INTEGRATING WASTE DISPOSAL POLICIES INTO ENERGY STUDIES: THE CASE OF LANDFILL GAS IN SOUTH AFRICA

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ABSTRACT

Current research into the pattern of energy usage in South Africa reveals an extraordinarily heavy reliance on coal-fired electricity, a strategy that is not only unsustainable but which has been responsible for the generation of serious air pollution problems. This deleterious development, which has affected climate in the region, ought to be seen in the context of South Africa’s harmful waste disposal policy. The overwhelming bulk of South Africa’s municipal solid waste is landfilled, thereby generating a significant volume of landfill gas. The fact that landfill gas has a strong methane component carries serious implications for climate in the region. Methane is lighter than air and reacts with ozone (O_3) in the upper atmosphere, thereby posing a threat to the earth's ozone shield; at the same time, methane is a powerful 'greenhouse' gas that absorbs the earth's infrared radiation and contributes to global warming. Against this background, this paper seeks to explore the use of landfill gas as a renewable energy source, thereby integrating waste disposal policies into energy studies. It is argued that this approach encourages the adoption of a more holistic consideration of policies which affect climate, and thereby contributes to more effective protection of the global commons.

1. ENERGY AND THE ENVIRONMENT IN SOUTH AFRICA

South Africa's energy development path has been shaped primarily by the interplay of two factors: relatively limited water resources and seemingly abundant reserves of coal. The country’s two major sources of water are surface runoff (80%) and groundwater (20%). The former is dependent upon meagre rainfall which, in turn, places a severe constraint on the use of water as a source of energy. However, South Africa's recoverable coal reserves are estimated to be in the region of 58 million tons which, at present rates of consumption, will last beyond the end of the next century (Eberhard & Williams, 1988, 10). In these circumstances, it is not surprising to find that coal provides 76% of South Africa's primary energy needs, followed in distant second place by oil (16%), with biomass (6%) and nuclear sources (2%) far behind (Huntley *et al*, 1989, 63).

The net result of this pattern of energy consumption is that South Africa's dependence upon coal – a non-renewable resource – is among the highest in the world (EMG, 1992, 57). Half of domestic coal consumption is used by the Electricity Supply Commission (Eskom), a government-controlled parastatal, to generate electricity; a quarter is used by Sasol’s oil-from-coal plants; and another quarter is burnt directly by industry or is used for cooking and heating in the black townships (Gandar, 1991, 97). Coal-fired electricity is therefore central to South Africa's energy consumption.

Not only is South Africa's present energy strategy based upon the exploitation of a non-renewable resource, and is therefore unsustainable, it has also exacted an exorbitant cost in terms of environmental decay. Although most of Eskom's power stations are fitted with electrostatic precipitators to remove dust and ash particulates, they are not equipped with the costly flue-gas scrubbers needed to remove sulphur and nitrogen oxides (Lumby, 1992, 120). When these air pollutants are combined with water vapour, they fall to earth in the form of 'acid rain'. Furthermore, the concentration of approximately three-quarters of South Africa's coal reserves and electricity generation in Mpumalanga province, combined with unfavourable meteorological conditions in the area, has made this one of the worst air pollution regions in the world (Tyson *et al*, 1988). To make matters worse, 'half of South Africa's agriculturally productive land and commercial forests and a quarter of its surface water runoff are in this region [Mpumalanga] giving rise to considerable concern about the environmental and economic impact of acid rain' (EMG, 1992, 59).

Against this background, there have been repeated calls for greater attention to be paid to the use of 'renewable energy technologies' in South Africa, including further research on the viability of landfill gas (LFG) as an alternative, sustainable energy source (President’s Council, 1991, 98). These calls are highly opportune because LFG contains a high percentage of methane, a powerful 'greenhouse' gas, which absorbs the earth's infrared radiation and contributes to global warming. Therefore, any attempt to make use of LFG as an alternative source of renewable energy will not only contribute to the development of a more sustainable energy strategy for South Africa, but will also help to curb the despoliation of the global commons. Thus, through this example of the integration of waste disposal policies into energy studies, it becomes possible to take a more holistic approach to environmental management in South Africa.

2. THE EXPLOITATION OF LFG AS A SOURCE OF ENERGY

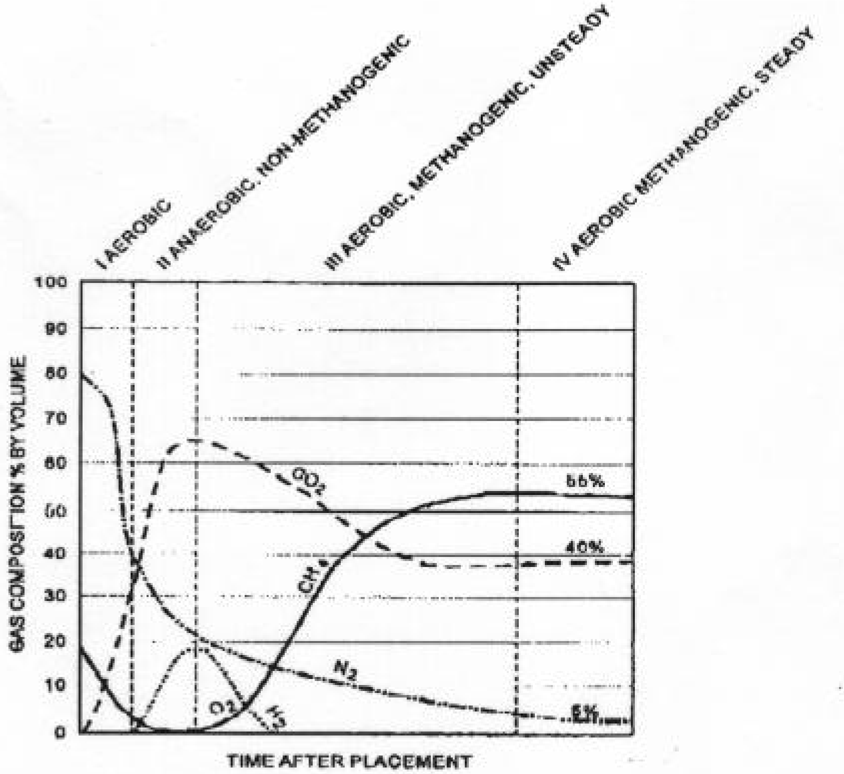
It has been estimated that approximately 80% of the municipal solid waste (MSW) generated throughout the world is landfilled, although the figure for South Africa may be as high as 85% (Richards, 1989, 38-41; DEA, 1991, 7). Although the composition of landfilled MSW varies considerably between countries of different socio-economic backgrounds, it usually includes organic material (such as paper and paperboard, wood, textiles, food residues and garden waste), as well as inorganic material (such as builders' rubble, metal, glass and plastics) (Clayton & Huie, 1973, 1). The organic material – consisting of cellulose, carbohydrates and protein – is readily decomposed by microbes into carbon dioxide (CO_2) and methane (CH_4), and contributes some 6-18% to global methane production (Bingemer & Crutzen, 1987, 2186).

Consequently, landfill sites cannot be regarded merely as an unfortunate but necessary nuisance, but ought to be seen as a significant environmental and health hazard (see Brown, 1983, 52-61). Methane gas is explosive at concentrations of between 5% and 15% by volume in air, and is therefore regarded as dangerous (White & Plaskett, 1981, 148; Wojcik & Hausman, 1993, 495-499). Furthermore, methane is lighter than air and reacts with ozone (O_3) in the upper atmosphere, thereby posing a threat to the earth's ozone shield. At the same time, methane is a powerful 'greenhouse' gas, and, like carbon dioxide, it absorbs the earth's infrared radiation and contributes to global warming (Dickinson & Cicerone, 1986, 109-115; Pearce, 1989, 37-41). Therefore, the conversion of LFG into usable energy not only represents a shift towards a renewable (and therefore sustainable) energy source, but would also contribute a solution to the problem of climate change in the region.

2.1 THE LFG PRODUCTION PROCESS

During the 1960s, feasibility studies on the digestion of MSW were conducted in several centres in the United States, and the recovery of LFG has been practiced since the early l970s (Baccini, 1988). At the present time, LFG is being extracted from sites in numerous countries, including the United States, Canada, Germany, Britain, the Netherlands, Brazil and South Africa (McGeer & Durbin, 1992, 61).[1]

The production of LFG can be seen as a four-stage process, as depicted in Figure 1. After the dumping of MSW, biodegradable carbon compounds in the MSW are first attacked by aerobic bacteria, and these convert organic material into primarily carbon dioxide, water and heat, consuming oxygen. Continuous dumping of MSW leads to the depletion of oxygen and moisture which tends to inhibit the aerobic process, and the second stage of anaerobic decomposition is initiated. During this stage, the principal gas produced is carbon dioxide, but quantities of this gas decrease over time until the third stage is reached when methanogenic bacteria begin to produce a higher rate of methane than carbon dioxide. Eventually, during the fourth stage, a plateau is reached when steady quantities of carbon dioxide and methane are produced. The initial production of methane may take from two to five years (depending upon conditions in the landfill), and methane production can continue for a period of thirty to forty years (depending on the size, and therefore the life, of the landfill) (Augenstein *et al*, 1976, 103).



Source : Owels & Khera (1990, 113).

Figure 1 : Gas composition and Evolution in a Typical Landfill Site

Figure 1: Gas composition and evolution in a typical landfill site

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[1] In South Africa's case, research into LFG recovery and conversion has been pioneered by Professor T.M. Letcher, formerly of Rhodes University (Grahamstown), and presently Head of the Department of Chemistry and Applied Chemistry, University of Natal (Durban). My considerable debt to him is reflected in my numerous references to his research publications.

The rate of LFG production will depend upon the interplay of a number of factors which may be summarised as follows:

1. **Temperature.** Anaerobic decomposition is exothermic, and therefore landfill temperatures are higher than the ambient air temperatures. Ideally, the temperature in the landfill should be in the mesophilic range (20-40^{o}C) (Pfeffer, 1974, 771-787).

2. **Absence of Oxygen.** This is essential if anaerobic conditions are to be maintained. Air infiltration is minimised by the use of an impermeable cover (ideally, a multilayer of soil and clay which will not crack in dry weather) and by the use of deep landfill sites (with a minimum depth of 10 metres) (White & Plaskett, 1981, 149).

3. **Moisture Content.** A minimum moisture content of about 20% is needed for biodegradation to proceed. Although the optimum moisture content for anaerobic decomposition is 40-60%, it has been found that a moisture content of 75% can result in a tenfold increase in the conversion rate for short periods of time (Buvid *et al*, 1981, 3).

4. **Nutrients.** The presence of nitrogen is necessary for optimum bacterial growth, and the low rate of nitrogen to carbon usually found in MSW is one reason for the slow rate of biodegradation. It has been found that the rate of decomposition can be speeded up by seeding the MSW with sewage sludge which also serves as an additional source of moisture (Wilson ,1981, 210).

5. **Compaction.** The rate of compaction, or settlement, within the landfill is significant in that it reduces air space and oxygen content, thereby establishing more favourable conditions for anaerobic decomposition. Gunnerson and Stuckey (1986, 24) have suggested that this ‘probably reduces the time before methane is produced’.

6. **Decomposition Rate.** The rate of decomposition varies significantly between the different component parts of MSW. The half-life of biodegradable MSW – that is, the time it takes for half of the material to decompose into carbon dioxide and methane –has been classified by Hoeks into three categories: (a) readily degradable food residues (with a half-life of one year); (b) moderately degradable soft plant waste (with a half-life of five years); and (c) slowly degradable paper and wood (with a half-life of ten to fifteen years) (Hoeks, 1983, 323-335).

Assuming that the conditions noted in (1) to (5) above are met, that the half-life values of the biodegradable MSW are known (6), and that the volume of biodegradable MSW deposited each year is known, then Letcher has shown that it is possible to develop a simplified kinetic model to estimate the potential methane production over the life of the landfill (see Appendix 1).

Despite the lack of uniformity among landfill sites because of differences among the above-mentioned variables, empirical equations have been developed to predict the volume of carbon dioxide and methane that can be produced from organic waste (Letcher, 1990, 15; Kipsert *et al*, 1876, 245-255). Thus the chemical equation for LFG production, using cellulosic waste, is given as:

$$C_6H_{12}O_6 + (O)H_2O \ = \ 3CO_2 + 3CH_4 \qquad (1)$$

While it is true that the chemicals which comprise organic waste have different molar masses, the above equation is still appropriate because most food and plant materials are composed of carbon, hydrogen and oxygen in the ratio of 1:2:1. Furthermore, the above equation shows that LFG is composed of 5O% carbon dioxide and 5O% methane; in practice, however, LFG will contain less carbon dioxide because part of it becomes dissolved in the landfill water (Bingemer & Crutzen, 1987, 2181). The range of landfill gas composition is shown in Table I, and most studies assume that the methane content of LFG will be in the region of 5O% (Letcher & Schutte, 1993, 28-29; Oweis & Khera, 1990, 114).

TABLE 1

TYPICAL COMPOSITION OF LANDFILLED MSW

COMPONENT	MASS %
Hard Organic Material	24
Other Organic Material	18
Soft Organic Material	18
Builders' Rubble, Metal, Glass & Plastics	20
Water	20

TYPICAL COMPOSITION OF LANDFILL GAS

COMPONENT	MOLE %
Methane	50-56
Carbon Dioxide	40-45
Nitrogen	0,5-1
Trace Compounds	0.5-1
Oxygen	0-0.1

(Sources: Letcher *et al*, (1988, 333) and Rider (1981, 234).

From equation (1) it may be deduced that one mole of biodegradable MSW (with a molar mass of 180 gms) will produce three moles of methane (with a molar mass of 25 litres each at standard temperature and pressure) (Letcher *et al*, 1988, 333). It follows, therefore, that one kg of biodegradable MSW will yield 417 litres of methane. (Expressed differently, one metric tonne of biodegradable MSW will yield 417m^3 of methane.) It has been estimated that each individual disposes of one kg of MSW per day – an assumption that would appear to hold true for South Africa (President’s Council, 1991, 92). However, not all of that waste will be biodegradable. In fact, the evidence summarised in Table 1 suggests that the typical composition of MSW is likely to be 60% dry biodegradable waste, 20% non-biodegradable waste and 20% water.

It must also be noted that not all of the dry biodegradable MSW decomposes into methane, and not all of the methane produced is collected. Small quantities of methane are decomposed by aerobic action in the first stage of the conversion process (see Figure 1); some of the methane produced in the later stages is likely to be lost through lateral diffusion (Oweis & Khera, 1990, 126-134); and some of the biodegradable MSW may not in fact decompose because of inadequate moisture or the presence of toxins in certain sections of the landfill (Wilson, 1981, 210). From a case-study of landfill gas extraction in

San Jose, Costa Rica, Wolff (1992, 15) concluded that the 'most cost-effective spacing for wells was found to be approximately 50 feet. Under these circumstances, approximately 96% of the methane is captured.' The more conservative figure of 70% is used in the following calculation. If 60% of MSW consists of dry biodegradable waste (see Table 1) and 70% of the methane produced is actually collected by sinking suitable wells into the site, then 1 kg of MSW per capita per day will yield:

(417 x 0,365 x 0,60 x 0,70)m^3 CH_4 per capita per annum =
63,9 m^3 CH_4 per capita per annum (2)

2.2 THE ENERGY POTENTIAL OF LFG

Methane gas is combustible and burns according to the reaction:

$$CH_4 + 2O_2 = CO_2 + 2H_2O \; \Delta H = 890 \text{ kJ per mole} \qquad (3)$$

This reaction is exothermic: for each mole of methane produced, 890 kJ of energy is produced. If one mole of methane is equal to 25 litres (or 25 dm^3) at standard temperature and pressure, then:

$$1 \text{ m}^3 \; CH_4 = 890/0{,}025 \text{ kJ} = 35\,600 \text{ kJ or } 36 \text{ MJ} \qquad (4)$$

From equations (2) and (4), it may be deduced that the potential energy produced by 63,9 m^3 of methane is 2,300 mJ per capita per annum or 73 watts per capita per annum. Therefore, a landfill site serviced by 100,000 persons could produce 7,3 MWatts of energy, *assuming* a 100% energy conversion efficiency. In fact, the conversion efficiency for methane is estimated to be about 33% (Letcher, 1990, 11),[2] in which case the useful energy is reduced from 7,3 MWatts to 2,4 MWatts (which can be expressed as 57,6 MWatt hours or 57,600 units). Letcher *et al* (1993, 3) have estimated that the average annual electrical energy used per household is in the range of 2,000-3,000 units, in which case LFG may provide only some 2% of the domestic electricity needs of 100 000 persons (Letcher *et al*, 1993, 3). However, it ought to be borne in mind that the majority of blacks living in small homes or shacks in the peri-urban and urban townships, who do not have access to electricity, do not have high energy-intensive demands. In fact, officials in the Electricity Department of the Durban City Council have indicated that the energy demands of these 'informal communities' may be no more than a quarter of that of typical urban households. In these circumstances, LFG may well supply a significantly higher proportion of their more basic energy needs.

Furthermore, we should not ignore the wider economic and environmental advantages which can flow from the commercial utilisation of LFG. It makes use of a necessary byproduct of urban living, and in the process can contribute to a significant lowering of the costs of operating landfill sites. In addition, a more rapid rate of settlement of wastes within the landfill (which results from managed decomposition and gas extraction) can extend the life of the landfill by several years, thereby generating sizable capital savings for the municipal authority (Ryder, 1981, 227). It also reduces the pressure, even if only marginally, on non-renewable fossil fuels and encourages a shift towards a more sustainable energy path. Furthermore, the commercial use of this non-conventional energy source will help to reduce the potential levels of air pollution, especially the threat posed to the global

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[2] Bridgewater (1984, 48) has calculated that the energy efficiency of methane may be as high as 39-48%, depending upon the method of conversion. The more conservative figure of 33% is used here.

commons by way of ozone depletion and the 'greenhouse' effect (Bingemer & Crutzen, 1987, 2186). Although it is extremely difficult to quantify some of these advantages, this does not lessen the benefits which can be derived from utilising LFG.

2.3 THE COST-EFFECTIVENESS OF LFG

Of course, the key issue in determining the practical viability of this sustainable energy option is that of cost-effectiveness. Unless LFG is affordable relative to other commercial sources of energy, there will be an understandable reluctance to become involved in such a project. While there are a number of studies relating to the cost-effectiveness of LFG projects in the United States, Britain and Germany (see, for example, Kispert *et al*, 1981, 95-109; Wise & Kispert, 1991, 137-142), attention here is focused on LFG projects that have been undertaken (or have been investigated) in South Africa. Apart from the Robinson Deep landfill site (located near Johannesburg), which was unique in that it utilised LFG as a chemical feedstock for the neighbouring Klipspruit cyanide factory operated by AECI,[3] there are three LFG projects in South Africa.

In 1986, the municipal authority in Grahamstown (located in the Eastern Cape) opened a new one-hectare landfill site which was designed to serve some 70 000 people. Thereafter, the Grahamstown municipality, working in conjunction with the Department of Chemistry at Rhodes University, tested the feasibility of collecting LFG from this site as a source of energy (Letcher *et al*, 1988, 336-337). It was found that, at its maximum capacity, the site will produce methane at a rate of 3 300 m^3 per day; and although the methane collected from this site was burned (or ‘flared’) and not used for commercial purposes, an analysis has been made of the potential cost-effectiveness of methane as an alternative energy source for electricity production and water heating. The results of this analysis, based on 1992 prices, revealed that LFG could be used to produce electricity at a cost of approximately 13c/kWhr, which was comparable with Eskom's electricity tariff (which ranged from 9c/kWhr to the Grahamstown municipality to 17c/kWhr to the end-user). It was also shown that LFG could be used to heat water at a cost of approximately 4c/kWhr, which was considerably lower than 12c/kWhr for coal, 20c/kWhr for paraffin and 42c/kWhr for liquid petroleum gas. Therefore, it was concluded that, for these specific energy uses, LFG from the Grahamstown site was more cost-effective than coal, paraffin and LPG, and could be used to produce electricity at a price comparable with Eskom's charges (Letcher & Schutte, 1992, 28-29).

In 1992, following the experiment conducted at Grahamstown, the Department of Chemistry and Applied Chemistry at the University of Natal (Durban) collaborated with Waste-Tech (Pty) Ltd in a landfill project located in the Umlazi township (near Durban).[4] It was found that LFG at this location had a methane content of 57% and that the site had a potential for producing at least 2 MWatts of electricity. On the assumption that this energy would be used by the local black community for water heating, cooking, for ablution blocks fitted with showers and for brick-making, it was estimated that the cost of electricity produced from the Umlazi landfill site would be in the region of 2-3c/kWhr instead of Eskom's charge of 10-

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[3] This project was phased out during 1995 because AECI (African Explosives and Chemical Industries) was able to secure methane supplies from Sasol.

[4] The city of Durban and its immediate environs are served by three landfill sites. The Bul-Bul landfill site comprises 8 hectares operated by Waste-Services (Pty) Ltd, and primarily services the Indian district of Chatsworth (south of Durban). The Umlazi landfill site comprises 15 hectares operated by Waste-Tech (Pty) Ltd, and primarily services the black township of Umlazi (south-west of Durban). The Bisasar landfill site, operated by the Durban City Council to service the city, comprises 44 hectares (located north of Durban) and is one of the largest landfill sites in South Africa.

15c/kWhr (Letcher, 1992, 27). It must be said, however, that these two case-studies cannot be regarded as complete. They do not take into account other benefits: that the commercial use of LFG could contribute to the cost of maintaining these landfill sites; that intensified settlement within the landfills will extend their life and so generate capital savings for the control authorities; and, less easily quantifiable, that the use of LFG will ease the pressure on fossil fuels and the damage that these inflict upon the environment by way of air pollution and climate change.

The third and most recent LFG project is that which has been investigated for the Bisasar landfill site (north of Durban).[5] Landfilling at the site commenced in 1980, and, at current waste deposition rates, it is estimated to have a life of 40 years. In view of the potential environmental hazard posed by LFG emanating from the site for nearby residential and light industry areas, the Durban City Council ordered an investigation into the feasibility of LFG recovery (Louden & Partners, 1994). It was found that the site contained a steady-state methane content of 40-45% (a lower rate than the Umlazi landfill because of the larger volume of builders' rubble deposited at the Bisasar landfill), and that the site could be expected to produce LFG for a period of some fifty years. It was also estimated that, initially, the site would supply 2,000 m^3/hour of LFG which, at a conversion efficiency of 30%, would yield 2,7 MWatt of electrical power. By 2004, the anticipated LFG yield would rise to 8,000 m^3/hour (and remain at about this figure for another 20-30 years), which would produce 6-8 MWatt of electricity.

It is of particular interest to note, however, that the major finding of the Bisasar investigation was that the primary economic benefit of LFG extraction would be the extended life of the landfill. This is a benefit which has not received the attention which it deserves in most other LFG studies. It was pointed out that the closer management of the site, together with LFG extraction, will result in a faster rate of settlement of compacted MSW. While it is acknowledged that roughly the same amount of settlement may be expected from 'passive escape', this will take place over a greatly extended time period, extending well after the closure of the landfill, so that the additional space that could have been used for MSW disposal is lost. In the case of the Bisasar site, intensified settlement was estimated to be in the region of 5-15%. With a projected total landfill volume of 20 million m^3, the additional space made available was estimated to be in the region of 2-3 million m^3. This additional space has substantial value in that the capital outlay required to develop a new landfill site would be postponed for several years. It was estimated that the capital savings from a 15% increase in settlement, with an extension of 7,3 years in the landfill's life, would amount to approximately R60 million (net of operating expenses). Notwithstanding the fact that the estimated cost of establishing and operating a LFG recovery programme (with a total of 52 wells for flaring the gas) was in the region of R10 million (Louden & Partners, 1994, 16-17), it is evident that there are substantial net gains to be derived from undertaking the project.

Assuming that the methane gas was not simply flared, but collected for conversion into energy, the investigation found that the LFG recovered from the Bisasar site could be used most effectively for heating (space, water and steam for both domestic and industrial use), firing kilns (for asphalt, ceramics and bricks) and for the generation of electricity to meet the low-intensity demands of the local black community. It was estimated that a capital investment of R10 million would be required for the energy conversion process (Louden & Partners, 1994, Appendix D); and although the investigation did not embark on a comparative cost analysis of LFG and alternative commercial energy resources, if it is

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[5] The following disucssion on the Bisasar Landfill site is based on information supplied by Mr D.R. Turner, Director of the Solid Waste Department, and Ms D. Dorkin, Research and Development Officer of the MSW Department, both of the Durban Metropolitan Authority. I am most grateful to both of them for their kind cooperation.

assumed that the cost figures for the Umlazi site need to be raised by at least 15% in order to account for the lower methane content of the Bisasar site, then it would appear that LFG from this site will still be cost-effective. And, of course, earnings from the sale of this non-conventional source of energy could be used to redeem the capital investment cost. Furthermore, it must be borne in mind that the foregoing analysis relates only to the potential economic benefits, whereas it has been argued throughout this paper that there are significant environmental benefits to be gained as well.

3. CONCLUSIONS

South Africa's heavy dependence on coal has entrenched the country's reliance upon a non-renewable energy source – a strategy that is unsustainable and which has already resulted in severe air pollution problems in the region. Therefore, it is not surprising that calls have been made to explore the feasibility of 'renewable energy technologies' which would also have less harmful impact upon the global commons. One such option has been explored in this paper: the contribution which LFG can make towards the formulation of a sustainable energy strategy for South Africa. The experience with LFG, both elsewhere and in South Africa, indicates that not only is LFG extraction technically feasible, but that it is cost-effective as well. It is readily acknowledged that this option would make only a small contribution to South Africa's total energy needs – probably no more than 4-6% – but it is only one of several 'renewable energy technologies' open to us, and we should take advantage of all such energy options.

Moreover, it should be borne in mind that LFG has a strong methane component which carries serious implications for climate in the region. Methane is lighter than air and reacts with ozone (O_3) in the upper atmosphere, thereby posing a threat to the earth's ozone shield; at the same time, methane is a powerful 'greenhouse' gas which absorbs the earth's infrared radiation and contributes to global warming. Therefore, when the environmental benefits of LFG extraction are factored into South Africa’s current energy strategy, then it becomes clear that the adoption of this option will benefit the global commons – and indeed the climate – upon which we all depend.

APPENDIX 1

A SIMPLIFIED KINETIC MODEL FOR LFG PRODUCTION

The rate at which LFG is produced is a direct function of the decomposition rate of the organic material in the landfill. The decay of MSW, and hence methane production, can be assumed to be a simple, first order process:

$$d\,P_t/dt \;=\; -kP_t \qquad (1)$$

where P_t is the quantity of biodegradable material at time t (kg), k is the degradation rate in years; and t is time in years.

The integration of equation (1) gives rise to an exponential term:

$$P_t \;=\; P_o\exp(-kt) \qquad (2)$$

where P_o is the quantity of biodegradable material at time $t = 0$.

Differentiating equation (2) with respect to time leads to:

$$dP_t/dt \;=\; -kP_o\exp(-kt) \qquad (3)$$

Now given that gas production is dependent on the decomposition of organic material:

$$\alpha dP_t \;=\; -d[CH_4] \qquad (4)$$

where $[CH_4]$ is equal to the quantity of gas produced and α is equal to 0.417 m^3/kg

Using equations (3) and (4):

$$d[CH_4]/dt \;=\; \alpha kP_o\exp(-kt) \qquad (5)$$

where k is dependent on the nature of the organic material and is a function of its half-life:

$$k \;=\; 1n2/t_{\frac{1}{2}} \qquad (6)$$

Substituting α for k in equation (5), the rate equation becomes:

$$d[CH_4]/dt \;=\; (0.417 \text{ x } 0.693 \text{ x } P_o/t_{\frac{1}{2}})\exp(-0.693 \text{ x } t/t_{\frac{1}{2}}) \qquad (7)$$

Therefore, the potential methane production (in m^3/hour) can be calculated over the lifetime of a landfill, provided that ideal conditions exist at the site, that the amount of biodegradable MSW deposited at the site each year is known and that the half-life of the MSW is known.

Source: T.M. Letcher *et al* (1991)

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