BIOMASS UTILIZATION THROUGH BIOGAS SYSTEMS: RELATIONSHIPS TO RESPIRATORY HEALTH AND GLOBAL CLIMATE CHANGE

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ABSTRACT

Direct combustion, the traditional method for utilization of biomass fuels, results in the emission of a great variety of gases and particulates which have numerous deleterious effects on users' health. Additionally, while the complete combustion/oxidation of biomass fuels to carbon dioxide may be neutral in regard to atmospheric levels of greenhouse gases, the inefficient and incomplete combustion of these materials is not. Given the increasingly vast multitude of the majority of humanity who rely upon direct combustion of biomass for most cooking and heating needs, the products of incomplete combustion appear to be responsible for a surprisingly large contribution to the overall level of greenhouse gases in the atmosphere.

Utilization of the natural process of anaerobic decomposition offers potential for substantial amelioration of both of these problems. Health-related gaseous and particulate emissions from the burning of biogas are not only far less than those from other methods of biomass fuel use, but also compare favorably with the emissions from natural gas -- far the cleanest burning of all fossil fuels. Additionally, anaerobic digestion followed by biogas combustion permits the use of biomass energy at far closer to the ideal of neutrality in regard to greenhouse gas levels in the atmosphere.

INTRODUCTION

THE LOCAL DIMENSION

Human Health-Related Pollutant Emissions from Household Biofuel Combustion

In 1985, the World Health Organization concluded that in developing countries, respiratory diseases are the chief cause of mortality and that acute respiratory infections are a major cause of infant mortality. While there are numerous factors involved, one of the most likely causes is the exposure to the pollutant emissions from biomass-fueled cooking and heating fires.

De Koning et al., and Smith offer excellent introductions to the range of considerations regarding emissions from household fuel combustion and health in developing countries. The emissions figures presented in **Table 1** are `typical, not average' and `Actual efficiencies and emissions depend on fuel quality and combustion conditions'. Since these efficiency figures are based on heating stoves under conditions in the USA, the emissions would be much higher from the less efficient combustion which occurs in most situations. Emissions from direct combustion of crop stalks and dung would be most similar to those from wood. For comparison, likely emissions levels from biogas combustion have been added to the table.

TABLE 1

Comparison of Air Pollutant Emissions from Energy-Equivalent Fuels in Residential Situations (kg)

Fuel	Wood	Coal	Distillate Oil (Kerosene)	Natural Gas	BIOGAS [Anticipated Levels]
Efficiency Under U.S. Conditions	40 %	50 %	85 %	85 %	[Similar to Natural Gas]
Fuel Equivalent to 1 Million MJ Delivered	144 metric tons	69 metric tons	32,900 liters	30,000 m^3	[50,000 m^3 at 60% CH_4]
Suspended Particulate Matter	2,170	520	11	7	[Similar to Natural Gas]
Sulfur Oxides	86	1,200	1,170	Negligible	[Slightly > Natural Gas]
Nitrogen Oxides	110	270	71	38	[Slightly < Natural Gas]
Hydrocarbons	1,450	430	4	4	[Slightly < Natural Gas]
Carbon Monoxide	18,790	2,380	20	10	[Similar to Natural Gas]

(Adapted from De Koning, H.W., K.R. Smith, & J.M. Last. 1985. "Biomass fuel combustion and health." Bulletin of the World Health Organization, Vol. 63.)

THE GLOBAL DIMENSION

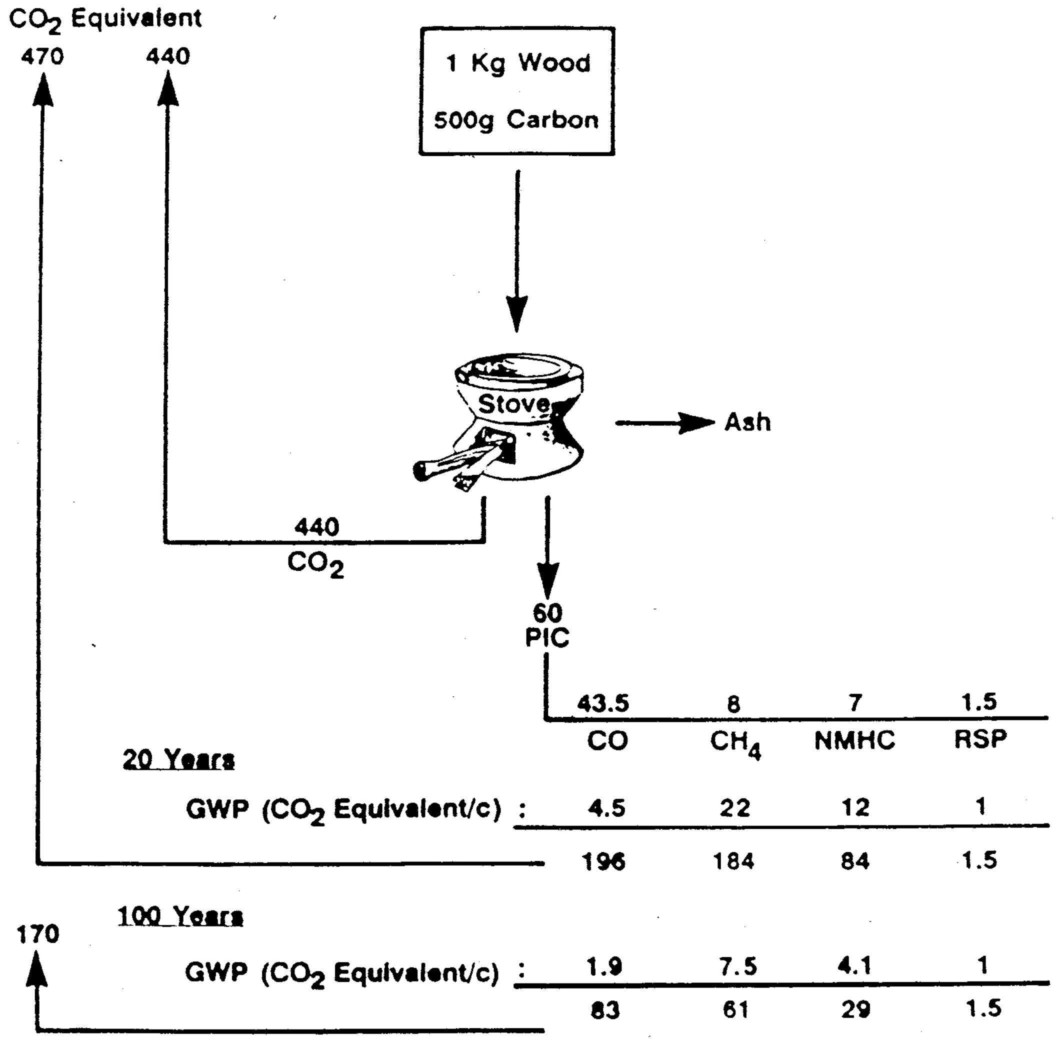
Impacts of Household Biomass Combustion on Greenhouse Gas Levels

It has often been argued that, since the carbon dioxide released upon combustion of biomass fuels is actually carbon dioxide which was incorporated into the fuel by photosynthetic growth, the use of biomass fuels is **neutral** in respect to Greenhouse Gases (GG) levels in the atmosphere. This is indeed a valid argument if the biomass is harvested sustainably and if all of the carbon present in the fuel is **completely** oxidized to carbon dioxide. Unfortunately, as the generally high levels of pollutant gases and particulate emissions indicate, there are significant amounts of a broad range of **products of incomplete combustion** which are released by the direct combustion of biomass fuels in household situations.

Figure 1, developed by Smith and Thorneloe, depicts a carbon balance for the "typical" wood cookstove used in less-industrialized areas of the world. Although the products of incomplete combustion -- methane, carbon monoxide, and non-methane hydrocarbons -- contain only 11% of the original carbon in the wood, the much higher Global Warming Potential (GWP) of these emissions (relative to carbon dioxide) is about equal to that of the carbon dioxide emissions. It thus appears that typical household biomass combustion, rather than being a neutral influence on GG concentrations, results in a near-doubling of the GWP from released carbon over a 20-year horizon and that this increased GWP continues, albeit at decreasing levels, through the 100-year horizon.

FIGURE 1

The Cookstove Carbon Cycle



The same carbon balance for the woodstove is shown In this case, the PICs are weighted by the Global Warming Potentials (GWPs) appropriate for 20-year and 100-year time horizons. Note that the PIC GWP is about equal to that of the CO_2 for a 20-year time horizon. Sources: Smith et al. (1992a&b); Smith et al. (1991); IPCC (1992); Lelieveld & Crutzen (1992); Joshi et al. (1989).

(Source: Smith, K.R. and S.A. Thorneloe. 1992.)

THE DATA

THE LOCAL DIMENSION

Human Health-Related Pollutant Emissions from Household Biofuel Combustion

Extensive data from formal investigations of the health-related gas and particulate emissions and concentrations from biomass stoves have been relatively scarce and anecdotal until the past decade. (See Smith, K.R., Biofuels, Air Pollution and Health for a comprehensive review.) Studies which have included investigation of biogas emissions are far more rare. [A multi-national, multi-fuel is study currently in progress under the auspices of the World Health Organization and should go far toward the development of definitive information on a very broad range of biomass fuel emissions.]

Nevertheless, some useful data has been collected in the People's Republic of China. These are summarized in **Table 2**, which shows results from sulfur dioxide monitoring, **Table 3**, which includes a variety of stove emissions, and **Table 4**, which presents a range of health-related indicators.

The data from **Table 2** indicate that concentrations of sulfur dioxide from biogas combustion are not only far below those from other biomass fuels and coal but that they compare quite favorably with those from natural and liquid petroleum gas. The figures in **Table 3** indicate that emission-related benefits of biogas combustion are quite broad and include relatively low concentrations of nitrogen dioxide, carbon monoxide and total suspended particulates. The parameters shown in **Table 4** indicate that those persons using biogas as their cooking fuel are exposed to lower levels of airborne bacteria and that they manifest healthier levels for a range of indicators.

TABLE 2
Sulfur Dioxide Concentrations

Fuel Type	Concentration Range	Mean Concentration	Standard Deviation	Number of Observations	Notes	Data Source
"Cooking Area Concentrations" -- [ppm]						
Biogas	0-3.9	0.86	1.12	16	8-hr SO_2 levels	Henan, PRC
Coal	1.7-9	3.5	2.29	15	Re:Biogas/Coal $p<0.01$	(Hamburg, 1989)
Stalks	0-13	3.2	5.5	5		
"Indoor Concentration" -- [mg/m³] -- * = below detection limit						
Biogas	*-0.17	0.03	0.03	Unreported	Re:Gases/Coal $p<0.01$	Szechuan, PRC
Natural Gas	0.01-0.18	0.04	0.04	Unreported	~2% Sulfur in Gas	(Lo, 1986)
Bituminous Coal	0.05-29.0	1.42	3.49	Unreported	~4% Sulfur in Coal	
"Indoor Concentration Before and After Cooking" -- [mg/m³]						
Before cooking						Szechuan, PRC (Lo, 1986)
Biogas	0.01-0.10	0.03	0.02	Unreported		
Natural Gas	0.01-0.08	0.03	0.02	Unreported	~2% Sulfur in Gas	
Bituminous Coal	0.09-14.0	1.07	2.01	Unreported	~4% Sulfur in Coal	
After cooking						
Biogas	0.01-0.11	0.03	0.03	Unreported		
Natural Gas	0.01-0.18	0.07	0.05	Unreported	~2% Sulfur in Gas	
Bituminous Coal	0.05-29.03	1.65	4.42	Unreported	~4% Sulfur in Coal	
"Concentration in Kitchens, Bedrooms and Outdoors" -- [mg/m³] -- * = below detection limit						
Kitchens						
Biogas	*-0.17	0.03	0.04	Unreported		Szechuan, PRC
Natural Gas	0.01-0.18	0.04	0.05	Unreported	~2% Sulfur in Gas	(Lo, 1986)
Bituminous Coal	0.05-29.03	2.55	4.46	Unreported	~4% Sulfur in Coal	
Bedrooms						
Biogas	0.01-0.11	0.03	0.03	Unreported		
Natural Gas	0.01-0.10	0.04	0.03	Unreported	~2% Sulfur in Gas	
Bituminous Coal	0.07-4.55	0.81	1.06	Unreported	~4% Sulfur in Coal	
Outdoors						
Biogas	0.02-0.11	0.05	0.03	Unreported		
Natural Gas	0.03-0.18	0.08	0.05	Unreported	~2% Sulfur in Gas	
Bituminous Coal	0.02-0.68	0.25	0.16	Unreported	~4% Sulfur in Coal	
"Concentration in Villages using Biogas and Briquettes" -- [mg/m³] -- * = below detection limit						
7:00-8:30						Henan, PRC (Yen et al., 1990)
Biogas	0.04-0.26	0.12	0.10	[10?]		
Coal Briquettes	0.15-1.83	1.00	0.52	10		
12:00-13:30						
Biogas	0.02-0.26	0.09	0.09	[10?]		
Coal Briquettes	0.04-1.05	0.43	0.38	10		
17:30-19:00						
Biogas	*-0.52	0.14	0.21	[10?]		
Coal Briquettes	0.04-1.33	0.73	0.47	10		
Average						
Biogas	*-0.52	0.12	0.14	[10?]		
Coal Briquettes	0.04-1.83	0.72	0.50	10		
Outdoors						
Biogas	*-0.06	0.02	0.03	[10?]		
Coal Briquettes	*-0.56	0.26	0.22	10		
"Concentration in Kitchens" -- [mg/m³] -- n.a. = not available						
Biogas	n.a.	0.02	0.03	13		Shanghai, PRC
Firewood	n.a.	0.04	0.02	25		(Chen et al., 1987)
Coal Briquettes	n.a.	0.49	0.20	25		
Liq. Petrol. Gas	n.a.	0.02	0.01	26		
Outdoors	n.a.	0.01	0.01	13		
"Median Indoor Concentrations" -- [mg/m³] -- n.a. = not available						
Cow/Sheep Dung						Inner Mongolia, PRC (Chong, 1990)
Summer	n.a.	0.02	n.a.	15		
Winter	n.a.	0.03	n.a.	15		
Coal						
Summer	n.a.	0.01	n.a.	6		
Winter	n.a.	0.03	n.a.	6		

TABLE 3

Other Emissions Parameters (All data reported by Hong, C.J., 1991)
Nitrogen Dioxide Concentrations

Fuel Type	Concentration Range	Mean Concentration	Standard Deviation	Number of Observations	Notes	Data Source
"Indoor Concentration" -- [mg/m^3]						Szechuan, PRC
Biogas	0.01-0.22	0.02	0.03	Unreported	Re:Gases/Coal $p<0.01$	(Lo, 1986)
Natural Gas	0.01-0.21	0.04	0.02	Unreported		
Bituminous Coal	0.01-1.95	0.16	0.15	Unreported		
"Indoor Concentration Before and After Cooking" -- [mg/m^3]						
Before cooking						Szechuan, PRC
Biogas	0.01-0.22	0.02	0.04	Unreported		(Lo, 1986)
Natural Gas	0.01-0.10	0.05	0.02	Unreported		
Bituminous Coal	0.01-0.19	0.06	0.01	Unreported		
After cooking						
Biogas	0.01-0.2	0.02	0.02	Unreported		
Natural Gas	0.01-0.05	0.03	0.01	Unreported		
Bituminous Coal	0.01-1.95	0.07	0.22	Unreported		
"Concentration in Kitchens, Bedrooms and Outdoors" -- [mg/m^3]						
Kitchens						Szechuan, PRC
Biogas	0.01-0.22	0.02	0.04	Unreported		(Lo, 1986)
Natural Gas	0.01-0.06	0.04	0.01	Unreported		
Bituminous Coal	0.01-1.95	0.07	0.09	Unreported		
Bedrooms						
Biogas	0.01-0.29	0.02	0.01	Unreported		
Natural Gas	0.01-0.10	0.04	0.02	Unreported		
Bituminous Coal	0.01-0.30	0.05	0.05	Unreported		
Outdoors						
Biogas	0.01-0.02	0.01	0.01	Unreported		
Natural Gas	0.01-0.05	0.03	0.01	Unreported		
Bituminous Coal	0.01-0.24	0.04	0.04	Unreported		
"Median Indoor Concentrations" -- [mg/m^3] -- n.a. = not available						
Cow/Sheep Dung						Inner Mongolia, PRC
Summer	n.a.	0.03	n.a.	15		(Chong, 1990)
Winter	n.a.	0.03	n.a.	15		
Coal						
Summer	n.a.	0.03	n.a.	6		
Winter	n.a.	0.02	n.a.	6		
"Concentration in Kitchens" -- [mg/m^3] -- n.a. = not available						
Biogas	n.a.	0.01	0.01	13		Shanghai, PRC
Firewood	n.a.	0.03	0.03	24		(Chen et al., 1987)
Coal Briquettes	n.a.	0.06	0.05	24		
Liq. Petrol. Gas	n.a.	0.03	0.02	26		
Outdoors	n.a.	0.04	0.02	13		

TABLE 3, cont.
Carbon Monoxide Concentrations

Fuel Type	Concentration Range	Mean Concentration	Standard Deviation	Number of Observations	Notes	Data Source
"Concentration in Villages using Biogas and Briquettes" -- [mg/m^3]						
7:00-8:30						Henan, PRC
Biogas	1.37-8.24	3.05	2.31	[10?]		(Yen et al., 1990)
Coal Briquettes	2.29-20.61	8.16	6.79	10		
12:00-13:30						
Biogas	0.92-2.86	1.83	0.63	[10?]		
Coal Briquettes	3.21-24.05	10.66	7.51	10		
17:30-19:00						
Biogas	0.92-2.06	1.53	0.60	[10?]		
Coal Briquettes	2.21-12.60	5.79	3.53	10		
Average						
Biogas	0.92-8.24	2.14	1.52	[10?]	$t=4.87$, $p<0.01$	
Coal Briquettes	2.21-24.05	8.20	6.28	10		
Outdoors						
Biogas	0.92-3.66	1.59	0.82	[10?]		
Coal Briquettes	0.92-2.06	1.78	0.38	10		
"Median Indoor Concentrations" -- [mg/m^3] -- n.a. = not available						
Cow/Sheep Dung						Inner Mongolia, PRC
Summer	n.a.	3.36	n.a.	15		(Chong, 1990)
Winter	n.a.	16.45	n.a.	15		
Coal						
Summer	n.a.	3.58	n.a.	6		
Winter	n.a.	12.25	n.a.	6		
"Concentration in Kitchens" -- [mg/m^3] -- n.a. = not available						
Biogas	n.a.	2.86	0.50	7		Shanghai, PRC
Firewood	n.a.	5.70	2.35	24		(Chen et al., 1987)
Coal Briquettes	n.a.	14.08	3.87	22		
Liq. Petrol. Gas	n.a.	2.38	0.88	24		
Outdoors	n.a.	2.79	0.58	7		

TABLE 3, cont.
Total Suspended Particulate Concentrations (TSP)

Fuel Type	Concentration Range	Mean Concentration	Standard Deviation	Number of Observations	Notes	Data Source
"Concentration in Villages using Biogas and Briquettes" -- [mg/m^3]						
7:00-8:30						Henan, PRC (Yen et al., 1990)
Biogas	0.24-0.44	0.31	0.12	[10?]		
Coal Briquettes	0.57-1.86	1.19	0.64	10		
12:00-13:30						
Biogas	0.05-0.31	0.17	0.13	[10?]		
Coal Briquettes	0.49-1.18	1.27	0.69	10		
17:30-19:00						
Biogas	0.09-0.33	0.24	0.13	[10?]		
Coal Briquettes	0.34-1.19	0.70	0.44	10		
Average						
Biogas	0.05-0.84	0.24	0.12	[10?]	$t=4.08$, $p<0.1$	
Coal Briquettes	0.34-1.36	1.06	0.59	10		
Outdoors						
Biogas	0.04-0.13	0.09	0.05	[10?]		
Coal Briquettes	0.25-0.38	0.33	0.06	10		
"Median Indoor Concentrations" -- [mg/m^3] -- n.a. = not available						
Cow/Sheep Dung						Inner Mongolia, PRC (Chong, 1990)
Summer	n.a.	1.06	n.a.	15		
Winter	n.a.	1.94	n.a.	15		
Coal						
Summer	n.a.	0.50	n.a.	6		
Winter	n.a.	1.74	n.a.	6		
"Concentration in Kitchens" -- [mg/m^3] -- n.a. = not available						
Biogas	n.a.	0.18	n.a.	[13]		Shanghai, PRC (Chen et al., 1987)
Firewood	n.a	0.79	n.a.	[25]		
Coal Briquettes	n.a.	0.49	n.a.	[25]		
Liq. Petrol. Gas	n.a.	0.19	n.a.	[26]		
Outdoors	n.a.	0.18	n.a.	[13]		

TABLE 4

Health-Related Parameters (All data reported by Hong, C.J., 1991)

Fuel Type	Concentration Range	Mean Concentration	Standard Deviation	Number of Observations	Notes	Data Source
Amount of Airborne Bacteria						
"Concentration in Villages using Biogas and Briquettes" -- [colonies/petri-dish]						
7:00-8:30						Henan, PRC
Biogas	32-332	101	89	[10?]		(Yen et al., 1990)
Coal Briquettes	16-320	151	115	10		
12:00-13:30						
Biogas	16-228	62	68	[10?]		
Coal Briquettes	42-512	164	156	10		
17:30-19:00						
Biogas	13-124	48	35	[10?]		
Coal Briquettes	46-376	166	126	10		
Average						
Biogas	13-332	70	69	[10?]	t=3.19, p<0.01	
Coal Briquettes	27-512	161	130	10		
Outdoors						
Biogas	15-240	87	65	[10?]		
Coal Briquettes	16-300	79	92	10		
"Total Bacteria Count" -- [colonies/petri-dish] -- n.a. = not available						
Cow/Sheep Dung						Inner Mongolia, PRC
Summer	n.a.	220	n.a	15		(Chong, 1990)
Winter	n.a.	204	n.a	15		
Coal						
Summer	n.a.	236	n.a	6		
Winter	n.a.	184	n.a	6		
Amount of Lysozyme in Saliva of Residents (A non-specific indicator of immune index to exposure to emissions)						
"Concentration in Saliva of Residents Exposed" -- [$\mu g/m^1$]						
Housewives						Henan, PRC
Biogas	57.5-140	94.7	23.[illegible]	20	t=3.35, p<0.01	(Yen et al., 1990)
Coal Briquettes	12.5-125	63.3	37.[illegible]	22		
Teenagers						
Biogas	90.0-155	124.0	21.[illegible]	20		
Coal Briquettes	50.5-140	89.1	23.[illegible]	20		
Total						
Biogas	57.5-155	109.4	26.[illegible]	40	t=4.91, p<0.01	
Coal Briquettes	12.5-140	75.6	33.[illegible]	42		
Carboxyhemoglobin (COHb) Content in Residents (Indicator of haemoglobin bound to carbon monoxide)						
"Percentage of Carboxyhemoglobin (COHb) Content in Residents" -- [%]						
Housewives						Henan, PRC
Biogas	0.8-1.7	1.[illegible]	0.[illegible]	21	t=2.66, p>0.05	(Yen et al., 1990)
Coal Briquettes	0.9-3.4	1.4	0.[illegible]	18		
Teenagers						
Biogas	0.1-0.8	0.6	0.[illegible]	19		
Coal Briquettes	0.1-1.5	0.8	0.[illegible]	19		
Total						
Biogas	0.1-1.8	0.9	0.[illegible]	40	t=2.03, p<0.05	
Coal Briquettes	0.1-3.4	1.[illegible]	[illegible]	37		

THE GLOBAL DIMENSION
Impacts of Household Biomass Combustion on Greenhouse Gas Levels

It is likely the largely assumed, GG neutrality of renewably harvested biomass fuel that has resulted in very little formal investigation of broader, global atmospheric interrelationships until quite recently. The work of Smith and others involved with the stove emissions studies mentioned above indicates that traditional biomass fuel use does in fact have a significant effect on GG levels due to the products of incomplete combustion. [Similarly to the case with pollutant emissions data, another multi-national, multi-fuel investigation of GG emissions from biomass combustion -- including biogas -- is currently in progress under the auspices of the United States Environmental Protection Agency and should shed further light on the situation.]

Certainly, given the relatively minuscule level of current exploitation, anaerobic digesters and biogas combustion cannot now be considered to have any significant effect upon global GG levels. [This is not the case with the anaerobic decomposition and methane release from rice fields or the unmanaged anaerobic decomposition of livestock residues.] Nevertheless, envisioning any future which includes more intensive and extensive utilization of biomass resources requires that such global implications be considered. While definitive data may not be currently available, it is quite reasonable to extrapolate, at least qualitatively, from the range of data which is accessible.

Unscrubbed biogas is a mixture of gases with the exact composition depending on numerous operational and design parameters. Methane is generally the chief component, varying from 50 to 70%, occasionally higher, but typically about 60%.

Carbon dioxide is the other primary component and generally varies within a range of 30-40%. These two gases usually comprise well over 90% of the gas. Biogas is also saturated with water vapor and other gases may include varying amounts of carbon monoxide, hydrogen, nitrogen, ammonia, oxygen, a few larger hydrocarbons, and hydrogen sulfide.

The flame temperature of biogas with a composition of 60% methane and 35% carbon dioxide is about 1200° C. With reasonably complete combustion at this temperature, the carbon dioxide and water vapor would be unchanged; the methane, other hydrocarbons and any carbon monoxide, hydrogen or oxygen would primarily form water vapor and carbon dioxide. Some of the nitrogen would be unchanged while some would likely result in nitrogen oxides (although less than with natural gas), and the hydrogen sulfide would be converted to sulfur dioxide and perhaps a small amount of sulfur trioxide.

Natural gas is also composed of a mixture of gases although methane generally comprises over 90%. The average fuel carbon content of natural gas is 13.5 gC/MJ (compared to 23.7 for bituminous coal and 19.9 for oil). The fuel carbon content of biogas with 60% methane is be about 17.9 gC/MJ due to the carbon dioxide content. It must be emphasized, however, that in stark contrast to natural gas, all of the carbon in the biogas is the result of recent photosynthesis.

The pollutant emissions from biogas combustion must be very similar to those from natural gas. Suspended particulate matter and hydrocarbons would tend to be lower since there are few larger hydrocarbons in biogas; nitrogen oxides would also tend to be lower due to the lower flame temperature; carbon monoxide would be about the same; only sulfur oxides may tend to be higher, although this was not the case in the Chinese study cited in Table 2.

CONCLUSIONS

THE LOCAL DIMENSION

Human Health-Related Pollutant Emissions from Household Biofuel Combustion

The exposure of human beings to the pollutant emissions from traditional household biofuel combustion is being increasingly recognized as a major cause of a wide range of respiratory diseases and premature death. Measurements of the emission levels and household concentrations of a range of pollutants resulting from combustion of various biofuels, coal, and liquid petroleum and natural gas indicate that the gaseous fuels provide for far the lowest levels of pollution. While all figures for the gaseous fuels considered were fairly similar in pollution levels, **biogas** performance was equal to or better than the others in every instance. Additionally, **biogas** is the only gaseous fuel considered that is generated from biomass resources and is potentially sustainable in the long-term.

Simply put: Anaerobic digestion and household biogas use offer the least polluting option for utilization of the solar energy annually stored in biomass resources.

THE GLOBAL DIMENSION
Impacts of Household Biomass Combustion on Greenhouse Gas Levels

Although the carbon in biomass fuels is entirely the result of recent photosynthetic activity, their use can only be neutral in terms of Global Warming Potential if they are harvested renewably and the carbon in the fuel is completely oxidized to carbon dioxide. When considered at the biospheric level, the impact of the large quantities of the products of incomplete combustion -- largely carbon monoxide, methane, and non-methane hydrocarbons -- from traditional biomass fuel use appears to be significant.

The levels of emission of products of incomplete combustion from biogas use compare quite favorably with those of natural gas -- far the cleanest burning of fossil fuels. It would thus appear that anaerobic digestion and biogas combustion offer a means for biomass fuel use to much more closely approach the ideal of neutrality toward radiatively active, greenhouse gases.

Simply put: Anaerobic digestion and household biogas use offer the means for utilization of annually stored solar energy which most closely approaches the ideal of complete recycling of carbon dioxide through plants and the atmosphere. [In fact, the process can actually result in a net removal of carbon from the atmosphere due to its being sequestered in long-enduring humus.

FINAL NOTE

The financial, economic and in some cases social viability of anaerobic digestion systems continues to be argued. Nearly all of the financial and economic analyses have contained rather detailed delineations of the monetary costs for these systems. However, none have incorporated a truly comprehensive valuation of all of the undeniable beneficial aspects which include:

* provision of a very clean-burning and renewable household fuel which is close to the ideal of neutrality in regard to atmospheric concentrations of greenhouse gases;

* all of the human and ecosystem health-related benefits which may be associated with a clean-burning household fuel;

* conservation of nearly all plant nutrients in available forms (in contrast to situations in which dung or crop residues are burned directly);

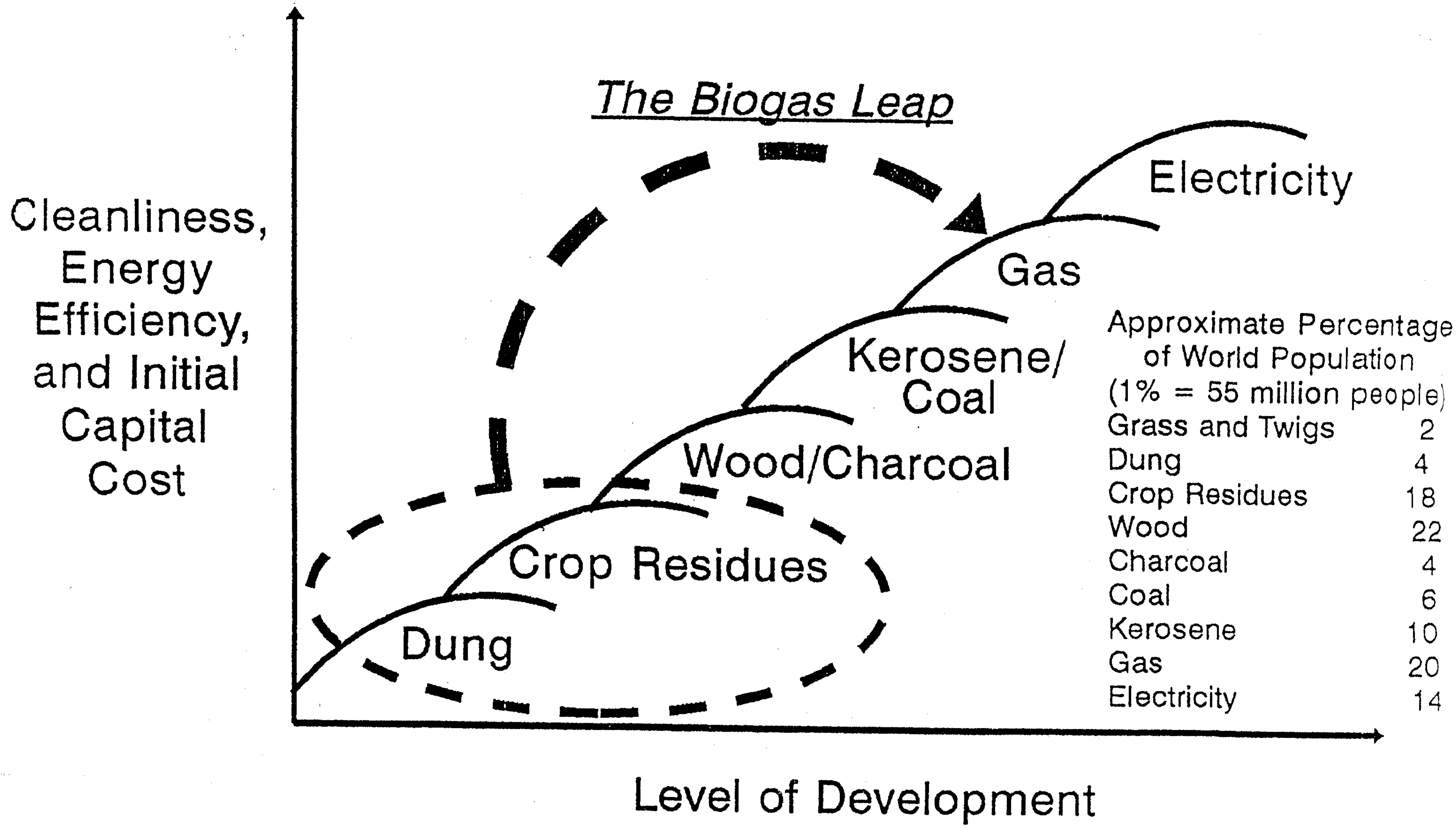
* provision of a high quality soil amendment for tilth maintenance and improvement and erosion control for terrestrial agricultural production and/or a nutrient-rich liquid for aquaculture systems; and

* sanitary destruction of nearly all enteric disease vectors and reduction of other disease vectors such as flies.

With increasing worldwide attention being given to both the concept and practicality of "sustainability," and the Intergovernmental Panel on Climate Change suggesting figures like $100-150 US as the value of a ton of carbon either not emitted or sequestered, it is, perhaps, time to once again rework the figures.

FIGURE 4

Generalized Household Energy Ladder



(Source: After Smith, K.R. and Y.C. Liu. 1993. "Indoor Air Pollution in Developing Countries," in EPIDEMIOLOGY OF LUNG CANCER, ed. by J. Samet. New York: Marcel Dekker.)

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