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CO_2 Emissions by the Residential Sector: Environmental Implications of Inter-fuel Substitution

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by

Willem Floor and Robert van der Plas
The World Bank

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Summary and Conclusions

Carbon dioxide (CO_2) accounts for 55% of the buildup of greenhouse gases based on radiative equivalence and atmospheric residence time. The most important emitters of CO_2 are fossil fuels and deforestation. Biomass fuels are mainly consumed in the LDCs and provide about 14% of the world's primary energy consumption. From existing forestry policies and legislation, ongoing LPG and other substitution programs and reforestation projects financed by bi- and multi-lateral development agencies it is clear that many Governments, NGOs and staff of international development agencies link deforestation with biomass fuel use, and, therefore want to substitute modern fuels for biomass fuels. These Governments and institutions also assume that fossil fuels, which have a lower carbon content and are combusted more efficiently than biomass fuels, will reduce man-made CO_2 emissions. This paper tries to determine whether this assumption is correct and concludes that it is not.

This paper focusses on the situation in Sub-Saharan Africa because of the importance of the household sector on the emission of CO_2 and other greenhouse gases. This is mainly due to the dominant role that biomass fuels play in the economies of these countries. The authors are aware that, in absolute terms, biomass fuel consumption is higher in Asian countries, but that the prospects for reducing CO_2 emissions through actions in the household energy sector are much less in the Asian countries. Most of the arguments put forward in this paper, nevertheless, also hold for Asian countries.

Based on evidence of CO_2 emissions from household stoves - the major end-use for biomass fuels - and taking into account the complete CO_2 cycle for all of the fuels used (production, conversion, transport, and end-use of fuel), the paper finds that the incremental net volume of CO_2 will usually be ***higher*** in case LDC households substitute hydrocarbon fuels for biomass fuels, with the exception of charcoal. Only charcoal adds more CO_2 than any other fuel and, therefore, should be substituted to the extent possible, based on environmental considerations.

The paper concludes that there is a clear case to carry out so-called household energy strategies in all sub-Saharan countries. These strategies encompass (i) management of the woodfuels supply; (ii) inter-fuel substitution; (iii) energy demand management; (iv) fuel pricing policies; and (v) appropriate institutional arrangements. Finally, the paper also recommends that further research should be carried out to establish a reliable data base on greenhouse gas emissions by biomass-fuelled combustion equipment.

Background

1. The 1989 total estimated CO_2 emissions as a result of human activities is estimated at 5.8 - 8.7 billion metric tons, of which combustion of fossil fuels contributes 71% - 89% and deforestation 10% - 28%. Deforestation stems from population expansion and agricultural activities, as well as from industrial logging and production of commercial firewood and charcoal. Wood does not make a net contribution to the build-up of greenhouse gases as long as the resource is replenished, which is usually the case when firewood is collected but not so, if commercially marketed firewood is being mined.

2. Several gases contribute to the warming of the atmosphere, and their effectiveness ("relative forcing") is different for each gas. It depends on the gas' absorbing characteristics, concentration in the atmosphere, and lifetime. Although the other gases are more potent on a per molecule basis, manmade CO_2 emissions effectively still make up the bulk. According to "Changing by Degrees, Steps to Reduce Greenhouse Gas Emissions" (OTA, Feb. '91), the contribution of each of the manmade greenhouse gases to the relative forcing from 1980 - 1990, is the following:

Table 1: **Distribution of Man-Made Greenhouse Gases**

CO_2	55%
CFCs -11, -12	17%
CH_4	15%
Other CFCs	7%
N_2O	6%

Source: [11]

3. The regional contribution of these gases weighted by their contribution to relative forcings between 1980 and 1990, is the following:

Table 2: **Regional Contribution of Man-Made Greenhouse Gases**

United States	21%
Rest of OECD	23%
Eastern Europe, USSR	22%
China, centrally planned Asia	7%
Other Developing countries	27%

100% equals 5.8 - 8.7 billion metric tons
Source: [11]

4. From these data it is clear that the real culprit will not be found in LDCs but in the industrialized countries. However, the capacity to alleviate the situation can substantially be found in LDC's, i.e. the capacity to regenerate and capture CO_2 from the atmosphere through existing forests and other biomass resources. Given that biomass provides about 14% of the world's primary

energy - mostly for use in LDCs - it makes sense to determine whether substitution of biomass by fossil fuels reduce manmade CO_2 emissions, both from gains in combustion efficiency and reduced deforestation.

5. This paper shows that incremental CO_2 gases to the atmosphere can be reduced by:

(i) ensuring that woodfuel consumption is met from a sustainable biomass resource base; and

(ii) substituting with petroleum fuels that part of the woodfuel consumption that is met from a non-sustainable biomass resource that would not be removed primarily for other reasons (e.g. land clearing for agriculture).

6. Initiating Household Energy Strategies to manage the natural forest cover and stimulate inter-fuel substitution to the extent that this will supplant non-sustainable biomass fuel consumption will reduce incremental emission of CO_2 gases, save foreign exchange by impeding or slowing down biomass fuel substitution with imported LPG or kerosene, as well as protect the environment by promoting sustainable biomass production.

Level and pattern of Biomass Fuel Consumption and CO_2 Emissions

7. As mentioned before, biomass is mainly used in LDCs, particularly in Africa. Its contribution to the total energy use typically ranges from 80% - 90% in poor, 55% - 65% in middle, and 30% - 40% in high-income LDCs. Unfortunately, data on biomass energy consumption are poor, but it is estimated that biomass provides 35% of the energy to about half of the World's population [4]. Although in absolute terms Asian countries consume much larger quantities of biomass fuels than African countries, the focus of this paper is on Africa. This is for three reasons:

(i) biomass dominates the total end-use energy consumption and the household sector is the single largest energy consumer in African countries (60-90%);

(ii) action against the incremental build-up of CO_2 gases in Africa, therefore, is most effective if, and should be taken by, the household energy sector; and

(iii) in most Asian and Latin American countries biomass is not dominant (30% - 40%) and therefore the household sector is not the major contributor of CO_2 gases but the industrial sector is.

Table 3 below shows the biomass share in the total energy consumption for a few selected countries.

Table 3: Woodfuel Use in Several Countries

Country	Woodfuel Consumption 1990 (million ADT 1/)	Biomass as % of final energy consumption
Burkina Fa	6.0	95
Côte d'Ivoir	6.9	65
Etniopia	29.4	96
Ghana	6.2	74
Niger	3.2	86
Nigeria	74.0	65
Senegal	4.7	64
Zambia	[illegible]	64
Africa 2/		74
India		27
Indonesia		48
China		23
Bolivia		18
Peru		18
Brazil		35
sia, Latin America 3/		

1/ ADT: Air Dry Metric Tonne
2/ weighted average; Source: [13]
3/ Source: [10].

8. Most of the LDCs' woodfuel consumption is done in 3-stone open fires, fixed clay stoves, or portable metal 'traditional' stoves. Because of perceived linkages between deforestation and wood use for energy purposes, many Governments and development organizations want to facilitate substitution of hydrocarbon fuels. This view is supported by environmental considerations - particularly health risks for users especially when they cook inside their houses (smoke, CO emissions), and added atmospheric CO_2 emissions when the original wood resource is not replaced/replanted.

9. The urban centers, especially those in Sub-Saharan Africa that consume mainly charcoal, are supplied from land clearings for agricultural purposes as well as from areas that are specifically mined for the production of charcoal. In East-African countries such as Kenya and Zambia about 20% of charcoal production is from mined wood, while in West-African countries such as Senegal, Ghana and Zaire the percentage of mined wood is much higher and may reach 50%. Instead of being reabsorbed during the growth cycle of the renewable biomass resource base, CO_2 gases emitted during carbonization and combustion add considerably to that which has already been accumulated in the atmosphere [see Annex I].

10. Because of the dominant role of biomass fuels in total energy consumption, the contribution of other sectors of the economy to CO_2 emissions is negligible in most African countries. Currently, CO_2 emissions in Senegal, excluding the household sector, are estimated at 0.01 T/capita per year [24]. The estimated amount emitted by the household sector is 0.4 ton per cap/yr, or *40 times higher than the non-household sector* [3]. For the Sahelian countries it is estimated that 28% of the total 15.8 million tons CO_2 emissions add to the global CO_2 balance: mainly from energy use stemming from a non-sustainable biomass resource base.

Table 4: Fuel Use and CO_2 Emissions in Zaire, Senegal, and Sahel

		Zaire	Senegal	Rest Sahel
habitants	million	32.6	7	31
fuel consumption/user				
- charcoal	kg/hab/day	0.5	0.3	0.3
- wood	kg/hab/day	1.1	1	1
- kerosene	liter/hab/day	0.23	0.06	0.06
distribution of fuel use				
% use charcoal		6%	45%	1%
% use wood		93%	48%	97%
% use kerosene		1%	2%	2%
total CO_2 emissions				
- charcoal	million MT	1.0	1.0	0.1
- wood	million MT	14.6	1.5	13.2
- kerosene	million MT	0.1	0.01	0.03
	million MT	15.7	2.5	13.3
	MT/capita	0.48	0.35	0.43

Source: [3]

11. The situation is somewhat different in more industrialized developing countries because of the smaller contribution of household energy to the total energy consumption in these countries. Table 5 shows end-use energy consumption and related carbon emissions in a group of 9 industrialized developing countries [1]. It is shown that in these countries the industrial sector emits three times more CO_2 than the residential sector. Even though the present paper will concentrate on countries where the industrial sector is not yet developed, its conclusions also hold for the more industrialized developing countries.

Table 5: Delivered Energy and Carbon Emissions in 9 Industrialized Developing countries, 1985

Sector	Delivered Energy (Exa-Joules)		Carbon Emissions (Million Tons)	
Industry	19.0	40%	450	56%
Residential	17.8	38%	140	17%
Transport	6.1	13%	120	15%
Services	2.4	5%	60	7%
Agricultural	1.5	3%	40	5%
Other	0.1	-	-	-
Total	46.9	100%	810	100%

Source [14]

12. Table 6 shows energy and environmental characteristics of different household fuels. Traditional fuels as well as substitution fuels are included to allow comparison between these fuels. The end-uses considered in this paper are limited to cooking and water heating, which are the most common and energy intensive household tasks.

[1] China, India, Korea, Indonesia, Argentina, Brazil, Venezuela, Mexico, Nigeria.

Table 6: CO_2 Emissions and Fuel End-Use 1/

	MJ/kg	effic. stove	daily use (kg)	daily use (MJ)	Emissions gr C per MJ	kg C emitted per day	kg CO_2 emitted per day
natural gas	50	50%	1.3	63	15	0.9	3.4
kerosene	46	35%	1.6	71	19	1.4	5.0
coal	24	20%	5.2	125	22.1	2.8	10.1
charcoal	31	25%	3.2	100	28.7	2.9	10.5
wood	16	18%	8.7	139	29.7	4.1	15.1
dung	14	15%	11.9	167	33.9	5.7	20.7
agres	15	15%	11.1	167	31.7	5.3	19.3

based on a 25 MJ_{eff} energy consumption for a household of 7.
Source: [2] [6] [7] [8] [9] [16] [17] [19]

1/ Note: Fuel conversion, transport, CO_2 sequestering are not incorporated in these figures; See Table F_1 and F_2 (Annex 1) for more complete results.

13. As shown, more efficient stove/fuel combinations emit smaller quantities of CO_2 while accomplishing a similar cooking task. Relative to the cleanest fuel (kerosene and natural gas), (char)coal emits typically 2.5 times more CO_2, wood 3.6 times more, and agricultural residues and animal dung 4.8 more. A word of caution: nothing is said here about other emissions such as CO, CH_4, etc; CO_2 emissions are influenced by the quality of the fuel, its carbon content and impurities, as well as the combustion device, its power output, efficiency, etc. Improved biomass stoves tend to have higher CO emissions per kg of fuel than traditional stoves because of a restricted air supply, but effectively use less fuel which reduces the total emissions.

14. However, for a proper environmental comparison, one needs to take into account all factors leading to greenhouse gas emissions. This means that the whole CO_2 cycle needs to be investigated, to identify the net effect on the global CO_2 balance: this includes combustion, but also conversion, transport, and replenishment of the fuel. It is essentially wrong to only consider combustion when comparing different fuels since it is only part of the whole story. CO_2 emissions from using firewood and coal or petroleum fuels cannot be compared by measuring their respective combustion emissions: twigs and dead tree branches are gathered locally while fossil fuels are usually transported over long distanc[illegible] resulting in considerable CO_2 emissions from operating trucks and tankers.

15. Similarly, it is n[illegible] adequate to look at CO_2 emissions from charcoal combustion, while substantial additional emissions are made during the carbonization process. Other noxious gases are emitted during extraction and refining/conversion: CO is emitted along with CO_2; although it strongly depends on the stove characteristics, in general the higher the power output, the higher the CO/CO_2 coefficient (for wood, a figure of between 5% and 10% is normal [volume percentage]); about 3.5% of natural gas production is emitted into the atmosphere [23] which means that for every kg of natural gas used, 35 g CH_4 is emitted. Similarly, charcoal production causes several gases to escape: emissions per kg of charcoal produced (in a relatively modern charcoal kiln) are 1.35 kg of CO_2, 0.70 kg of CO, 0.17 kg of CH_4, and 0.01 kg of H_2 [1]. Figures for kerosene and coal are not known at this time. More data are needed on this subject; the current document only considers combustion and conversion for as far data are available. A sensitivity analysis (see

Annex IV) is done to investigate the importance of the missing data. However, transport has *not* been taken into account which gives a bias in favour of petroleum fuels and to a lesser extent to charcoal.

16. Biomass fuels, particularly non-commercial fuels such as wood, agricultural residues and animal dung, as well as commercial biomass fuels if grown on a sustainable basis, do not, in principle, contribute to net *additional* CO_2 emissions. Wood is grown through photosynthesis while capturing CO_2 from the atmosphere, which is again released during combustion. For the global CO_2 balance, it makes no difference whether wood decomposes naturally or is burnt in a stove (note: this is valid for the CO_2 balance but not when looking ay, the Carbon balance: when wood decomposes naturally, CO is emitted as well which is a much more dangerous greenhouse gas than CO_2). As long as the fuel stems from sustainable production, the normal CO_2 cycle is undisturbed. This is also the case with agricultural residues and animal dung as long as the build-up of organic matter in the soil is not disrupted. In this paper, it is assumed that 80% of all wood consumption stems from sustainable resources, 20% is mined for commercial purposes which results in net atmospheric CO_2 increments. The sensitivity analysis in Annex IV provides more details on this assumption.

Available Options to Reduce CO_2 Emissions by the Household Sector

17. The dominant role of the urban household sector as a CO_2 emittor as well as the increasing consumption of charcoal in hitherto wood consuming cities in combination with the high urban population growth (it doubles every decade whereas the national population doubles only every 25 years) require the need to slow down urban CO_2 emissions. However, action in this area has until now been skimpy and haphazard. In fact, the only ongoing comprehensive Household Energy Strategy (HES) project is in Niger and what often has been labelled as such are but single issue actions (stoves, charcoal production, etc.) or are disconnected multi-issue interventions, and unfortunately often proved to be failures.

18. To play a meaningful role in the development of more environmentally benign situation to supply and use household fuels, it is necessary that both the public and private sectors in developing countries develop and assess realistic household energy strategies particularly in Sub Saharan Africa.

19. To achieve the interconnected goals outlined in an HES, such as protection of the natural resource base, energy conservation, and consumer satisfaction, the following operational elements come into play: (i) better management of the woodfuels supply; (ii) inter-fuel substitution; (iii) energy demand management; (iv) fuel pricing policies; and (v) appropriate institutional arrangements. The HES is restricted by realistic expectations of growth in the country's economy and its financial resources. The following paragraphs provide more details on the generic components of an HES.

Better management of the woodfuels supply

20. To help ensure that urban wood supplies can be maintained on a sustainable basis which minimizes incremental CO_2 emission, schemes for the systematic management of the local resources

and environment need to be developed. The lack of financial and other resources places this task beyond the capacity of the forestry services in most LDCs. As a result, if management and protection is to take place, it will require an effective devolution of control to local people and communities. This means that local people need to have secure rights to an adequate return from the resources that they are managing. Questions of land tenure and revenues will therefore have to be resolved in a manner satisfactory to the rural populations involved. To encourage local population to manage the supply of woodfuels rationally [2], a regulatory framework should be created which induces rural managers and urban traders to behave in an environmentally sound manner. The government should use administrative and fiscal policies to provide the necessary incentives to support this more rational situation. Using the fiscal mechanism, such a system will provide additional revenues, which governments should use to improve the effectiveness of the forestry service or other mechanisms for productive investment in the rural areas.

Inter-Fuel Substitution

21. Rising standards of living among urban dwellers, including changing urban diets and cooking habits, will inevitably lead to a greater use of modern fuels. By anticipating and directing the change in the fuel mix and fuel savings, an optimum allocation can be achieved with minimal incremental $C0_2$ emissions. However, the possibility of climbing the energy ladder will be very limited in the short run since average incomes in most poor LDCs will not increase greatly. Even keeping energy services at current levels will become very difficult in the middle income LDCs, where fuel substitution has already made great progress, often as the result of heavy subsidization.

22. Continuing to use biomass fuels is in the national interest, for it prevents foreign exchange expenditures on imported oil products when urban households switch to modern petroleum based fuels. Woodfuel consumption in the LDCs is about 1,070 million TOE [12], of which 80% is used for cooking. If current urban cooking demand (or about 1/3 of total demand) was substituted for modern fuels, then 80 million TOE (570 million barrels of oil) would be required. This implies a 10% increase in total annual oil demand by LDCs and an additional $11,400 million per year at $20 per barrel of crude oil.

Energy Demand Management

23. Managing the demand of energy, in addition to substitution, comes down to one activity - conservation. Measures can be taken to reduce fuel consumption by promoting more efficient use of households fuels through the utilization of more efficient end-use equipment such as stoves, ovens, lamps, water heaters and air-conditioners. That this is more than a hope or a promise has been demonstrated by a number of stove programs in for example Kenya, Mali, Niger and Rwanda. Experience from these and other end-use savings programs also demonstrated the need for financing or leasing schemes to facilitate the purchase c.q. use of these more efficient devices.

Fuel Pricing Policies

24. The pricing and fiscal mechanism should be used to guarantee that the market price of household fuels reflect their economic cost to the nation. Adequate stumpage fees can be assessed and woodfuel and/or transport taxes can be collected at the city limits so that the real cost of

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[2] See e.g. [25] for issues related to improving the charcoaling efficiency.

sustainable fuelwood production is incorporated in the final price of woodfuels. Household fuels should attain price levels that are affordable to the consumer, while encouraging conservation and/or interfuel substitution.

Appropriate Institutional Issues

25. The comprehensive scope of activities to reduce $C0_2$ emissions as outlined above are to control forest cover exploitation to satisfy rural energy needs, to meet urban energy needs in part, to avoid environmental degradation or at least to keep it within acceptable limits, and to provide rural and urban employment. This will require, at the national level, the institutional capacity to decide where wood should be harvested, provide for regeneration of stocks, and ensure that regeneration and management cost are covered, and monitor that the various policies are efficiently implemented.

Fuel Substitution - Environmental Implications

26. Environmental implications from inter-fuel substitution can be determined as follows (see Annex I). Section A shows the amount of each fuel used (first column) to satisfy a specific cooking task and the amount of $C0_2$ emitted (column 2). Sections B through D are required to calculate the net relative forcing for each of these fuels taking into account the complete $C0_2$ cycle (except transport). Section E shows the net result. Section F_1 shows the amounts of each fuel required to replace 1 kg of wood (first column), and the resulting net forcing: environmental benefits are exclusively obtained in case of agricultural residues and animal dung. Petroleum fuels, coal or charcoal only result in higher net emissions, which would be higher if transport emissions were incorporated. Section F_2 shows the amounts of each fuel required to replace 1 kg of charcoal: substitution of charcoal makes environmentally sense for *all* fuels, however, higher benefits are obtained with agricultural residues, animal dung and firewood than with petroleum fuels. Constraints to effectively implementing these substitution options include financial, technical and social implications which are not considered here.

27. This section discusses a theoretical model to calculate a country's total $C0_2$ emissions resulting from energy use in the residential sector - which in LDC is the major source of $C0_2$ emissions. Data from an 'average' West African country are used in this analysis. Three cases are considered:

(i) the 1990 situation (see Table 7);

(ii) a "trend scenario" for the year 2000, in which no corrective action is undertaken (such as implementing a household energy strategy); the average annual population growth is 2.5% (see Table 8); and

(iii) an "action oriented scenario" for the year 2000, in which corrective action was undertaken and households were urged to start using different fuels (see Table 9); the population growth is the same as with the trend scenario.

28. It is shown that, first of all, 75% of the emissions stem from the urban areas, even though only one-third of the population lives there. Secondly, if no action is undertaken, the fuel use patterns will shift over time and more emissions will result due to increased utilization of charcoal and modern fuels such as kerosene and gas; action recommended under a household energy strategy will effectively reduce $C0_2$ emissions to the point that it will slow down incremental emissions due to population growth. Thirdly, realistic inter-fuel substitution programs can reduce emissions by approximately 25%. Fourthly, by far the most $C0_2$ emitting fuel is charcoal; improved charcoal stove programs can reduce emissions from charcoal combustion by another 30% or so.

Table 7: Current 1990 Scenario

Country Population		6.7 million	
-urban	33.0%	2.211 ,,	
-rural	67.0%	4.489 ,,	
Energy use	urban	net CO_2 forcings	
gas	35%	209 kT/yr	
kerosene	0%	0 ,,	
charcoal	54%	1,883 ,,	
wood	11%	37 ,,	
total		2,128	75%
Energy use	rural		
kerosene	0%	0	
wood	83%	570	
charcoal	2%	142	
agres	15%	0	
total		712	25%
urban + rural		2,840	100%

data for a fictive, "average" Sub-African country

Table 8: Substitution Scenario 2000

Energy use	urban	net CO_2 forcings	
gas	40%	412	
kerosene	20%	194	
charcoal	31%	1,833	
wood	5%	30	
agres	5%	0	77%
total		2,469	
Energy use	rural		
kerosene	2%	24	
wood	76%	548	
charcoal	2%	149	
agres	20%	0	23%
total		721	
urban + rural		3,190	

Table 9: Trend Scenario 2000

Energy use	urban	net CO_2 forcings	
gas	40%	412 kT/yr	
kerosene	0%	0 ,,	
charcoal	54%	3,299 ,,	
wood	6%	20 ,,	
total		3,747	84%
Energy use	rural		
kerosene	2%	24	
wood	76%	548	
charcoal	2%	149	
agres	20%	0	16%
total		721	100%
urban + rural		4,468	

Policy Implications

29. The most important conclusion is that household energy consumers in Africa should continue to utilize biomass fuels for as long as the resource is replenished, with the exception of charcoal. However, if the use of biomass fuels implies mining of wood, it is advantageous to use petroleum fuels. If such a pattern of energy consumption, moreover, is embedded in a national

household energy strategy, the environmental impact goes beyond the reduction of $C0_2$ emissions. Implementation of such a policy will also safeguard the remaining natural forest cover, save foreign exchange, and nevertheless allow gradual and affordable inter-fuel substitution.

30. Although the gas emission data given in Annex I are robust, we nevertheless recommend that further additional research be done to establish a better data base. After all, the data given here were not produced with a view to environmental issues, but rather to measure the quality of combustion. This research effort need neither cost much money nor take much time and could be executed by any well equipped laboratory. It is recommended that data on C0, CH_4, N_2O etc. be collected at the same time.

ANNEX I - CO_2 Emissions and Fuel Use

The following tables show emissions as a result of fuel use for cooking. Each table is based on a standard cooking task for a 7 person household. Section A shows the different fuels and how much of it is used during this standard cooking task. It also shows how much CO_2 is emitted for this task, and how much CO_2 is emitted per kg of fuel used. It is shown that (when only combustion is considered) petroleum fuels effectively emit 30% to 75% less CO_2 than biomass fuels during the same cooking task. Among biomass fuels there is a wide disparity, with charcoal emitting twice as much CO_2 as dung or agricultural residues (agres) for the same cooking task. The difference in stove efficiency accounts for most of these variations.

A COMBUSTION

	fuel used (kg)	kg CO_2 emitted	kg CO_2 /kg fuel
natural gas	1.0	2.8	2.8
kerosene	1.6	5.0	3.1
coal	5.2	10.1	1.9
charcoal	3.2	10.5	3.2
wood	8.7	15.1	1.7
dung	11.9	20.7	1.7
agres	11.1	19.3	1.7

As mentioned earlier, the complete CO_2 cycle needs to be taken into account for an accurate comparison. Therefore, production/conversion of the fuels and sequestration (capturing) are considered also. Section B shows the production aspects of the different fuels and concentrates on CO_2 and CH_4. It shows emissions per kg of fuel produced; unfortunately several blanks exist in this table. A rule of thumb shows that approximately 3.5% of the natural gas escapes into the atmosphere during production, which also holds for LPG. The refining process will also emit certain gases into the atmosphere, but which at this point in time are not taken into account. The process of charcoal production could be closely examined and Annex III gives more details.

A second table could be constructed for transport, based on the average transport distance of the different fuels and the mode of transportation. That has not been done for now.

B PRODUCTION 1/

	kg CO_2	kg CH_4
natural gas	?	0.04
kerosene	?	?
coal	?	?
charcoal	1.35	0.07
wood	0	0
dung	?	?
agres	0	0

1/ kg of gases emitted per kg of fuel produced/converted
? precise data are lacking

Section C is the result of combining A and B, and represents the total emissions of CO_2 and CH_4 during production and end-use of these fuels. Emissions during transport have been excluded.

C

TOTAL emission 1/		
	kg CO_2	kg CH_4
natural gas	2.7	0.04
kerosene	3.1	0.00
coal	1.9	0.00
charcoal	4.5	0.07
wood	1.7	0.00
dung	1.7	0.02
agres	1.7	0.00

1/ kg of gases emitted for the cooking task

Section D shows sequestering capacity of the different fuels: how much CO_2 can be captured per kg of fuel used. Fossil fuels do not sequester at all, nor does charcoal [3]. Dung and agricultural residues merely recycle CO_2: there is no difference to the CO_2 balance whether or not they are used as fuel. Wood does normally not add CO_2 to the balance if it stems from a sustainable source. In this case, 20% of the wood consumption is assumed to contribute to deforestation and hence, cannot be considered a sustainable resource.

D

SEQUESTERING 1/	
	kg CO_2 per kg fuel
natural gas	0
kerosene	0
coal	0
charcoal	0
wood	1.4
dung	1.7
agres	1.7

1/ kg of gas captured per kg of fuel

Section E shows the net result of sections A through D, whereby a relative forcing of 70 for CH_4 is taken into account. As mentioned before, different gases have a different impact on global warming, and their 'effectiveness' consequently varies.

E

NET emission 1/	
natural gas	5.1
kerosene	3.1
coal	1.9
charcoal	9.4
wood	0.3
dung	0.0
agres	0.0

CH_4 is 70 times as effective as CO_2 (on a per kg basis) in capturing heat in the atmosphere [23].

1/ kg of CO_2 equivalent emitted per cooking task

[3] The main reason is that in most countries charcoal production is a highly organized commercial activity which contributes to deforestation since often mainly wood from non-sustainable sources is used.

Section F shows the $C0_2$ emissions (net forcings) for substitution of different fuels for wood (F1) and for charcoal (F2). It shows that substitution of wood is not worth the effort from an environmental point of view, while substitution of charcoal is worth every effort.

F_1 **substitution relative to wood**

	kg of fuel to replace 1 kg of wood	net additional emission
natural gas	0.12	0.25
kerosene	0.18	0.22
coal	0.60	0.79
charcoal	0.37	3.16
wood	1.00	0.00
dung	1.37	-0.34
agres	1.28	-0.34

F_2 **substitution relative to charcoal**

	kg of fuel to replace 1 kg of charcoal	net additional emission
natural gas	0.31	-7.8
kerosene	0.48	-7.9
coal	1.61	-4.4
charcoal	1.00	0.0
wood	2.69	-8.5
dung	3.69	-9.4
agres	3.44	-9.4

ANNEX II - Wood Composition

The typical chemical composition of wood as measured through ultimate analysis is shown in the following Table (given as percent of bone dry weight):

wood	mole	hardwood	bark	softwood	bark
C	12	50.8%	51.2%	52.9%	53.1%
H	1	6.4%	6.0%	6.3%	5.9%
N	14	0.4%	0.4%	0.1%	0.2%
O	16	41.8%	37.9%	39.7%	37.9%
S	16	0.0%	0.0%	0.0%	0.0%
ashes	28	0.6%	4.5%	1.0%	2.9%
		100.0%	100.0%	100.0%	100.0%
weight of one mole		25.7	26.5	24.7	25.1

If one assumes that wood contains 10% bark, the average mole weight (average for soft and hardwoods) equals 25.3 g. In other words, one mole of a "wood molecule" which contains exactly one mole of Carbon (C), weighs 25.3 g. This is a simplification of the real chemical world, but can be used as a first approximation to describe the problem.

<u>Charcoal Composition</u>

The chemical composition of charcoal through ultimate analysis is the following (presented as percentage of bone dry weight):

charcoal	mole	composition	mole weight
C	12	90.2%	10.8
H	1	2.4%	0.0
N	14	0.8%	0.1
O	16	2.9%	0.5
S	16	0.8%	0.1
moisture	18	2.0%	0.4
ashes	28	1.0%	0.3
		100.0%	12.2

This means that one mole of a "charcoal molecule" which contains exactly one mole of Carbon, weighs 13.5 g (12.2 / 90.2%).

Combustion of Fuels

The following figures are theoretically calculated on the basis of the following chemical reaction:

$$1 \text{ mole "wood"} \rightarrow 1 \text{ mole } (x\%\ CO_2 + (1-x\%)\ CO), \text{ whereby } 0 \leq x \leq 1.$$

A "wood molecule" in this case is characterized by its chemical composition based on ultimate analysis, and normalized to contain one mole of C atoms. A mole of such a wood molecule weighs approximately 25 g. The figure x is chosen according to what was most often reported in the literature, 5% for kerosene, 8% for wood, and 12% for charcoal. With these figures, one can calculate how many kg of CO and CO_2 are emitted if one kg of fuel is completely burnt:

	$[CO/CO_2]$	CO_2 (kg)	CO (g)	unit
kerosene	5.0%	2.3	79	l
wood	8.0%	1.2	65	kg
charcoal	12.0%	2.9	248	kg

The following Table gives the fuel requirements for a cooking task which requires 25 MJ_{eff} to complete, as well as the resulting CO_2 and CO emissions:

	use (MJ_{eff})	eff stove %	use (unit)	CO_2 (kg)	CO (g)
kerosene	25	45%	1.6	3.7	125
wood	25	18%	7.7	9.0	500
charcoal	25	25%	3.0	8.7	753

Two relationships have been observed describing the emission of gases during combustion:

(i) the CO/CO_2 ratio as a function of the power of the stove (Fig. 1); and

(ii) the CO emissions as function of the power of the stove (Fig. 2).

These relationships have separately been documented by Bussmann [2] and Prasad [6] and have been measured for a large number of different wood stoves. One can conclude from these data that: (i) the higher the power of the stove, the more emissions occur (both CO and CO_2); and (ii) each stove has an optimum for which the ratio of CO/CO_2 is minimal; for most stoves this stays within the range of 4 - 5 kW.

For the current comparison, a 5 kW woodstove is taken which emits 26 mg/s of CO and 600 mg/s of CO_2. Such a stove uses 0.09 kg/s of wood, and delivers effectively approximately 0.75 - 1.0 kW_{eff}.

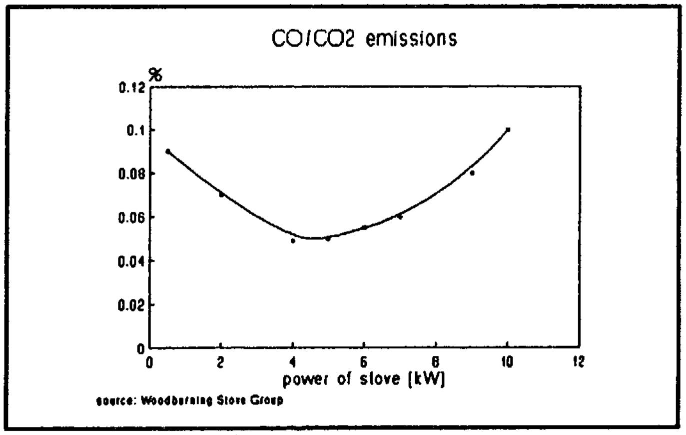


Figure 1 [2], [6]

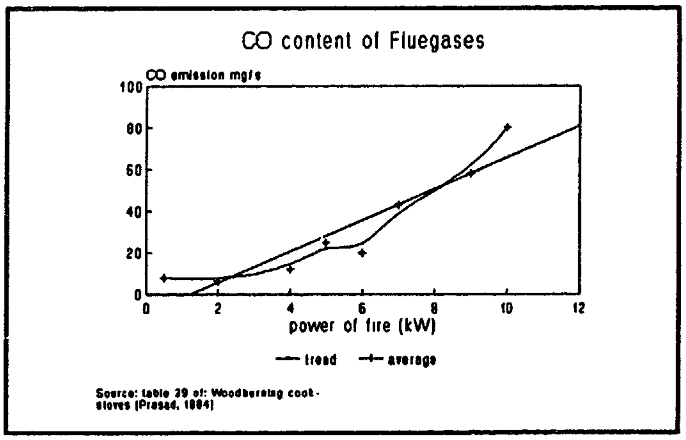


Figure 2 [7]

ANNEX III - Charcoal Production

One kg of wood results [1] (under laboratory conditions, 500 °C) in 0.31 kg of charcoal with a fixed carbon content of 90%. The remaining volatiles (0.69 kg) were measured and have the following composition:

compound	volume	weight
CO_2	42.7%	0.418
CO	34.8%	0.217
CH_4	14.8%	0.053
H_2	5.4%	0.002

Per kg of charcoal produced, the following emissions are r ·: 1.35 kg of CO_2, 0.70 kg of CO, 0.17 kg of CH_4, and 0.01 kg of H_2. In practice, charcoalers obtain conversi. · fficiencies of approximately 10% - 20% (on a weight basis) compared to the 31% of the above example. This means that emissions in practice will be substantially higher, although it is difficult to estimate the total without further measurements.

ANNEX IV - Sensitivity Analysis

This Annex provides the result of a limited sensitivity analysis which looks at the most important factors introducing a certain degree of uncertainty. The first two factors, the rate of urbanization, and the fuel use pattern, are investigated for the trend scenario (no corrective activities undertaken): the current rate of urbanization of 33% is varied between 33% and 50% for the year 2000, and it is shown that emissions rapidly increase with the degree of urbanization. Similarly, a reduction of traditional fuel use in urban areas (mainly charcoal, and to a limited extend wood) from the current 65% in 1991 to 60% and 55% in 2000 results in substantial higher $C0_2$ emissions.

Figure 3

HIGHER CO2 EMISSIONS WITH URBANIZATION
trend scenario

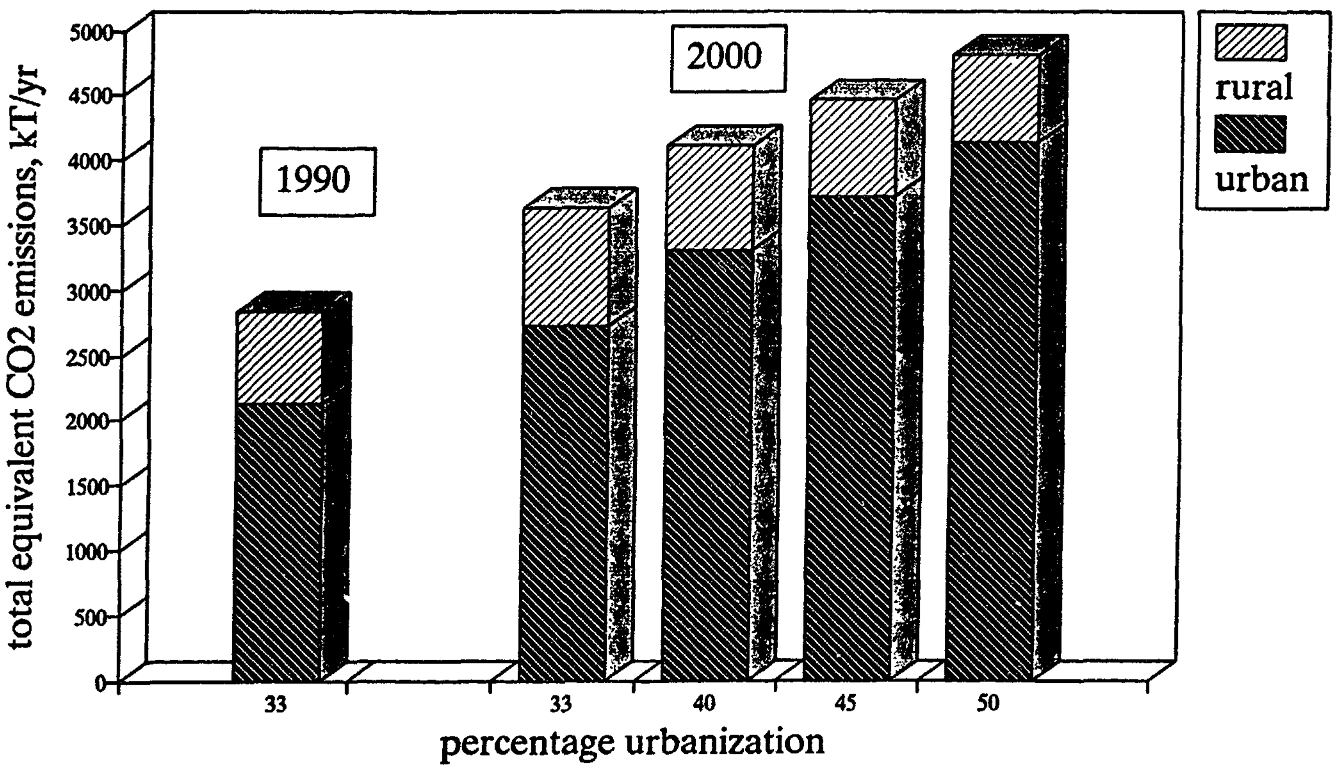
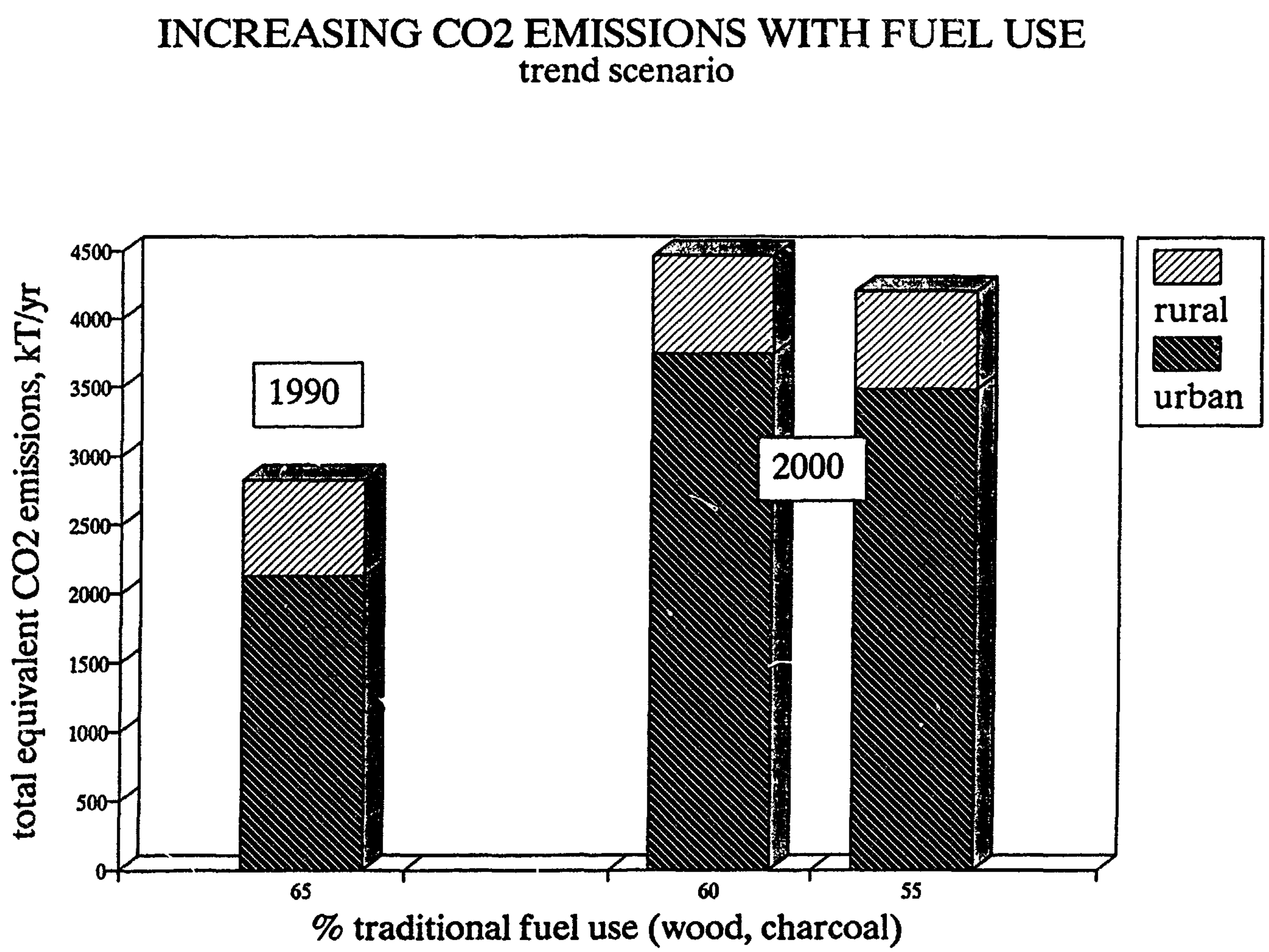


Figure 4


INCREASING CO2 EMISSIONS WITH FUEL USE
trend scenario
total equivalent CO2 emissions, kT/yr
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1990
2000
rural
urban
65
60
55
% traditional fuel use (wood, charcoal)

In case of the substitution scenario, two cases are considered: (i) for a constant charcoal use pattern (30% of the households), the use of fossil fuels is changed from 55% to 65%. It is shown that it does not have a large influence on the total CO_2 emissions; (ii) improved charcoal stoves are used from 0% to 30% among charcoal using households; it is shown that the total amount of CO_2 emitted greatly varies with the dissemination rate.

Figure 5

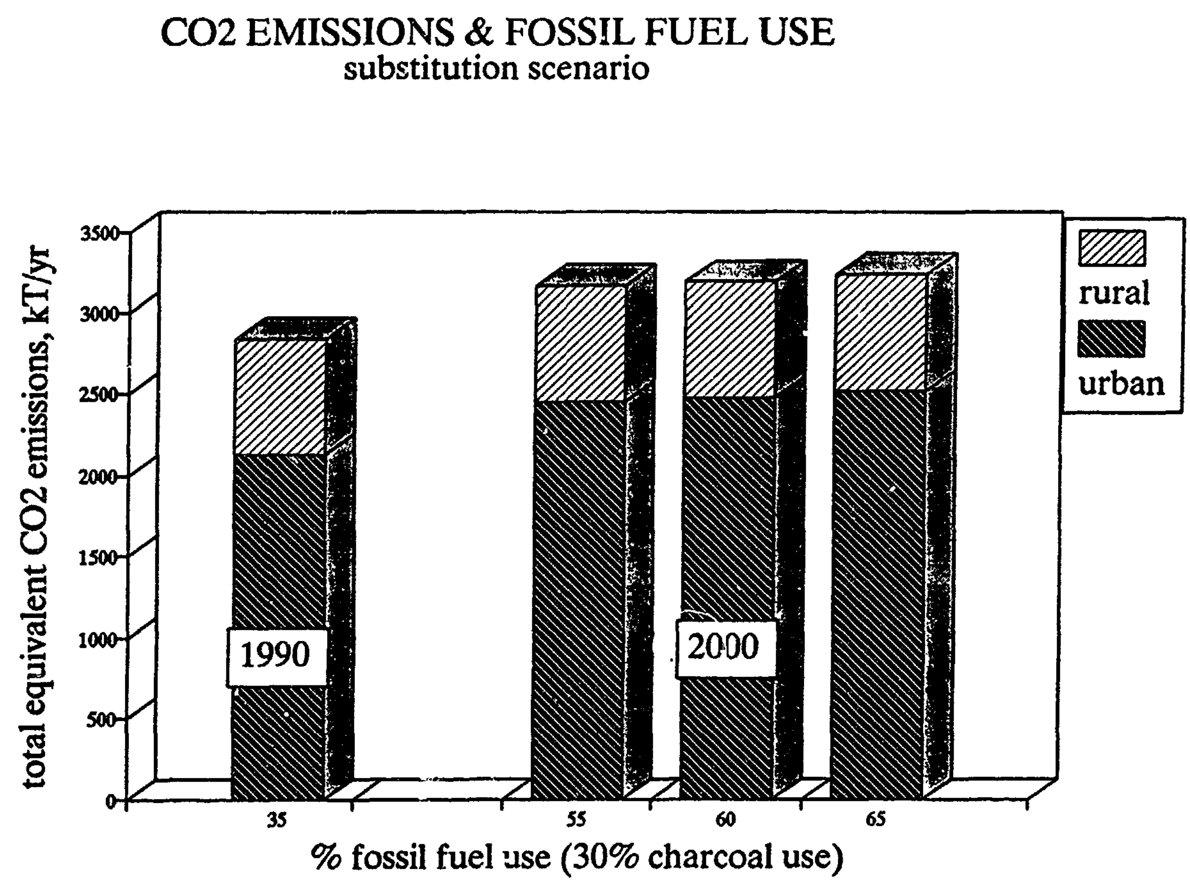
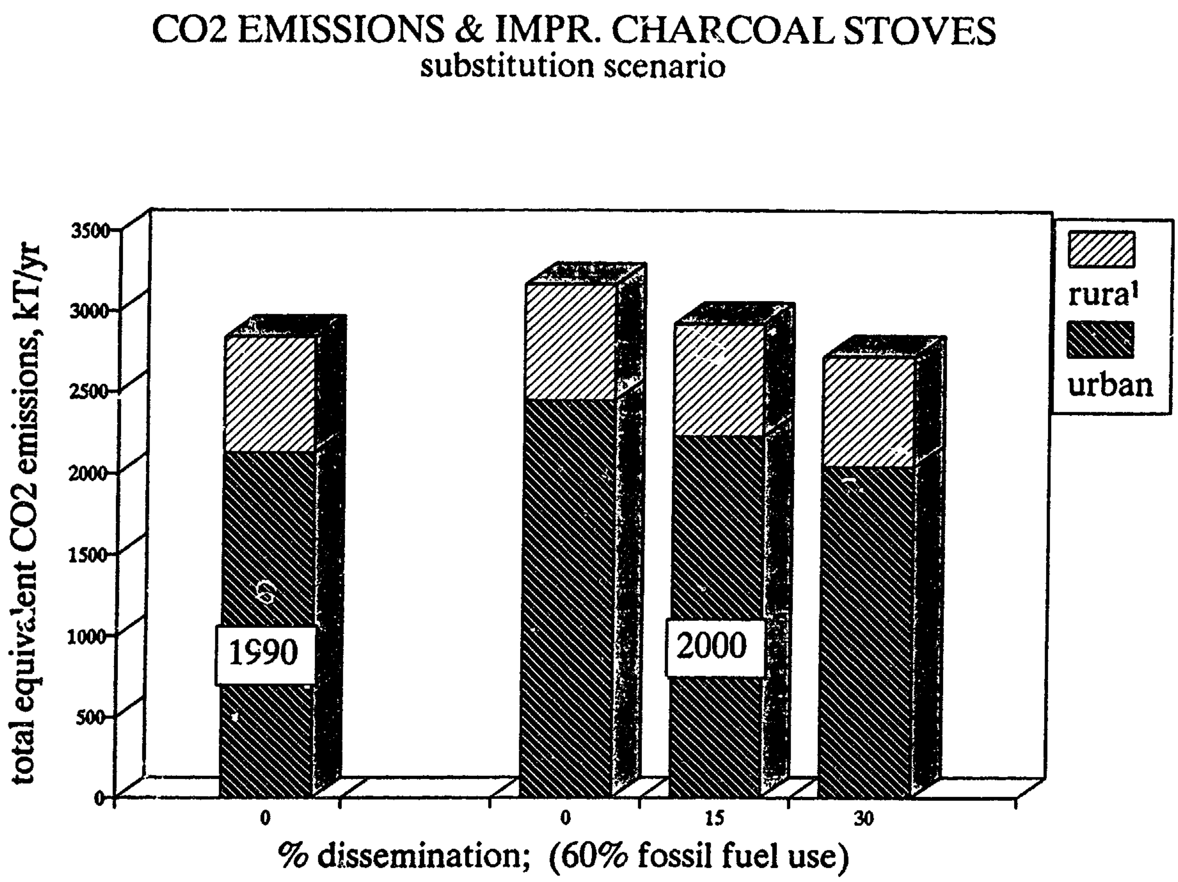


Figure 6

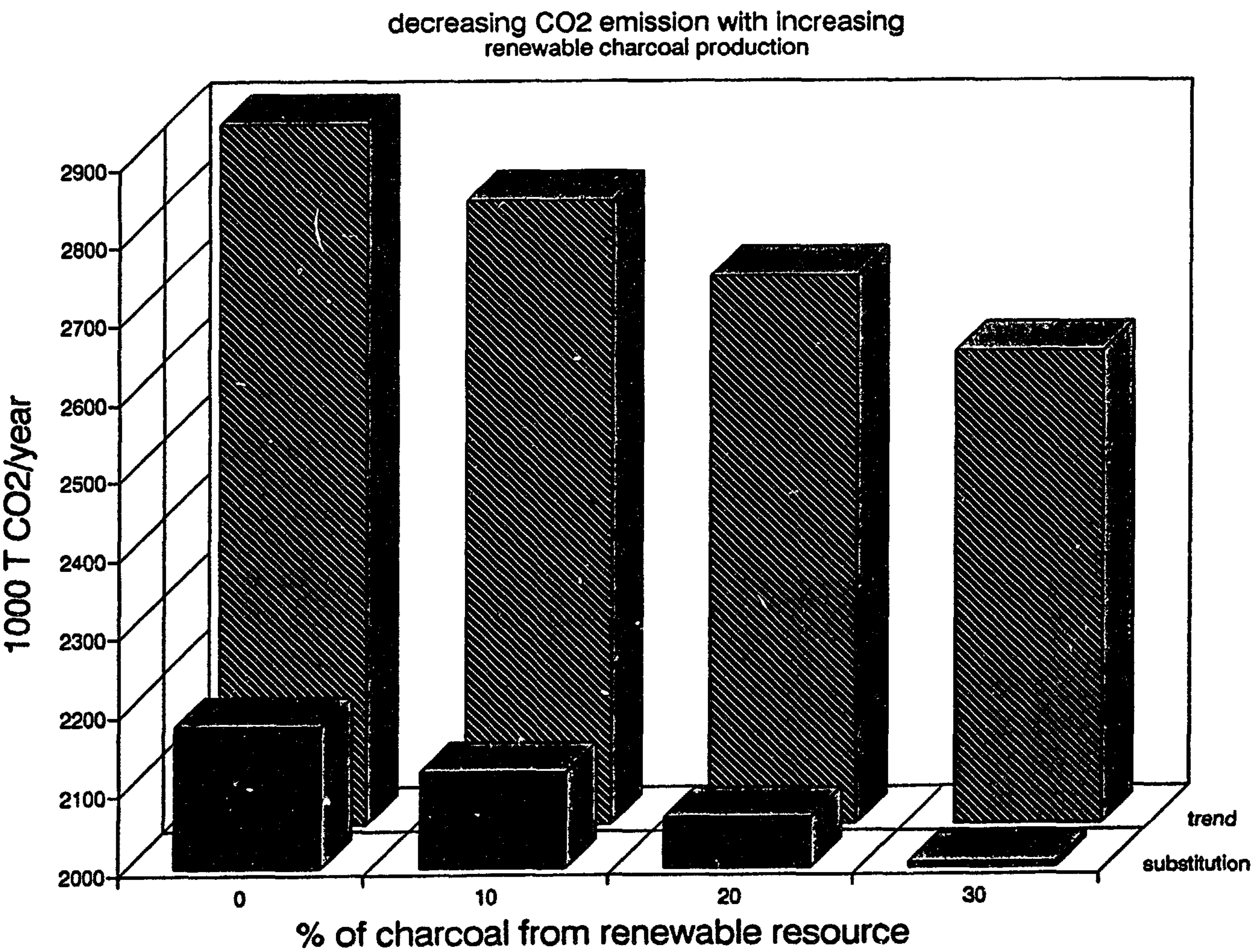

CO2 EMISSIONS & IMPR. CHARCOAL STOVES
substitution scenario
total equivalent CO2 emissions, kT/yr
3500
3000
2500
2000
1500
1000
500
0
1990
2000
rural
urban
0
0
15
30
% dissemination; (60% fossil fuel use)

The last factor of importance, viz. the degree of mining of wood resources is discussed below. The analysis in the paper assumed a charcoal production method in which wood is used in an unsustainable manner: it therefore has environmental consequences. This assumption can be questioned, and a sensitivity analysis has therefore been carried out to determine the importance of the use of mined wood vs wood produced sustainably for charcoal production.

If 30% of the wood used for charcoal production stems from sustainable resources, i.e. when wood is replanted to make up for 30% of the wood cut for making charcoal, or when agricultural crops are planted on the clear cut area, this reduces the total additional equivalent CO_2 emissions by about 5% to 6%. See Figure 5 which presents the total additional CO_2 emissions when wood for charcoal production is cut from sustainable sources for 0%, 10%, 20% and 30%.

The reason why total CO_2 equivalent emissions are not very sensitive to the sustainability of wood for charcoal production is that during the carbonization process other gases than CO_2 are emitted, which occur in much more limited quantities when wood rots or is burnt directly in a simple cooking stove. These gases amount for more than half of the CO_2 equivalent emissions of the production process. Therefore the assumption used in this paper, that charcoal is mined for 80%, is quite reasonable.

<u>figure 7</u>



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