ASSESSING THE EMISSIONS AND COST EFFECTIVENESS OF TRADITIONAL AND TRANSITIONAL HOUSEHOLD FUEL BURNING APPLIANCES IN SOUTH AFRICA

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1. INTRODUCTION

The provision of energy for domestic uses, principally for cooking and heating is a fundamental human requirement which, with rapid population growth in the developing world, threatens the global environment. Current domestic fuel burning practices depreciate the earth's biomass and fossil fuel resources while polluting the atmosphere environment, often creating ambient levels of pollutants which are hazardous to human health.

As personal equity improves, populations of developing countries have been observed to progress through a series of preferred domestic fuel choices moving from dirty, inefficient fuels, such as dung, to cleaner fuel such as LPG. This progression has become known as "the household ladder".[1] The fuels immediately above traditional biomass fuels on the energy ladder (coal, paraffin and LPG) have become known as "transitional fuels", before the final adoption of electricity at the top. However the multiple fuel use patterns of many South African households are not accounted for in this linear progression model and its validity in the South African context has been questioned.[2]

South Africa's unique history has resulted in the simultaneous existence of first and third world societies in the same country and widespread use of both transitional and traditional fuels. Thus a broad range of different domestic fuel and appliances are used in South Africa today. Moreover regional variations in economic and meteorological conditions within the country complicate attempts to achieve a national domestic energy policy. For example, while winter temperature inversions are key to human exposures from household fuel burning in Highveld regions, in coastal regions ventilation conditions play a more significant role. Therefore maximum exposures in each region occur through different pathways and policies for their abatement policy will differ. This paper provides pertinent additional information on emissions, efficiency and cost-effectiveness of domestic appliances for future household energy policy decisions in South Africa and elsewhere.

2. ASSESSING THE IMPACT OF POLLUTION FORM DOMESTIC FUEL BURNING

While recognising that multiple sources contribute to ambient pollutant concentrations, assessments of the impact of pollution from domestic fuel burning in South Africa have in the main, based their conclusions on measurement ambient pollution levels.[1,4,5,6] An alternative approach to assessing pollution from household fuel burning is to determine the emission rates of domestic appliances under controlled conditions and thus allow comparative evaluation of appliance performance in terms of cooking and space heating efficiencies. This study controlled the air exchange rate through a test cell and measured emission rates directly by sampling the air leaving the cell. The results compare total environmental emissions from appliances and no distinction has been drawn between effects of indoor out outdoor emissions in terms of human exposures.

3. EXPERIMENTAL METHODOLOGY

3.1 Determining Cooking Efficiency

The cooking task required that each appliance was lit from a cold start and consisted of two sequential phases. During the first high power phase 3kg of water were brought to the boil as quickly as possible. During the second low power phase the appliance was operated at the lowest power output level needed to maintain the water at that temperature for an hour. The cooking efficiency of an appliance was expressed as:

$$N_c = M_w C_w (T_f - T_i) + (H.t) / (F. Cv)$$

where

N_c = measured cooking efficiency (%)
M_w = mass of water boiled (kg)
C_w = specific heat of water (MJ/kg/°C)
T_f = boiling temperature of water (°C)
T_i = initial ambient temperature of water (°C)
H = heat loss from the pot (W)
t = time of simmering (s)
F = mass of fuel burnt (kg)
Cv = fuel calorific value (MJ/kg)

The heat losses from the pot with its lid on were determined in advance of the cooking tests using an immersion heater.

3.2 Appliance Overall Efficiency during Cooking Test

The space heating output of an appliance while cooking is useful energy during winter months. The overall efficiency of an appliance during the cooking test was calculated as being the fraction of heat in the fuel delivered as cooking energy, heat to the surrounding space, and in steam generation. (This assumes that the steam from the pot condenses within the dwelling). Heat from an appliance to the surrounding space was calculated both as the thermal inertia of the cell and the sensible heat to the air passing through the cell.

3.3 Space Heating Efficiency Determination

The space heating efficiency of appliances was determined by a method similar to that used previously by Allison and Dutkiewicz.[8] Appliances were placed inside an insulated test cell and operated at steady state bum conditions. The space heating output of each appliance was measured by drawing outside ambient air through the cell at a constant rate and measuring the temperature difference between air entering and leaving the cell, which was maintained between 15 and 20°C. Heat losses from the cell walls were also measured as useful energy output. Knowing the fuel bum rate and calorific value, the space heating efficiency of the appliance was then calculated.

3.4 Expressing Emission Rates

Emissions during the cooking test were expressed in two forms. Firstly as grams per task, indicating the emissions from each appliance accompanying completion of the same task. And secondly as grams per useful MJ energy, incorporating the cooking and space heating energy outputs of the appliances, representative of a winter scenario. Emissions during the space heating test were measured as grams per hour but expressed as grams per useful MJ energy delivered to allow comparison of emission from appliances of varying power output.

4. RESULTS and DISCUSSION

4.1 Cooking Tests

4.1.1 Appliance Efficiencies during the Cooking Test

The experimentally determined efficiencies of appliances during the cooking test are given in Table 1. The cooking efficiencies of all appliances indicate that only small proportion of the energy in the fuel is realised as useful cooking energy. In most cases heat to the surrounding space accounted for significant losses, evident in the higher overall efficiencies.

The cooking efficiencies of the LPG and paraffin burning appliances were significantly higher than those of the solid fuel burning appliances (Table 1). The lower combustion efficiencies of solid fuel burning appliances resulting in higher emissions do not fully account for these differences. Some inefficiency is derived from the fact that the cooking test had a cold start. During cooking tests of commercially available stoves the pot was placed on the stoves before the appliance was ignited. However, after lighting a wood fire or coal brazier, there is an initial time during which the fire establishes it self before the pot is placed on the fire. As a result there is a short period during which fuel is burned and no energy is realised as cooking energy. The overall efficiency of the coal brazier was not measured because high CO emissions require room ventilation, dissipating an unquantified amount of space heating energy.

Table 1. Appliance Efficiencies during Cooking Test

	Cooking Measured	Efficiency Adjusted	Overall Efficiency
LPG Ring Burner	27.0	38.6	82.6
Paraffin Primus Stove	33.0	34.3	67.6
Paraffin Wick Stove	27.6	31.4	72.6
Three-Stone Wood Stove	7.4	7.6	64.1
Coal Brazier	5.4	5.8	-
Wood Stove	3.8	3.9	38.5
Coal Stove	2.0	2.0	27.8

The cooking efficiencies of the wood and coal stoves were even poorer than those of the three-stone wood stove and the coal brazier (Table 1). In addition to sensible heat loss in the flue gases, the thermal inertia of the two stoves represented a large heat loss in the cooking test. This was especially significant for the coal stove which weighted 220kg and required about 7.5MJ to overcome its thermal inertia. This inertia is considerable when compared to the task cooking energy of 1.05MJ. One of the consequences of this was that it took about 60 minutes to boil water using the coal stove compared to 25-35 minutes for the other solid fuel burning appliances.

The low cooking efficiency of the commercial wood and coal stoves reflects their unsuitability for performing the standard cooking task. It is questionable whether such a task is representative of normal field operating conditions for these appliances. Common sense suggests that lighting a coal stove to boil one pot of water, especially in summer (i.e. when space heating output is not useful energy), i.e. not prudent. It is more likely that a stove would be lit to perform a number of concurrent cooking tasks, employing its multiple pot facility and thereby increasing the useful cooking energy output substantially. The overall efficiencies of the wood and coal stoves are significantly increased over their cooking efficiencies (Table 1), but the thermal inertia of the stove bodies remains a considerable heat loss.

4.1.2 Emissions from Appliances during the Cooking Test

(i) Grains per Task (g/task)

Table 2 Adjusted Emissions of Appliances during Cooking Test (g/task)

	Gases				Particulates	
	CO_2	CO	NO_2	HC	PM2.5	TSP
LPG Ring Burner	155	0.7	0.05	0.2	0.0018	0.0019
Paraffin Primus Stove	195	0.8	0.06	0.6	0.0038	0.0025
Paraffin Wick Stove	215	2.8	0.00	1.1	0.0059	0.0076
Three-Stone Wood Stove	1131	53.4	0.8	30.2	1.6	4.5
Coal Brazier	1026	63.1	1.3	22.2	4.0	7.3
Wood Stove	1993	57.1	2.1	13.0	1.2	1.6
Coal Stove	2311	1500.4	3.5	31.7	3.9	7.9

Appliances performed the standard cooking test three times and Table 2 contains the mean results of these tests. CO_2 emissions were indicative of the amount of fuel burned to complete the cooking task, thus the appliance with the lowest cooking efficiency (coal stove) also has the highest CO_2 emissions (g/task).

CO emissions were indicative of both mass of fuel burned and combustion efficiency. Coal burning appliances had the highest CO emissions associated with the lowest combustion efficiency (Table 2). Emissions of CO from paraffin stoves indicated a higher combustion efficiency in the primus than the wick stove. Under test conditions NO_2 was the only NO_x detected (Table 2). Trace amounts of NO_2 produced by the LPG ring burner and paraffin primus stove were caused by fixation of atmospheric nitrogen at high flame temperature. NO_2 was detected in the wick stove tests as a result of insufficient flame temperatures. For the solid fuel burning appliances NO_2 production is predominantly from oxidation of chemically bound nitrogen. NO_2

emissions therefore reflected fuel nitrogen content and mass of fuel burned. Wood (<1%[9]) has a lower nitrogen content than coal (2% dry ash free basis[10]). Thus NO_2 emissions were greater for the coal brazier than the three-stone wood stove and greater for the coal stove than the wood stove. However, NO_2 emissions were greater for the wood stove than the coal brazier, reflecting the larger mass of fuel burned in the wood stove during the cooking test.

The LPG ring burner has the lowest HC emissions, followed by the paraffin primus and paraffin wick stoves (Table 2). The three-stone wood stove had higher HC emissions than the coal brazier because of the high volatile content in wood. These volatiles are vapourised from the wood during the preliminary stages of wood combustion and released directly into the living area. In the Falcon 600 wood stove the volatiles undergo secondary combustion at the high temperatures inside the stove, lowering the HC emissions (Table 2). The coal stove has higher HC emissions than the wood stove, both as a result of the increased time of the test, associated with the thermal inertia of the stove and from the lower combustion temperature, limiting the degree of secondary combustion.

Fig. 1 shows particulate emissions from various appliances during the cook test. Particulate emissions are perhaps the most hazardous of all domestic combustion products. In addition to elemental carbon, particulates contain condensed and adsorbed organic matter, such as polyaromatic hydrocarbons, which are recognised carcinogens. Particulate size distribution is critical in determining the health effects of emissions. Smaller particles penetrate furthest into the respiratory system and pose the most serious health risks.[11] Furthermore smaller particles have longer residence times in the atmosphere, magnifying their potential impact. Emissions of both total suspended particulate (TSP) and particulates less than 2.5μm aerodynamic diameter (PM2.5) were measured during the cooking test.

The particulate emissions from the LPG ring burner and paraffin stoves were hard to resolve from background particulate levels. Almost all particulates from these sources were in the PM2.5 size fraction. Maximum TSP levels inside the cell suggested that paraffin primus and wick stoves do not pose a serious health risk in terms of particulate emissions.

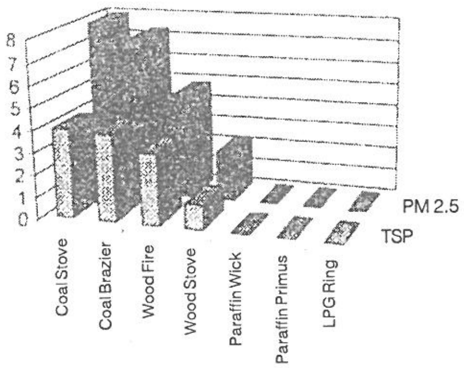

Figure 1. Particulate Emissions

Particulate emissions from solid fuel burning appliances were orders of magnitude greater than those from LPG and paraffin burning appliances (Fig 1). Although particulate emission rates (g/kg fuel) are greater for wood than for coal[12], TSP emissions (g/task) were greater for the coal burning appliances (brazier and stove) as a result of the increased mass of fuel burned. The PM2.5 size fraction was larger for the wood burning appliances than for the coal burning appliances. The effect of this unequal distribution is that PM2.5 emissions from the three-stone stove, coal brazier and coal stove are very similar. Emissions from the wood stove were the lowest of all the solid fuel burning appliances resulting from secondary combustion of particulates and deposition of soot inside the stove. Given that the coal stove vents its emissions outside the home, and assuming that the coal brazier is left outside during the smoky light-up period, the three-stone stove can be regarded as the most hazardous appliance in terms of particulate emissions.

(ii) Grams per Useful MJ (g/MJ)

In winter heat losses to the surrounding space during the cooking test can be regarded as useful space heating energy. Now the emission rates of appliances can be compared by expressing them as grams per useful MJ delivered, including cooking and space heating outputs. The main effect of expressing emissions as (g/MJ) instead of (g/task) is to reduce the emissions of the solid fuel burning appliances relative to those of the LPG and paraffin burning appliances. However, the emissions of the latter remain significantly smaller than those of the solid fuel burning appliances (Table 1).

Table 3 Emissions of Appliances during Cooking Test (g/MJ)

	Gases				Particulates	
	CO_2	CO	NO_2	HC	PM2.5	TSP
LPG Ring Burner	67.8	0.33	0.02	0.08	0.0008	0.0008
Paraffin Primus Stove	94.6	0.38	0.03	0.31	0.0019	0.0012
Paraffin Wick Stove	86.5	1.17	-	0.44	0.0023	0.0030
Three-Stone Wood Stove	127.4	6.02	0.09	3.40	0.40	0.51
Wood Stove	177.8	5.13	0.18	1.17	0. 1	0.14
Coal Stove	160.3	10.62	0.24	2.18	0.30	0.62

4.2 Space Heating Tests

4.2.1 Space Heating Efficiencies

The space heating test was carried out at steady state operating conditions, nullifying the effect of appliance inertia on the efficiency determination. The LPG and paraffin heaters tested had been specifically designed for space heating, whereas the wood and coal burning appliances were those used in the cooking tests. Table 4 contains the mean results of the space heating tests, performed three times by each appliance.

Table 4. Efficiencies and Emissions of Appliances during Space Heating Tests

	Gases						Particulates	
	Output	Efficiency	CO_2	CO	NO_2	HC	PM 2.5	TSP
	(kW)	(%)	(g/MJ)	(g/MJ)	(G/MJ)	(g/MJ)	(g/MJ)	(g/MJ)
LPG IR Heater	1.26	82.0	79.6	0.52	0.02	0.27	-	-
Paraffin Heater	1.97	84.7	85.1	0.13	0.14	0.17	0.02	0.01
Open Wood Fire	3.32	80.0	118.2	6.59	0.09	3.57	0.76	1.06
Wood Stove	3.85	72.0	122.0	2.67	0.07	0.73	0.04	0.06
Coal Stove	2.10	37.1	124.9	7.81	0.26	3.36	0.31	0.66

In contrast to the results of the first study using the same methodology[8], which tested a different LPG heater, the space heating efficiency of the open fire measured here was lower than that of the LPG (Table 4). The losses from the open fire were, however, almost entirely accounted for by incomplete fuel combustion. The space heating efficiency of the open fire (80%) greater than the overall efficiency of the three-stone stove (64%) because for the stove there are inefficiencies associated with the thermal inertia of the cell floor and the three-stone themselves. The high bum rate of the wood stove during the space heating test resulted in a considerable fuel consumption although conversion to useful energy was at a high efficiency (72%). The wood stove was less efficient in terms of space heating than the open fire due to flue gas heat losses (Table 4). However, the higher temperature inside the stove fire-box allow more complete fuel combustion, and therefore the space heating efficiency of the open fire (80%) does not exceed that of the wood stove by further.

The space heating efficiency of the coal stove was significantly lower than that of the other appliances (Table 4). In attempting to account for the losses associated with the coal stove it is postulated that a substantial amount of energy is lost in coal char and ash which fell through the grate in the combustion chamber. While developing an improved method for testing of solid fuel fired stoves, Clark[13] calculated the heat balance for a coal stove bum cycle lasting four hours. He found that 18 - 36% of the energy in the fuel added to the stove was left in the char and ash at the end of a test. Although an energy balance was not calculated for the tests, a significant amount of char and ash was observed to fall through the grate and some to accumulate in the combustion chamber during tests. Additional losses occur as sensible heat in the flue gas.

4.2.2 Emissions during Space Heating Tests

Table 4 contains the mean emission rates of appliances during space heating tests. The LPG and paraffin heaters had low CO, HC and particulate emissions compared to those of the solid fuel burning appliances, associated with their significantly higher combustion efficiencies (Table 4). The paraffin heater actually had a higher combustion efficiency (in terms of CO/CO_2 ratio) than the LPG heater and a slightly higher space heating efficiency. Given the flow rate of air necessary to maintain a temperature increase of no greater than 20°C across the cell it was not possible to resolve the LPG heater particulate emission from background particulate levels in the dilution air. A study of TSP levels in gas and paraffin burning home in Cape Town confirmed that background particulate levels had a greater influence on indoor air quality than appliance emissions.[3]

Incomplete fuel combustion in the solid fuel burning appliances produced proportionally more products of incomplete combustion and proportionally less CO_2. HC emissions from the open fire were especially high (Table 4). The emission rates (g/MJ) of the three-stone wood stove and the open wood fire are generally in good agreement. The only significant differences are in the particulate emission rates perhaps as a consequence of the different bum cycles in each test. Regular additions to the fuel bed were made during the space heating tests but the fire was allowed to die back during the simmering phase of the cooking test. The TSP emission rates for the wood fires in the cooking and space heating tests were 6.1 and 14.8 g/kg oven dry fuel respectively. These are in reasonable agreement with figures reported by Ellegard[14] (7.7 g/kg) and the US EPA AP-42 emission factor17 for PM10 from wood burned in a fireplace at a steady state (17.3 g/kg). However, the results measured here are significantly greater than those reported by Ahuja et al[15] for three biomass cookstoves in India (1.1 - 3.9 g/kg). Particulate and HC emissions from household burning indoor open fires pose serious health risks to their occupants.

Particulate emissions from wood burning are expected to contain about 50% elemental carbon and 50% condensed hydrocarbons.[11] At high combustion temperatures experienced in the wood stove during the space heating test, the condensed hydrocarbons are burnt in secondary combustion leaving formation or element carbon as the principal source of particulates. Particulate emissions from the coal stove were expected to drop relative to the cooking test given the absence of the smoky light-up period in the space heating test. However, regular addition of fresh charges to the fuel bed maintained a smoky bum throughout and actually slightly increased the PM2.5 and TSP emissions (g/MJ).

Despite increasing concern over the environmental and public health effects of domestic fuel use, appliance cost effectiveness is understandably, of paramount importance to most low income households.

4.3 APPLIANCE COST EFFECTIVENESS

The cost effectiveness of domestic fuel/appliance combinations depend on both running costs and capital costs. The capital cost of an appliance is a one off investment which can be offset against its operating lifetime, which is variable. A previous study[8] found capital costs of domestic appliances to be a small proportion of total operating costs. Fuel prices can vary regionally, locally and seasonally. Here the unit cost of fuels were taken as the February 1997 figures of a longitudinal study by The Palmer Development Group[16] in Kameelrivier B, an area 160km north-east of Pretoria. Bought wood was assumed to have a moisture content of 9.9%. Electricity price was taken at February 1997 average rate for the domestic sector.[17]

4.4 RUNNING COSTS OF APPLIANCES

Having determined the cooking and space heating efficiencies of various appliances, and knowing the unit cost of fuels, the cost of useful energy as provided by each of the appliances can be simply calculated (Table 5). The cost effectiveness of each appliance during the cooking test was expressed both as cost per task (summer) and cost per useful joule of energy delivered (winter). The calculation of costs of electrical appliances assumed 41% cooking efficiency[18], 100% space heating efficiency and a cooking task requirement of 1.05MJ.

Apart from self-collected wood of no cash cost, electricity is the most effective energy source in terms of R/task. The LPG and paraffin burning appliances are generally cheaper to operate than the solid fuel burning appliances in terms of R/task, resulting from their higher cooking efficiencies. However, the situation is reversed when fuel costs are expressed as R/MJ, including space heating output in the cooking test. Table 5 suggests that a coal burning stove is more cost effective than electricity on the Highveld but this would not be the case in Cape Town.[19] It is important to remember that the standard cooking task used to calculate cooking efficiencies neglected the multiple pot capacity of the wood and coal stoves. Electricity, LPG and paraffin are less effective than solid fuels for space heating (Table 5). The multiple fuel use patterns of many South African households is partly a result of the recognition of the suitability of different appliances for different tasks. Thus even after electrification households have been found to rely on a variety of domestic fuels to provide for their energy requirements.[20]

Table 5 Appliance Running Costs

Cooking					**Summer**	**Winter**
Fuel	**Appliance**	**Fuel (kg/task)**		**Unit Price**	**Fuel Cost (R/task)**	**Fuel Cost (R/MJ)**
Electricity	Single Ring			19.49 c/k Wh	0.14	0.054
LPG	Single Ring		0.087	3.95 R/kg	0.34	0.104
Paraffin	Primus		0.073	2.20 R/l	0.16	0.075
Paraffin	Wick		0.090	2.20 R/l	0.20	0.070
Wood	3-stone Fire		0.847	0.21 R/kg	0.18	0.022
Wood	Stove		1.666	0.21 R/kg	0.35	0.030
Coal	Brazier	Coal	0.562	0.26 R/kg	0.21	-
		Wood	0.321	0.21 R/kg	-	-
Coal	Stove	Coal	1.9896	0.26 R/kg	0.58	0.040
		Wood	0.407	0.21 R/kg	-	-

		Space Heating			
Fuel	**Appliance**	**Fuel (kg/MJ)**	**Unit Price**		**Fuel Cost (R/MJ)**
Electricity	Heater	-	19.49 c/kWh		0.054
LPG	IR Element	0.027	3.95 R/kg		0.107
Paraffin	Heater	0.027	2.20 R/l		0.060
Wood	Open Fire	0.0080	0.21 R/kg		0.017
Wood	Stove	0.084	0.21 R/kg		0.018
Coal	Stove	0.110	0.26 R/kg		0.029

5. CONCLUSION

LPG and paraffin burning appliances had consistently higher efficiencies and lower emissions than solid fuel burning appliances. However the high prices of LPG and paraffin make them, at best, more cost effective than solid fuels only during the summer months, when electricity is an even cheaper option. Traditional methods of burning wood and coal were more efficient than commercial stoves for short cooking operations, having no flue gas heat losses and fractional appliance inertia losses. However, less complete combustion in the traditional appliances released large quantities of toxic emissions directly into the living space, posing potentially serious health risks. Conversely LPG and paraffin are convenient, have lower emissions and offer improved standards of living. In domestic fuel choices a fuel cost/ fuel convenience compromise is made by households. As a result households might use LPG or paraffin during the summer months and for short cooking operations but burn wood or coal during the winter months. Economic considerations have undoubtedly had a role in establishing the multiple fuel use patterns of many South African households.

6. ACKNOWLEDGMENTS

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