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An Analysis of the Costs of Fuel Supply for Wood-Fired Electric Power Plants in Rural Liberia

R. D. Perlack
W. F. Barron
G. Samuels
R. E. Rhinelander

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AN ANALYSIS OF THE COSTS OF FUEL SUPPLY FOR WOOD-FIRED ELECTRIC POWER PLANTS IN RURAL LIBERIA

R. D. Perlack
W. F. Barron
G. Samuels
Energy Division
Oak Ridge National Laboratory

and

R. E. Rhinelander
National Energy Committee
Republic of Liberia

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ABSTRACT

In Liberia, as in many developing countries, electrification of towns and cities throughout the country has long been a major development goal. Yet, in recent years the quality of "rural" electric services in Liberia has been declining and the future economic viability of these power stations is a growing concern. Each of the ten operating and each of the planned rural public power stations is designed to operate exclusively on gas oil (diesel fuel). Fuel expenditures by the Liberian Electricity Corporation (LEC) for the rural public stations represent a major and growing burden on the financially hardpressed utility. Liberia has two potentially significant alternatives to oil-fired electric power for its "up-country" towns: small (1-5 MW) hydroelectric facilities, and wood-fired steam or gasifier plants (0.2 to 2 MW). Although small hydroelectric facilities appear viable for several locations, they cannot serve all locations and will require substantial thermal back-up during a large part of the year because of Liberia's long dry season (about five months). The economics of supplying wood to a rural electric power plant or rural grid were evaluated under several scenarios involving: (1) different sources of the feedstock, and (2) differences in wood supply requirements for plants based on the use of steam or gasifier technology, and variation in the utilization level for such plants.

Liberia has an extensive wood resource base. With a few minor exceptions, wood energy supplies are plentiful throughout the nation. Liberia has four different potential sources of wood fuel supply. These are: (1) the commercial cutting of retired rubber trees; (2) the harvesting of secondary growth forest just prior to the land returning to temporary cultivation as part of a system of shifting agriculture;

(3) adding to the system of shifting agriculture the planting of fast-growing wood species and harvesting these trees when the land again is brought back under cultivation (generally after about five to seven years); and (4) the establishment of commercial short-rotation wood energy plantations. The analysis also included three levels of wood demand -- from 3,700 to 13,000 Mg/yr.

The results indicate that the use of wood to fuel rural power stations is a viable economic option. The delivered cost of wood for the three demand levels ranged from $1.01 to $1.08/GJ for retired rubber trees, $0.97 to $1.20/GJ for secondary forests, $2.12 to $2.35/GJ for a plantation with agriculture, and $1.67 to $1.75/GJ for a plantation without agriculture. The cost of gas oil (diesel fuel) delivered to rural power stations in Liberia ranges from $8.10 to $12.20/GJ.

1. INTRODUCTION

In Liberia, as in many developing countries, electrification of towns and cities throughout the country has long been a major development goal. Yet, in recent years the quality of "rural" electric services in Liberia has been declining and the future economic viability of these power stations is a growing concern [1,2,3]. Each of the ten operating and each of the planned rural public power stations (Fig. 1) is designed to operate exclusively on gas oil (diesel fuel). Fuel expenditures by the Liberia Electricity Corporation (LEC) for the rural public stations represent a major and growing burden on the financially hard-pressed utility [2,3].

Wood-fired electric power plants are operating in many parts of the world, including West Africa. Such plants have been proposed in Liberia as a means of reducing costs, utilizing domestic resources, and stimulating local economic development in the areas served [1,4,5]. A major determinant of the economic viability of wood electric power plants is the cost of the wood feedstock. In this paper we examine the economics of wood supply under Liberian conditions in order to develop a better understanding of the viability of converting part (and perhaps eventually the greater part) of Liberia's rural electric system to wood fuel.

The approach used here involves selecting the most likely "production function" (i.e., a particular combination of equipment and labor) and then determining associated costs and

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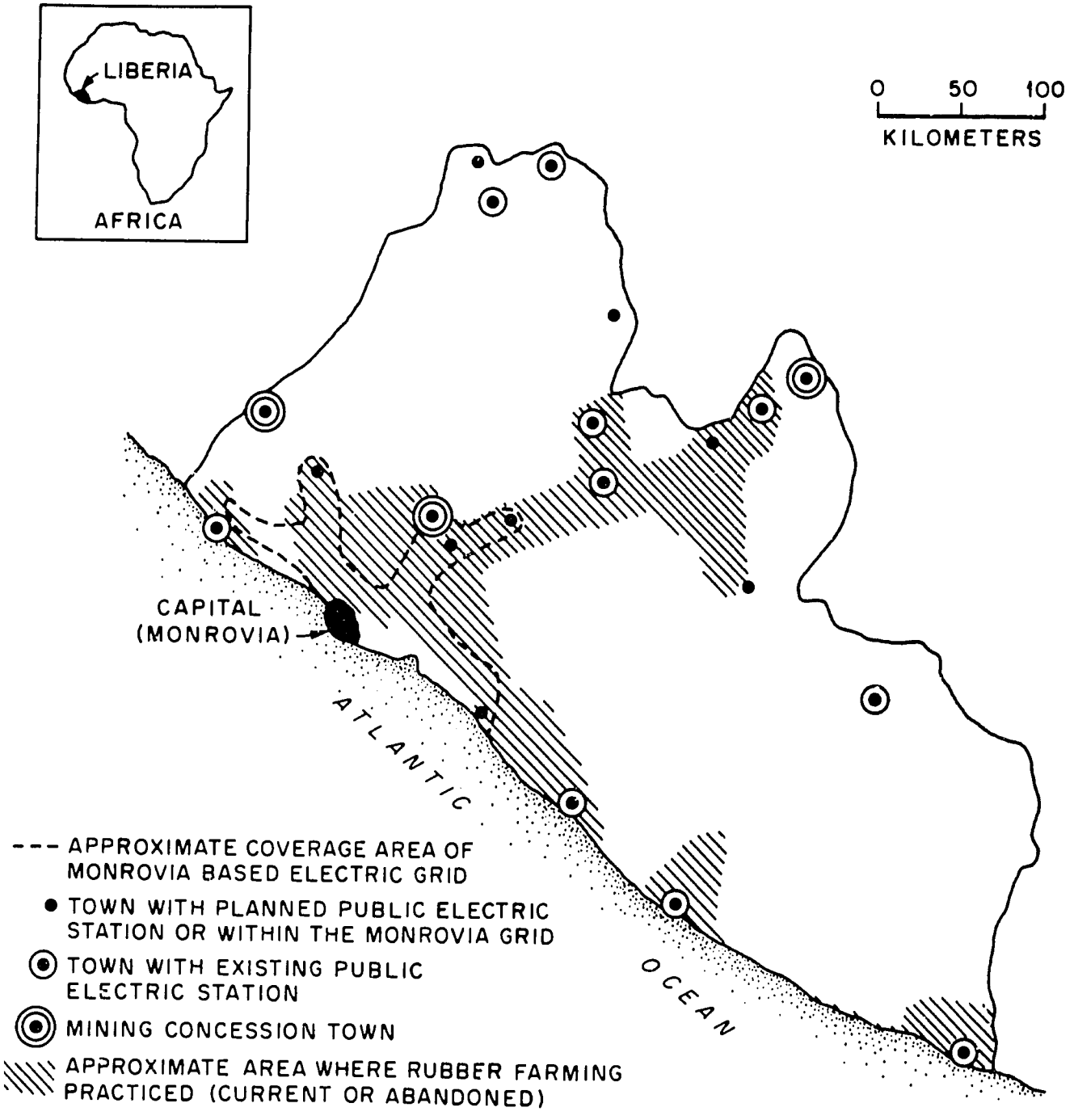

Fig. 1. Reference map of Liberia

productivity.[1] This information was gathered through field interviews in Liberia with operators engaged in wood production and related activities.

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[1] Originally, several production systems were considered involving different labor/capital intensities. However, in the end only one system (a relatively labor intensive one) was studied because experience with more capital-intensive energy-type wood growing and harvesting systems in Liberia are limited and available results suggest such systems are likely to be significantly less competitive than more labor-intensive ones.

2. BACKGROUND ON THE LIBERIAN RURAL ELECTRIC SYSTEM

Installed capacity at individual public rural power stations ranges from 0.33 to 1.65 MW. Combined operational generating capacity of the rural stations operated by the LEC is just under 8 MW, with an additional capacity of 4.2 MW temporarily out of service or available on site, but not yet installed. Fuel costs for the rural stations totaled $2.7 million for the July 1983-June 1984 Liberian fiscal year [3]. In recent years, fuel costs for the rural public stations have accounted for about 20% of total public electric power fuel bills for the nation, while costs for the rural system are generally above $0.25/kWh while tariffs average only $0.15/kWh. Under these conditions system financial losses will rise as the size of the oil fired rural generation base expands.

The LEC also operates the Monrovia-based central electric power system with a peak demand of 66 MW, and financial losses associated with the operation of the Monrovia grid have made it increasingly difficult for the LEC to absorb the growing financial losses from its rural stations. The result has been inadequate maintenance, frequent system breakdowns, and periodic and prolonged outages because of fuel shortages.

Liberia has two potentially significant alternatives to oil-fired electric power for its "up-country" towns: small (1-5 MW) hydroelectric facilities and wood-fired steam or gasifier plants (0.2 - 2 MW). Although small hydroelectric facilities appear viable for several locations, they cannot serve all locations and

will require substantial thermal backup during a large part of the year because of Liberia's long dry season (about 5 months). Existing wood resources are adequate to serve many of Liberia's rural stations. It may also be feasible to interconnect several of the rural stations currently served by individual power plants, supplying electricity in the future from both a small hydro facility and from a wood fueled plant. This approach has the advantage of capturing economies of scale in small hydro plants and to a lesser extent in wood-fired plants, but with Liberia's low rural population density, it may be feasible in only a few locations.

3. METHODOLOGY

In this paper we examine the economics of wood supply on a commercial basis to a rural electric station or rural grid in Liberia. The separate cost components of the wood supply system and the scale of operations are based for the most part on known conditions prevailing in Liberia. Costs of supplying wood are developed under several scenarios involving: (1) different sources of the feedstock [i.e., retired rubber trees (Hevea brasiliensis)], secondary growth forest ("low/medium bush"), and short rotation wood energy plantations), and (2) differences in wood supply requirements for plants based on the use of steam or gasifier technology, and variation in the utilization level for such plants.

The purpose of this analysis is to compare the costs of different wood supply systems and to evaluate the overall economic and financial viability of wood-based electric generation in Liberia. Appendices A, B, and C summarize the detailed components of the production function for the wood supply system costs presented in the text. Our emphasis here is on refining the cost estimates for wood supply to electric power plants. Wood combustion technologies for Liberia have been examined at least on a preliminary basis in previous studies [5,6,7]. In this paper we limit the investigation of wood combustion technologies to the question of the gross wood requirements to fuel a particular proposed technology (i.e., steam or charcoal gasifiers) to meet a specific level of

electrical demand. Appendix D provides a brief overview of the economics of wood-fired power systems. By adding the cost of wood supply to that of the power plant, it is possible to determine the overall economic and financial viability of a wood power system for rural Liberia.

4. OVERVIEW OF END-USE TECHNOLOGIES

Several sizes of wood-fueled rural electric power plants may be viable in Liberia. The principal concern here is the annual wood supply requirements and the impact on the cost stream of seasonal variation in wood demand or supply capability. To cover a range of relevant possibilities, we have outlined three demand cases. Cases 1 and 3 set the upper and lower bounds, respectively, on total wood requirements. Case 2 varies the seasonal output of the larger wood-fired power plant and explores the cost implications of the subsequent seasonal shift in the level of demand for the wood feedstock.

The upper bound on the wood feedstock requirements for this investigation is set by a 1.5-MW wood-steam plant operating at an annual average utilization level of 60%. Assuming 190 harvest days per year for operation of the wood delivery system, a 15% combustion to thermal electric output efficiency and wood delivered on a 25% wet-basis moisture content, about 70 Mg/d would be harvested under case 1. In the following analyses, equipment requirements for case 1 are scaled to meet this daily level. Calculated total annual wood requirements are 13,250 Mg. The detailed calculations used to derive this and other such figures for wood requirements are outlined in Appendix A.

To take account of discontinuities in the production function, it is also important to consider a situation in which the wood electric plant must meet a peak seasonal demand and

operate during other times at a lower utilization level. This situation could occur where the wood plant was combined with a small run-of-the-river hydro facility. It could also result from difficulties in maintaining a steady supply of wood during the height of the rainy season and where the wood-fired plant might be supplemented during such times by a diesel engine back-up system. Case 2 considers a 1.5-MW wood-steam plant operating as a dry season base load plant (5 months) with an average weekly load factor of 60%, an interseason intermediate load plant (5 months) with an average weekly load factor of 30%, and an idle period during the height of the rainy season (2 months). Equipment requirements and certain annual personnel costs (e.g., management staff) are set by the peak demand, while annual variable costs, including most labor costs, are set by average annual demand. Peak harvest requirements for case 2 are 60 Mg/d while requirements for the intermediate demand period are 30 Mg/d. Calculated total annual wood demand for case 2 is 8,280 Mg.

In case 3, a 400-kW gasifier engine system is assumed to operate with an average annual load factor of 50%. This engine would, at least initially, probably be operated on charcoal to reduce operating and maintenance problems. With a wood-to-charcoal thermal efficiency of 30%, a gasifier engine operating efficiency from combustion to thermal electric output of 20%, and a 25% wet-basis moisture content for the wood, requirements for wood supply are 20 Mg/d. Total annual wood requirements are 3,750 Mg. To keep this anlysis focused on the cost of supplying the wood feedstock, we assume that the charcoal kilns are on the

grounds of the electric power plant and are the responsibility of the plant operator and not that of the wood supplier.[2] Likewise, under each of the three cases, storage facilities for the wood are assumed to be the responsibility of the plant operator and not that of the wood supplier.

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[2] In practice, a charcoal system would probably be located near the wood harvest site so that the higher energy density charcoal could be transported in place of wood, thus lowering transport costs per unit of energy. We do not consider this likelihood here in order to keep the analysis consistent with regard to different wood supply sources utilized at various levels of supply.

5. OVERVIEW OF WOOD SUPPLY SYSTEM POSSIBILITIES FOR LIBERIA

Liberia has an extensive wood resource base. With a few minor exceptions, wood energy supplies are plentiful throughout the nation.[3] In urban areas fuelwood and charcoal are typically traded commercially in small quantities at retail prices ranging from roughly $3.00 to $5.00/GJ, depending on fuel quality, location, and season [8]. In most rural areas and smaller towns, wood is gathered freely from nearby forests, and such collection activities typically represent a very modest level of effort for low-income households. In 1982, an estimated 75% of total domestic energy consumption in Liberia was in the form of fuelwood and the wood used to make charcoal, mostly to meet residential cooking needs [9].

During the 1960s and 1970s rubber farming was a major developing growth sector for the Liberian economy. In 1983 an estimated 160,000 ha of rubber tree farms existed in Liberia [10]. Of this total, approximately one-third was in the form of

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[3] Liberia is experiencing a major problem in the rapid depletion of its virgin rainforests. The rainforests are gradually being incorporated into the pattern of shifting agriculture widely practiced in Liberia. While the loss of the ecological diversity is a significant concern, Liberia is not experiencing a "deforestation" problem as such, due to the relatively long bush-fallow rotation period (7-10 years). It is also important to note that the current depletion of the high forest is not the result of energy demand and that future industrial-scale energy requirements seem unlikely to contribute to the further loss of this important natural resource. The long transport distances from the remaining high forest areas to the potential industrial-scale wood energy demand centers should preclude additional pressure on the virgin forest areas from the type of activities under consideration in this paper [1].

large holdings (i.e., those 2500 ha and above), with the remainder in middle and small holdings. Starting in 1980 much of this resource, particularly middle-sized holdings (i.e., 100-2500 ha) was left idle because of political and social upheavals following the military takeover of the government and a low-world market price for rubber. Many of the small- and middle-sized stands consist of trees of inferior rubber producing quality compared to newer hybrids, and a large proportion is now too old to make retapping economically attractive. In the Monrovia area, retired and abandoned rubber trees provide much of the commercial charcoal and fuelwood supplies. In other areas, including those near a number of existing or potential power plant sites, older stands of rubber tree stands more typically sit idle, apparently because of a lack of attractive alternative uses for the wood, or the unavailability of capital to redevelop the site.

An inactive rubber tree farm has several important advantages as a wood energy resource. First, such farms in Liberia are typically located adjacent to roads and are often found relatively close to urban centers. This location advantage results from the transport cost considerations for raw latex and from the previously extensive practice by higher income Liberians to develop small- to middle-sized rubber holdings as weekend and vacation retreats. A second advantage of mature rubber farms is that they contain relatively large amounts of wood (i.e., 220-330 cubic m/ha), of relatively uniform quality, in easy to harvest stands (i.e., large boles and trees in evenly spaced rows without

extensive underbrush). Based on site visits to areas around several Liberian towns, an average distance of 10 km from power plant to rubber farm seems reasonable. The base case round-trip transport distance for use of retired rubber trees is 20 km.

Clearly, the use of this rubber tree resource for wood energy would constitute a "mining" of the resource base in the general area of the power plant. In the longer term, other sources of wood supply would be required. However, the size of the rubber tree resource base in Liberia and its proximity to a number of important potential rural wood-fired power plant sites favors its careful consideration as a transition resource, possibly providing sufficient feedstock supply at a number of locations for 5 to 10 years. The use of this transition resource would allow time for market forces to encourage the development of long-term sustainable sources of industrial-scale wood energy supply.

Shifting cultivation ("slash and burn") is the predominate form of agriculture in Liberia. The typical pattern is for a site to be cultivated for 1 to 2 years (usually with upland rice and/ or cassava), and then is left to return naturally to "bush" by lying fallow for 5 to 7 years [11]. The woody biomass presently consumed when these areas under bush fallow return temporarily to cultivation constitutes another major potential feedstock source. With a 7-year fallow period, a substantial amount of woody biomass is available (about 91 Mg/ha). Although the removal of this material in lieu of burning it in situ would reduce nutrient recycling, this problem could be overcome with either

commercial fertilizers or an application of ash from the power plant, either of which could be included as part of a "stumpage fee" to the farmers. It may be possible to combine the planting of fast-growing species with shifting agriculture to provide a higher yield of more uniform quality at the time of the second land clearing prior to recultivation. The secondary forest resource is generally located at longer distances from the townsites than the retired rubber trees. The base case round-trip distance between forest cutting sites and the power plant is 40 km. The same distance is assumed appropriate for shifting agriculture sites that might be combined with planting of fast-growing trees.

Finally, considerable experience exists in Liberia with the management of tree crops (e.g., rubber, coffee, and oil palm), and experiments have been going on for a decade or more in several locations with short-rotation pulpwood plantations [12]. Liberian experiences with such systems and studies from other parts of the world [13] suggest the feasibility of wood energy plantations, based on fast-growing species, especially hardwoods with good coppicing ability.[4] Wood energy plantations would be located as close as possible to the power plant. Under Liberian conditions, a round-trip transport distance of 10 km from plantation site to power plant seems reasonable.

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[4] Coppicing is a term denoting the ability of many broadleaf wood species to vigorously resprout new trunks from a recently cut stump. In a wood plantation this ability offers a major cost saving since new trees need to be planted only every 3 to 4 harvests. In addition, growth rates for the coppicing stands are generally higher than those for new stands, because the tree's root system is already established.

With this Liberian wood resource picture, four different sources of wood supply appear relevant to the economic analysis of a 20- to 70-Mg/d wood-fired steam or gasifier electric power plant. These sources are (1) the commercial cutting of retired rubber trees, (2) the harvesting of secondary growth forest just prior to the land returning to temporary cultivation as part of a system of shifting agriculture, (3) adding to the system of shifting agriculture the planting of fast growing wood species and harvesting these trees when the land again is brought under cultivation (generally after about 5 to 7 years), and (4) the establishment of commercial short-rotation wood energy plantations.[5] In practice it is likely that some combination of systems 1 and 2 would be used at the start of operations and, over time, that systems 3 and 4 would be utilized eventually to lessen pressure on the wood resource base.

The following analyses assume that a commercial wood supplier acquires rights to the trees, harvests them, and delivers the wood to a storage facility near the electric power plant. Delivery occurs either on a regular around-the-year basis, with seasonal peaks in supply requirements and periods of very low or no supply because of road conditions during part of the rainy season. The term "commercial wood supplier" means that we assume that the wood supply system is in the hands of a private firm which establishes a contract with the electric utility (public or private) for the provision of a certain amount of wood

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[5] The development of cooperatives which provide cut wood from various sources at roadside pick-up points could be an alternative to these wood supply systems, but is not considered here.

(possibly with seasonal variations) at a predetermined price. Obviously, this price must be sufficient for the supplier to recover his capital investment and provide a reasonable return for management services and compensation for accepting the risk involved.

Real and pecuniary externalities related to the additional demand for wood in the area of interest are not considered here. Ample opportunities appear to exist to locate the power plants in areas where the wood resource base is sufficiently large to prevent significant increases in environmental stress in the face of the new demand. In such areas, only moderate impacts will occur with regard to the market prices or the time costs for collection of fuelwood as a result of the increased competition from the power plant for available feedstock supplies. This is not to say that real and possibly relevant pecuniary externalities (i.e., those with socially important income redistribution implications) will not be of concern. However, with care taken in the location of the power plants, such impacts can probably be kept within acceptable bounds.

In the descriptions and analyses that follow, the assumed production techniques, productivity rates, and component costs are based primarily on field data gathered in Liberia. All major elements of the assumed production function already exist at a number of individual sites throughout the country, although generally at a scale toward the lower end of the range of outputs considered here. It should be noted, however, that the existing wood supply systems often involve special circumstances, such as

the cutting of wood on a firm's own land, hauling relatively short distances, or providing wood to numerous small purchasers. The absence of some of these special circumstances in the wood supply system for an electric power plant will raise costs, while the absence of others will lower them compared to the existing wood supply systems. Thus, it is important to develop disaggregated cost estimates based on the specific conditions expected to apply in the case of a wood-burning power plant.

Where examples of a particular wood feedstock supply system envisioned here do not presently exist in Liberia, an attempt is made to extrapolate information from the closest similar situation. For example, data for the wood energy plantation system were developed largely from the Liberian experience with dense plantings of fast-growing pulpwood species [12]. In a few cases where local data are totally lacking, we have drawn from experiences in other countries [13].

6. ECONOMICS OF WOOD SUPPLY

The general methodology employed in the cost calculations and the results for each of the four types of wood supply systems operating at the three demand levels are outlined in this section. Appendix B outlines the basis for the energy yields from the various resources, and Appendix C provides the detailed basis for the cost calculations.

Each of the wood supply systems envisioned here is relatively labor intensive. Use of mechanical equipment is limited to powersaws for cutting the trees and trucks for transporting wood to the power plant. Nonpower hand tools are used for clearing, underbrushing, weeding, and planting. Manual labor is used for the site removal, loading, and unloading of the wood. Material inputs are limited to hand implements, fuel, oil, replacement parts for the powersaws and trucks (and seedlings for wood energy plantations). This balance of factor inputs in the production function reflects their relative costs in Liberia and is typical of current operations in the Liberian agricultural and forestry sectors.[6]

The cost of a Mg of wood delivered to the storage area of the electric power plant is calculated as the sum of the costs of

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[6] Logging operations in Liberia are somewhat more mechanized than the systems considered here. Mechanized logging is primarily a result of the loggers' interest in high-valued large trees where mechanical power is required to haul, load, and unload heavy individual logs. Attempts to develop more mechanized regimes for the pulpwood plantation experiments in Liberia are considered to have been largely unsuccessful [12].

stumpage (or growing), harvesting, and transporting, relevant to a particular supply system. A profit margin is calculated as a fixed percentage of total material, equipment and labor costs, and resource acquisition fees. The margin represents a return to the investor sufficient to compensate for managerial initiative, responsibility, and effort, as well as an allowance to cover calculable and noncalculable risks. Long-run marginal costs of wood from wood energy plantations are calculated using the FIRSTCUT Model -- a cost accounting model for short-rotation wood energy plantations [14].[7]

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[7] To take advantage of the flexibility and convenience of micrccomputers, the FIRSTCUT computer code was reprogrammed and modified [15]. The microcomputer based model, BIOCUT, retains many of the essential features of the mainframe model while being transferable and field analysis oriented--a major advantage in conducting on-site economic evaluations.

7. THE ECONOMICS OF WOOD SUPPLY TO ELECTRIC POWER PLANTS

7.1 WOOD SUPPLY SYSTEM 1: RETIRED RUBBER TREES

Information on the stumpage, harvesting, and transporting of retired rubber trees was obtained from an organization currently involved in industrial-scale rubber wood purchases for energy [16], from a firm which has conducted studies in preparation for bidding on contracts in this field [17], and from interviews with local charcoal producers [18]. Stumpage fees from these sources are estimated to range between $2.27 to $2.96/Mg.

The harvesting cost for retired rubber trees is largely dependent on the rate at which trees can be felled and crosscut with power saws. This rate will vary according to tree size, topography, and seasonal conditions. Based on the data obtained from the references listed above, we estimate that on the average, a felling and crosscutting rate of 20 trees (or 10 Mg/d) can be consistently maintained by a power saw operator and assistant. Wage rates for forest operations in Liberia are relatively standardized and are generally set at about $12.00/d for the chain saw operator and about $4.50/d for the assistant. Other harvesting labor costs include the removal of the crosscut pieces to a loading site. A wood removal rate for crosscut pieces to the loading site of about 4 Mg per person-day appears to be consistent with existing Liberian wood supply systems. Wage rates for unskilled laborers in rural areas are generally about $2.00/d.

Equipment costs are limited to the use of power saws and small hand tools. The total costs for harvesting the retired rubber tree resource are estimated at about $4.10/Mg (see Appendix C).

Transport costs were estimated for each of the three demand scenarios. These costs vary somewhat with the level and seasonality of the wood demand, because the cost estimates are based on the number and size of trucks, which are determined by the peak, rather than the average demand level.

A margin for return to investment is assumed to be 20% of production costs and stumpage fees.

Table 1 summarizes the costs for each of the three demand levels. Estimated total delivered costs range from $14.40 to $15.50/Mg (25% wet basis moisture). These differences are largely reflected in the transport costs, where the suppliers of the largest volumes can take advantage of transportation economies.

Table 1. Annual costs of retired rubber trees

Cost component	Case 1	Case 2	Case 3
Stumpage[a]	$ 34,700	$ 21,700	$ 9,800
Harvesting	54,400	34,000	15,400
Transportation[b]	69,800	47,400	23,200
Margin for risk	31,800	20,600	9,700
Total annual costs	$190,700	$123,700	$ 58,100
Annual harvest, Mg	13,250	8,280	3,750
Average annual cost, $/Mg	$ 14.40	$ 14.90	$ 15.50
Average annual cost, $/GJ[c]	$ 1.01	$ 1.04	$ 1.08

[a] An average stumpage cost of $2.62/Mg is used.

[b] Average round trip transport distance for use of retired rubber trees is assumed to be 20 km.

[c] Energy content of wood is assumed to be 14.3 GJ/Mg.

7.2 WOOD SUPPLY SYSTEM 2: SECONDARY GROWTH FORESTS

A second source of immediately available woody biomass is the secondary growth forests, removed as part of the slash and burn cultivation systems. The basic change from existing systems, which we envision here, is that the burning of the slashed underbrush would occur within a few days of cutting, thus providing a relatively cool burn that leaves most of the wood intact.[8] This wood would then be harvested by the commercial wood supplier.

The utilization of secondary forest would probably involve very low stumpage fees. Outside of urban areas, land rentals (where they exist at all) are generally well under $1/ha/year for areas under intermittent cultivation, implying a low opportunity cost for the site. Presently, some landholders in Liberia hire others to cut the underbrush and burn a site, in preparation for returning a parcel of land to temporary cultivation. Fees for this service are about $65/ha [12]. The commercial wood supplier could enter into an agreement with the local farmers to clear the site and possibly pay a small fee for the wood itself. This payment for site clearing is counted here as part of harvesting costs.

Harvesting operations for secondary forests will depend primarily on the age of the forest and the seasonal conditions. Information on the practicality of harvesting secondary forest

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[8] The practice for site preparation for farming is to allow the slash to thoroughly dry out before burning. Drying creates a "hot burn" that consumes all but the largest of the trees on the site.

was obtained from two principal sources--the German Forestry Mission to Liberia (GFML) and the Liberian Forestry Development Authority (FDA) [12].

It is assumed here that the forest is harvested after 5 to 7 years of growth to ensure nutrient recycling. Harvesting of secondary forest would include the following sequence of operations: underbrushing, burning, felling and crosscutting, and removal to the loading site. Because the secondary forest is composed of relatively small and low-density species, the felling and crosscutting operations are assumed to be carried out with axes and crosscut hand saws. Harvesting costs are estimated at approximately $4.40/Mg. As with the harvesting of retired rubber trees, no significant difference in estimated harvesting costs among the three demand levels exists due to the absence of large machinery.

Transportation costs per Mg are based on a round-trip transport distance of 40 km and vary with each of the three demand scenarios. With 20% of direct production costs for return to investment, costs for the use of secondary growth forest are calculated as shown in Table 2. Costs for utilizing secondary forest range from $13.90 to $17.20 Mg. Estimated total delivered costs are about 4% lower than those for the retired rubber trees for the high demand case and about 12% higher for the two lower demand levels.

Table 2. Annual costs of secondary growth forests

Cost component[a]	Case 1	Case 2	Case 3
Harvesting	$ 57,700	$ 36,300	$ 16,300
Transportation[b]	95,400	79,700	37,500
Margin for risk	30,600	23,200	10,800
Total annual costs	$181,700	$130,800	$ 64,600
Annual harvest, Mg	13,250	8,280	3,750
Average annual cost, $/Mg	$ 13.90	$ 16.80	$ 17.20
Average annual cost, $/GJ[c]	$ 0.97	$ 1.18	$ 1.20

[a] Stumpage cost is assumed to be zero in this case. In practice some charges may occur, but these are expected to be low.

[b] Average round-trip transport distance for use of secondary forest is assumed to be 40 km.

[c] Energy content of wood is 14.3 GJ/Mg.

7.3 WOOD SUPPLY SYSTEMS 3 AND 4: WOOD ENERGY PLANTATIONS

Short-rotation wood energy plantations could become a necessary long-term sustainable resource as existing local supplies of woody biomass are depleted and as demands for wood energy feedstocks increase. Operational procedures and cost data on short-rotation forestry in Liberia were obtained from two principal sources--the GFML and FDA [12]. These agencies have been successful in reforesting mined and logged-over areas with plantings of fast growing wood species. Although the purpose of their studies is to evaluate possibilities for supplying pulpwood, much of the data developed in the experiments are directly or indirectly applicable to the development of wood energy plantations. The GFML and FDA data were used to develop a basecase scenario for the wood energy plantation economic evaluation models [14, 15].

Under Liberian conditions it has been demonstrated that gmelina (Gmelina arborea), the principal reforestation species in the pulpwood experiments, can achieve productivity rates of 13 to 20 Mg/ha/year using a 3 square meter spacing. Mortality typically is low (about 5%) provided that extensive weed control is practiced prior to canopy closure (about 3 to 4 years). Other cultural management practices such as fertilization to increase productivity have generally proven not to be cost-effective [12].

Typical wood energy plantation operations would include nursery activities, site clearing and preparation, planting, weed control, and harvesting. The production of seedlings is assumed to take place at a Liberian nursery. Data from existing nurseries

in Liberia indicate that seedling costs are likely to range between $7 and $28 per hundred, depending on the species and the source of the seeds [12].

Site clearing and preparation costs are similar to costs associated with the harvesting of secondary-growth forests and will depend on site and seasonal conditions. It is assumed that the existing secondary-growth forest will be harvested and utilized at the start of plantation operations. Planting costs will be directly related to the initial planting density and the costs of acquiring planting stock. Here we assume a seedling cost of $20 per hundred and a planting density of 1,100/ha (3 square meter spacing).

Weed control is perhaps the key factor in ensuring low mortality and high productivity. To avoid soil erosion while the seedling root system is developing, ring weeding is practiced in the first year of growth. In the second and third years more extensive weed control is practiced. Generally, weeding ceases in the fourth year of growth after a canopy is formed [12].

The harvesting of wood energy plantations is similar to the operations associated with the harvesting of retired rubber trees. The major difference is that felling and crosscutting rates are estimated at 5-Mg/man-day rather than 10, because of the greater number of smaller diameter trees. Removal rates are set at 4-Mg/man-day. As with the other resource systems, additional information on the production, harvesting, and transportation costs of wood energy plantations is given in Appendices B and C.

Wood from energy plantations can be derived from two different arrangements. One arrangement would be to establish gmelina after upland rice, cassava, or similar crops, and harvest the trees when the land is brought back into cultivation. Presumably, the local farmers could be hired to do the weeding. The other arrangement would be to acquire land under a long-term contract that would preclude shifting agriculture over the life of the plantation. The principal difference between these two systems is that the latter would rely on the coppicing ability of gmelina to regenerate after harvesting, thereby limiting or precluding agriculture. At least two coppice rotations are feasible from a single gmelina establishment before deterioration of the root system [12].

For both wood supply systems, a 30-year planning period with a rotation age of 5 years was used[9]. The costs shown in Tables 3 and 4 are calculated using the FIRSTCUT and BIOCUT models [14,15]. The benefit to the wood supplier from precluding agriculture is that the trees are free to coppice quickly after harvest. If agriculture were practiced during this period, the rapidly sprouting trees would compete with the food crops for available nutrients. Because system 4 allows for the coppicing of the gmelina following harvesting, plantation reestablishment costs are avoided, resulting in a 27 to 35% cost advantage over wood supply system 3. To be sure, this result does not take into consideration the value of the crops produced, part of the return

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[9] Rotation ages of 5 to 10 years were evaluated. The 5-year rotation age was found to be optimal for both systems.

Table 3. Annual costs of short-rotation wood energy plantations with shifting agriculture

Cost component	Case 1	Case 2	Case 3
Production	$ 137,500	$ 85,900	$ 38,900
Harvesting	101,500	63,700	28,700
Transportation[a]	95,400	79,700	37,500
Margin for risk	66,900	45,900	21,000
Total annual costs	$401,300	$275,200	$126,100
Annual harvest, Mg	13,250	8,280	3,750
Average annual cost, $/Mg	$ 30.30	$ 33.20	$ 33.60
Average annual cost, $/GJ[b]	$ 2.12	$ 2.32	$ 2.35

[a] Average round trip transport distance for this case is assumed to be the same as for use of secondary forest.

[b] Energy content of wood is 14.3 GJ/Mg.

Table 4. Annual costs of short-rotation wood energy plantations without shifting agriculture

Cost component	Case 1	Case 2	Case 3
Production	$ 95,800	$ 59,900	$ 27,100
Harvesting	101,500	63,700	28,700
Transportation[a]	66,800	45,500	22,300
Margin for risk	52,800	33,800	15,600
Total annual costs	$316,900	$202,900	$ 93,700
Annual harvest, Mg	13,250	8,280	3,750
Average annual cost, $/Mg	$ 23.90	$ 24.50	$ 25.00
Average annual cost, $/GJ[b]	$ 1.67	$ 1.71	$ 1.75

[a] Average round-trip transport distance for the plantation is assumed to be 10 km.

[b] Energy content of wood is 14.3 GJ/Mg.

from which might be provided to the wood supplier as cash or in the form of services (e.g., weeding), rendered to the wood plantation during the cropping period.

8. COMPARISON WITH EXISTING INDUSTRIAL-SCALE WOOD SUPPLY SYSTEMS IN LIBERIA

To check the reasonableness of our cost estimates we compared the final results with costs for existing industrial-scale wood supply systems. The closest models for relatively large-scale commercial harvesting of wood are found in Liberia's three large foreign-owned rubber plantations, Firestone, Uniroyal, and Guthrie, each of which utilizes wood for process heat. Although some information from these rubber plantations was used to develop our own estimates, we utilized data from numerous other sources as well and developed our estimates component-by-component in the production function. Thus, the following comparison provides a limited validation test for our analysis.

Firestone utilizes about 20/Mg of wood per day and Uniroyal and Guthrie each use somewhat smaller amounts. Using private contractors, each of the plantations pays for the wood on a weight basis delivered to its boiler site. Firestone and Guthrie use retired rubber trees. Uniroyal is a newer plantation and does not have rubber trees which have yet reached retirement age (25 to 30 years). It relies on the cutting of secondary growth (medium forest) for its wood supply. Guthrie also uses some "bush wood" to supplement its supply of rubber wood. In all three applications, the wood is cut on the plantation's own lands [16,19].

Costs for the wood delivered to the rubber plantation boilers range from $12 to $15/Mg. Firestone hopes to eventually

reduce their cost to $10/Mg [15]. These costs do not reflect a stumpage fee and are based on round-trip transport distances of 30 to 50 km. With these considerations, the cost estimates developed in our analysis are within the range currently experienced in Liberia for industrial-scale applications and are probably somewhat on the high side, because of our use of a number of conservative assumptions.

9. CONCLUSIONS

The results of our analysis indicate that the use of wood to fuel rural station electric power plants in Liberia is a viable economic option; that is, wood fuel can be delivered for considerably less than the cost of an equivalent amount of energy from petroleum fuels. In addition, Liberia has at least four wood resource base options, each of which provides the prospect of wood energy delivered at highly competitive prices.

The cost advantages of systems utilizing currently existing biomass stand out sharply in comparison with those requiring the growing of trees. Clearly, wood suppliers will prefer to utilize the standing biomass resource base as long as it is available within acceptable transport distances. The cost disadvantages of wood energy plantations relative to the "mining" of existing resources must be evaluated in view of the transport cost advantages and security of supply considerations.

The costs of acquiring and harvesting secondary forest are less than those costs associated with the use of retired rubber trees. However, the greater transport distances involved with the use of secondary forest eliminate this cost advantage. A cautionary note is needed on the utilization of secondary forest. In the absence of data on the impact on fuel quality because of species variation, we have treated all woody biomass from secondary forests as being of equal value. Yet some of this wood, especially that from younger stands, will consist of

"pulpy", high-moisture content species (e.g., musanga), which typically are the first colonizers of newly opened sites in Liberia [12]. In addition, there are likely to be greater variations in the amount of harvestable wood from different secondary forest sites than from different retired rubber stands. These factors could outweigh the possible cost advantages of secondary forest in the calculations of wood suppliers.

Table 5 summarizes the cost data for the four wood resource systems and three demand levels considered in this analysis. The cost of petroleum fuel is provided for comparison purposes.

Over time, Liberia's still low, but gradually mounting population pressure, will tend to slowly reduce the availability of underutilized standing biomass to meet industrial-scale energy applications.[10] The retired rubber tree resource, in particular, will likely be "mined" locally near wood burning power plants within a few years, even if the emerging boom in the planting of new rubber trees continues for some time into the future. Likewise, it is probable that the length of the fallow period for shifting agriculture will shorten as population pressures increase, reducing the amount (and possibly the quality), of the wood available from this resource. In the longer term, it seems

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[10] Results of the 1984 population census in Liberia are not yet ready as of this writing. Extrapolations from the 1974 Census and other studies indicate that Liberia has an average population density of 18 to 20 persons per square km [20]. This level is below that of neighboring countries, but population growth is generally assumed to be about 3.5% annually.

Table 5. Summary of costs of alternative fuel supply systems

Supply system		Case 1	Case 2	Case 3
Retired rubber trees	$/Mg	14.40	14.90	15.50
	$/GJ	1.01	1.04	1.08
Secondary forests	$/Mg	13.90	16.80	17.20
	$/GJ	0.97	1.18	1.20
Plantation with agriculture	$/Mg	30.30	33.20	33.60
	$/GJ	2.12	2.32	2.35
Plantation without agriculture	$/Mg	23.92	24.50	25.00
	$/GJ	1.67	1.71	1.75
Gas Oil (diesel fuel)[a]	$/GJ	8.10 to 12.20		

[a] Prices of delivered fuel vary by location in Liberia, with prices rising with increasing distance from Monrovia; LEC receives fuel at the "concession" price which reflects landed import costs (roughly $1/U.S. gal). This price is well below that paid by nonconcession customers (i.e., about $2.30/gal in Monrovia). To the concession price, LEC must add transport charges of $0.10 to $0.40/gal) and take into account the substantial losses in diesel fuel because of theft at the rural stations.

likely that some form of tree planting will be required to provide a sustainable wood supply within an acceptable transport distance from the power plants. The cost penalties associated with the planting of trees are clear from the preceding analysis, but even these higher cost wood systems offer major price advantages over petroleum-based fuels in Liberia.

Within each of the wood resource systems, the economies present in the higher demand situation (case 1) reduce average costs by 4 to 24% compared with those in the lowest demand situation (case 3). The greater fractional reductions occur with the standing biomass resources, where transport costs represent a larger share of total delivered costs than they do in the tree planting systems.

The seasonal variation in wood demand or supply ability raise costs for case 2 by 3 to 21% compared with those for case 1. Again, the rubber tree and secondary forest resources show the greater sensitivity to changes in demand, because average transport costs represent a larger share of delivered costs for these systems.

To conclude, our analysis indicates that wood can probably be delivered to small rural power plants at costs that make this feedstock highly competitive for some, and perhaps most, of Liberia's rural electric stations. Furthermore, the wood supplier has at least four resource base alternatives to choose from, and will probably have the ability to shift over time from one to another to ensure reliability of supply and the continued competitiveness.

APPENDIX A

WOOD FEEDSTOCK REQUIREMENTS

CASE 1

The 1.5 MW of steam electric capacity is assumed to operate as a baseload plant having an average capacity factor of 60%. Total annual electricity generation required is

$$1.5 \text{ MW} \times 0.60 \times 8{,}760 \text{ h/year} = 7.88 \text{ GWh/year.}$$

Fuel requirements for this plant are dependent on the plant's thermal efficiency and the average wood energy content. A thermal efficiency of 15% is assumed to be representative of generating facilities of this size. We assume that air-dried wood with a residual moisture content of 25% is utilized in the plant, resulting in an average energy content of 14.3 MJ/kg. Wood required per kWh of generation, assuming a plant net efficiency of 15%,

$$3.6 \text{ MJ per kWh}/(0.15 \times 14.3 \text{ MJ/kg}) = 1.68 \text{ kg/kWh.}$$

Total annual wood requirements are

$$7.88 \text{ GWh/year} \times 1.68 \text{ kg/kWh} = 13{,}250 \text{ Mg/year}$$

Daily harvesting is set at 70 Mg/d assuming 190 harvest days per year (9 months at 5 working days per week).

CASE 2

The 1.5 MW of capacity is assumed to operate in concert with a run-of-the-river hydroplant, or a diesel powered rainy season plant. The wood steam plant is assumed to operate at an average capacity factor of 60% during 5 months of the dry season (January

to May) and at an average capacity factor of 30% during the interseason (May, June, September, October, November, and December). The plant is shut down at the height of the rainy season for maintenance (July and August). The average annual capacity factor for this plant is 38%. Total annual generation requirements are

$$1.5 \text{ MW} \times 0.38 \times 8{,}760 \text{ h/year} = 4.93 \text{ GWh/year},$$

assuming 1.68 kg/kWh results in annual wood requirements of

$$4.93 \text{ GWh/year} \times 1.68 \text{ kg/kWh} = 8{,}280 \text{ Mg/year}.$$

The pace of harvesting is carried out to match the utilization levels. During the peak season (60% capacity) 60 Mg/d are harvested and during the offpeak season (30% utilization), 30 Mg/d are harvested. Equipment requirements are set to meet the annual maximum daily demand.

CASE 3

The 400-kW wood gasifier is assumed to operate as an intermediate load plant having an average capacity factor of 50%. Total annual generation is

$$400 \text{ kW} \times 0.50 \times 8{,}760 \text{ h/year} = 1.75 \text{ GWh/year}.$$

Charcoal requirements for this plant are dependent on the gasifier engine operating efficiency (assumed here to be 20%), and the average heat content of the charcoal (assumed here to be 28 MJ/kg). Charcoal required per kWh of generation is

$$3.6 \text{ MJ per kWh}/(0.20 \times 28 \text{ MJ/kg}) = 0.643 \text{ kg/kWh}.$$

Total annual charcoal required is

$$1.75 \text{ GWh/year} \times 0.643 \text{ kg/kWh} = 1{,}130 \text{ Mg/year}.$$

Charcoal is assumed to be produced with kilns having an operating efficiency of 30%. Production of 1,130 Mg of charcoal requires 3,770 Mg of wood per year. Harvesting wood 188 d/year requires a daily cutting rate of 20 Mg/d.

APPENDIX B

ESTIMATION OF WOOD RESOURCE YIELDS

Estimates of wood resource yields from retired rubber trees are derived from data provided by the Firestone Rubber Plantation [15]. Firestone's measurements on individual trees show an average volume of 0.5 cubic meters in the main trunk and an equal amount in the limbs, branches, and leaves. A somewhat higher estimate is provided by Atlanta [5]. For reasons of nutrient recycling, difficulty in handling of small pieces, and storage, only the trunk, larger limbs, and branches are removed. Total recoverable wood volume is conservatively estimated at 188 cubic meters/ha assuming a stand density of 250 trees/ha. Estimates of wood resource yields from smallholder plantations are more variable as planting densities may be 2 to 3 times higher than those for the large plantations. Recoverable biomass is estimated at 330 cubic meters assuming a stand density of approximately 500 trees/ha [16]. With an assumed wood density of 667 kg/cubic meter (25% residual moisture content), approximately 125 Mg/ha of rubber wood are available for energy use from large plantations and about 220 Mg/ha from smallholder plantations.

Studies of secondary forest [21,22,23] indicate that the rate of regrowth is about 13 Mg/ha/year during the first 8 years following the end of cultivation. A similar estimate is provided by Gatter of the GFML of 100 to 120 Mg/ha for a 7 to 12 year old forest [12]. Furthermore, these studies indicate that

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approximately 90% of the total biomass is attained during the first 8 years of regrowth. Shortly after the abandonment of cultivation, the natural forest regrowth forms a canopy that reduces soil temperatures and soil erosion. The "bush litter" additions to the site are rapidly decomposed adding nutrients to the soils [23]. This nutrient recycling process increases over time and eventually reaches a plateau in about 8 years on tropical soils. Approximately 40 to 50% of the total biomass is recycled to the soil, mostly as leaves, smaller branches, and roots. The proportion of the secondary forest main components is fairly constant, about 75% consisting of trunks and limbs, 15 to 20% of roots, and 1 to 2% of leaves [23]. To avoid disruption of the nutrient recycling process and handling difficulties involved in removal of smaller limbs and branches, it is estimated that total biomass available for energy following cultivation in a 5 to 7-year fallow period would be approximately 50 Mg/ha.

Liberian experience with short-rotation plantations, primarily through the GFML and FDA, has been limited to reforestation programs using gmelina, eucalyptus, and various species of pines. Of these species, gmelina is the most suitable for short-rotation wood energy crops because of its wide site adaptability, pest tolerance, high-growth rate, and coppicing ability. Mean annual growth rates of 13 to 20 Mg/ha/yr at a stand density of 1,100 trees/ha have been reported on nonfertilized sites by Hahnlouser of the GFML [12] and Atlanta [5]. In our study, an average mean annual growth rate of 16

Mg/ha/yr is used. As with other sources of wood energy feedstocks, we assume here that only larger limbs are removed from the site resulting in a realized productivity rate of 12 Mg/ha/yr.

APPENDIX C

WOOD RESOURCE COST CALCULATIONS

Table C.1. Stumpage costs--retired rubber trees

	Plantations	
	Large	Smallholder
Stumpage cost, ha[a]	$ 370	$ 500
Yield, Mg/ha	125	220
Stumpage cost, $/Mg	$ 2.96	$ 2.27

[a] Stumpage costs on individual trees are set at $1.50 per tree on large rubber plantations and range from $0.50 to $1.00 per tree depending on size on smallholder plantations.

Table C.2. Wood energy plantation production costs[a]

Site clearing and preparation costs	
Underbrushing (10 man-days)	$ 20
Burning (2 man-days)	4
Felling and crosscutting (25 man-days)	50
Removal to loading site (50 man-days)	100
Equipment (e.g. axes, cutlasses, etc.)	30
Total site clearing and preparation costs	$ 204
Planting costs	
Seedling stock (1100 trees/ha at $20/100)	$220
Planting (8 man-days)	16
Total planting costs	$ 236
Weed control costs	
Ring weeding year 1 (4 man-days)	$ 8
Slash weeding, years 2 & 3,(12 man-days/year)	24
Total weed control costs	$ 32
Total plantation production costs, $/ha	$ 472

[a] For each of the demand scenarios the plantation is sized at 1308, 818, and 372 hectares for cases 1, 2, and 3, respectively.

Table C.3. Harvesting costs--retired rubber trees[a]

	Case 1	Case 2	Case 3
Labor costs			
Felling and crosscutting	$ 21,945	$ 13,662	$ 6,204
Removal to loading site	6,650	4,140	1,880
Supervision	2,860	1,780	808
Total labor costs	$ 31,455	$ 19,582	$ 8,892
Equipment and operating costs			
Power saws	$ 6,889	$ 4,405	$ 1,948
Spare chains	1,050	600	300
Other consumables	794	500	225
Fuel and oil	9,311	5,796	2,632
Total equip.& operating costs	$ 18,044	$ 11,301	$ 5,105
Miscellaneous costs	$ 4,950	$ 3,088	$ 1,400
Total annual harvesting costs	$ 54,449	$ 33,971	$15,397
Annual harvest, Mg	13,250	8,280	3,750
Total cost, $/Mg	$ 4.11	$ 4.10	$ 4.11

[a] Harvest rates are set at 70 Mg/d for case 1, 60 and 30 Mg/d for case 2, and 20 Mg/d for case 3. The number of harvests days per year are 190, 184, and 188 for cases 1,2,and 3, respectively. Felling and crosscutting rates are 10 Mg/d for one saw operator and assistant with wage rates of $12/d and $4.50. Removal rates are set at 4 Mg/man-day at $2.00. Supervision is 10% of labor costs. Power saw purchase costs are $1100 and have a useful life of 1600 h. Saws are used on the average of 7 h/d. Depreciation and interest costs are calculated over 1600 h at 12%. Hourly costs under cases 1 and 3 are $0.74/h and for case 2 is $0.76/h. Spare chains have a useful life of 200 h and cost $25/chain. Consumables (e.g. cutlasses, fuel cans etc.) are 10% of power saw and chain costs. Fuel consumption is 0.25 gal/h and costs $3/gal. Oil consumption is 10% of fuel and costs $10/gal. Miscellaneous expenses are estimated at 10% of labor and equipment and operating costs.

Table C.4. Harvesting costs--secondary growth forest[a]

	Case 1	Case 2	Case 3
Labor costs			
Underbrushing	$ 5,320	$ 3,312	$ 1,504
Burning	1,064	662	301
Felling and crosscutting	13,300	8,280	3,760
Removal to loading site	26,600	16,560	7,520
Supervision	4,628	2,882	1,309
Total labor costs	$ 50,912	$31,696	$14,394
Equipment costs			
Axes	$ 350	$ 300	$ 100
Crosscut saws	182	156	52
Cutlasses	196	168	56
Wedges	700	600	200
Other items	143	122	41
Total equipment costs	$ 1,571	$ 1,346	$ 449
Miscellaneous costs	$ 5,248	$ 3,304	$ 1,484
Total annual harvesting costs	$ 57,731	$ 36,346	$16,327
Annual harvest, Mg	13,250	8,280	3,750
Total cost, $/Mg	$ 4.36	$ 4.39	$ 4.36

[a] Harvest rates are set at 70 Mg/d for case 1, 60 Mg and 30 Mg/d for case 2, and 20 Mg/d for case 3. The number of harvest days per year are 190, 184, and 188 for cases 1, 2, and 3, respectively. Man-days for labor activities are: underbrushing- 5 Mg/man-day, burning- 25 Mg/man-day, felling and crosscutting- 2 Mg/man-day, removal- 1 Mg/man-day. Wage rates for all labor activities are $2/man-day. Equipment costs are: axes- $10, cutlasses- $4, wedges- $10, and other items- 10% of all equipment. Miscellaneous expenses are set at 10% of labor and equipment.

TABLE C.5. Harvesting costs--wood energy plantations[a]

	Case 1	Case 2	Case 3
Labor costs			
Felling and crosscutting	$ 43,890	$ 27,324	$ 12,408
Removal to loading site	6,650	4,140	1,880
Supervision	5,054	3,146	1,429
Total labor costs	$ 55,594	$ 34,610	$ 15,717
Equipment costs			
Power saws	$ 14,337	$ 9,390	$ 4,053
Spare chains	2,100	1,200	600
Other consumables	1,644	1,059	465
Fuel and oil	18,620	11,592	5,264
Total equipment costs	$ 36,701	$ 23,241	$ 10,382
Miscellaneous costs	$ 9,230	$ 5,785	$ 2,610
Total annual harvesting costs	$101,525	$ 63,636	$ 28,709
Annual harvest, Mg	13,250	8,280	3,750
Total cost, $/Mg	$ 7.66	$ 7.69	$ 7.66

[a] Harvesting costs are estimated in a similar manner as those for retired rubber trees. Harvest rates are 70 Mg/d for case 1, 60 and 30 Mg/d for case 2, and 20 Mg/d for case 3. The number of harvest days per year are 190, 184, and 188 for cases 1, 2, and 3, respectively. Felling and crosscutting rates are 5 Mg/saw operator and assistant with wage rates of $12/d and $4.50/d. Removal rates are 4 Mg/man-day at $2.00/man. Supervision is 10% of labor. Power saw purchase costs are $1100/saw and have a useful life of 1600 h. Saws are used 7 h/d. Depreciation and interest costs are calculated over 1600 hours at 12%. Hourly costs are $0.74 for cases 1 and 3 and $0.76 for case 2. Spare chains have a useful life of 200 h and cost $25/chain. Other consumables are 10% of equipment costs. Fuel consumption is 0.25 gal/h and costs $3/gal. Oil consumption is 10% of fuel and costs $10/gal. Miscellaneous expenses are 10% of labor and equipment and operating costs.

TABLE C.6. Transportation costs[a]

Case 1

Ownership costs (under 20 km)	
Trucks 3-8 Mg (invoice $92,400)	$ 25,630
Maintenance (15% of invoice)	13,860
Consumable spares (10% of invoice)	9,240
Insurance (5% of invoice)	4,620
Total ownership costs ($/d)	$ 281
Ownership costs (30 to 40 km)	
Trucks 1-20 Mg (invoice $66900)	$ 18,560
2- 8 Mg (invoice $61600)	17,100
Maintenance (15% of invoice)	19,300
Consumable spares (10% of invoice)	12,850
Insurance (5% of invoice)	6,420
Total ownership costs ($/d)	$ 391
Operating costs (under 20 km and 30 to 40 km)	
Loading (12 Mg/man-day)	$ 2,280
Unloading (20 Mg/man-day)	1,520
Drivers (3 at $250/month)	6,750
Total operating costs ($/d)	$ 56

Computation of transportation costs as a function of distance

Round trip distance (km/d)	Ownership and operating costs ($/d)	Fuel Oil ($/d)	Transported Cost ($/Mg)
10	337	16	5.04
20	337	33	5.27
40	447	57	7.20

TABLE C.6 (continued)
Case 2

Ownership costs (under 20 km)	
Trucks 1-20 Mg (invoice $66900)	$ 18,560
Maintenance (15% of invoice)	10,040
Consumable spares (10% of invoice)	6,690
Insurance (5% of invoice)	3,340
Total ownership costs ($/d)	$ 210
Operating costs	
Loading (12 Mg/man-day)	1,470
Unloading (20 Mg/man-day)	920
Drivers (1 at $250/month)	2,250
Total operating costs ($/d)	$ 25
Ownership costs (30 to 40 km)	
Trucks 1-20 Mg (invoice $66900)	$ 18,560
2- 6 Mg (invoice $45800)	12,700
Maintenance (15% of invoice)	16,900
Consumable spares (10% of invoice)	11,270
Insurance (5% of invoice)	5,640
Total ownership costs ($/d)	$ 354
Operating costs	
Loading (12 Mg/man-day)	$ 1,470
Unloading (20 Mg/man-day)	920
Drivers (3 at $250/month)	4,500
Total operating costs ($/d)	$ 37

Computation of transportation costs as a function of distance

Round trip distance (km/d)	Ownership and operating costs ($/d)	Fuel Oil ($/d)	Transported Cost ($/Mg)
10	235	10	5.49
20	235	21	5.73
40	391	42	9.62

TABLE C.6 (continued)
Case 3

Ownership costs (under 20 km)	
Trucks 1-8 Mg (invoice $30800)	$ 8,540
Maintenance (15% of invoice)	4,620
Consumable spares (10% of invoice)	3,080
Insurance (5% of invoice)	1,540
Total ownership costs ($/d)	$ 95
Operating costs	
Loading (12 Mg/man-day)	750
Unloading (20 Mg/man-day)	380
Drivers (1 at $250/month)	2,250
Total operating costs ($/d)	$ 18
Ownership costs (30 to 40 km)	
Trucks 2-6 Mg (invoice $45800)	$ 12,700
Maintenance (15% of invoice)	6,880
Consumable spares (10% of invoice)	4,580
Insurance (5% of invoice)	2,290
Total ownership costs ($/d)	$ 141
Operating costs	
Loading (12 Mg/man-day)	750
Unloading (20 Mg/man-day)	380
Drivers (2 at $250/month)	4,500
Total operating costs ($/d)	$ 30

TABLE C.6. (continued)
Case 3 (continued)

Computation of transportation costs as a function of distance

Round trip distance (km/d)	Ownership and operating costs ($/d)	Fuel Oil ($/d)	Transported Cost ($/Mg)
10	113	6	5.95
20	113	11	6.20
40	171	29	10.00

[a] Depreciation and interest costs are computed at 12% for 5 years. Mileage is 15 Km/gal for the 6 and 8 Mg capacity trucks, respectively. Diesel costs are $2.50/gal. Oil is 10% of diesel fuel.

APPENDIX D

ECONOMICS OF WOOD-FIRED POWER SYSTEMS

Wood-fired power systems are an old, and, in many parts of the world, reemerging technology that offers an alternative to fossil fuels in countries with adequate wood resources. Two systems with potential applications in Liberia are wood-fired boilers coupled to either a steam turbine or engine, or gasifiers to produce a combustible gas for a spark-ignition or diesel engine (operating in a dual-fuel mode).

One of the most ambitious national programs to displace petroleum products with wood is that of the Philippines. This program envisions the development of tree farms to supply wood to small (under 3 MW) steam-turbine plants for electricity for both stationary and mobile applications [13]. Initial plans for the program include 70 steam plants to be built during the 1980s. Capital cost estimates for the plants are summarized in Table D.1. Based on fairly conservative assumptions, the estimated cost of electricity from steam-turbine plants is less than half of the current regulated price of electricity in Liberia.

The efficiency of steam-turbine systems decreases for smaller sizes, while gasifiers coupled to internal combustion engines can maintain a relatively good efficiency in sizes down to tens of horsepower. The complementary nature of the two systems is illustrated by the Philippines gasifier program in which gasifiers are commercially available for applications ranging in sizes from ten to a few hundred horsepower [24]. The applications

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Table D.1. Cost estimates for steam-turbine plants[a]

Capital costs	
Equipment ($1100/kW * 3000 kW)	$ 0.017
Civil works ($376/kW * 30000 kW)	0.006
Total capital costs ($/kWh)	$ 0.023
Operating costs	
Operations	$ 0.005
Wood	0.018
Total operating costs ($/kWh)	$ 0.023
Total cost of electricity ($/kWh)	$ 0.046
Regulated price of electricity in Liberia ($/kWh)	$ 0.150

[a] Costs are based on early 1980s costs. Depreciation and interest costs are computed at 6% and 20 years for equipment and 9% and 20 years for the civil works. Annual generation is 16,500 MWh/year. Plant operations include wages for 23 employees. Plant efficiency is 20%.

range from small fishing boats to irrigation pumps, rice mills, and trucks.

The economics of gasifiers are primarily dependent on the capital cost of the equipment, the plant or load factor for the equipment, the relative cost of wood, and the fuel being replaced. The capital cost of the gasifiers (expressed in terms of system power output), ranges from a low of $15/hp to $20/hp to several times this value depending on the degree of sophistication [25]. Simpler units are more appropriate for developing countries, which are generally characterized by low labor costs, high unemployment, shortage of capital, and difficulty in maintaining adequate spare parts.

To illustrate the economics of small gasifiers, consider a small rural power station with a peak load of 250 kW, 24-hour operation, and an average load factor of 50%. The cost of the gasifiers (based on Philippines prices and an allowance for engine adaptions to dual fuel operation of $37.50/hp) is assumed to be three times the Philippines cost, or $112.50/hp, to allow for shipping and installation. Other assumptions are (1) diesel fuel costs are typical of Liberian rural stations--$1.20/gal, (2) the gasifiers operate at an efficiency of 75% and replace 85% of the normal diesel fuel use (allowing for a pilot charge of 15% for ignition), and (3) wood costs are $1.50/GJ. The costs, benefits, and payback for the system are shown in Table D.2. One interesting aspect of these results is that even if the wood costs are doubled (from higher delivered costs, lower equipment efficiencies, or a combination of both), the payback period is

Table D.2. Wood gasification costs and benefits for rural electrification

Capital costs	
Gasifier: 3 engines (125 kW) for reliability, heat rate of 14000 GJ/kWh, total capacity of 502.5 hp at $112.5/hp	$ 56,530
Shed, chipper, and dryer	40,000
Total	$ 96,530
Operating costs ($/year)	
Maintenance (3% of capital)	$ 2,900
Operations (4 employees - $150/month)	7,200
Wood costs (16,100 MJ/yr) (250 kW * 0.5 * 14,000 GJ/kWh * 8760 h * 0.85 / 0.75) * $1.50/GJ	26,100
Total	$ 36,200
Benefits	
Value of diesel fuel displaced 89250 gal/year (250 kW * 0.5 * 14000 Gj/kWh * 8,760 h * 0.85 / 146,000 GJ/gal) * $1.20/gal	$107,100
Total net benefits	$ 70,900
Undiscounted payback period (years)	1.36

still very attractive--2.15 years. However, for operation with charcoal and a wood-to-charcoal thermal efficiency of 30%, wood costs become $5.00/GJ and the payback period becomes 9.5 years.

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