Producer Gas, Economic Development and the Role of Research

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PU/CEES Report No. 187

April 1985

the
center for
energy and
environmental
studies

princeton university

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Producer Gas

Producer gas, a synthetic gas deriving its name from the "gas producer" in which it is made, is a combustible mixture of gases -- primarily carbon monoxide, hydrogen, carbon dioxide, and nitrogen -- having a heating value 10-15% that of natural gas (hence its French name "poor gas"). While of lower heating value than natural gas, it is a far higher quality fuel than the biomass from which it is derived. It can be made from essentially any solid biomass feedstock, including charcoal, wood and crop residues, through an operationally simple thermochemical conversion process (Kaupp and Goss, 1981; Reed, 1979). The use of producer gas dates back well into the 1800s, although it had fallen into disuse in the three decades following WWII due to the ready availability and low cost of gaseous and liquid fossil fuels (Kaupp and Goss, 1981).

Worldwide interest in producer gas has been renewed as a result of the dramatic increase in the world oil price over the last decade. Interest is particularly high in developing countries, many of which already spend a large fraction of their export earnings on oil imports (see Table 1). In most developing countries there are biomass supplies that could be used as feedstocks for gasification, and in fact biomass used directly in solid form is already a major source of energy (see Table 2). Producer gas as an alternative to solid biomass is a more versatile, more convenient to use fuel, which can often be used more efficiently than raw biomass, in readily available combustion devices.

Producer Gas For Industrial Boilers: The most successful recent application of producer gas has been as a replacement for oil or natural gas in industrial boilers (1). Gasifiers for boiler operations (with rated wood inputs in the range 10 to 150 tonnes/day) are typically 85-90% efficient (Reed, Jantzen, Corcoran and Witholder, 1979). In the US, the capital cost of retrofitting an industrial oil-fired boiler for producer-gas operation (which involves installing a new burner and coupling a gasifier to the boiler) is of the order of 2/3 of the alternative of installing a new wood-fired boiler (Reed, Jantzen, Corcoran and Witholder, 1979). Retrofits of gasifiers to boilers at forest-products industries in North America, in locations where wood costs are relatively low, have led to significant total annual cost savings over continued oil or natural gas use in the systems they replaced (Hodam, Williams, and Lesser, 1982).

In addition to the forest-products industry in North America, a number of Brazilian industries (ceramics, cement, lime, baked food) are also using gasifiers for industrial heat production (Furtado and Antunes, 1985). The use of producer gas in industrial heat applications is currently largely restricted to the US, Canada, and Brazil, in locations where wood feedstocks are relatively inexpensive and abundant enough to support the large scale operations involved.

Producer Gas For IC Engines: Producer gas is also an attractive fuel for internal combustion (IC) engines, particularly in remote areas of developing countries where the IC engine powered by gasoline or diesel fuel has already proven itself as a versatile, durable technology capable of providing small amounts of power as needed, e.g., for irrigation, electricity generation, motive power, or for cottage industries and agricultural processing facilities (2). In dispersed rural areas of LDCs, petroleum fuels (frequently imported) are often expensive and subject to disruptions in supply, if they can be obtained at all. A biomass-derived fuel like producer gas, therefore, is an attractive alternative in many cases, primarily because of its lower cost and the widespread availability of biomass feedstocks. The producer gas generators needed for IC engines are much smaller than those required for typical industrial boilers, requiring biomass inputs in the range 0.01 to 10 tonnes per day.

Biomass-derived liquids (e.g., ethanol or methanol) can also be substituted for gasoline or diesel fuel in IC engines. Operation on producer gas, however, is significantly cheaper than either ethanol or methanol at the small scales and high load factors typical of engines (3).

Producer gas used in engines -- sometimes called "suction gas" because the engine suction is used to draw the required combustion air into the gasifier -- has a history dating back well before 1900 (National Research Council, 1983; Solar Energy Research Institute, 1979). Its use peaked worldwide during WWII when petroleum fuels for civilian vehicles were scarce. By 1944, more than 80% of trucks and other large vehicles and 26% of all civilian automobiles (260,000 cars) in Europe were running on producer gas (National Research Council, 1983). Interest in producer gas for engines waned following the war, but rose again with the world oil price in the 1970s. Over 800 charcoal-fueled producer gas generators have been sold commercially in the Philippines since 1981 and a number of charcoal-fired units are also in use in Brazil (Foley and Barnard, 1983).

<u>Producer Gas For Cooking</u>: Producer gas is also attractive as a potential cooking fuel, particularly in developing countries, in which some 2 billion rural dwellers currently depend on solid biomass for almost all of their cooking needs. Traditional wood and charcoal cookstoves have very low end-use efficiencies (typically 10-15%), so that much of the biomass used in

these countries today literally goes up in smoke. Several improved wood cookstoves have been designed that cut by as much as 1/2 the wood needed for cooking, (Geller, Baldwin, Dutt, Ravindranath, 1985), but using gaseous cooking fuels would probably lead to an even greater decrease in fuelwood demand that could help further ameliorate the "fuelwood crisis" that exists in many areas in the developing world today (Eckholm, Foley, Barnard, and Timberlake, 1984).

As shown in Figure 1, the current energy consumption for cooking with wood in developing countries ranges from 1/2 to 1 tonne per person per year (or 250-500 continuous Watts/person), while in developing and industrialized countries alike, cooking with gaseous fuels typically requires only 50-60 watts/person -- a 5 to 10-fold reduction in final-energy use. The energy savings apparently arises from the greater efficiency and from the greater controllability of gas stoves. Aside from the energy savings, cooking with gas instead of wood represents an increase in living standard, because it brings with it a number of other benefits: reductions in smoke and particulate levels in the kitchen, greater control of the flame, decreased risk of burns, shorter cooking times, and less time involved in collecting cooking fuel (4).

Producer gas has apparently never been widely used for cooking, although it is currently being used in a few isolated installations (5). However, a coal-derived gas containing the same major combustible components as producer gas (carbon monoxide and hydrogen) was used in a number of cities around the world in the 1800s and early 1900s. Today, this so-called "town-gas" is used in Calcutta (Williams, 1985), Beijing, where 60% of the households use it for cooking, and Shanghai, where 40% of the households use it (Zhu, Brambley, and Morgan, 1983). The existence of these town-gas systems suggests the feasibility of using producer gas on similar scales. While developmental work in China on biomass gasifiers for cooking which consume wood at a rate of only 2-8 kg/hr (Xu, Luo, Zhou, Cai, and Yan, 1983), suggest that it may be feasible to make producer gas at the individual household level as well.

Producer Gas and Deforestation

Gasifiers and Fuelwood Supplies: Much of the biomass fuel now consumed in many developing countries is used for cooking in traditional, inefficient stoves. The cutting and gathering of fuelwood to meet the cooking demands of a rapidly growing population is intensifying the pressure on biomass resources already being depleted by tree-felling (to create agricultural land and for use as commercial timber), fodder collection for animals, and widespread fires during the dry seasons (Eckholm, Foley, Barnard, and Timberlake, 1984). Deforestation is a major factor behind soil erosion, river siltation, desertification, and other environmental degradations.

Substantial savings in biomass used for cooking would probably result from widespread switching to gasified biomass, thereby slowing the process of deforestation. If switching to gaseous cooking fuels were combined with successful fuelwood-growing programs, large quantities of biomass could also be made available to displace the use of imported oil in existing applications for which petroleum is used and to support the expanded use of IC engines, or other devices that require high quality fuels.

Widespread use of gasifiers would require the development of fuelwood resources, but the conversion of solid biomass into a high quality gaseous energy carrier will add considerable value to raw biomass, which may result in a synergistic effect on the development of fuelwood-generation programs: the higher price (per unit of energy) for the gaseous fuel may lead to higher primary biomass prices, providing greater incentive for people to grow trees (Williams, 1985).

Raw-Biomass or Charcoal For Gasifiers? Both charcoal and wood are currently used as gasifier feedstocks. In addition, there is significant interest, particularly in developing countries, in using crop residues (rice husks, wheat straw, coconut shells, etc.) as gasifier feedstocks. Most gasifiers used to provide fuel for industrial boilers use raw biomass. Although little cooking has been done with producer gas, raw biomass would appear to be a workable feedstock in this application as well.

The exclusive feedstock for gasifiers used commercially today in small-scale engine applications is charcoal. Charcoal was also the preferred feedstock for vehicle gasifiers used in Europe during WWII. Charcoal making drives off most of the dirty volatile components of the raw biomass -- tars and acids. Subsequent charcoal gasification, therefore, does not generate excessive levels of tar that often accompany the direct gasification of raw biomass -- the main source of problems in raw-biomass gasifier-engine systems recognized in the 1940s, but as yet unsolved.

Capital costs for charcoal systems were lower than those for raw-biomass systems, but significantly lower fuel costs (typically 1/2 to 2/3 on an energy basis) resulted in lower total costs for raw-biomass systems (6). Despite the unfavorable economics, charcoal was chosen for its higher energy density, allowing vehicles to travel further with a given weight of fuel, and perhaps more importantly, because charcoal gasifiers generally produced a cleaner gas, were operationally simpler, and were more reliable

(Kaupp and Goss, 1981). The situation has changed little since WWII: charcoal is still the preferred fuel, despite the fact that total costs (capital plus operating) are lower using raw biomass (7).

However, traditional charcoaling techniques still widely used in developing countries involve losses of up to 3/4 of the energy in the original wood. Even the advanced charcoaling techniques being developed in Brazil yield energy efficiencies of only 55 to 60% (8). Thus it takes considerably more primary biomass to fuel a charcoal gasifier-engine system than a raw-biomass system.

To appreciate the extent of the difference in fuelwood required to use raw biomass rather than charcoal in a gasifier-IC engine system, consider the case where a gasifier-engine-pumpset is used to irrigate say 20 hectares of land, supplying 75 cubic meters per day of water [a reasonable water requirement in many areas of the world (Stassen and van Swaaij, 1981)] through a 12 meter head. Expressed in terms of fuelwood plantation area (producing an annual yield of 10 tonnes per hectare), the land required to grow the feedstock for a raw-biomass gasifier-engine-pumpset would be about 1.4 hectares, while about 5.2 ha would be needed if charcoal, produced at 25% efficiency, were used instead (or 2.6 ha at 50% efficiency) (9).

It is estimated that there are currently about 8.5 million small irrigation pumpsets in rural areas of India, with the number growing at a rate of 1/2 million per year (Jain, 1985). The total potential demand for small irrigation pumpsets in rural areas of all developing countries in 1980 has been estimated to be about 40 million (Meta Systems, 1980). A significant fraction of this demand could be met with biomass fuel only if biomass were used efficiently. If 40 million small irrigation pumpsets were to be fueled with producer gas, say by the year 2000, the annual rate of plantation development needed for biomass production to support charcoal gasifiers* would be about 14 million hectares per year. For comparison, the annual rate of expansion of global cultivated area, 1950-1975, was about 11 million hectares per year (Bolin, 1975). With wood gasifiers, the land requirements could be reduced by nearly a factor of four.

In addition to water pumping, a host of other uses for gasifiers exist as well, including remote electricity generation, motive-power supply, shaft power production, cooking and boiler fuel supply. In conjunction with fuelwood-growing programs, many more of these activities could be fueled by biomass if raw-biomass instead of charcoal were to become the predominant gasifier fuel in gasifier-engine applications.

The Tar Problem

Excessive tar production is the biggest technical problem to be overcome before raw-biomass gasifiers can be widely used. Tar entering an engine will deposit on the intake manifold, valves, cylinder walls, and other important components, causing loss of performance and, if unchecked, costly engine damage. Tar-induced problems are reported almost routinely (10), and are usually dealt with today by adding scrubbers and filters to a gas cooling-cleanup train that might be used on charcoal gasifiers. Several undesirable effects arise from this approach to solving the tar problem.

Filtering out the tar results in a significant energy loss. Tar has a

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* With charcoal produced at 25% efficiency.

calorific value higher than that of any other component in producer gas, including the primary combustible gases (Kaupp and Goss, 1981). Every 1% of the total tar fraction removed from raw producer gas made from wood results in about a 2% loss of usable energy from the gas (Rambush, 1923).

Operational difficulties also arise with the addition of scrubbers and filters. Charcoal gasifiers generally use a cyclone filter to remove most of the particulate matter carried by the gas out of the gasifer, followed by a relatively simple fabric filter (e.g., of the type commonly found in automobile engines today) which removes the finest particles that could cause abrasive damage to the engine. Cyclones are extremely simple, efficient, reliable, and durable, the only maintenance requirement being the occasional emptying of the ash hopper, while the filter requires only simple cleaning or replacement at regular intervals.

Cyclones and fabric filters are also used with raw biomass gasifers. Gas temperatures leaving the gasifer are usually high enough that tars will not condense on the cyclone walls. If the gas is still at a high enough temperature after passing through the cyclone, tars will pass through the filter in vapor form, but if the temperature is below the tar's dew point, tar will condense on the filter, eventually plugging the gas cleaning train and choking the flow to the engine.

In all gasifier-engine systems, cooling of the gas is required to raise its volumetric energy density so that it will combust in the engine cylinders. For charcoal systems, this is often accomplished through a heat exchanger coupled to the engine's cooling fan. In the case of irrigation pumps, the water being pumped can be used as a coolant. Since both cooling and tar removal are required for raw-biomass systems, a wet scrubber is commonly used following the cyclone and/or filter. Water sprayed or guided through a circuitous path contacts the hot producer gas as it passes through the scrubber. As a result, the gas is cooled and the water carries away condensed tar, often creating a waste disposal problem in the process. The gas is finally passed through a drying unit -- a packed bed of rocks, cork, or charcoal, for example -- to remove entrained moisture that would prevent its combustion in the engine.

Cracking the Tar Problem

There exist a few raw-biomass gasifiers, designed using careful empirical methods, which can generate a nearly tar-free gas when operated on a strictly defined feedstock (usually uniformly sized wood blocks or chips) at relatively steady loads. One is the small (~5 kg/hr) downdraft gasifier operated on casuarina wood recently developed at the Indian Institute of Science in Bangalore, India (Shrinivasa and Mukunda, 1983). The design was based on careful study of the detailed physical geometry of many gasifiers that were built in the 1930s and 1940s. While the gasifier produces a relatively clean gas, any deviation in its original design or feedstock properties leads to high levels of tar production, although the fundamental reasons for this are not well understood (Shrinivasa, 1984).

Susanto, while at Twente University of Technology in The Netherlands, designed a 20 kg/hr WWII-type downdraft gasifier extensively modified to incorporate an internal recycle of the pyrolytic gases, insuring that during steady-state operation they would be very nearly completely burned and/or cracked before passing out of the gasifier. Extremely low levels of tar are reported in the product gas when operating at steady-state on pine-wood chips, although to reach steady-state operation requires 60-90 minutes

(Susanto, Beenackers, and van Swaaij, 1983).

A few more-or-less ad hoc gasifiers, such as the two described above, have succeeded in producing an acceptably tar-free gas from wood blocks or chips, but it has not generally been possible to easily adapt these designs to other gasifiers operating on different feedstocks (e.g., no gasifier exists which can produce a low-tar gas from crop residues), at other scales, or under more widely varying loads. From one gasifier to the next, tar problems arise due to a number of factors, including variations in feedstock properties (size, ash content, moisture content, etc.) and changes in gasifier geometry.

The small number of successfully operating raw-biomass gasifiers attests to the fact that no rules currently exist for designing simple, reliable raw-biomass gasifiers that can consistently produce an adequately tar-free gas for use in IC engines. This is due in large part to the fact that there is no accepted understanding of how biomass gasifiers actually work (Reed, Levie, and Das, 1984). In particular, the phenomenon of tar formation and degradation in gasifiers is not well understood. However, evidence suggests that the tar problem could be "cracked" if a serious research effort were undertaken.

The Role of Research

A better understanding of the chemical and thermal kinetics (particularly tar formation and destruction) associated with raw-biomass gasification may result in progress toward standardizing the design of effective raw-biomass gasifiers, much as basic research in fossil-fuel combustion has contributed to solving important technical problems in that field (11).

While the science of fossil fuel combustion is well developed [see, e.g., (Glassman, 1977)], and coal gasification has received considerable attention as well [see, e.g., (Probstein and Hicks, 1982)], biomass gasification for producer gas generation holds low priority in the scientific community. This may be because producer gas is currently of greatest interest to developing countries, while it is the industrialized countries that have some of the best diagnostic capabilities required to conduct fundamental research. In addition, research priorities in developing countries are generally determined by the immediacy of high oil import bills and shrinking biomass resources, so that nearly all funded research is extremely application-oriented. Dr. Naksitte Coovattanachai at the Prince of Songkla University in Hatyai, Thailand has highlighted the situation common in most developing countries where gasifier work is done:

> As I have been under pressure to come up with systems which can be used in actual practical operation quickly, my work has been rather empirical in nature. I have not been able to use much scientific principle in the design of my gasification systems. I must admit that I still don't know very much about the science of gasification at present. Although I would like very much to initiate research work which will enable me to understand the gasification process better, I have not been able to do it because of lack of essential equipment and instrumentation here. Even basic equipment for the gasification work such as gas analyzer and gas calorimeter are not available. Although I have been trying to obtain these for my research, it is not certain that I will be able to get them (personal communication, August 1984).

While developmental work such as Coovattanachai's may produce gasifiers that work under carefully specified conditions, it is unlikely that such work will lead to major breakthroughs in understanding the fundamental processes involved in gasification -- an understanding which appears to be neede to provide a basis for formulating rules for designing simple, reliable, low-tar raw-biomass gasifiers for operation under a variety of conditions.

While little fundamental research has been done to date on producer gasification, a good infrastructure of diagnostic capabilities exists at a number of laboratories which have extensive research experience in fossil-fuel combustion, coal gasification, and biomass liquifaction and gasification for synthesis gas production. With this infrastructure in place, it is very likely that relatively small investments could result in rapid and significant advances in producer gas science and technology.

Lessons from Improving Cookstoves

There may be lessons to be learned by gasifier researchers from the recent experience with improving wood cookstoves. The widespread realization in the mid-1970s that in many developing countries fuelwood was in short supply and that what was available was being consumed non-renewably led to the formation of many well-intentioned stove improvement programs. But most such programs suffered from insufficient technical input, and yielded disappointing results (Geller, Baldwin, Dutt, and Ravindranath, 1985). Most programs failed either because new stoves did not actually save any wood relative to traditional models (some actually consumed more wood), or new stove designs were insensitive to local needs (Manibog, 1984).

Recently, however, principles of heat transfer, combustion, and fluid mechanics have been applied to stove design. This, together with an increased awareness of the social concerns associated with stove use, has led to the design and production of socially acceptable and inexpensive cookstoves that consume 1/3 to 1/2 less fuel in actual use than traditional stoves (Geller, Baldwin, Dutt, and Ravindranath, 1984).

Gasifier hardware design, as in the case of stoves, must be approached both with a good technical understanding of gasification, as well as with an appreciation of the social context in which gasifiers will be used. In contrast to the case of stoves, however, the basic principles of biomass gasification in small-scale gasifiers are not yet well understood. Therein lies the need for fundamental research.

Relatively little support is currently being provided for this type of research, possibly because with the present, generally low level of technology, especially in rural areas of developing countries, the commercialization of existing technologies seems to merit the highest priority (12). However, without support for a serious research effort, the scientific understanding necessary to acheive breakthroughs in the design of raw-biomass gasifiers is not likely to be developed, constraining the use of biomass to power small engines to a much smaller role than would otherwise be possible.

Conclusion

Producer gas from biomass is a high quality energy carrier that promises to be an important fuel for use in direct heat applications (as it already is in parts of the US, Canada, and Brazil), shaft power production (particularly in remote rural areas of developing countries, where petroleum fuels are expensive and scarce), and cooking (in developing countries where solid biomass is currently the predominant cooking fuel). Only relatively minor problems exist in using producer gas in direct combustion systems, but its use in IC engines is currently restricted largely to the use of charcoal-fed systems by a lack of understanding of how to produce a clean (low-tar) gas from raw biomass. If producer gas is to become widely used in the future, raw biomass (not charcoal) should be the predominant feedstock, as this would considerably enlarge the options for utilizing available biomass resources, including crop residues and fuelwood from plantations. To develop simple, reliable raw-biomass gasifiers will require a good understanding of how tar is formed and destroyed in such gasifiers. To understand the tar problem will require a broadening of gasification programs from an exclusive focus on development and dissemination, as is common today, to give a greater emphasis to research aimed at understand the underlying science of biomass gasification, the application of which could lead to breakthroughs in establishing design rules for good raw-biomass gasifiers.

Table 1: Value of energy imports as a percentage of the value of all exports.*

Brazil	52
Ethiopia	44
India	81
Honduras	18
Kenya	63
Senegal	77
Tanzania	50
Thailand	43
Upper Volta	71

* Because data on energy imports do not permit a distinction between petroleum imports for fuel and for use in the petrochemicals industry, these percentages may somewhat overestimate the dependence on imported energy.

Source: (World Bank, 1984).

Table 2: Estimates of biomass as a percentage of total energy consumption.

Brazil	33
Ethiopia	93
India	36
Honduras	45
Kenya	70
Senegal	63
Tanzania	94
Thailand	63
Upper Volta	94

Source: (Eckholm, Foley, Barnard, and Timberlake, 1984)

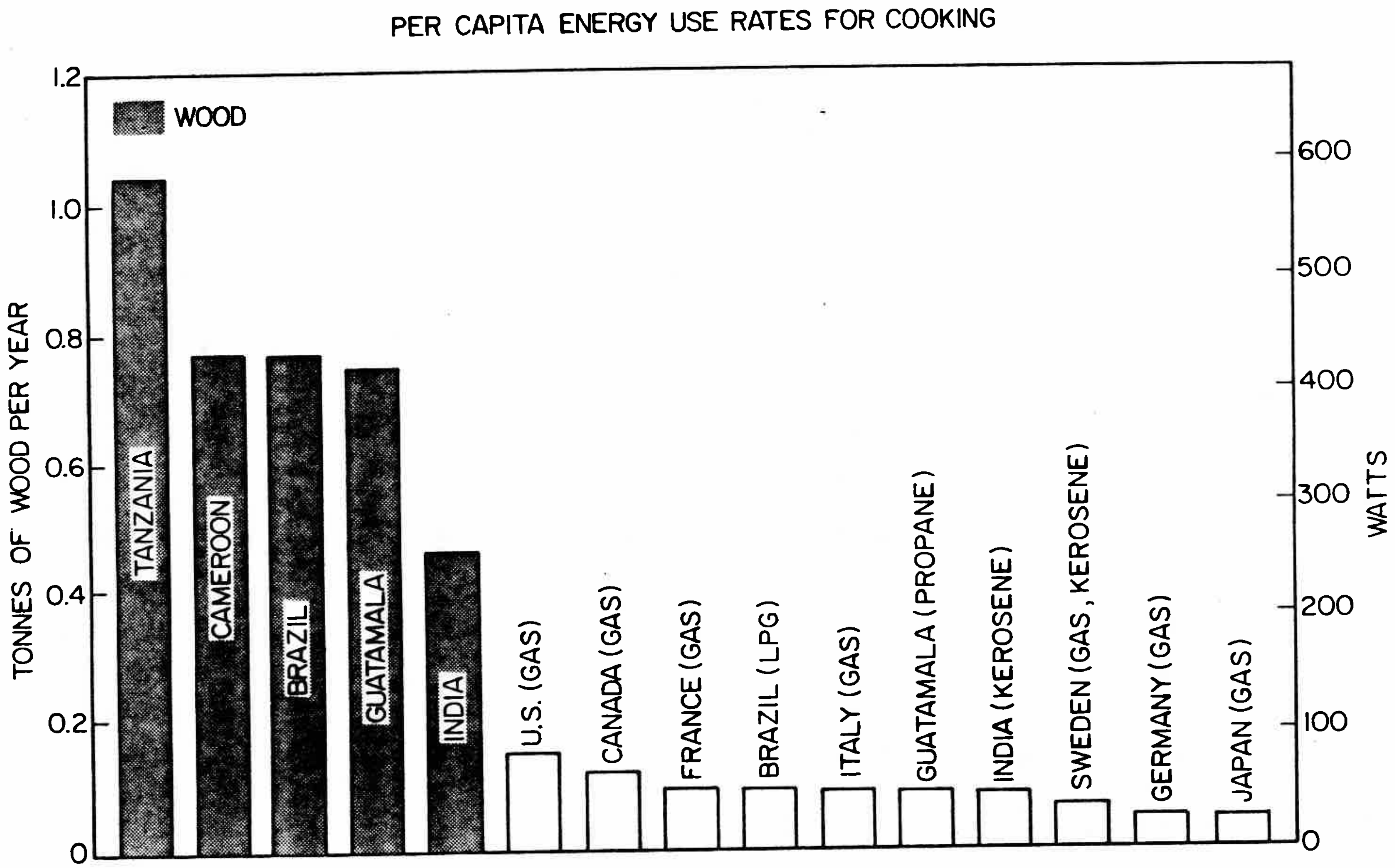

Figure 1: Source, (Williams, 1985)

Notes

1. Other biomass-derived fuels could be used in place of producer gas in industrial boilers, including ethanol, methanol, and synthesis gas (a gas having a heating value 2-3 times that of producer gas. However, the higher quality (and cost at the high capacity factors typical for industrial equipment) of ethanol, methanol, and synthesis gas makes their use unattractive.

2. Millions of IC engines (excluding those used in vehicles) are already being used in LDCs. In India alone, some 3.5 million small engines are used soley for driving irrigation pumpsets (Jain, 1985), each engine consuming energy at about the same rate as the average automobile in the U.S. -- about 1500 liters of diesel fuel annually (Shrinivasa and Mukunda, 1984).

3. The cost differences in using alcohol and producer gas in small spark-ignition engines can be appreciated by taking as an example a rough estimate of the costs of generating electricity in a 15 kW engine-generator set. The following is a breakdown of the additional costs required to generate electricity using a producer gas system instead of a gasoline-fuelled system:

	$/kWh
Producer gas	
Capital (a)	0.016
Operating Labor (b)	0.040
Maintenance & Service (c)	0.004
Wood (d)	0.084
Total	0.144
Ethanol (e)	0.27
Methanol (f)	0.43

(a) Based on available off-the shelf producer gas generating-cleaning systems (produced in Europe) estimated to cost $307/kWe (Kjellstrom, 1985), a 6 year plant life, a 10% real interest rate, and a 50% capacity factor.

(b) For 0.3 hours of operating labor per operating hour and a wage rate of $2.00/hr (Kjellstrom, 1985).

(c) Estimated to be 5% of the capital cost for every 1000 hours of operation (Kjellstrom, 1985).

(d) For wood consumption of 1.8 kg/kWh, wood containing 17 MJ/kg (Coovattanachai, 1983), and a wood cost of $2.80/GJ.

(e) Fuel costs only (exluding transportation and storage) for ethanol produced in Brazil costing $0.264-0.295 per liter (Geller, 1985), for an engine consuming 0.8 liters of gasoline per kWh generated [same engine cited in (d)], and for 1.2 liters of ethanol replacing 1 liter of gasoline.

(f) Fuel costs only (excluding transportation and storage) for projected methanol costs in Brazil of about $0.27 per liter [if wood costs $2.80/GJ, (see note 48 in (Williams, 1985)], for an engine consuming 0.8 liters of gasoline per kWh generated [see (d)], and for 1.5 liters of methanol replacing 1 liter of gasoline.

At current prices, only extremely low capacity factors would make ethanol competitive with producer gas, while both low capacity factors and substantially higher wood prices would be required to make methanol competitive.

4. Some of the dangers and disagreeable aspects of using solid biomass as a cooking fuel in rural areas of developing countries have recently been better documented. Some households in parts of India spend an average of 2 hours per day gathering fuelwood for cooking (ASTRA, 1980). The exposure to smoke and particulate levels that comes with cooking over an open flame indoors, as is commonly done in many developing countries, is very high. For example, the measured intake of the carcinogen, benzo(a)pyrene, by some Indian women during cooking is the equivalent of that received by smoking 20 packs of cigarettes per day (Smith, Aggarwal, and Dave, 1983).

5. The use of producer gas for cooking has been reported in India at the canteen of Jyoti Ltd., Vadodara (Jain, 1985). The system has operated for about 6 months (5 hrs/day), consuming 27 kg/day of wood to produce gas used to cook lunch, snacks and twice-daily tea for 100 people. The producer gas daily replaces 15 kg of hard coal plus 5 kg of charcoal.

Use of producer gas for cooking at an individual household level has also been reported in Vanuatu in the South Pacific, though details on this installations could not be obtained (Deamer, 1985).

6. Cost estimates for gasifier systems must generally be made on a case-by-case basis, since a large number of variables can affect cost, including: the capital cost of the gasifier (the cost per kW of capacity can vary over an order of magnitude from one country to another (Foley and Barnard, 1983)); the local wage rate; the cost of fuel, as influenced by where the fuel is located in relation to the gasification site (dispersed, concentrated, easily accessible, etc.), competing uses for biomass, and the type of biomass (plantation wood, natural-forest wood, crop residues, etc.); the properties of the fuel (calorific value, size and size distribution, elemental composition, reactivity, moisture content, ash fraction, etc.); and the fuel preparation (air dried, chipped, briquetted, carbonized, etc.).

The best documented and most detailed case studies of the differences in cost between gasifier operation with wood and that with charcoal during WWII are found in a review of the Swedish experience with gasifier-powered vehicles during WWII (Solar Energy Research Institute, 1979):

- Annual fixed costs for the fleet of 3-ton wood-gas trucks operated by the Stockholm Breweries Co. in the 1930s and 40s were 20% less than those for its charcoal-gas trucks, while hourly operating costs were about 14% lower. Within the lower operating costs are 44% higher repair and maintenance costs for the wood gas trucks, but 46% lower fuel costs, leading to the total operating cost advantage for the wood-gas trucks.

- For another set of 3-ton trucks owned jointly by Stockholm Breweries and Apothcaries' Mineral Water, Ltd., total hourly costs were 16% lower. (Hourly repair costs were 18% higher for the wood-gas trucks, but hourly fuel costs were about 45% lower.)

- The operating costs of buses run by Stockholm-Saltsjon Railroads, Inc., including amortization, maintenance, and service, are reported to be about 30% less using wood instead of charcoal.

The Swedish review cites a number of other case studies as well, with the total cost of wood gas operation reported consistently and significantly lower than charcoal gas operation at the then prevailing biomass costs -- on a weight basis, charcoal cost about 3 times as much as uncarbonized wood.

7. Up-to-date and complete case studies are scarce. Probably the best systematic, though not site-specific, analysis available is Kjellstrom's (1985). He made detailed calculations of the capital-plus-operating cost of diesel engine-shaft power systems compared to wood and to charcoal gasifier-shaft power systems producing 15 or 50 kW under a variety of capacity factors. With fuel prices of $8.5/GJ (~$0.32/lit) for diesel, $2/GJ (~$32/tonne) for wood, and $5.50/GJ ($165/tonne) for charcoal, he concludes that the 15 kW system operating on wood must produce at least 60 MWh/yr (capacity factor = 1/2) in order to compete with diesel, while charcoal is not competitive even at this relatively high capacity factor. In the 50 kW system, wood is the most attractive fuel at capacity factors greater than 10%, while again charcoal does not compete even at a capacity factor of 1/2.

Earl (1975), among others, has argued that the cost of producing and transporting by truck a unit of energy in the form of charcoal drops below that of wood beyond a transport distance of about 80 km (primarily due to savings in transport fuel costs), conceivably leading to favorable charcoal-gasifier economics beyond a certain transport distance. However, a recent analysis by Baldwin (1985) points out that Earl assumed a fixed cost of transport fuel per tonne-km carried, whereas in reality, trucking charges are most often levied on a volume basis, reflecting the fact that most of the truck's fuel is required to move the empty truck against wind and road resistance. Thus, the size of the load has only a small influence on overall fuel consumption, in addition to which fuel is only a small part of total fixed and operating costs of trucking. Baldwin provides a breakdown of fixed and operating costs of truck transport and concludes that the cost of hauling wood or charcoal (per unit of energy carried) over any distance is roughly the same.

8. Because of their heavy dependence on charcoal, Brazilian steel companies have probably the most intensive ongoing research program anywhere to improve the efficiency of charcoal production. The current average maximum energy conversion efficiency of the beehive kiln in

converting eucalyptus to charcoal is reported to be 53% [although in practice, since charcoal fines are undesirable for steel making, small branches and twigs are left in the forest, lowering the forest-to-charcoal efficiency to around 42%] (Florestal Acesita, 1983). The heating values of air-dry eucalyptus and charcoal made from it are reported by Florestal Acesita to be 12.6 MJ/kg and 29.3 MJ/kg, respectively, giving a mass conversion efficiency of 53*12.6/29.3 = 22.8%.

Florestal Acesita has recently developed beehive kilns which permit the condensation and recovery of tar evolved during carbonization, which can be used as a substitute for fuel oil required in relatively small quantities in the steel factories of its parent company, Acesita Steel. Twenty production versions of these units were scheduled for installation in 1984. The current energy efficiency of these units (forest-to-charcoal + tar) is 59%, an 11% gain over the traditional beehive kilns (Florestal Acesita, 1983).

Florestal Acesita also estimates that continuous retort kilns (now under study) which also recover tar, could operate with overall efficiencies as high as 78%, but accompanied by a capital cost per unit of charcoal-making capacity 46 times that of the present beehives.

By comparison to these more advanced charcoal technologies, traditional pit kilns, used widely to produce small volumes of charcoal in rural areas of developing countries, are about 30% energy efficient, while earth-covered mounds still used in many parts of the world have conversion efficiencies of only about 20% (Hall, Barnard, and Moss, 1982).

9. The capacity of a system pumping 75 cubic meters/ha/day of water at 60% efficiency through a 12 meter head (assuming 10 hours of operation per day) would be

[(75/10)*9.8*12]/[0.6*3600] = 0.41 kW/ha

To irrigate 20 hectares would require an engine producing about 8 kW. Assuming a 1000 hour pumping season, the total shaft power produced would be 8000 kWh. At a rate of wood consumption of 1.8 kg/kWh, as measured by Coovattanachai for the raw-biomass gasifier, this amounts to [8000*(1.8*10^-3)] = 14.4 tonnes of wood annually. Assuming an average yield of 10 tonnes/ha from a fuelwood plantation, the land requirement per engine would be about 1.4 hectares.

Under controlled laboratory conditions, Coovattanachai measured the rate of mass consumption of charcoal in a charcoal gasifier to be 1/2 that of wood in a wood gasifier driving the same engine (heating values: wood, 16.89 MJ/kg; charcoal, 30.61 MJ/kg) (Coovattanachai, 1983). Therefore, for a charcoaling efficiency of 25%, the annual primary wood required for the charcoal gasifier would be [8000*(1.8*10^-3)*(0.5)*(30.61/16.89/.25)] = 52 tonnes, corresponding to a land requirement of 5.2 ha. At 50% efficiency, the land requirement would be 2.6 ha.

10. Some quotes from the producer gas literature indicate the pervasiveness of tar problems: "(After) only a few hours of operation (with wood), tar deposited on the valves and ultimately seized up the engine." (Coovatanachai, Chongchareon and Kooptarnond, 1982); "The piston of cylinder No. 2, that is, the cranking side has the oil ring completely seized within the

groove." (S. Kumar, et al., 1984); "Blocking of fuel injector nozzles was noted with all engines in dual fuel operation at irregular intervals, while in some cases also tar formation necessitating engine clean up became apparent." (T. Zijp and H.E.M. Stassen, 1984).

11. For example, emissions of nitric oxides (NO) from fossil fuel burning facilities are controlled by applying the understanding that has been developed of the alternative kinetic pathways by which NO could form and be reduced to inert nitrogen (N2). It is now common practice to control NO emissions from smokestacks by injecting a small quantity of ammonia (NH3) at a point in the stack where the temperature is between 1000 and 1500 K (Rosenberg, Curran, Slack, Ando, and Oxley, 1980). To control automobile pollution, catalytic converters were developed that convert NO and carbon monoxide into N2 and carbon dioxide (Kummer, 1980).

12. Most gasifier research/development projects today have relatively short-term goals. For example, the United Nations Development Program, in conjunction with the World Bank, has launched an ambitious effort to collect worldwide technical and economic data on gasifiers currently operating in developing countries in order to establish standards for evaluating future proposed gasifier projects, to identify successful gasifiers and aspects of the technology in need of further research and development, and to define the scope for further applications of gasifiers in developing countries (Mendis, 1984). If successful, this program will produce a valuable database on gasifier use worldwide through standardized measurements of capital and operating costs and actual field performance. It is unlikely, however, to produce information leading to important advances in understanding how to design a good raw-biomass gasifier.

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