16.87 ± 0.0
Organic/Putrescible	17.50 ± 0.1	16.28 ± 0.1	16.73 ± 0.1
Paper and cardboard	16.82 ± 0.2	17.30 ± 0.4	19.23 ± 0.2
Textile	16.95 ± 0.0	16.11 ± 0.2	16.97 ± 0.3
Equal % by wt	15.98 ± 0.2	14.40 ± 0.0	16.35 ± 0.0
Plastics and rubber	–	–	–
Mean gross energy	16.95 ± 0.2	16.85 ± 0.2	16.75 ± 0.2
Moisture content	62.2%	46.9%	39.8%

4.1   Energy efficiency of incineration

The economic and social trade-offs, of waste-to-energy conversion are presented under this discussion. This equation was adapted from Fobil et al. (2002):

Net energy (N_e) = gross total annual energy (G_{te}) – energy required in drying the waste (E_d).

$$N_e = G_{te} - E_d \tag{1}$$

But the energy required for drying MSW to a constant weight (E_d) is given by the sum of the energy required to raise the temperature of the water in waste from its initial temperature to a vaporisation temperature of 100°C (H_I) and the energy required to completely vaporise the water in the waste at 100°C or heat of vaporisation (i_V).

This means that $E_d = H_I + H_V$

Therefore, equation (1) becomes,

$$N_e = G_{te} - (H_1 + H_V) \tag{2}$$

But, H_I = mass (m) of moisture in MSW × heat capacity (c) of water in MSW × change in temperature ($\ominus$).

This implies that $H_I = m \cdot c \cdot \ominus$

But, $\ominus$ = final temperature (100°C) – initial temperature of water in MSW assumed to be the average annual temperature in Accra area (35°C).

Also, $\ominus = (100 + 273) - (35 + 273) = 65K$.

And H_V = mass (m) of moisture in MSW × latent heat of vaporisation (c_v).

This also implies that $H_V = m \cdot c_V$.

Therefore, equation (2) becomes $N_e = G_{te} - (m \cdot c \cdot \ominus + m \cdot c_v)$.

Substituting the values into equation (2):

$$N_e = 6.4 \times 10^6 \text{ MJ} - (1.78925 \times 10^7 \text{ kg} \times 4.2 \text{ KJ/kg/K} \times 65K$$
$$+ 1.78925 \times 10^7 \text{ kg} \times 2.26 \times 10^3 \text{ KJ/kg}).$$

$$= 6.4 \times 10^6 \text{ MJ} - [(7517 \times 65 \text{ MJ} + 4.5325 \times 10^9 \text{ KJ}) = 4.885 \times 10^9 \text{ KJ}]$$

$$= 2{,}540{,}746 \text{ KJ}.$$

N_e approx. $= 2.5 \times 10^6$ MJ.

Energy efficiency of an incineration programme = $N_e/G_{te} \times 100\%$.

$= 2.5 \times 10^6/6.4 \times 10^6 \times 100\%$.

$= 0.39 \times 100\%$.

$= 40\%$ approximately.

The potential energy efficiency of an incineration programme in Accra is approximately 40%. However, it is important to note that the energy values for plastics and rubber components, which constitute 8% by weight in the waste stream, could not be determined due to equipment limitations and the energy efficiency value that could be obtained would be a little lower or higher with the plastic and rubber components.

The potential energy efficiency value means that only approximately 40% of the gross annual energy is potentially recoverable from MSW incineration programme in a typical urban economy such as that found in the Accra metropolis on the basis that no energy losses (this is of course an idealised situation) to the surrounding atmosphere occur during the incineration process. This is the maximum obtainable proportion of energy locked up in urban solid waste, which would have been lost if the refuse were landfilled. The potential net maximum recoverable energy depends largely on inherent physical characteristics such moisture content and heating value of urban refuse in a given waste stream and cannot be increased easily unless there is some cheap means of lowering the moisture content of the refuse without necessarily raising the amount of input energy.

Table 2   Hydro energy source non-SLT* tariffs in Ghana as in March 2000 (PPAL, 2000)

	Charge of KWh/US$/Month				
Customer Type	*0–50*[**] KWh	*51–150* KWh	*151–300* KWh	*301–600* KWh	*600+* KWh
Residential	66.67	2.00	2.50	3.67	5.83
Non-residential			3.67		5.33

*Speacial load tariffs, i.e. consumption above 100 KVA.

**Block charge on a threshold of electricity consumed in US$ per month in Ghana.

Source: Technical Advisory Services.

The net energy benefit accruing to a region that is embarking upon a waste-to-energy conversion programme is the difference between the capital cost of the technology plus the operational and maintenance cost and the monetary equivalent of the electrical power generated. The net energy from incineration can be calculated from the energy balance in equations (1) and (2). The viability of the process depends on the economic rent obtainable after weighing the sum of capital and operational costs against the value of the net annual energy obtainable from MSW.

However, this does not tell us anything about the cost per unit of energy in kilowatt/hour (KWh) of biomass energy from incineration. If such an incineration programme were to be economically feasible, then the cost of recovered energy should be very competitive and cheaper compared to other energy sources, such as hydropower that is widely used in Ghana (see Table 2) and available in the region. For this comparison to be made intelligible, it is necessary to take into consideration, the input cost per KWh of energy generated from MSW and then calculate the range of economic rents that are realistic within the existing income regimes. Thus, if the final tariffs are based upon calculation of the sum of input cost of energy produced from solid waste and the marginal profit compares favourably with the cheapest source of energy in the region, and in the case of Ghana, hydroelectric power, such a scheme can be economically and commercially sustainable. For instance, as of March 2000 if it cost an energy supply authority to generate a threshold electric power of 0–50 KWh of electricity at US$ 66.67, then consumers in the low-income class zone would not get connected to the electricity or metered to benefit from the power supply produced from that scheme unless some form of power subsidy existed so as to enable the low income group to enjoy the benefit of the power produced. Under that circumstance, only consumers in high-income class residential areas would have afforded to purchase power from this power supply

authority. Although our study did not determine the input cost of energy generated from MSW, we made our prediction based upon market prices of materials that the cost of generating 0–600 KWh of electricity from MSW in 2000 will not cost less than US$ 3.67. This means that implementing such a scheme will deprive electricity to over 70% of the population. This therefore makes such a power supply scheme less attractive compared to hydroelectric power, which is relatively cheaper to produce.

Furthermore, in terms of heating value, raw solid waste has a calorific value between 4000 Btu/lb and 7000 Btu/lb compared to coal, which releases about 10,000 Btu/lb (Kreith, 1994). Therefore on the basis of heating value, coal will be a more attractive fuel than raw solid waste. The major setbacks in waste-to-energy combustion as an attractive energy source are the high cost of incineration facilities and the level of sophistication needed to operate them safely. Their adoption in developing countries would therefore raise serious questions about whether the existing technical skills and capacity would meet the required criteria for their safe operation and whether such countries can finance the huge capital cost of equipment installation without external aid. Such huge initial costs of equipment installation would also make final recovered energy a less competitive alternative, as it would be much more expensive per unit consumed than parallel energy sources available in the given region. The other drawback to the adoption of waste-to-energy is the stricter international environmental regulation on emission control requiring additional installation of expensive scrubbers whose cost of installation and operation would raise the recovered energy tariffs to levels that would make waste-to-energy process much less competitive compared to other energy sources.

However, in the equatorial regions and in the tropics where there is abundant solar energy that could be deployed cheaply to effect the drying process, such a provision may lower the initial energy inputs and therefore reduce the cost of energy recovered so as to make it more attractive to investors. In other words, the process should proceed at operational conditions that yield energy at tariffs that are competitive with those presented by alternative sources or they must yield attractive rates of return to investors. The caution here is that there are problems associated with solar drying – an easy means of saving cost of input energy and thereby achieving attractive recoverable energy tariffs. Normally, large land space would be required for the drying process and this may raise input costs to levels that could in turn raise the levels of MSW energy tariffs. Nevertheless, the required land space would be much less than that required for solar energy, hydropower and wind energy per unit of energy produced (IAEA, 1991). The greatest point in favour of waste-to-energy combustion in developing countries is that, a considerable amount of weight reduction, between 60% and 80% of the original weight of raw solid wastes would be achieved (Fobil, 2001). Furthermore, large fluctuations in heating value of urban solid waste make it (urban solid waste) a less attractive biomass fuel in terms of equipment design specification, although the wastes may be available on sustainable basis. Moreover, it would be very difficult to fabricate equipment that would produce steady energy. This is because calorific values can fluctuate by as much as 6% of the mean and due allowance should be made for this in well-regulated energy recovery incinerators (Kreith, 1994). Also, one major issue that discredits waste-to-energy technologies is the cost of carting bulky raw wastes to incineration facility sites from homes. But in contrast, many other energy technologies that require fuel to cart the waste from transfer stations and homes to the MSW facilities pay the waste suppliers a fee (known as a 'tipping fee'). The tipping fee is comparable to the fee charged to dispose of garbage at a landfill. Therefore, if these fees are high enough, they should be able to

compensate for high cost of MSW carting to facility sites and this could potentially offset the expected marginal profit.

5   Conclusions

The two most important aspects of urban solid waste as a fuel are that it has a low calorific value, typically between 30% and 40% than that of an industrial bituminous coal and a density as fired, of about $200 \, kg/m^3$ (Fobil, 2001; Kreith, 1994). The final recoverable energy output is strongly influenced by moisture content of urban solid waste (Kreith, 1994; Fobil, 2001). It is amply clear that waste-to-energy incineration, like any other energy source, has its merits and demerits, but the decision to select a given energy source for development would depend on a number of factors such as economic, social and environmental benefits that would be achieved in the implementation of such a scheme. This will also include the evaluation of alternative energy sources and social as well as political acceptability of such a scheme in the region. There are a lot of public and environmental health concerns with respect to the quality of emission from incinerators and a final decision to adopt waste-to-energy source for a given region rests firmly upon a careful consideration of all technical and non-technical issues prevailing in its implementation. The implementation of such schemes should not be done in haste, but should first proceed cautiously in pilot schemes, which may then transform into large-scale schemes. This study concludes that waste-to-energy conversion schemes might not be economically sustainable on the basis that MSW has a low energy recovery efficiency, approximated at 40% recovery, far less than 50% or half of the total heating value of fresh wastes. This is because the capital outlay for equipment installation and plant maintenance costs are so high that the energy benefits accruing may not suffice to offset this minimum balance.

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