Renewable and Appropriate Energy Laboratory Report

Review of Technologies for the Production and Use of Charcoal

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Table of Contents:

Abstract

Charcoal constitutes the primary urban fuel in most of Africa and is a major source of income and environmental degradation in rural areas. The production, transport and combustion of charcoal constitutes a critical energy and economic cycle in the economies of many developing nations. Far from decreasing, the use of charcoal has remained constant or grown in many countries. Because of this, it is critical to assess and to develop long-range charcoal policies for African and other developing nations. In this paper, we review the current status of biomass harvesting and transport for charcoal production, efficiency of pyrolysis in various kilns as well as efficiency in end-user application, emissions of trace gases, and the relative economics of charcoal and its fuel substitutes. We compare the efficiencies of over thirty kilns with dry weight yield efficiencies ranging from 12 to over 40% along with production volumes up to 13 tonnes. We also discuss the transport and marketing economics for a range of urban African charcoal markets. The analysis of these factors highlights the importance of matching the charcoal production technology, batch size, and marketing to the available resource and the end-user population. This analysis is critical to the design of sensible biomass energy policies at the national and international aid and donor level.

Introduction

Half of the world's population uses biomass fuels for cooking. In 1992, 24 million tonnes of charcoal were consumed worldwide. Developing countries account for nearly all of this consumption, and Africa alone consumes about half of the world's production. Charcoal production has increased by about a third from 1981 to 1992, and is expected to increase with the rapidly growing population in the developing world.

Despite the cooking advantages of charcoal and charcoal's ranking on the cooking ladder, this preliminary review suggests that charcoal may be far more damaging to the environment than the less preferable biomass fuels, biomass residues and fuelwood. Contrary to popular assumptions that charcoal is an old technology and thus will phase out on its own, this study indicates that charcoal is problematic from an energy, environmental and social perspective and is likely to be used as long as the feedstock supply and the demand from impoverished people in the developing world exist.

On a local scale, the effects of charcoal use are mostly related to the inefficiency of production, forestry and land degradation, and the transportation distances. Because most of the energy of the fuelwood is lost in the production process, charcoal users ultimately use much more fuelwood than direct fuelwood users. Because charcoal is typically produced in sizable batches, it is rarely linked with sustainable forestry practices, and is more often linked with clear-cutting. At best, charcoal may be produced from plantations, but it is more likely to be produced from land cleared for agricultural purposes or from smaller areas cleared specifically for charcoal production.

In many countries, the rural people and even charcoal producers are too poor to use charcoal, and the demand for charcoal is found in the urban areas. This often means that the charcoal is produced far from the demand and must be transported, typically via truck, to the user. As the fuelwood supply and potential agricultural land supply dwindles, transport distances may approach 1000 km. Easily accessible fuelwood is then also co-opted for the urban dwellers, leaving rural areas with fewer accessible biomass supplies.

Intertwined in charcoal production and use are global environmental effects. Because much of the charcoal feedstock is not plantation wood, the unsustainable harvesting of biomass results in net carbon dioxide emissions. In addition to the production of charcoal, pyrolysis of biomass also produces incomplete combustibles, such as methane, which may have a higher global warming impact than carbon dioxide. In fact, the main global warming impact of the charcoal cycle may result from the biomass pyrolysis and not the end-use of charcoal burning.

Although charcoal policies and kiln improvements have been studied since the 1800's, many aspects of the social and environmental impacts have received little or no attention. The intent of this review is to identify the impacts of charcoal production and use, assess preliminary data and determine where data is lacking or insufficient.

Charcoal consumption

The Food and Agriculture Organization (FAO) has estimated that total charcoal production in 1992 was 24 million tonnes. Figure 1 shows the FAO charcoal production estimates from 1981 to 1992. About half of the world's charcoal use is in Africa, where traditional production techniques lead to a low conversion efficiency. Using the FAO dry weight conversion efficiency of 23%, one finds that about 100 million tonnes of wood are annually cut for charcoal production. Due to the large and rapidly increasing African share of charcoal consumption, this paper focuses mainly on African charcoal systems.

Charcoal production/consumption figures are difficult to estimate in developing countries. The FAO estimates charcoal production using constant charcoal consumption per capita factors for each country. Because these factors do not change for the 1981-1992 period shown, the changes in charcoal production shown are due entirely to the population increases. In reality, there is likely to be a subset of the country population which is dependent on charcoal fuel and charcoal consumption rates may differ from the FAO rates. Even in countries where charcoal is regulated and taxed, illegal charcoal production makes governmental figures inaccurate. In Rwanda, Karenzi [1994] found that the charcoal use calculated from ground surveys was much greater than recent energy statistics published by governmental Ministry of Public Works, Water and Energy (MINITRAPE)[1]. He found annual charcoal consumption in Rwanda to be 9.1 GJ, compared to the 1.2 GJ determined by MINITRAPE. In Senegal, official harvest levels are often exceeded through the use of special contracts which may increase total charcoal production by 30-100% [Ribot, 1993]. These examples underscore the need for accurate data collection.

Rural and Urban uses of woodfuels and charcoal

Biomass users prefer charcoal over other biomass fuels such as wood, residues and dung. Charcoal has a higher energy density than other biomass fuels and can be stored without fear of insect problems. It has excellent cooking properties: it burns evenly, for a long time, and can be easily extinguished and reheated. Even in developed countries, such as the US, charcoal is desired for the flavors which it imparts to grilled food. As users become more affluent, they typically switch from woodfuels to charcoal and then to petroleum fuels such as kerosene or LPG. Charcoal's position in the middle of the cooking ladder implies that with economic growth, charcoal users will switch to more modern fuels, but other biomass users, on the order of two billion people, may switch from other biomass fuels to charcoal. Household energy consumption in rural Kenya is shown in Figure 2 as a function of income group. Together, the three middle income groups represent over 80% of the total urban households, and charcoal is their dominant fuel. Within these three income groups we see fuelwood being phased out with increasing income, and some kerosene, electricity, and LPG substitution at higher incomes. Even in the highest income group, it may be found that charcoal is not replaced, but rather supplemented by fossil fuels.

The disparity in urban and rural incomes corresponds with household fuel choice. For example, of urban Kenyan household energy use, 66% is supplied by charcoal and 18% by fuelwood. Of rural household energy, 90% is from fuelwood and only 5% from charcoal [O'keefe, Raskin and Bernow 1984]. This large disparity in fuel use implies that the urban migration which many countries are witnessing may have a large effect on charcoal consumption. In the early 1990's the average growth of population in Africa was 2.9%. The average rate of urbanization, however, was 4.6%. In eastern Africa, growth rates were even higher, with Kenya's population growth at 3.4% and urbanization growth at twice that. It is not clear from the literature that charcoal consumption is better correlated with population growth or increased urbanization.

The fact that charcoal consumption is dominated by urban users fuels the accusation that rural users subsidize and bear the brunt of urban energy use, as the supplies taken from rural areas directly affect local availability of woodfuels. The rural woodfuel users are adversely affected through increasing amounts of time spent collecting woodfuels, and through the cutting of their

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[1] Karenzi's estimates are based upon a survey of charcoal trade and use in industrial and residential households.

forests and destruction of an ecosystem that may indirectly affect them via increased erosion, soil fertility, or loss of animal habitat. (footnote this)

	kg/capita/yr charcoal	kg/capita/yr wood eqv of charcoal
Kigali charcoal users	219	1750
Kigali woodfuel users		1140
rural woodfuel users		510

Table 1. The variation in wood equivalent per capita per year of household users of woodfuels [Karenzi, 1994]. Charcoal production for Rwanda is estimated at 12.5% dry weight efficiency.

Since charcoal is made from wood with typically low conversion efficiencies, the woodfuel equivalents of charcoal users can be quite high. Table 1 shows the result of surveys of per capita fuel use in Rwanda. Charcoal users ultimately consume substantially more wood than direct woodfuel users. Additionally, urban users consume more wood than rural users. The latter is believed to be an income effect.

energy source	Cameroon	Senegal	Northern Nigeria	Niger	Ethiopia
Fuelwood	1.0	1.0	1.1	1.0	1.0
Charcoal	3.4	0.9	2.4	1.4	1.6
Kerosene	10.0	1.7	0.6	1.7	0.7
Liquified petroleum gas	-	1.3-1.9	2.0	2.0	1.1
Electricity	11.1	3.3	1.1	2.8	2.0

Table 2. Relative costs of fuelwood, charcoal and commercial energy for cooking Anderson and Fishwick [1985]. Costs include thermal efficiencies and costs of cookstoves.

Price is not the only, or even the major factor of consideration in household fuel choices. Table 2 shows the relative prices of cooking with various fuels. Note that fuelwood, which is near the bottom of the cooking energy ladder, due to inconvenience and smoke, is not necessarily the cheapest of energy options. In many cases, the availability of fuel supplies determines preferences. Additionally, even in cases where petroleum fuels are used, charcoal is often used as a backup fuel or the main fuel for preparation of certain foods. In Senegal, where LPG penetration is increasing, households using LPG are still using as much or more charcoal than households which only use charcoal [Ribot, 1993].

Environmental Impacts

Although charcoal production accounts for only about a tenth[1] of primary energy use in charcoal intensive African countries, the impact of charcoal on forests is large for two reasons. First, the woodfuel equivalent is 4-6 times larger, due to the inefficiency of the production process. Perhaps more importantly, charcoal demand is in densely populated urban areas and the harvesting of wood for charcoal production is an intensive process, concentrated in as small an area as possible over as short a period of time as possible. In some cases, wood is taken illegally from state land, and producers are under pressure to harvest the wood make the charcoal as fast as possible. The rural woodfuel users typically collect small amounts of wood daily, and thus the forestry impact is dispersed and much less severe. Also the rural users may collect dead wood, or twigs and branches,

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[1] This does not include energy lost in production of the charcoal.

which allows the trees to regenerate. Charcoal production, on the other hand, is responsible for the large scale felling of wood, which may lead more directly to deforestation.

Armitage and Schramm emphasize that in most of Africa, more wood is cut down to clear land for agricultural or livestock purposes than is used for fuel, and that about 80% of charcoal wood is taken from land clearing [1989]. See Table 3. On the one hand, conversion of this wood, which would otherwise rot and be wasted, into charcoal, which can be stored and later used as a fuel, is a wise practice. On the other hand, combining the sustained activity of charcoal production with the unsustainable activity of forest clearing may result in forest clearing solely for charcoal production.

Urban market	**Supply Source**	**Type of Resource**	**Transp. Dist.**	**% of Market**
Nairobi	Aberdares	smallholder wattle	20-200	5
	Ukambani	rangeland clearing	80	15
	Mau/Narok	forest/range clearing	150	20
	Mtito Andei	forest/range clearing	200	10
	Laikipia	forest clearing	220	20
	Baringo	rangeland clearing	240	15
	others	-	-	15
Mombasa	Kwale	forest/range clearing	50	40
	Kilifi	range clearing	70	30
	Malindi	forest/range clearing	100	15
	Taita	range clearing	140	10
	others	-	-	5
Nakuru	Eldama Rav.	forest clearing	65	20
	Londiani	forest clearing	70	15
	Baringo	range clearing	80	40
	Elburgon	eucalyptus plantation	30	15
	others	-	-	10
Kisumu	Eldoret	plantation wattle	122	80
	others	-	-	20

Table 3. Origin of wood for urban charcoal [UNDP/WB 1987]. This data is from September 1985. Data taken today would certainly be very different: for example, in March, 1986, the Mau/Narok area was closed off to charcoal production. It is likely that transport distances are much greater today.

In fact, a detailed UNDP/WB study concluded that the nonexistence of a woodfuels availability crisis was due to the abundance of high agricultural potential land - forests and woodlands on relatively flat land which received good rainfall [1987]. They predicted that in the mid-1990's these lands would become more scarce, and charcoal producers would turn to other sources to obtain wood. A lack of alternative sources of wood, i.e., plantations or farmland, would result in large-scale land clearing *for the main purpose of providing wood for charcoal*. Already, clearing of forests in Kenya is beginning to subside due to decreasing potential land[1]. If the demand for charcoal does not simultaneously subside, then other areas will have to be exploited or charcoal prices will rise.

Energy Impacts

Energy Inefficiency of Charcoal Production

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[1] Stephen Karekezi, personal communication, April 1995.

Charcoal is traditionally produced in earth, brick or steel drum kilns in batches from about 1 to 5 tons. Kiln types and production methods are detailed in Foley's *Charcoal Making in Developing Countries* (1986). Fuelwood is gathered and cut to size, and placed in an underground or above ground kiln. The kiln is fired and the fuelwood heats up and begins to pyrolyze. The kiln is mostly sealed, although a few air pockets are initially left open for steam and smoke to escape. As the kiln emissions change color, the charcoaler may seal some air pockets. The production process may take up to a few weeks. About half of the energy in the fuelwood is typically lost in the process. When the process has ended, the kilns are opened or dug up and the charcoal is removed. The resulting charcoal resembles smaller, lighter pieces of blackened wood. These will have a higher energy content by weight than fuelwood. The larger pieces can be sold in the market; smaller pieces and powder, or *fines*, are disregarded.

The energy efficiency of the process is dependent upon many factors: kiln type, moisture content, wood species, wood arrangement, and the skill of the producer. Many programs over the past centure have been implemented to increase efficiency of charcoal kilns. Appendix A lists a number of these projects. Foley notes that few of these have had any significant or permanent effect on charcoal production in the developing world [1986]. Often new techniques are adopted for brief periods and then discarded: evidence of this is found by the remains of metal kilns and metal pit covers scattered in the Sengalese forest [Feinstein and van der Plas 1991].

The Casamance kiln is generally seen as a successful technology for increased efficiency. However its penetration has been very limited [Feinstein and van der Plas, 1991]. Tests results for the Casamance and traditional kilns are shown in Figure 6. Although the average Casamance kiln (22 tests) is much more efficient than the average traditional kiln (49 tests) here is a large amount of scatter in the plots indicate that the yield is highly dependent upon the skill of the producer and that very good traditional kilns can compete with very good Casamance kilns. In addition, the three data points for the Casamance kiln of 60-70% efficiency were performed on wood with a low moisture content. This indicates that perhaps kiln type is less important than proper treatment of the feedstock or kiln size.

Although improved efficiency stoves and kilns are desirable to conserve resources and reduce emissions, it should be stressed that the technology transfer must be appropriate for the region and accompanied by training and education. For example, of the various types of cookstoves used in Kigali, the improved cookstove was used in only 1% of the households surveyed [Hall and Mao 1994]. In institutions and restaurants, however, the penetration of improved cookstoves is greater. That the larger establishments use improved cookstoves more than individual households may be indicative of a large capital cost for improved cookstoves or lack of education concerning fuel savings with improved cookstoves.

The Petroleum Link

The UNDP/World Bank energy studies of Africa (through the Energy Sector Assistance Program) generally recommend one of two conclusions: either the country is too dependent upon petroleum and biomass use should be encouraged, or the country is on the verge of a woodfuel/deforestation crisis and petroleum use should be encouraged. Charcoal use does have large ramifications in domestic employment - in 1985, the Kenyan charcoal industry included 30,000 full-time producers, 400 transporters, and 800 retailers. In addition, this charcoal production provides jobs in the poorer, rural areas. Finally, woodfuel plantations would provide even more local employment. Petroleum, on the other hand has associated reliability and security of supply issues. For example, Zambian gasoline prices doubled during the Persian Gulf War[1]. Balance of payment problems and lack of hard currency also make petroleum unattractive to those African countries which are not endowed with large petroleum resources.

However, even though charcoal use may be encouraged for the above reasons, petroleum costs and petroleum dependency are an inextricable part of charcoal use in most countries. Figure

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[1] Stephen Karekezi, personal communication, April 1995.

4 shows the origin of charcoal which is sold in Kigali. In 1980, most charcoal consumed in Kigali was produced in the Bugasera region, about 10-60 km away. By 1987, the reduced resources forced charcoal production to the Kibungo region, about 160 km from Kigali [UNDP/WB, 1987]. The average transport distance of charcoal into Kigali is 124 km. In Malawi, the World Bank has sponsored fuelwood plantations (of mostly a single softwood species) to provide a sustainable feedstock for charcoal, but the charcoal must then be transported 300-600 km to the urban areas where it is utilized [Teplitz-Sembitzky and Zieroth 1990]. Table 4 shows that these transport costs can be a significant portion of the total charcoal cost.

	Hardwood Charcoal	Viphya plantation softwood charcoal					
	Wholesale Price	Production	Profit & Overhead	Transport[1]	Bagging	Stumpage	Total
early 1988	165-180	30	10	100	15	10	165
early 1989	265-290	35	10	200	25	10	280
mid 1989	265-290	50	10	200	15	10	285

Table 4. Charcoal costs for the urban market of Blantyre, Malawi [Teplitz-Sembitzky and Zieroth, 1990]. The range of hardwood charcoal prices is shown in the first column. The Viphya plantation charcoal price breakdown is shown in the next 5 columns. Transport costs make up 60-70% of total market price for the plantation charcoal.

These examples call into question the energy balance of the charcoal cycle, from feedstock to production through transportation and end-use. And as forest resources near urban centers are depleted, from how far away will people continue to import charcoal before it becomes economically unsound?

Production costs typically involve only labor and transportation of charcoal to the roadside, since wood is usually free. Where charcoal is used mainly for centralized, urban markets, it is likely that transport distances will increase with time, as nearby stocks of forests are depleted, so future transport costs may constitute a much greater amount of the total cost. When transport costs are such a significant fraction of total costs, any fluctuations in petroleum prices will likely have a great effect on real charcoal prices. This is demonstrated by the 70% increase in charcoal prices between 1988 and 1989 due to the doubling in transportation costs.

Therefore, although feedstock may be sustainably and locally grown, charcoal is strongly linked to petroleum, through both an energy and economic perspective. Due to the large transport distances involved, it would be interesting to examine the energy balance and flows of this system. With charcoal production and end-use energy losses already 70-85%, the amount of energy supplied to this system may exceed the energy yield of the charcoal fuel in urban areas.

Global Climate Change Impacts

Charcoal use in developing countries affects global warming in several interrelated ways. First, a significant portion of charcoal production wood is unsustainably harvested. Although forestry management is improving and projects in countries like Malawi have encouraged use of plantation wood, the bulk of charcoal wood is clear-cut from secondary and in some cases, primary forests. This is very different from small-scale rural forestry practices, where wood is often less intensively and more sustainably harvested [Bradley 1991]. Second, emissions during charcoal production are significant compared to those from charcoal burning. This is shown in the carbon/energy balance of charcoal production and combustion of Figure 3. The second number in brackets indicates the 20-year global warming potential, and these measurements indicate that the global warming potential of the emissions during production is greater than the global warming potential of the emissions during combustion.

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[1] 630 km

Charcoal is produced via pyrolysis, or thermal degradation, of biomass. This partial combustion, in an oxygen-poor environment, results in formation of products of incomplete combustion (PICs), such as CH_4, CO, alkanes, alkenes, oxygenated compounds and particulate matter. In ideal biomass combustion only CO_2 and H_2O would be formed; in practice, however, various amounts of PICs are produced, depending upon operating conditions.

The first measurements of CO_2 and trace gas emissions from a charcoal kiln in the field were performed by Lacaux, *et al* [1994] and are listed in Table 1. These data are from one burn cycle for a traditional mound kiln in West Africa. As expected, the charcoal kiln emission ratios of CO, CH_4, NMHC, and NH_3 to CO_2 are larger than those from savanna burning. Because CO, CH_4, NMHC have much higher global warming potentials than CO_2, emissions from charcoal production may pose a serious peril to the upper atmosphere. Even on a per kg of wood basis, the global warming impact of biomass pyrolysis for charcoal may be greater than that of biomass burning, and should be quantified.

Further data are Hao and Ward's preliminary measurements of CO_2, CO and hydrocarbons from three mound kilns in Zambia [1994]. As shown in Figure 5, their emissions of methane from biomass carbonization are much higher than those from biomass burning, for a given combustion efficiency ($CO_2/CO+CO_2$). Confirmation of these results and comparisons to other types of kilns under various combustion conditions and with various process parameters have not been done and are the subject of this proposal. For comparison, an EPA emissions inventory from a US charcoal plant, adjusted to reflect the low efficiencies of earthen kilns, shows much greater emission ratios for trace gases than shown in Table 1 [Smith and Thorneloe, 1992]. Whether this discrepancy is real or an artifact of testing and measurement methods is not known, but underscores the need for standardization of testing procedures.

A comparison of charcoal production emissions of the primary trace gas species during various measurements is shown in Table 5. The large variability in emissions is expected, as these pyrolysis technologies range from controlled continuous production with afterburners in industrialized countries to small-scale uncontrolled mound kilns in developing countries.

In addition to the recent measurements of charcoal kiln emissions, several measurements of charcoal stove emissions have been conducted [Smith and Thorneloe, 1992] and are summarized in Table 1. They suggest that charcoal production may be responsible for emissions of CO, CH_4, NMHC, and aerosols than charcoal combustion in a cookstove. The larger gross emissions coupled with the global warming potentials of these PICs cause the global warming contributions of charcoal production to be much greater than that from charcoal use. It is therefore crucial that the entire carbon balance of the charcoal cycle is assessed for impact on global warming.

	dry mass yield	**CO_2**	**CO**	**CH_4**	**NMHC**	**TSP**
Smith and Thorneloe	0.20	3300	443	147	405	320
WB1992/Briane and Doat 1985[1]	0.31	1350	700	170		
EPA AP-42			172	52	157[2]	133[3]
Lacaux, et al 1994	0.28	1540	233	40	8	5
Hao, et al 1994		2629	86	18		
EPA Moscowitz						
uncontrolled	0.25		160-179	44-57	7-60[4]	197-598
low controlled batch	0.25		24-27	6.6-8.6	1-9[5]	27-89
controlled continuous	0.25		8-8.9	2.2-2.9	0.4-3[6]	9.1-30

Table 5. Grams of emissions per kg of charcoal produced for several different studies. The production processes here range from modern kilns in the US [Smith and Thorneloe, EPA AP-42, EPA Moscowitz, Briane and Doat] to mound kilns in developing countries [Lacaux, Hao].

A crude estimation of fuel cycle emissions for various cooking fuels has been performed by the World Bank [Floor and van der Plas, 1992]. Using emissions from production, combustion in a cookstove, and sequestration by sustainable growth of biomass, they have estimated the net carbon dioxide equivalent emissions[7] for various fuels, as shown in Figure 5. It should be noted that transportation of the fuels was not included in this study, and that emissions are thus underestimated for fossil fuels and charcoal. From this data, and similar data for woodfuel substitution, analysts at the World Bank reached the conclusion that while substitution of wood was not environmentally and economically justified, substitution of charcoal was highly recommended.

Summary and Policy Recommendations

The environmental and social impacts of charcoal production and consumption are extensive and intertwined, such that an integrated view is essential in policy making. For each country or charcoal market, the following questions must be addressed on a case by case basis:

- What are the charcoal flows? Where is the charcoal wood grown and is it grown sustainably? Is charcoal produced by poor peasants in the off-season or by large, organized groups? Does the charcoal policy have the unintended impact of forcing the peasants to choose between fuel and food production? How far is the charcoal transported and what are the energy and monetary inputs? Who consumes the charcoal? How does the local industry work in each region?
- What are the local environmental impacts of charcoal production? Is there forest conversion to non-indigenous fast-growing species and monoculture plantation cropping?
- Pricing - what is the *real* cost of charcoal? How can the market price reflect these real costs without detrimentally affecting consumers? How can charcoal be priced such that sustainable plantation wood can be used cost-effectively? Charcoal is attractive in terms

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[1] relatively modern kiln

[2] includes condensibles and non condensibles

[3] includes tars and oils (condensibles)

[4] 67-76 g/kg of methanol and 102-116 g/kg of acetic acid are included in this figure.

[5] 10-11 g/kg of methanol and 15-17 g/kg of acetic acid are included in this figure.

[6] 3.3-3.8 g/kg of methanol and 5.1-5.8 g/kg of acetic acid are included in this figure.

[7] includes carbon dioxide and methane emissions, where methane is assumed to have 70 time the global warming potential as carbon dioxide on a per weight basis

of domestic energy policy projects in that all charcoal transactions involve money, so that projects *can* have financial returns.

- Should charcoal be substituted? Do policy-makers want to encourage use of charcoal, which is an indigenous product and stimulates a domestic industry, but which is currently being produced unsustainably and may lead to destruction of forest resources and all associated environmental ramifications? Or do they want to encourage substitution with petroleum fuels, upon which most of the developed world depends, but which may have to be imported and whose supplies are uncertain? How should charcoal be priced such that substitution to other fuels could be encouraged?

In this study, we've investigated a number of issues which must be considered in design of energy policy in traditional fuels. There is insufficient data of charcoal consumption in most countries, and charcoal use, like woodfuel use, does not appear to be phasing out globally. The environmental impacts include the current association with range and agricultural land clearing and the threat of land clearing for the sole purpose of producing charcoal. Transport issues play a larger role as the woodfuel source for charcoal production becomes scarcer near urban areas of charcoal demand. Finally, from a global warming perspective, charcoal use is among the worst, if not *the* worst, cooking energy source, and substitution or new production methods may be advisable.

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Appendix A: Summary of some past charcoal kiln studies

The following table summarizes various studies of the major kiln types over the past hundred years. The yields are typically given as dry weight ratios of charcoal output to wood input. In most of these studies, the moisture content (air dry versus oven dry) and the inclusion or exclusion of fines or partially carbonized wood are typically not stated. The large variation in yields is indicative of the lack of standardization in measurement as well as the strong dependence of kiln yields on operating conditions. None of these studies have measured emissions from kiln operation, to our knowledge.

kiln type	**dry weight yield [%]**	**remarks**	**country**	**ref.**
Mound				
traditional	15.5-26.2		India	1
small circular	23	horizontally stacked	India	2
traditional	31.4	vertically stacked	France	3
Mozambique long	10-15		Mozambique	4
large Suriname	20-25		Mozambique	4
traditional	2-17	various moisture contents; various weather and temperature conditions	Tanzania	5
	39-42	vertically stacked; covered with metal sheet; sized Acacia bussei logs with >15cm diameters	Somalia	6
Casamance	25-30	horizontally stacked; oil drum chimney; fast	Mozambique, Senegal	4
Pit				
	16-21	various species; 1Mg wood	India	7
Chinese	18	fast; green wood	India	8
	20-28	low yield for chir; high yield for sissoo; on a zero moisture basis	India	9
	13.7	small	Sri Lanka	10
commercial brick	30	coconut shells	Sri Lanka	11
Philippines	20-25		Philippines	12
improved	25-30		Liberia	13
	12.5-20		South Africa	14
Brick				
Siamese	30	mangrove wood	Malaya	15
Nilgiri	21		India	16
standard Beehive	33	36% yield with external fire chamber	Brazil	17
South African garage	12.5-23.5		South Africa	14
commercial half-orange	26.6	average annual yield in 1978	Argentina	18
Concrete				
Missouri	33		US	19
Fired Clay				
Japanese	14-20	higher yields gave poorer quality and more smoke	Japan	20

kiln type	dry weight yield [%]	remarks	country	ref.
Portable Steel				
Trihan	21.2-37		India	21
La Bastia	11.8-33.6		India	21
Magnien (Mark V)	20-20.4	low yield w/o chimney; high yield w/ chimney	France	22
Mark V	20-35	low yields for small kilns; high yields for large kilns	Côte d'Ivoire	23
Mark V	10-18	little controls	Tanzania	5
Mark V	25		Liberia	24
TPI	18.9-31.4		7 countries	18
TPI	21-24.4	low yields for oak; high yield for coconut shells		25
Oil Drum				
Tongan	22.7	exclusive of fines and inclusive of uncarbonized wood	Fiji	26
MINI-CUSAB	23.4	""	Fiji	26
	33-34		Montserrat	27

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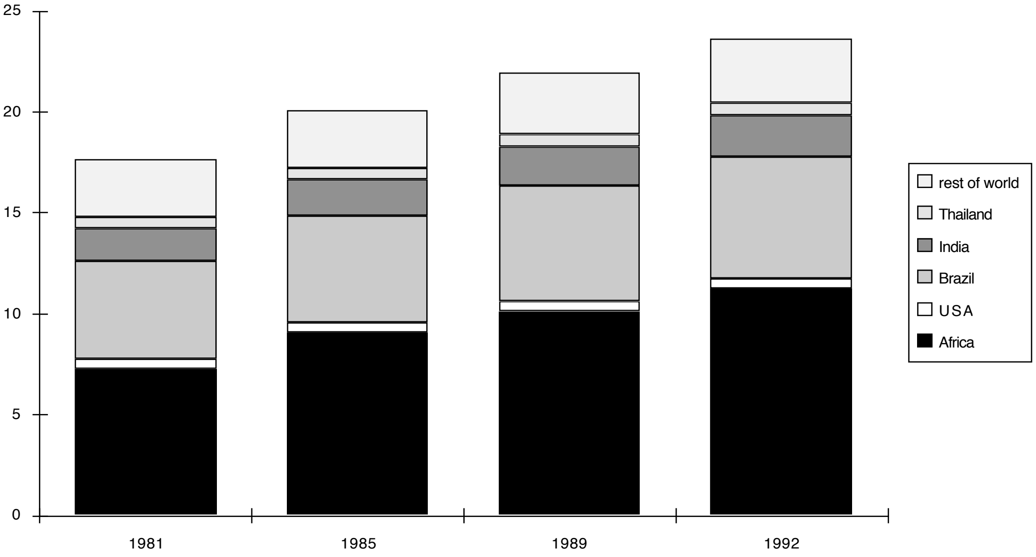

Figure 1. Charcoal production from 1981 to 1992 [FAO 1994]. Total production in 1992 was 24 million tonnes, about half of which occurs in Africa. According to these figures, production has been steadily increasing. The bulk of this increase is from Africa, where production has increased by 55% in this time period.

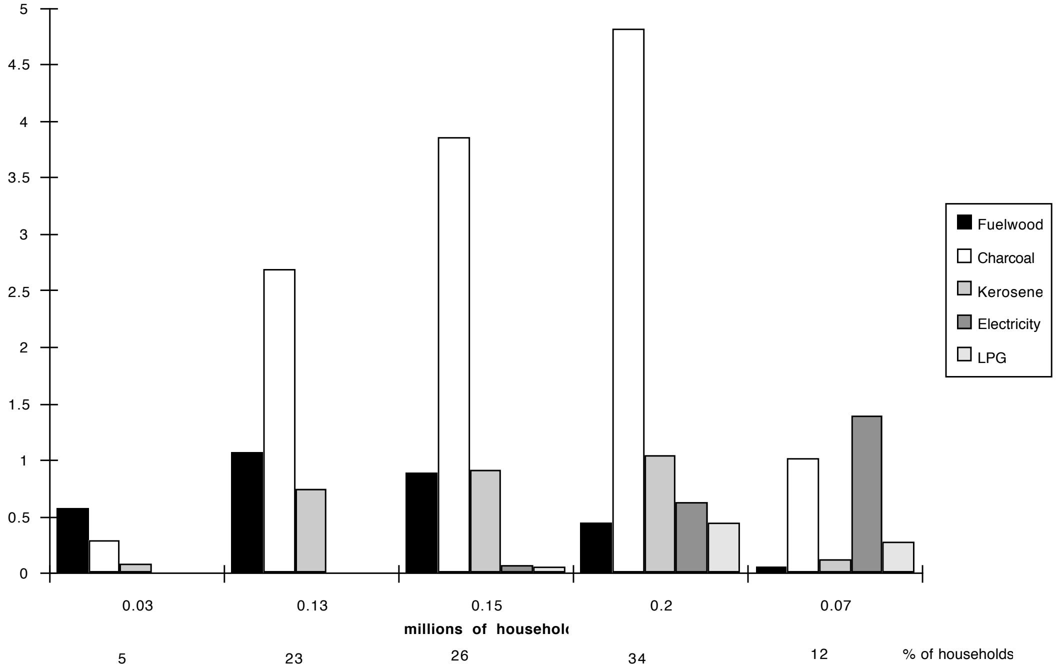

Figure 2. Kenyan urban household energy consumption by income group in 1980. [UNDP/WB 1987]

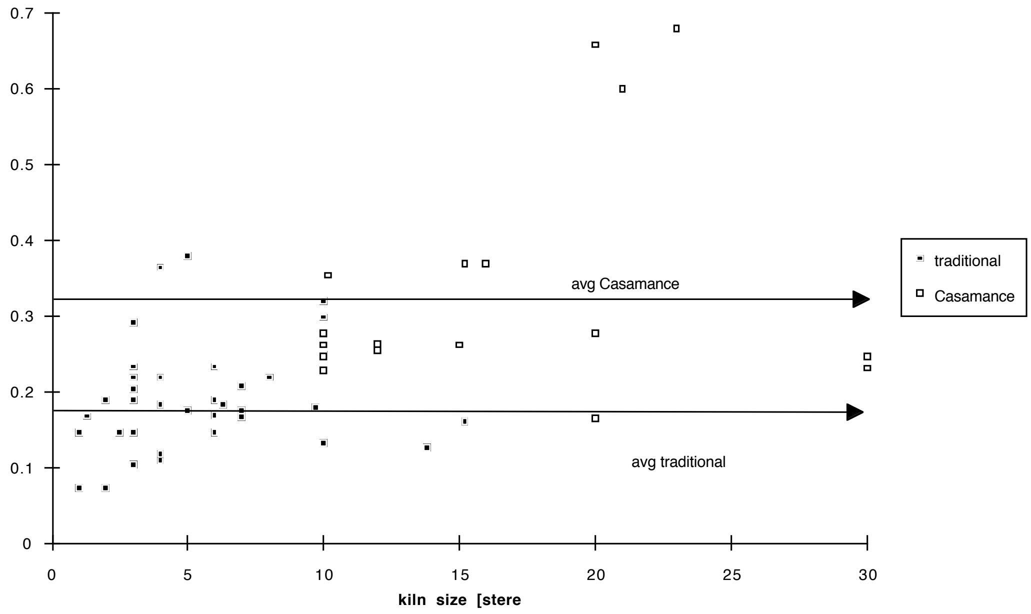

Figure 6. Kiln performance in Rwanda [UNDP/WB, 1991]. Charcoal energy yields are shown as a function of kiln size for the traditional and the Casamance kiln. The average energy efficiency is 18% for the traditional kiln and 32% for the Casamance kiln. All tests shown here were performed on eucalyptus wood.

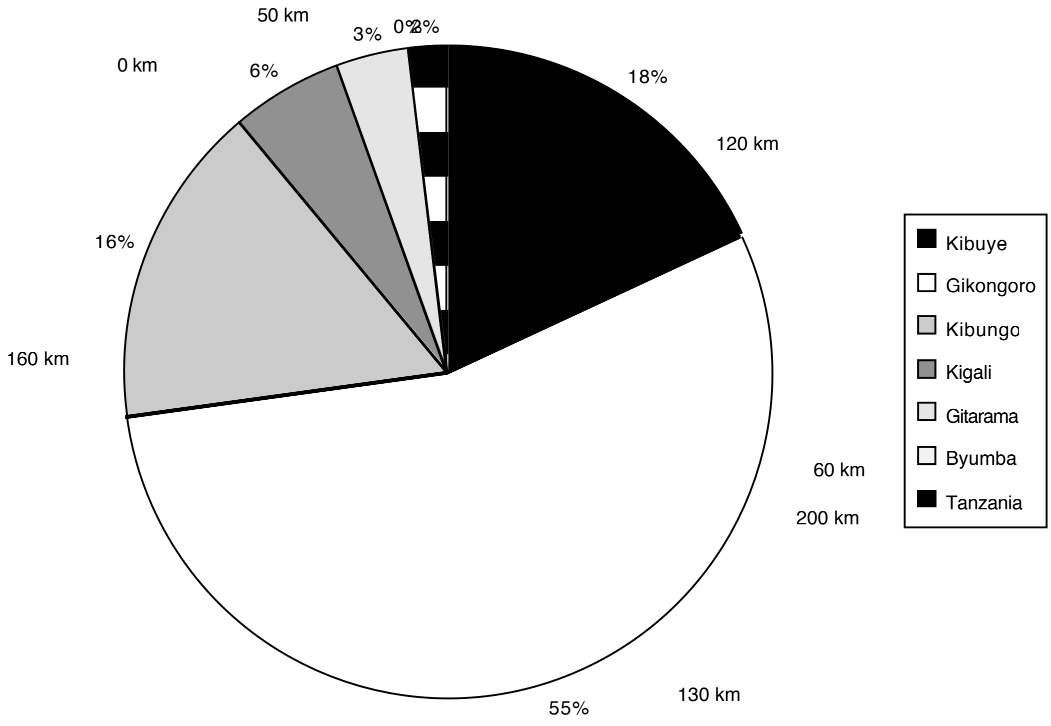

Figure 4. Origin of Kigali charcoal in 1987. [UNDP/WB, 1991] Kigali accounts for 83% of the charcoal consumed in Rwanda [UNDP/WB, 1987]. Eighty-five percent of this wood is from plantations and 15% is from natural forests, where it is illegal to harvest wood. Total charcoal consumed in Kigali in 1987 was 27,000 tonnes.

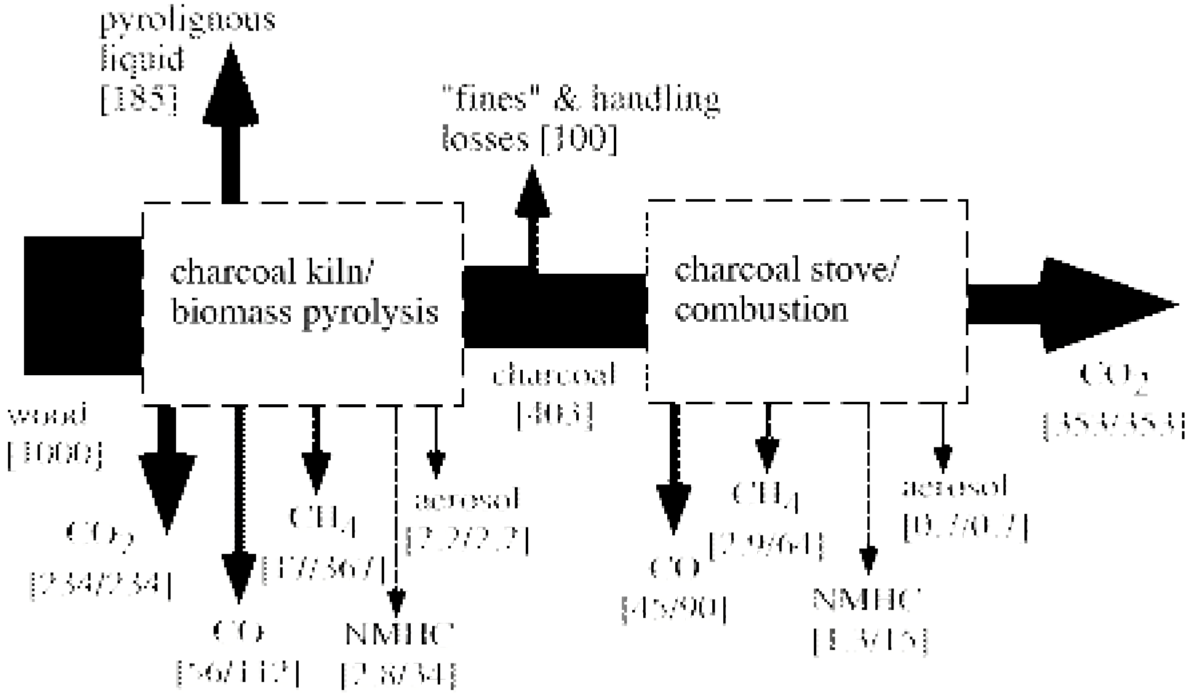

Figure 3. The carbon/energy balance for charcoal production and combustion. Carbon in grams is shown in brackets; where applicable, this is followed by the global warming potential on a 20-year time horizon as determined from the 1990 IPCC global warming factors (The global warming potential of CO has been variously quoted between 2 and 4.5 times that of CO_2 [Smith and Thorneloe, 1992]). Thus, "CO [56/112]" indicates 56 grams of carbon monoxide produced per kilogram of wood combusted in the charcoal kiln; with a global warming potential 2 times that of CO_2, this step alone is the equivalent of the emission of 112 g of CO_2. Although overall energy efficiencies of both kilns and stoves have been studied and improvements have been made, very little has been done to determine the emissions from these processes. The stove emission data is based upon a pilot project of six measurements [Smith and Thorneloe, 1992]; the kiln data is based upon a single measurement of a Côte d'Ivoire mound kiln [Lacaux, *et al*, 1994]; "fines", or charcoal powder losses can represent 20% of the output -- here fines plus handling losses are estimated at 10% [Foley, 1986].

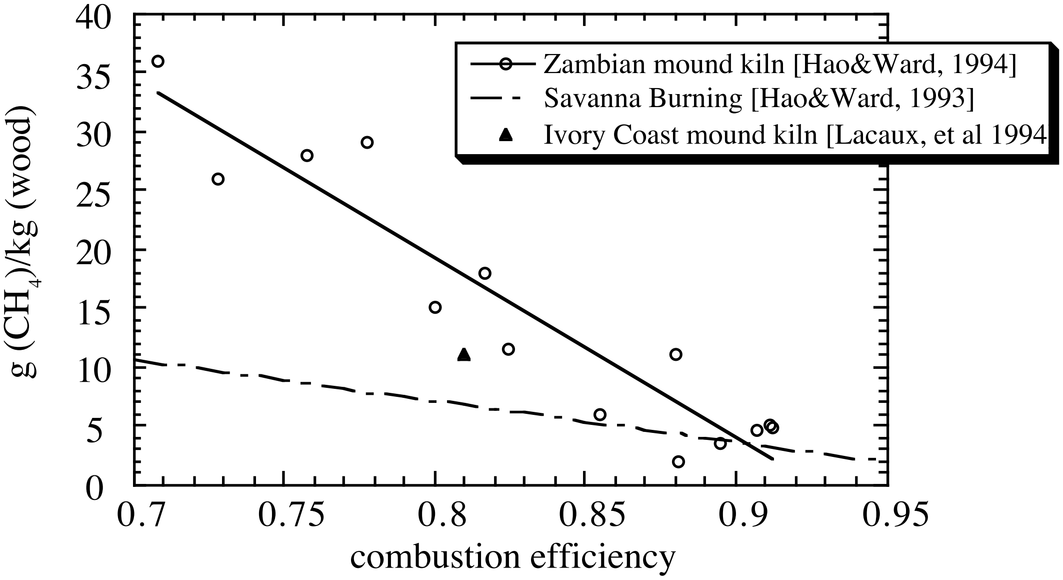

Figure 5. Emissions of methane as a function of combustion efficiency ($CO_2/CO+CO_2$) comparing wood burning and pyrolysis. Preliminary data from a Zambian mound kiln [Hao and Ward, 1994], assuming a 50% carbon conversion. Data from a Côte d'Ivoire mound kiln shown for comparison [Lacaux, *et al,* 1994].

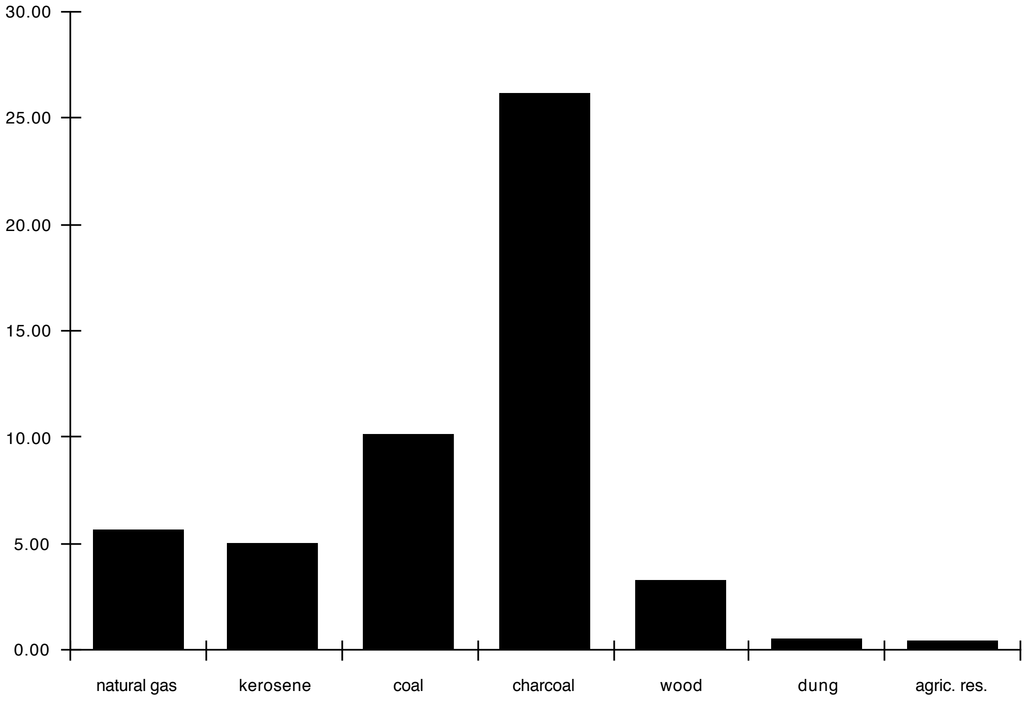

Figure 5. Net carbon dioxide equivalent emissions per cooking task for various biomass and fossil fuels. The fuel cycle includes production[1], combustion in a typical stove, and sequestration during biomass growth for various cooking fuels. Sequestration here is assumed to be 100% of the CO_2 in dung and agricultural residues, as these are assumed to be completely sustainably produced. Eighty percent of the wood and none of the charcoal are assumed to be sustainably harvested in this study [Floor and van der Plas, 1992].

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[1] Precise data for carbon dioxide emissions from production of natural gas, kerosene, coal and dung were lacking and thus excluded. Similarly, data for methane emissions from production of kerosene, coal, and dung were excluded.