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Use of Statistical Entropy and Life Cycle Analysis to Evaluate Global Warming Potential of Waste Management Systems

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ABSTRACT

The statistical entropy (SE) function has been applied to waste treatment systems to account for dilution or concentration effects on metals. We later extended it to account for carbon flows, especially in waste management systems involving thermal treatment. Now, a simple lifecycle "net energy" metric – encompassing the "lost energy" that would have been gained when high-calorific materials are landfilled rather than combusted with energy recovery – is introduced to account for additional influxes of carbon when using landfilling as the primary disposal method. When combining net energy calculations and long terms effects of landfilling, waste to energy (WTE) becomes a more attractive option for dealing with non-recycled municipal solid waste (MSW). A greenhouse gas-forcing factor is also introduced to account for the entropy generating effects of methane. When incorporating forcing and lost energy, WTE performs notably better than landfills with respect to entropy generation and carbon.

INTRODUCTION AND METHODOLOGY

There are many different methods available for quantifying the environmental impact of waste management systems [1, 2]. An intriguing alternative method was developed that accounts for the tendency of waste management systems to either concentrate or dilute hazardous substances or metals [3]. This method, called statistical entropy, is based on materials flow analysis, which is a system of accounting for the flows of materials that is predicated on the principle of conservation of mass [4]. In order to fully account for the flows of materials through waste management systems, however, it is necessary to be able to use statistical entropy to measure the tendency of carbon to be diluted or concentrated as well.

Brief Look at the Statistical Entropy Method

SEA is used to determine the extent to which an examined substance (in this case carbon) is concentrated or diluted when undergoing transformative processes in waste systems. To correct calculate SE, one needs a set of input goods with known concentrations of carbon; a "transfer coefficient" for the transformation of carbon in the system; and a set of output goods, also with known concentrations of carbon. The calculations steps are in the literature (RECH REF) but can be summarized as follows:

$$H(c_{ij}, m_j) = ld(\dot{X}_j - \frac{1}{\dot{X}_j} \cdot \sum_{i=1}^{k} \underline{\dot{m}_i} \cdot \underline{c}_{ij} \cdot ld(c_{ij}) \qquad (1)$$

where H is the statistical entropy (measured in bits); c and m are the concentration and mass flows, respectively; ld is the logarithm to the base 2 (allowing for conversion to binary units); and $\dot{X}_j$ is the total substance flow induced by the set of goods. The subscripts i and j are indexes for goods and substances, respectively.

$\underline{c_{ij}}$ is defined as

$$\underline{c}_{ij} = \begin{cases} c_{j.geog.g} /100 \\ c_{j.geog.a} /100 \\ c_{ij} \end{cases} \qquad (2)$$

where *geog* signifies the geogenic concentration of the examined substance, and *g* stands for gaseous and *a* stands for aqueous. $\underline{m}_i$ is defined as

$$\underline{m}_i = \begin{cases} \dfrac{\dot{X}_{ij}}{c_{j.geog.g}} \bullet 100 \\ \dfrac{\dot{X}_{ij}}{c_{j.geog.a}} \bullet 100 \\ \dot{m}_i \end{cases} \tag{3}$$

The maximum entropy for solid goods is calculated as shown in equation (2). When considering gaseous or aqueous, the maximum entropy is calculated as per equation (3).

$$H_{\max} = ld(k) \tag{4}$$

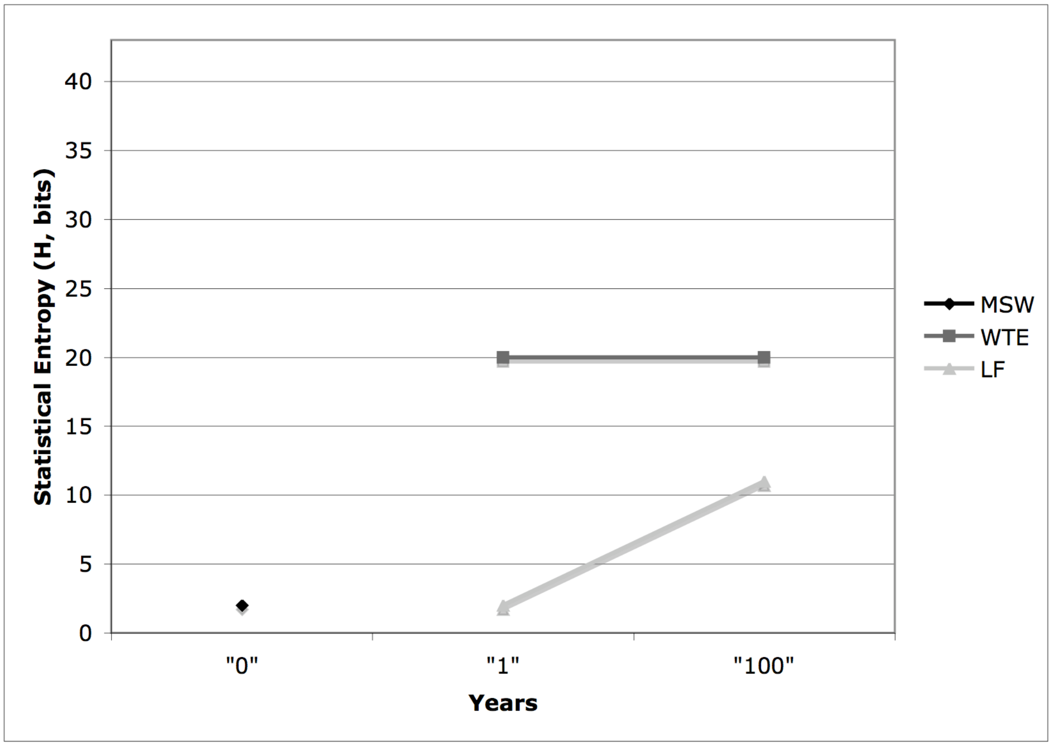
where the index *k* gives the number of goods in the set.

$$H_{\max,j} = ld\left(\frac{\dot{X}_j}{c_{j,geog,\min}} \bullet 100 \right) \tag{5}$$

Results of Carbon Analysis

Application of the statistical entropy method showed that, as expected, carbon is more diluted in combustion (WTE) systems than in landfills. This is expected – it has been shown in the literature that, over a hundred year time frame (the typical amount of time for lifecycle analyses of the effects of landfilling waste) – more than half of the carbon that is deposited in the landfill remains as “stock” [5]. Results from a statistical entropy analysis of landfills versus waste to energy facilities are shown in Figure 1.

Figure 1 Statistical Entropy Analysis Results for MSW LF (100 year) vs. MSW WTE



As Figure 1 shows, landfills "sequester" a good deal of the carbon input as part of MSW, though their performance gradually degrades over a period of 100 years. This is true even when considering energy offsets – electricity that has to be produced from the grid that could have been captured from combusted MSW in a WTE facility instead. It is important, however, to consider other lifecycle factors when evaluating the overall performance of waste management systems with respect to carbon. The heightened importance of considering greenhouse gas emissions – and their relative impact on global warming – is an important factor in this analysis.

To accomplish this for the statistical entropy analysis, we add a "forcing factor" to the set of entropy equations listed above. Earlier, the total substance flow $\dot{X}_j$ was introduced in equation (1). This can be more precisely defined as the product of the total mass flow of the good (m_i) and the concentration of the substance in that good (c_i). The forcing factor is added here to account for the effect of methane:

$$\dot{X}_j = \dot{m}_i \cdot f_k \cdot c_i \qquad (8)$$

where f_k is the forcing factor.

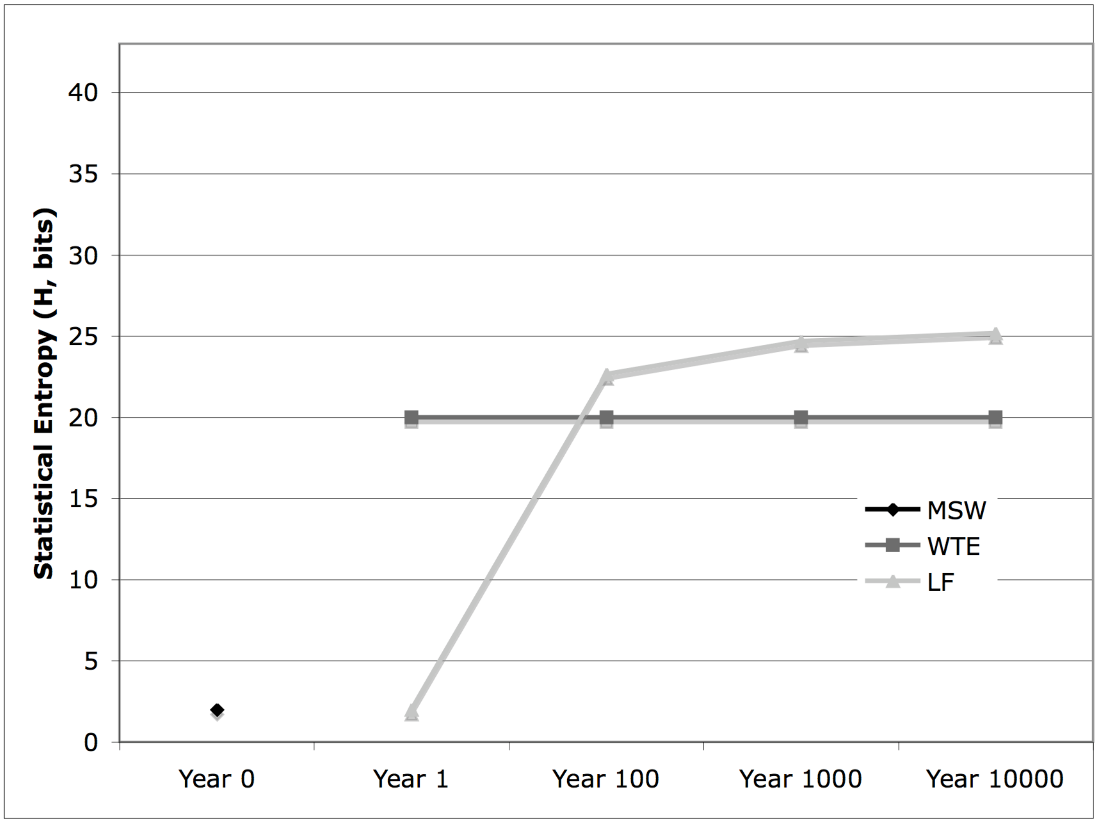
This forcing factor can also be used for other adjustments, both positive (e.g. “value-added” goods that are produced, such as ethanol) and negative (e.g. toxicity of produced goods).

Methane is 21 times more potent as a global warming gas than carbon dioxide [6]. When methane is added to the forcing factor, the results of the statistical entropy analysis for carbon in waste management systems changes dramatically. In addition to the forcing factor for methane gas, we added additional timescale scenarios to the landfill model – a 1,000-year model and a 10,000-year model. The results show that the effects of timescale and greenhouse gas forcing are dramatic. The graph is shown in Figure 2.

Conclusions

When considering carbon flows through landfills and WTE facilities, it is important to factor in global warming potential, energy offsets, and different timescales to have a full and accurate picture. Statistical entropy analysis allows for a quantification of these effects, and is a useful addition to lifecycle assessment and other tools to measure the environmental effects of waste management practices.

Figure 2 Statistical Entropy Results LF with GHG Forcing vs. WTE



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