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CURRENT AND PROJECTED WOOD ENERGY CONSUMPTION IN THE UNITED STATES

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ABSTRACT

The USDA Forest Service is preparing long-term projections of wood energy use as part of an assessment of demand for and Supply of resources from forest and rangelands in The United States to be published in 1989. To assess the lmpact of wood energy demand on timber resources, two systems dynamics simulation models are used to project residential and industrial/commercial fuelwood use from several fuelwood sources: stickwood, whole tree chips, logging residue, and mill residue.

The projections are driven by a projected increasing cost advantage of wood fuels over fossil fuels. There are numerous assumptions that other conditions will change relatively little over the projection period. Fuelwood use is projected to increase from 1.3 quadrillion Btu's (quad) or 5.2 billion cubic feet (BCF) in 1986, to 2.2 quad or 8.8 BCF by 2020, then decline to just under 2 quad or 7.8 BCF by 2040. If we add a modelate amount of black pulping liquor use, our total wood energy use would be less in 2010 than the DOE projected amount of 3.7 quad. Residential fuelwood will dominate consumption and is projected to increase 64% between 1986 and 2020. Much of this increase is due to a 50% increase in number of households. Use of chips and logging residue for industrial/ commercial fuel is projected to grow by a factor of 3 to 4 between 1986 and 2020 because mill residue is now fully utilized.

Fuelwood use (excluding bark) is projected to increase from 27% of roundwood harvested in 1986 to 29% in 2020, then decline to 25% in 2040. Fuelwood will likely become a relatively permanent part of the forest products economy and this may have important implications for forest management in the long term.

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INTRODUCTION

The Forest Service of the U.S. Department of Agriculture is directed under requirements of the Renewable Resources Planning Act of 1974 and the Renewable Resources Research Act of 1978 to make periodic assessments of the current and long-range demand for and supply of renewable resources from forest and rangelands in the United States. The Forest Service is preparing such an assessment with projections to 2040 to be published in 1989. The assessment of timber resource demand and supply has been prepared in draft form (13). This paper discusses one part of this assessment of the timber situation--the analysis of the demand for and supply of timber for energy.

Since 1980, faculty and staff at Dartmouth College have worked with the Forest Service to prepare long-range projection models of wood energy use, first for residential wood burning, and second, for industrial/commercial wood energy use. To project the demand for timber resources for fuel we must assess how economically many forms of wood energy may substitute for conventional fuels as used by many end users. The two models discussed in this paper, CHIPS and WOODSTOV, project how much of several types of wood energy will be used by 1) households, 2) pulp/paper/paperboard mills, 3) solid wood products mills, 4) large non-forest-products boilers, and 5) small non-forest-products boilers in response to the projected cost advantage of wood relative to oil, natural gas, electricity, and coal.

Wood for energy can come from many sources. It iS Of considerable interest in an assessment of timber demand to sort out wood energy supply sources because many sources are not used for sawlogs, veneer logs, or pulpwood. Wood energy supply sources used in this paper include

Roundwood, in the form of
- Stickwood (primarily residential use)
- Chips (made by whole tree harvesting and chipping)
- Logging residue (primarily industrial/commercial use)

Mill residue, wood and bark

Black pulping liquor

Fuelwood as used in this paper is defined to include both roundwood and mill residue. Currently, fuelwood used by households is almost entirely roundwood and fuelwood used by the industrial/commercial sector is mostly mill residue.

We exclude 1) waste wood products such as pallets, discarded furniture, and demolition waste, 2) wood used to

make liquid fuels, and 3) trees grown by short rotation intensive culture (SRIC). The first source was considered small compared to other wood energy sources, and the second and third face high economic uncertainty relative to other sources. If liquefaction processes or SRIC can produce wood for energy at a price competitive with other wood energy sources, they may displace or add to wood energy sources discussed in this paper.

Roundwood, which by definition comes directly from timber, is further subdivided into the categories traditionally used to assess timber supply: first, by hardwood and softwood species; second, by land source--timberland, woodland, and nonforest land; and third, (on timberland only) by type of timber volume--growing stock and other. Timberland produces growing stock growth of 20 cubic feet per acre per year; woodland produces less. For simplicity we divide roundwood into four categories:

- Growing stock volume
  - Hardwood
  - Softwood
- Other sources
  - Hardwood
  - Softwood

In 1986 about 90% of sawlogs, veneer logs, and pulpwood came from growing stock volume: only about 26% of stickwood used for residential wood burning came from growing stock volume.

This paper is divided into sections discussing historical trends in wood energy use, present wood energy use patterns, methods used to project wood energy use to 2040, and projections of use.

HISTORICAL BACKGROUND

Woodfuel was the major energy source of Native Americans as well as early colonists over most of North America. The availability of wood and its ease of use in agricultural and simple industrial activities made it an ideal fuel for a mobile and rapidly changing frontier society. The abundance of wood assured its dominant role in the early industrialization in North America through much of the 19th century even while coal had grown more important in Europe. In 1850, wood was the largest single energy source in the United States, and more wood was used for fuel than for any other purpose. Although coal use grew rapidly in the later 1800s, wood use continued to grow to a peak in the 1870s when it provided slightly less than 3 quad of energy or about 11 BCF (Figure 1) (10). The fuelwood used through the mid 1900s was almost entirely from roundwood. Relatively small amounts of mill residue may also have been used. After 1870, the total amount of roundwood used for fuel in the United States declined

steadily to a low in early 1970s. The Forest Service estimates a low of about 0.5 BCF in 1972 or 0.1 quad (12). The U.S. Department of Energy (DOE) estimates a low of about 22 million OD tons in 1972 or 0.4 quad (14). DOE estimates that by 1984 roundwood use by households alone increased to 3.9 BCF or 0.78 quad (15). Industry and commercial establishments burned an additional small amount of roundwood. Total roundwood use has since decreased with the decline in fossil fuel prices.

While roundwood use decreased in the 1950s, '60s and '70s, industry increased its use of mill residue and black pulping liquor for fuel. so total wood energy use (roundwood, mill residue, and black liquor) may not have dropped lower than 1.4 quad (Figure 1). Mill residue use increased as forest products industries produced additional residue, and more stringent environmental regulations restricted open burning, incineration, and landfill disposal of wood residue. More restrictive water pollution regulations increased the incentives to fully use black pulping liquor for fuel.

From 1974 to 1985, rapid increases in oil prices stimulated increases in wood energy use in several sectors of the economy. By 1986 DOE estimates total wood energy use had risen to 2.52 quads. High oil prices, combined with further pressure from environmental regulations, has created a situation in the forest products industries where most surplus wood residue is now being used for energy and increased quantities of wood are harvested as fuel for both industrial and residential sectors. Substantial improvements in energy efficiency have been made in most sectors that use wood so that the effective energy yield from the wood is greater now than in the past.

The use of wood for energy has expanded beyond the forest products industries and the residential sector to include commercial and institutional use, industrial steam production, electric cogeneration, and electric utility power production. Research and development work was in progress in both the public and private sectors to commercialize wood gasification, methanol and ethanol production, and synthetic petroleum fuels production. However, the fall in oil prices since 1985 has significantly reduced commercial interest in much of this work although considerable technical progress has been made in most areas.

PRESENT WOOD ENERGY USE PATTERNS

The most detailed information about wood energy supply in 1986 comes from the U.S. Forest Service and the American Paper Institute, and the most detailed information about demand comes from DOE.

On the supply side, an estimated 3.11 BCF of roundwood was used primarily by residential households in stoves,

furnaces and fireplaces (Table 1). An estimated 2.06 BCF of mill residue (wood and bark) was used primarily in industrial/commercial boilers. These amounts total 5.17 BCF of wood and bark. Additional amounts were burned in the form of mill residue from secondary processing plants and waste wood products. No estimates are available on these amounts, but they are significantly less than the amount from primary mill residue. The total of the available supply estimates for 1986 is 5.17 BCF or about 1.3 quad. If we add 0.90 quad of black pulping liquor used for fuel (2), partial total wood energy from supply side information sources is 2.2 quad. This is a partial total because it does not contain an estimate of secondary mill residue or waste wood products used for fuel.

On the demand side, DOE surveys and estimates for industries, commercial facilities and utilities show a consumption of 2.52 quad in 1986. If we deduct 0.9 quad for black liquor, this leaves 1.62 quad or 6.5 BCF in the form of roundwood and mill residues (wood and bark). The difference between supply and demand side estimates of roundwood plus mill residue use (5.2 BCF and 6.5 13CF) is due in part to the lack of information about use of secondary mill residue and waste wood products. This difference is also likely to be due to use of different conversion factors and differences in survey and estimation procedures.

To assess the impact of fuelwood use on timber resources, roundwood use in 1986 must be subdivided by timber source: growing stock and other sources. Of the 5.16 BCF of fuelwood, only 16% or 0.81 BCF came from growing stock (Table 1). So, relatively little fuelwood currently comes from the same supply category as most sawlogs, veneer logs, and pulpwood.

METHODS USED TO PROJECT WOOD ENERGY USE TO 2040

Wood energy demand and supply have been projected through the year 2040 with the use of a formal computer simulation modeling procedure, which has two parts corresponding to the industrial/commercial and residential sectors. These two sectors are very different in many respects, and in consequence, the models are also quite different, although they share some common characteristics. CHIPS and WOODSTOV III are both simulation models written in DYNAMO and originally conceptualized by people in the same research group.

The residential wood use model (WOODSTOV III) is a demand model that estimates residential woodfuel demand given a set of input parameters. It does not keep an inventory of available wood resources or estimate fuelwood prices, but uses the price and supply information from the industrial wood energy model (CHIPS). CHIPS is both a supply and a demand model, which keeps an inventory of wood fuels available through its forest inventory sector. CHIPS

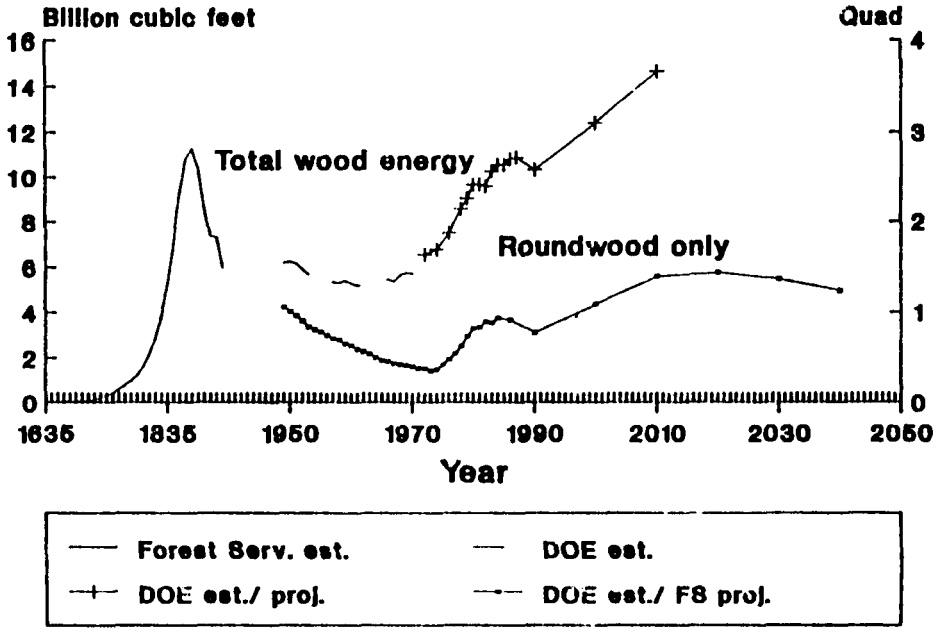

Figure 1. Historical and projected wood energy use. Sources: Refs. 10, 14, 17.

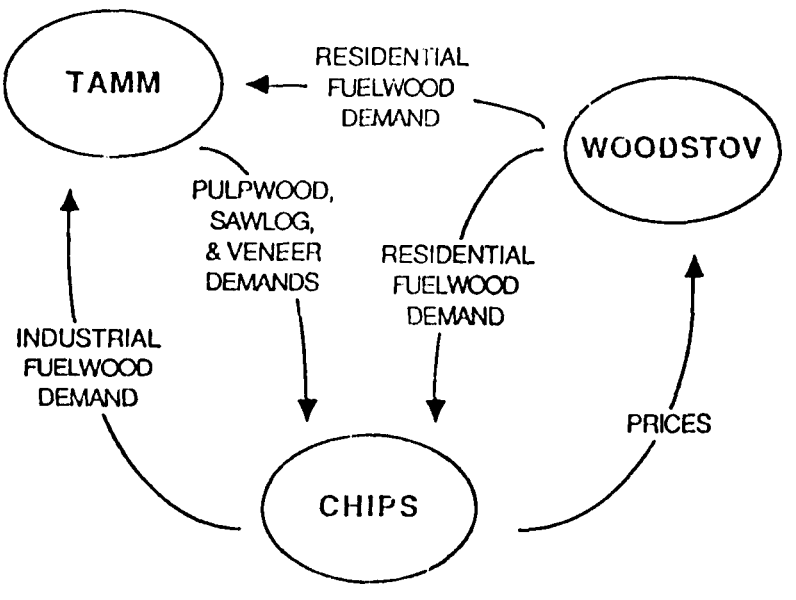

Figure 2. Data flow between the TAMM, WOODSTOV and CHIPS models.

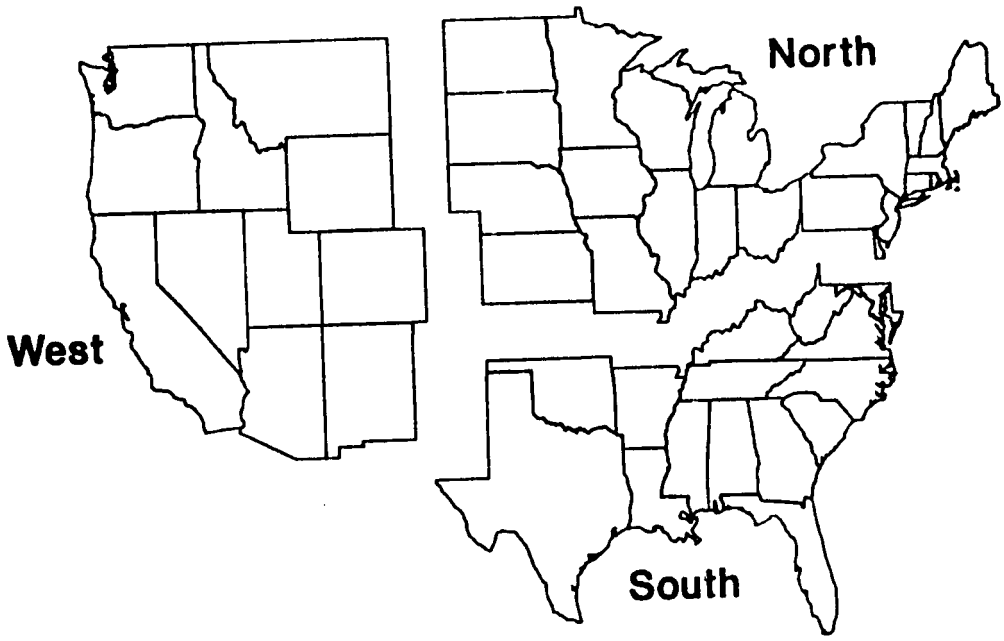

Figure 3. Division of United States into regions for projection models.

Table 1. Wood energy use estimates by the USDA Forest Service and U.S. DOE for 1986

Type of material	Total	Species		Timber Source	
		Hardwood	Softwoood	Growing stock	Other
	billion cubic feet				
USDA Forest Service					
Roundwood[a]	3.11	2.56	.55	.81	2.30
Mill residue[a]					
Primary processing	2.06	.50	1.56	NA	NA
Subtotal (BCF)	5.17	3.06	2.11	.81	2.30
Secondary processing[b]	?	?	?	NA	NA
Waste wood products[b]	?	?	?	NA	NA
	quadrillion Btu				
Subtotal (quad)[a]	1.29				
Black liquor[c]	0.90				
Total (quad)	2.19	(excludes mill residue from secondary processing and waste wood products)			
USDOE Estimates[d]					
Residential	0.85	(3.41 BCF)			
Commercial	0.02	(.08 BCF)			
Utilities	0.01	(.04 BCF)			
Industrial	1.64	(2.96 BCF plus 0.9 quad of black liquor)			
Total (Quad)	2.52	(6.49 BCF plus 0.9 quad of black liquor)			

NA - Not applicable.

[a]Roundwood and primary mill residue estimates (wood and bark) are from Ref. 13, Tables 3.30 and 3.31. One quad equals 4 billion cubic feet.

[b]Amount burned from secondary mill residue was less than primary mill residue but no estimates are available. Waste wood products include discarded products such as pallets and furniture and demolition wastes.

[c]Source: Ref. 2.

[d]Source: Ref. 17, Table B-1 & B-2. Estimate for Residential use is from Ref. 16.

CHIPS Overview

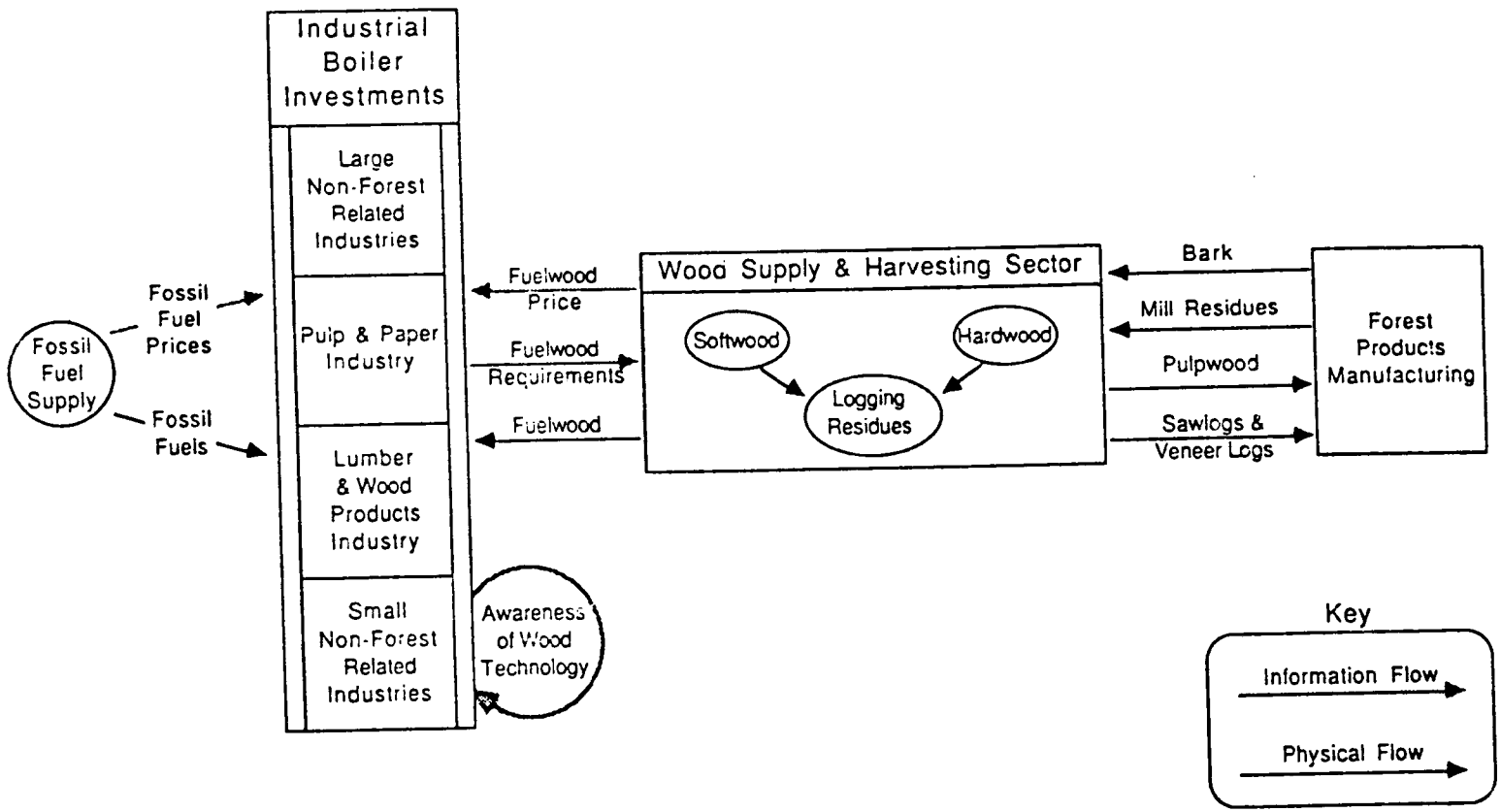

Figure 4. Components of the CHIPS model.

provides estimates of fuelwood prices to WOODSTOV and receives estimates of residential fuelwood demand from WOODSTOV. Both the demand and supply side of the CHIPS model are affected by the consumption of wood in the forest products industries, and CHIPS therefore exchanges information with the U.S. Forest Service forest Sector projection model, the Timber Assessment Market Model (TAMM) (1,5). TAMM incorporates estimates from other specialized models that project pulp and paper production, lumber and panel production, timber required to produce these products and resultant timber inventory. The interactions among the models is shown in Figure 2.

Both the CHIPS and WOODSTOV models are regionally disaggregated because of the strong regional differences in wood energy use patterns. Transporting wood fuel for long distances is not economical because of its low energy to weight ratio. Consequently, relatively local markets have developed. The results of the modeling are shown in this paper as national totals ancl totals for three regions- North, South, and West (Figure 3). The model regions (five in CHIPS and nine in WOODSTOV) have been aggregated to produce results for each of the three U.S. regions. Verification of the two models is conducted independently against separate data sets but both use consistent assumptions about future prices of conventional fuels.

The Industrial Fuelwood Projection Model (CHIPS)

Structure of the Model. The industrial/commercial fuelwood projection model (CHIPS) is a systems dynamics simulation model written in DYNAMO and run on a mainframe computer as five independent regional models with identical structures. The results of the five regional models are aggregated to produce the projections for the North, South, and West regions and the national projections. The North region is aggregated from the North-Central and Northeastern regional models. The West region is aggregated from the Pacific Northwest and Rocky Mountain regional models; the South region is identical to the South regional model.

The structure of each regional model is basically the model structure described by Van Wie (18). The model is a system of levels and rates controlled by a set of economic decision-making functions that simulate the behavior of numerous energy-using companies and fuelwood suppliers. The model has two main parts: an industrial boiler fuel selection submodel and a fuelwood/mill-residue supply submodel (Figure 4). The two submodels are connected by four variables:

1. Average prices paid by forest product industries for specific categories of fuelwood
2. Average prices paid by non-forest-products industries for specific categories of fuelwood
3. Total industrial fuelwood demanded by various users

4. Total fuelwood supplied from various sources

The boiler selection submodel is derived from a model known as WOODBLR3 (4). The boiler submodel has four sectors corresponding to the four major industrial sectors using wood energy. These are 1) pulp and paper, 2) lumber and wood products, 3) large nonforest industries, and 4) small nonforest industries. Roundwood and mill residue demand for fuel is tracked separately for each sector for each region. In the case of the pulp and paper industry, the contribution of black liquor is subtracted from the demand for total energy. In each sector, the same method is used in the model to allocate industrial. boiler investments among four boiler types: wood-fired, coal-fired, gas-fired, and oil-fired. The model simulates three specific rationales for boiler investments: 1) to meet new capacity requirements, 2) to replace old boilers,and 3) to switch from one fuel type to another.

New capacity and replacement capacity investments are allocated among the four boiler types by a logit function based on an adjusted lifecycle cost for each boiler system. The determinants of the adjusted lifecycle costs are 1) the actual lifecycle cost of building and operating each boiler system, 2) the perceived security of each fuel supply, and 3) the awareness of and confidence in wood bioler technology. Specifically, the actual lifecycle cost of each boiler type will be adjusted upward if there is a perceived insecurity in the fuel supply as indicated by an unsteady or unpredictable fuel price. Thus , CHIPS simulates the implied risk of an insecure fuel supply as an addition to the lifecycle cost of a boiler system. In addition, the lifecycle cost of a wood-fired boiler system is adjusted upward to reflect the low awareness of and confidence in wood boiler technology, especially among the non-forest-product industries. As wood boiler technology achieves greater levels of penetration into the industrial energy market, awareness and confidence grow, increasing the competitiveness of wood energy.

The decision to switch boiler fuels is based on the calculated payback period of the proposed installation relative to the alternative. Again, fuel supply securities and wood technology awareness can weigh in the decision-making process, reducing the extent to which fuel switching occurs even when the payback period is short.

The model addresses an important concern: that we prevent an unrealistic demand for wood fuel from plants located a long distance from wood supplies. To control fuelwood use in forest products plants, the model relies on wood prices to limit demand. We assume such plants are near wood sources. To control fuelwood use in non-forest-products plants, we rely on 1) wood price, which is adjusted upward to account for their higher cost for wood, due in part to higher transport costs, and 2) an upper limit on the proportion of non-forest-products boiler capacity that is likely to be near wood resources and would

have realistically low transport costs. As a result of these controls, wood energy does not account for more than 1% of energy consumed by non-forest-products plants in our projections and non-forest-products plants account for no more than 3.6% of all wood boiler capacity.

Demand for nonfuel timber products is exogenous but is included in the inventory and price structure of the CHIPS model so that fuelwood demand and the demand for other products are linked.

The demand for industrial fuelwood estimated by the boiler selection submodel is met from a fuelwood inventory that is tracked by the fuelwood supply submodel. The supply submodel accounts for five different fuelwood types within the industrial wood energy market: hardwood chips; softwood chips; logging residue; mill residue; and bark. A logit function is used to distribute fuelwood based on the price of each component of fuelwood supply. An Important assumption within the pricing sector of CHIPS is that prices will be set to favor the use of waste wood and residues, since these components have little value outside the wood energy market. Thus, the price of chips, the costliest component of fuelwood supply, places a practical upper limit on the price of the residual and waste components of fuelwood supply.

Assumptions and Limitations. The CHIPS model makes a number of important assumptions about the way in which wood energy use will evolve. The first of these is that decisions about fuel choices will be made in a free market by economically rational decision makers. No provision has been made for government intervention in the markets beyond the implementation of existing environmental regulations. Clearly, direct or indirect government intervention could significantly alter the attractiveness of specific fuels, as has occurred in the past. During the next 50 years, some changes in environmental regulations will most likely occur. Although the details of these are hard to predict, it seems unlikely, in view of the potential problems associated with the greenhouse effect and acid deposition, new regulations may be relatively more favorable to wood than to fossil fuels. This could have the effect of improving the competitivenes of wood fuels in the industrial sector. The case for the residential sector may be different, given the differences in conversion technologies.

The second assumption is that the supplies of fuelwood will be limited to categories described above. No allowance has been made for the possibility of the development of plantations of fast-growing wood or the significant recovery of waste wood products, such as demolition debris or waste pallets.

The third assumption is that wood energy conversion technology will remain relatively static through 2040. We assume that combustion technologies will remain dominant

and that liquid fuel production from wood will not be significant.

The CHIPS model is quite well suited to evaluating alternative scenarios that might include changes in any of the assumptions described above. Earlier versions of the model have been used to evaluate some of these issues (3). In general, the model should be considered as a long-term trend analysis tool and *not* as a predictor of short-term market fluctuations.

External Inputs. The CHIPS model has a number of important external inputs. These fall into two categories: inputs related to forest products and fuel price information. Projections of future consumption of pulp, timber, and residential fuelwood are received from the TAMM and WOODSTOV models. The pulp and timber consumption estimates received from TAMM are used for both submodels in CHIPS. The demand for pulp and timber affects the demand for energy in pulp, lumber and other wood products industries, which in turn affects the demand for fuelwood. Pulp and timber production also increase the supply of logging and mill residues and reduce the forest inventory of timber. CHIPS also uses and is very sensitive to the projected future price of competing fuels. Fuel price projections taken from DOE are used as one of the key exogenous variables in the model. The DOE industrial fuel price projections that *were* used in the model are shown in Figure 5.

Model Verification. The CHIPS model is initialized with 1970 data and simulates the system from 1970 to 2040. The model has been calibrated and validated on a limited set of variables for the period 1975 to 1985. Several difficulties are associated with validating this model. The most important is the dearth of continuous sets of historical records of wood energy use by fuelwood type and industrial sector. The most important record against which the model can be validated is the American Paper Institute (API) records of wood energy use among their member companies. This represents over 90% of the energy demand in the pulp industry in the United States. The results of the CHIP model simulations are shown plotted against the API record of wood energy use (excluding black liquor) for the period of 1975 to 1985 in Figure 6. As can be seen there is relatively good agreement between the model projections and reported data. Because the structure used for projecting woodfuel use in the other sectors is relatively similar to that used for pulp and paper, we may have some confidence in the other sectors also. However, in projecting as far into the future as 2040 we cannot be confident that the parameters established on the basis of the period 1975 to 1985 will hold for over 50 years. In general, the reliability of projections will decline further into the future and as the model deals with smaller supply and demand sectors. Because we have been able to verify the behavior of the model against real world data over a period of 10 years for the pulp and paper industry,

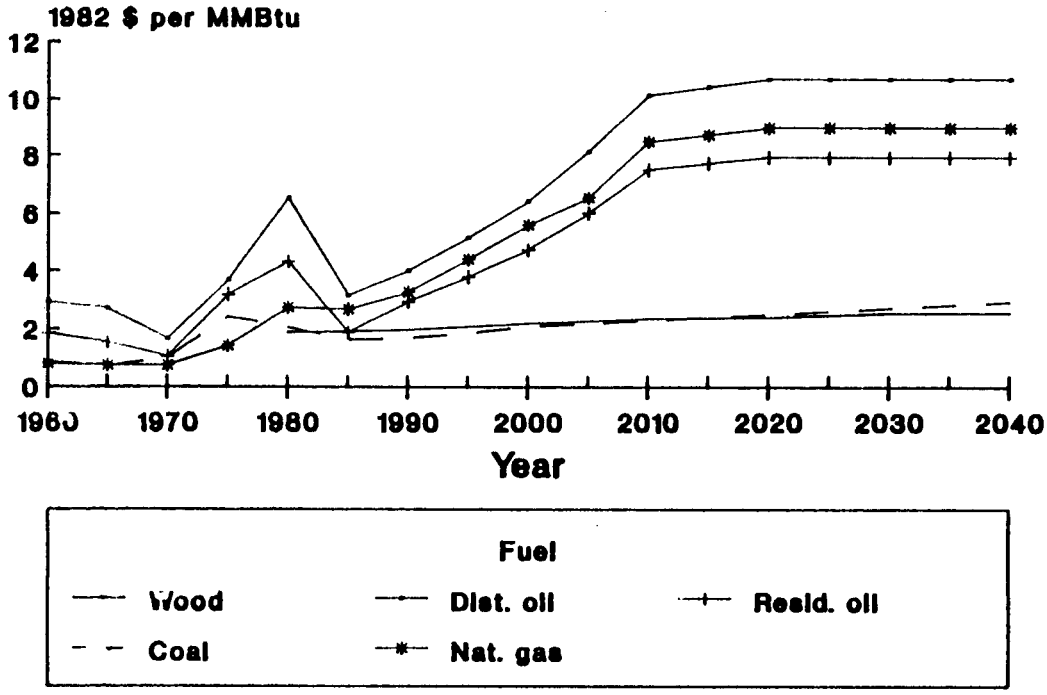

Figure 5. Industrial fuel price projections from DOE used in CHIPS model.
Sources: Ref. 17, USFS projections.

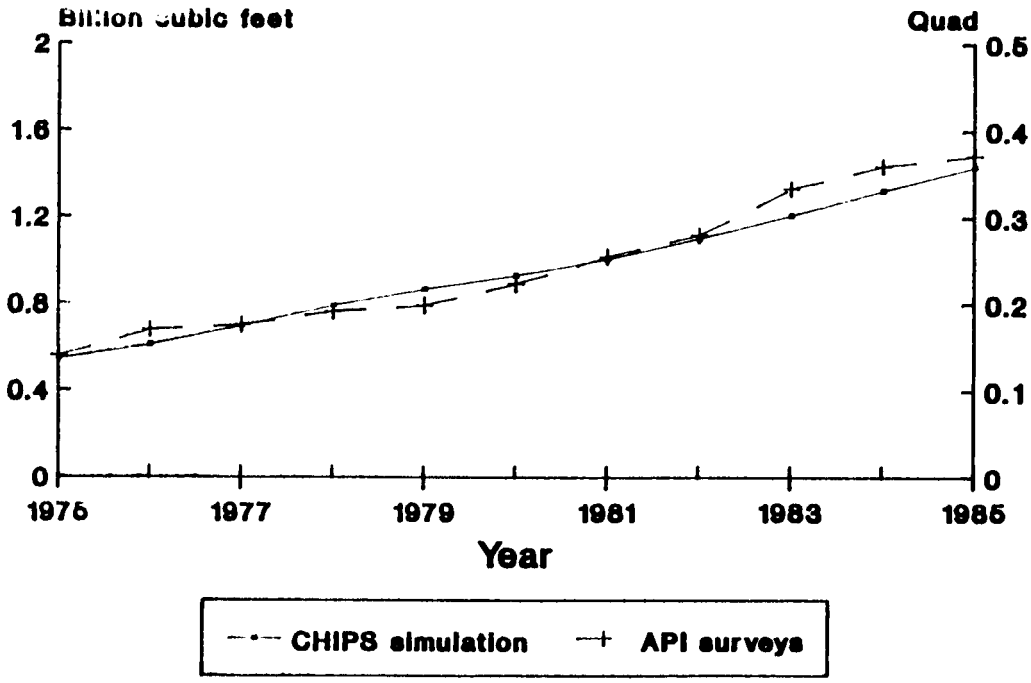

Figure 6. Reported fuelwood use (API) compared to CHIPS simulated use for the pulp and paper industry.
Sources: Ref. 2, USFS projections.

we have the most confidence in the results for that sector. The total industrial consumption estimates from the model have been checked against estimates made by DOE (17). After allowance is made for the treatment of black liquor, the model simulations and the DOE estimates generally agree for the 1980-1986 period, given the differences between the DOE and USFS estimates. This suggests that the model is reasol~ably representing the aggregate behavior of the nonpulp industries as well. Specific checks have been made of other parameters in the model against known data points or estimates made during the last 10 years. Parameters checked include biomass inventories, production of logging residues, use of mill residue for fuel and wood prices. After allowances for definitional differences there is broad agreement in both magnitudes and trends.

Sensitivity testing has been conducted on numerous parameters over many iterations of the model, and several changes have been made to make the model more robust in certain areas. Not surprisingly, the model is very sensitive to the price of competing fuels. Because fuelwood is a very small part (about 2%) of the national energy picture, wood enelgy use is strongly influenced by national energy trends but itself exerts relatively little influence on those trends. The results presented here only show projections based on one set of fuel price projections (Figure 5); but several other fuel price forecasts have been tested, and in nearly all cases, the general trend of fuelwood consumption follows the trend in real oil prices. The model is also sensitive in some sectors to changes In demand for other forest products. As described above, increased production of pulp or timber affects both the demand and supply side of the model, which makes the industrial fuelwood model quite sensitive to the results of the TAMM model. Overall, the CHIPS model is most sensitive to these exogenous variables, which is consistent with the situation in which fuelwood plays a relatively small part in two large national markets: the energy market and the forest products market.

The Residential Fuelwood Projection Model (WOODSTOV)

Structure of the Model. The residential fuelwood projection model is a systems dynamics simulation written in Dynamo and run on a mainframe computer. It has nine independent regional models with identical structures. The projections for the North, South, and West regions shown here are aggregated as follows. The North region is aggregated from the North-Central, Mid-Atlantic and New England model regions. The South region is aggregated from the Southeast and South-Central model regions. The West is aggregated from the Pacific Northwest, Southern Rocky Mountain, and Northern Rocky Mountain model regions.

The structure of the model was developed by Marshall and others (6,7,8). The model is a system of levels and

rates controlled by a set of economic decision-making functions that simulate the behavior of households. The model has two main parts simulating wood use in stoves and wood use in fireplaces (Figures 7 and 8).

The submodel that estimates wood use in stoves and furnaces (hereafter referred to as stoves) divides occupied housing units (equivalent to the number of households) into three types: single family, multifamily and mobile homes. Each of these types is further subdivided into households using oil, natural gas, or electricity as a primary fuel, or a backup fuel for wood.

Wood use in stoves is calculated separately for each of these nine categories of households in each region. The amount of wood used in each category is the product of the amount of fuelwod use capacity installed (stove or furnace) and the proportion of capacity used (Figure 7). The fuelwood use capacity is the product of the number of households with capacity and the *average* capacity in a home. Capacity is modified in each successive period by 1) equipment installation in new housing (determined by fuel cost savings if wood is used rather than the conventional fuel alternative), 2) retrofits to install wood-burning capacity (determined by the payback period for new wood-burning equipment), and 3) retirement of old equipment (influenced by wood fuel cost savings). The proportion of capacity actually used is determined by the fuel cost saving if wood is used rather than the conventional alternative.

A number of important adjustments are made in calculating capacity additions and removals, and capacity utilization. First, stove capacity installations in new homes are influenced by installation costs that vary by housing type and 1) increase as the fraction of households with stoves Increases and 2) increase as wood heat provides a greater fraction of heating needs in the average wood-heating home. Second, cost of fuelwood is increased as the proportion of wood-burning households increases. This is to reflect the fact that late adopters tend to be households that 1) have less access to wood they can cut themselves and therefore must purchase or 2) live further from wood sources and must purchase wood, which includes higher transport costs. Third, wood fuel cost savings are influenced by the fact that a given amount of heat provided by a wood stove will displace a greater quantity of conventional fuel than the same amount of heat provided by a central furnace. In other words, when a wood stove is used, fewer rooms are heated. This behavior increases wood fuel cost savings compared to fuels burned in furnaces.

Wood use in fireplaces is calculated in a simpler way than wood use in stoves. Wood use in fireplaces is the product of the number of households using fireplaces and the average amount of wood used per household (Figure 8). The number of households using fireplaces is influenced by stove fuel cost savings. Fuel cost savings for stove use

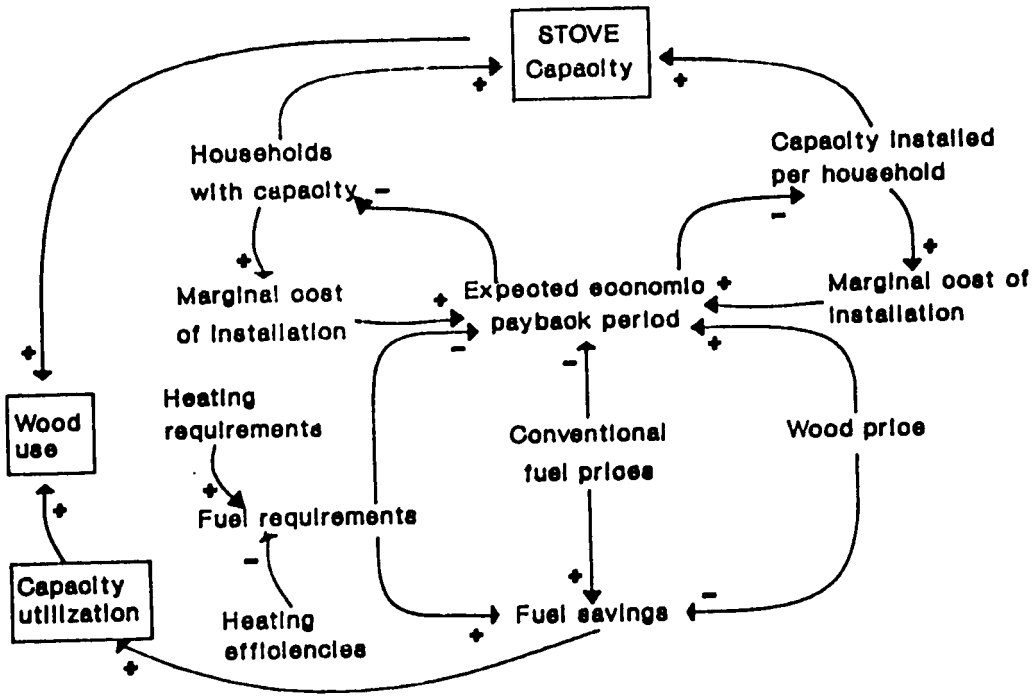

Figure 7. WOODSTOV-III model structure for wood use in stoves.

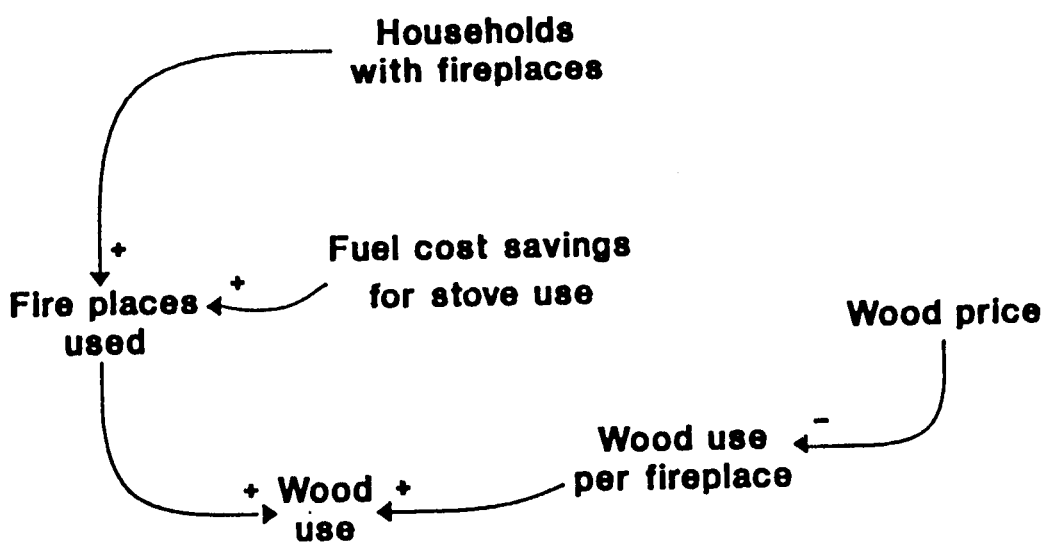

Figure 8. WOODSTOV-III model structure for wood use in fireplaces.

is taken as a proxy for the perceived desirability of using fireplaces. The average amount burned is influenced by fuelwood price.

Assumptions and Limitations. The WOODSTOV model makes a number of assumptions about the behavior of households, regulations, conversion efficiency, and housing characteristics.

First, it is assumed that households make decisions about fuel choices based on perceived economic benefit. The ecolmmic benefit for early adopters includes access to relatively inexpensive wood supplies that they purchase or cut themselves. It is assumed the net economic benefit for late adopters is reduced because they must pay more for wood supplies they purchase *or* cut themselves. The model assumes wood users place a cost on the extra effort required to use wood. This extra effort is assumed to increase for late adopters but does not increase generally over the projection period.

Second, in our base case projections, the effect of regulations on wood-burning equipment and use is assumed to be minimal. We discuss a test of this assumption in the model verification section below.

Third, it is assumed that the *conversion* efficiency for conventional fuels and fuelwood will improve through 2000, but the average wood fuel conversion efficiency will remain somewhat less than for conventional fuel. After 2000 conversion efficiencies for all fuels are assumed to remain constant.

Fourth, it is assumed that the mix of housing types and conventional fuels used in various regions will remain constant over the projection period. Fuelwood use would decrease to the extent that households moved from single family to multifamily housing units. Fuelwood use would also decrease to the extent that households shifted to lower cost conventional fuels, thus decreasing the advantage of wood burning. However, the effect of fuel switching on wood use will be minimized under the projections used here where natural gas and oil are expected to cost about the same on average nationwide (Figure 9).

External Inputs. The WOODSTOV model uses three important external inputs. Residential prices for fuel oil, natural gas, and electricity through 2010 are from DOE projections (17). By 2020 and thereafter, prices are assumed to level off at the equivalent of $50 per barrel of oil (1982 dollars) (Figure 9). Fuelwood prices are projected by increasing regional prices from a 1980 survey (9) at *t)ie* same rate as whole chip prices projected by the CIIIPS model. The number of households is projected to increase at the rate projected for the 1989 Forest Service Assessment (13).

Model Verification. The WOODSTOV model is initialized in 1970 and simulates residential fuelwood use from 1970 to 2040. The model has been calibrated and validated using several sources of information about trends in fuelwood use between 1970 and 1986, and detailed survey data on fuelwood use characteristics for 1980. Three sources of information were used to establish the national trend in residential fuelwood use between 1970 and 1986:

1. Forest Service (FS) surveys/ estimates for 1970, 1980, and 1986
2. DOE estimates for 1970 to 1983
3. DOE surveys for 1981 to 1986

The first two sources agree on a rapid increase in use between 1970 and 1980 but do not agree on the level of fuelwood use in 1970. *The* DOE *sources agree* on a continuing increase in the early 1980's. Tile FS and DOE surveys suggest a decline by 1986. The FS surveys also suggests use in 1986 was lower than in 1980. Using this information, the WOODSTOV model was calibrated to increase from a 1970 level of 12 million cords, to the 41 million cords in 1980, then decrease to 38.9 million cords in 1986 (Figure 10).

In addition to tracking national total use, the 1980 model estimates for the North, South, and West are close to 1980 survey estimates (Table 2), and separate 1980 model estimates of wood use in stoves and fireplaces are close to 1980 survey estimates.

Sensitivity testing, conducted with many model runs, shows the model to be relatively insensitive to modest changes in single assumptions about how stove capacity additions or removals will respond to a given fuel cost savings *or* payback periods. The model is quite sensitive though to changes *in* projected prices *for* fuelwood and conventional fuels.

To assess the possible impact of EPA stove standards and more widespread restrictions on fireplace use we prepared a high regulation impact projection. In the base case, the cost of stove installation increases in response to increased proportion of households owning stoves and increased proportion of a home's heat that is supplied by wood. In the high regulation impact case four changes are made:

1. Stove costs increase 35% starting in 1990.
2. Stove efficiency is 5% higher by 2000 than in the base case.
3. The number of fireplaces In homes is 10% lower by 2000 than in the base case.
4. Wood use in fireplaces is 10% lower by 2000 than in the base case.

Under the high regulation impact assumptions, residential fuelwood use would increase 41% rather than

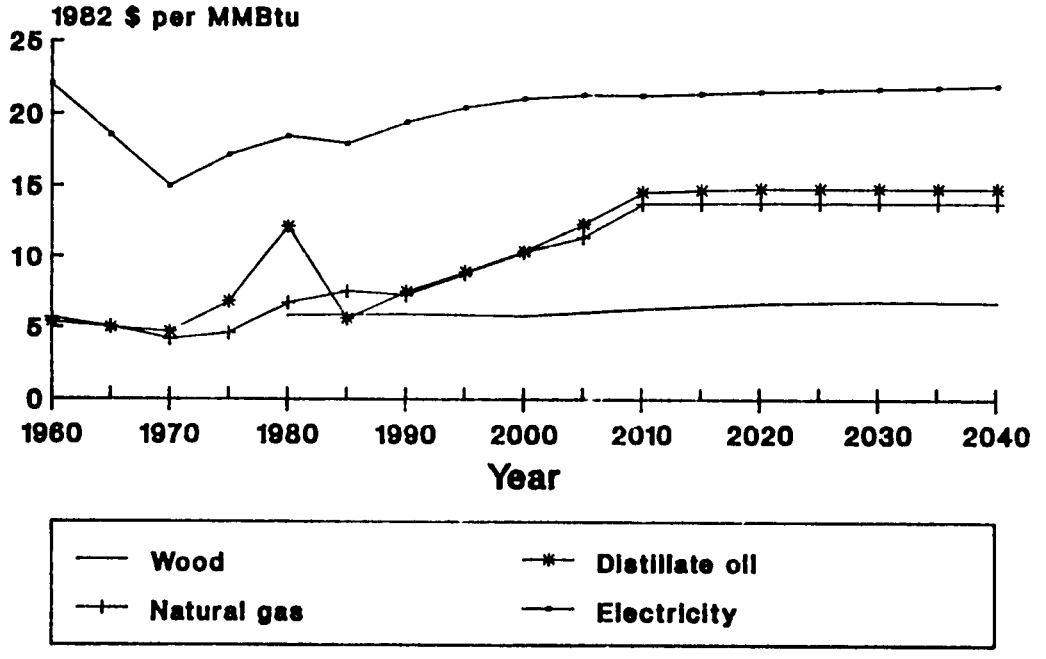

Figure 9. Residential fuel costs from 1960 to 1986, with projections to 2040.
Sources: Ref. 17, USFS projections.

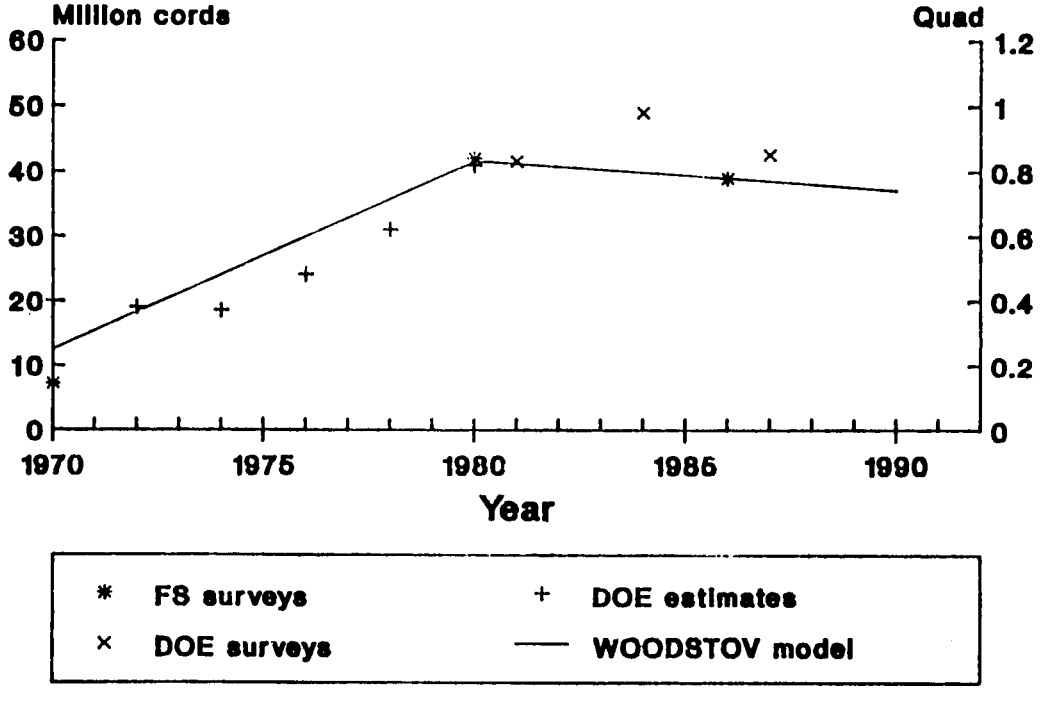

Figure 10. Reported fuelwood use compared to WOOSTOV-III simulated fuelwood use in-residences.
Sources: Refs. 9, 13, 14, lb, USFS projections

Table 2. Residential fuelwood use: Total households, fraction using stoves, fraction using fireplaces, wood use per household using a stove, wood use per household using a fireplace, and total wood use, 1986, with projections to 2040

Year	Total Households	Households burning wood: Stoves	Households burning wood: Fireplaces	Wood use per household: Stove(s)	Wood use per household: Fireplace(s)	Total fuelwood use		
	millions	percent	percent	cords	cords	million cords	billion cu. ft.	Quad
				United States				
1980	80.5	9	20	2.8	1.2	40.5	3.24	0.81
1980	80.5	7	21	3.5	1.2	41.6	3.33	0.83
1986	--	6	21	3.1	1.1	38.9	3.11	0.78
2000	109.3	7	22	2.8	1.1	46.8	3.74	0.94
2010	121.8	11	23	2.6	1.0	62.4	5.00	1.25
2020	132.9	11	23	2.5	0.9	64.0	5.12	1.28
2030	140.3	9	22	2.3	0.9	60.0	4.80	1.20
2040	145.5	9	22	2.1	0.9	56.8	4.54	1.14
				North				
1980	40.7	10	18	3.4	0.8	21.3	1.70	0.43
1980	40.8	9	18	4.2	1.1	23.5	1.88	0.47
1986	--	--	--	--	--	22.8	1.82	0.46
2000	55.4	8	18	3.2	1.0	23.6	1.89	0.47
2010	61.7	12	19	3.0	0.9	31.2	2.50	0.62
2020	67.3	11	19	2.8	0.8	30.7	2.46	0.61
2030	71.1	10	18	2.6	0.7	27.4	2.19	0.55
2040	73.6	9	18	2.4	0.7	24.8	1.98	0.50
				South				
1980	24	10	20	2.5	1.4	12.1	0.97	0.24
1980	24.0	7	23	2.4	1.5	12.2	0.97	0.24
1986	--	--	--	--	--	9.3	0.75	0.19
2000	32.5	6	23	2.1	1.4	14.3	1.14	0.29
2010	36.2	9	24	2.0	1.4	18.8	1.50	0.38
2020	39.5	10	24	1.9	1.3	19.7	1.57	0.39
2030	41.7	9	24	1.8	1.3	19.7	1.57	0.39
2040	43.3	8	24	1.6	1.4	19.9	1.59	0.40
				West				
1980	15.8	7	28	2.8	0.9	7.1	0.57	0.14
1980	15.8	4	28	3.2	0.9	6.0	0.48	0.12
1986	--	--	--	--	--	6.8	0.54	0.14
2000	21.4	6	29	2.9	0.8	8.9	0.71	0.18
2010	23.9	10	31	2.8	0.8	12.4	0.99	0.25
2020	26.1	10	31	2.6	0.8	13.6	1.09	0.27
2030	27.5	10	30	2.5	0.8	13.0	1.04	0.26
2040	28.6	9	30	2.3	0.7	12.1	0.97	0.24

Sources: The first 1980 row is from Ref. 9, Tables A-1, 13 and 14. The second 1980 row and rows 2000 - 2040 are estimates from the WOODSTOV III model. Estimates for 1986 are from Ref. 13, Table 3.30. Projection of number of households is from Ref. 13, Table 6.2.

65% between 1966 and 2020. Fuelwood use would be 12% less in 2020 for the high impact case (Figure 11).

PROJECTIONS OF FUELWOOD CONSUMPTION 1986 TO 2040

The projections of fuelwood use from the industrial/commercial and residential fuelwood models have been aggregated into three regional projections and into a projection for the United States as a whole (excluding Alaska and Hawaii). These projections are presented in Figures 12 to 15 and Tables 2 and 3. Although the overall trend for 1980 to 2040 is one of increase in all. regions, there are some notable differences between the regions and among the component parts of the total.

As a result of a projected cost advantage of fuelwood over nonwood fuels in all regions, the industrial and residential fuelwood use is projected to increase from about 1.3 quad or 5.2 BCF in 1986 to 2.2 quad or 8.8 BCF in 2020, and to fall to just below 2.0 quad or 7.8 BCF in 2040 (Figure 12). Total fuelwood use declines after 2020 because residential use is expected to decline as fuelwood becomes less competitive with other fuels. Residential fuelwood use is also projected to decline from 1986 to 1990 because of lower oil prices. This projection is supported by reports of current trends in the residential sector.

Although residential fuelwood use is currently much larger than industrial./commercial use, the industrial/ commercial sector is expected to continue to grow more rapidly, with most increased supply coming from logging residues and whole tree chips. Mill residue use will grow slightly as the pulp and timber industries expand, but most growth in wood energy outside the forest products industries will be supplied by roundwood (Table 3) (Figure 12).

The North has the highest wood energy consumption, with more than double the consumption in the West throughout the period. The northern regions show the general patterns of consumption described for the nation, except that the fluctuations in residential use are sufficiently large to cause greater variation in the total fuelwood consumption (Figure 13). Residential and consequently, total fuelwood consumption are projected to decline from 1986 to 1990 even though some small growth still occurs in the industrial and commercial sectors. Residential use also falls again after 2020 for the reasons already described. Generally higher than average energy costs in the North make the region more sensitive to fuel price competition.

Although the South starts off with lower levels of fuelwood consumption in both the residential and industrial/commercial sectors, it is projected to increase its consumption more rapidly overall, so that by 2040 fuelwood consumption Levels will exceed those in the North

(Figure 14). Residential consumption in the south is not projected to fall as sharpiy from 1986 to 1990 while industrial/commercial use is expected to increase quite rapidly as a result of the growth in use in the forest products industries in the region. A far greater share of the totaL industrial fuelwood supply is provided from mill residues in the South, although the rate of growth in the the use of chips and logging residue should be much more rapid than in either of the other two regions. Unlike the North, residential use remains almost level after 2020, while the overall decline in fuelwood use is accounted for by a reduction in the logging residue supply after 2020.

The West is a very large and diverse region in which overall fuelwoad use is relatively less important. Although tile fuelwood use trend is projected to increase through 2020 and then decline in line with the other regions, the relative changes in residential and industrial/commercial use are quite different (Figure 15). Unlike the rest of the nation, no significant increase in industrial fuelwood is projected through the period, and most industrial/commercial fuelwood is expected to be supplied by mill residues. Almost all the total fuelwood increase through 2020 is projected to come from increases in the residential sector, which should double fuelwood use in the West from 1990 to 2020, after a flat period from 1980 to 1990. Residential use is projected to fall after 2020 as fuelwood loses some of its competitiveness against other fuels.

Figure 1 shows how our projections compare to recent and long term historical trends. Between 1990 and 2010, the roundwood portion of wood energy use is projected to increase more slowly than it did during the late 1970s and early ‘80s. Its rate of increase will also be slower than the rate of increase in all wood energy use projected by DOE . Although DOE projects total wood energy use will climb well above the 2.8 quad (11 BCF) level attained in the 1870s, roundwood used for fuel will increase to just over half the level attained in the 1870s. Roundwood use for fuel is projected to peak in 2020 at 6.7 BCF.

Nationally, the proportion of all U.S. roundwood consumption that is used for fuel is not expected to change dramatically between now and 2040. Using the projections from this study and the roundwood use projections from the TAMM model (13), Figure 16 compares the projected consumption of roundwood for fuel and nonfuel use. Roundwood use for fuel as a percentage of total roundwood use is expected to go from 27% in 1986 to about 29 % at the projected peak of fuelwood consumption in 2020, before falling back to 25% in 2040. Fuelwood’s share of roundwood consumption is projected to remain higher than during the last three decades. Fuelwood will probably become a relatively permanent part of the forest products economy.

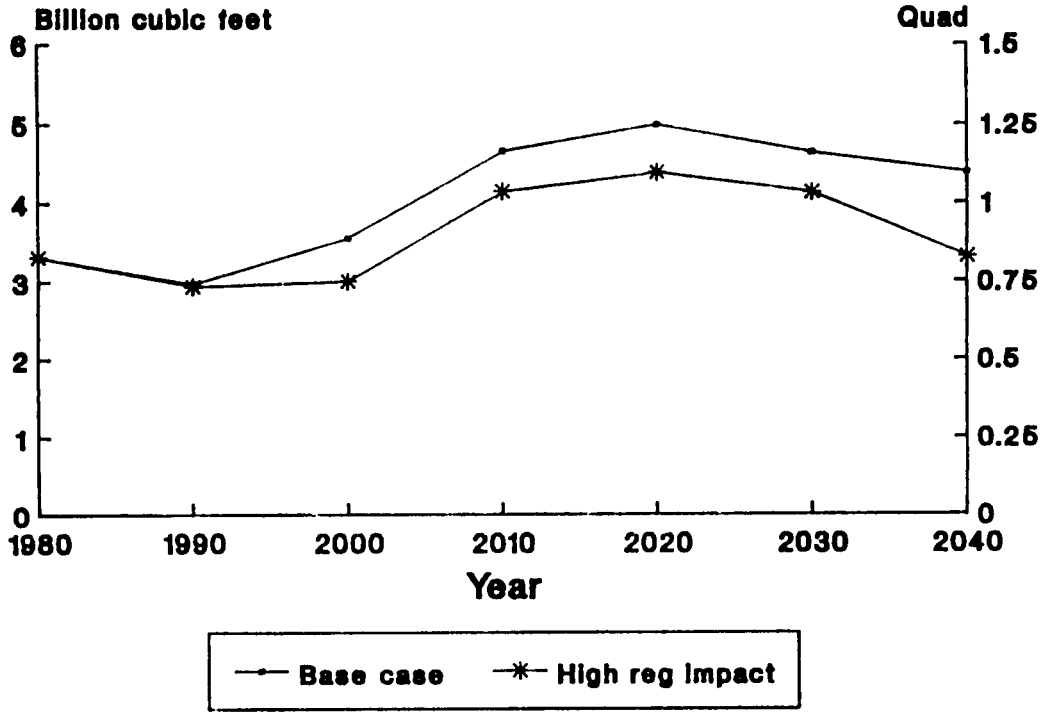

Figure 11. Residential fuelwood use projections: base case and high regulation impact case.
Source; USFS projections

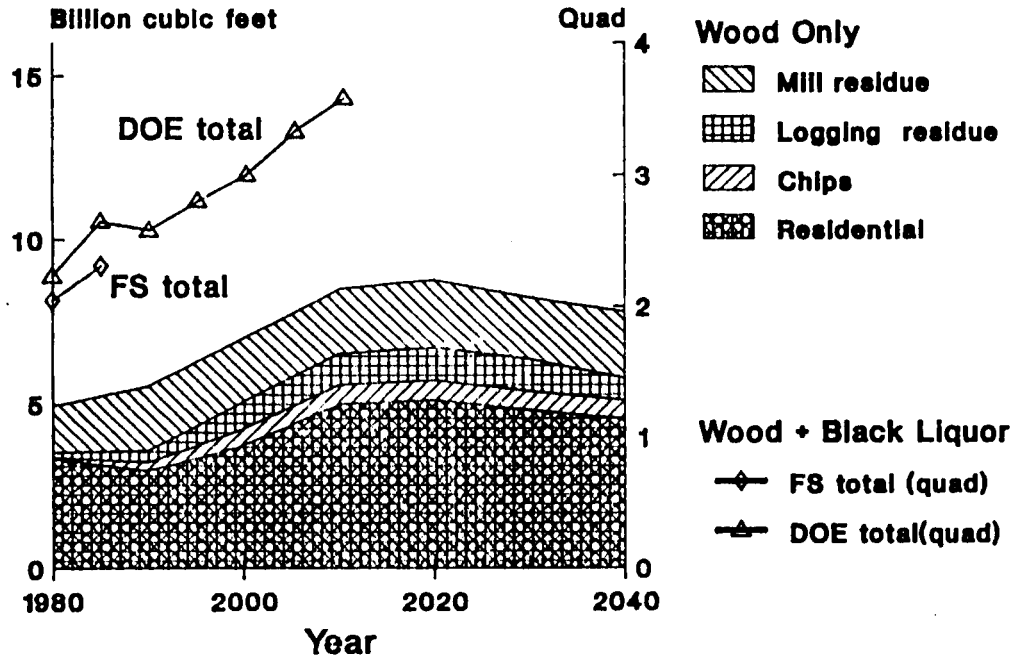

Figure 12. Wood energy projections for wood and black liquor to 2040.
Sources: Ref. 17, USFS projections.

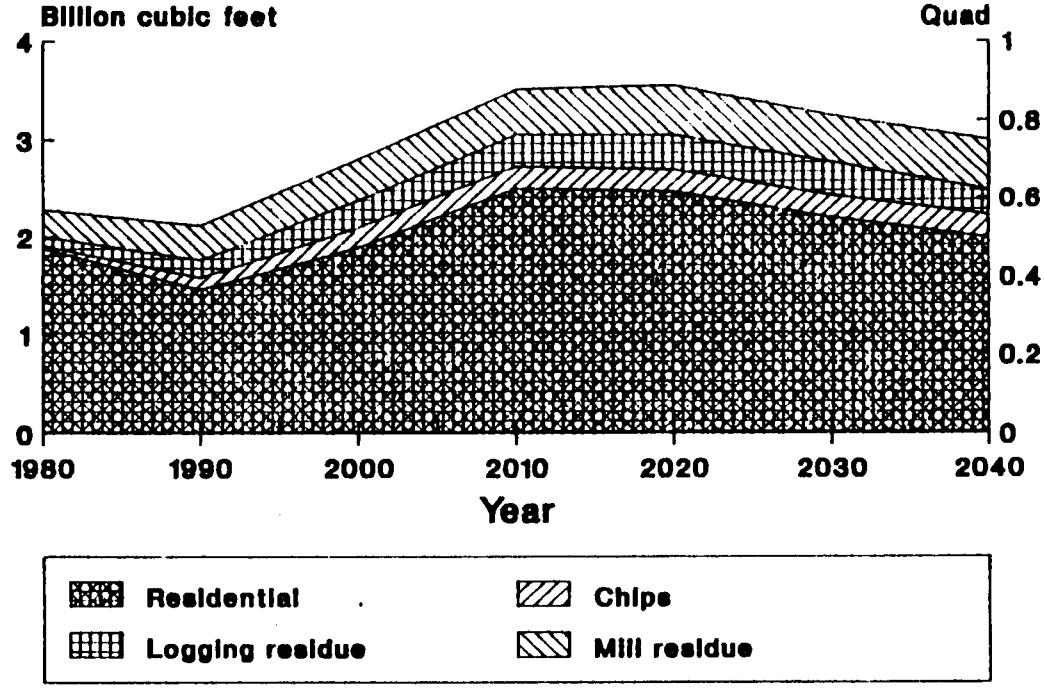

Figure 13. U.S. North fuelwood consumption projected to 2040.
Source: USFS projections.

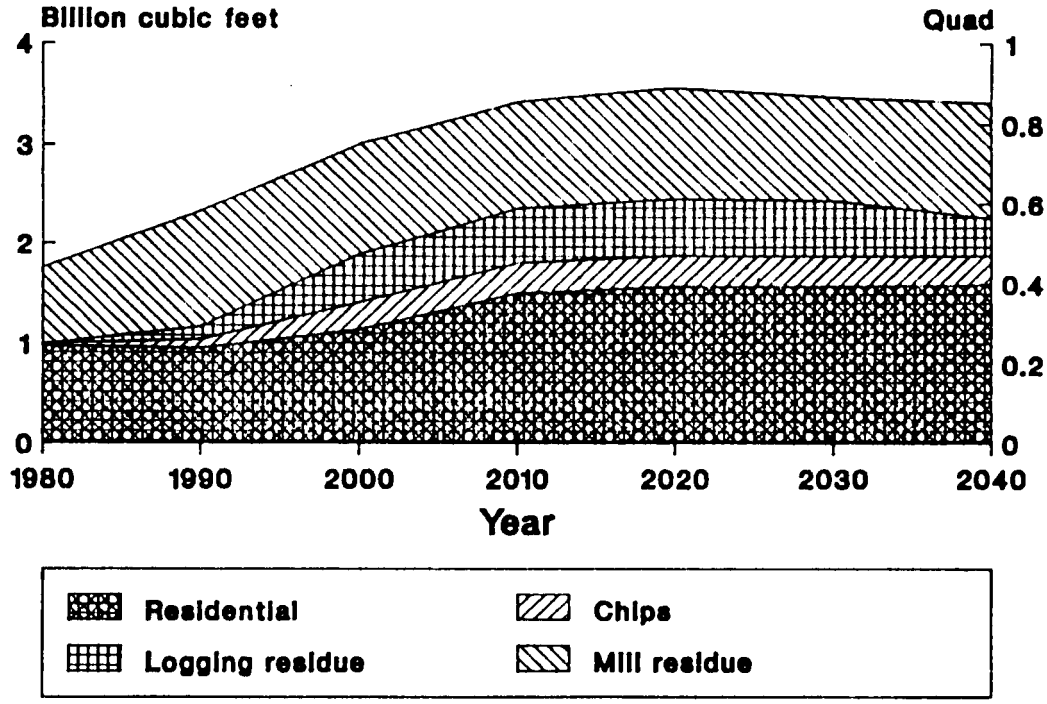

Figure 14. U.S. South fuelwood consumption projected to 2040.
Source: USFS projections.

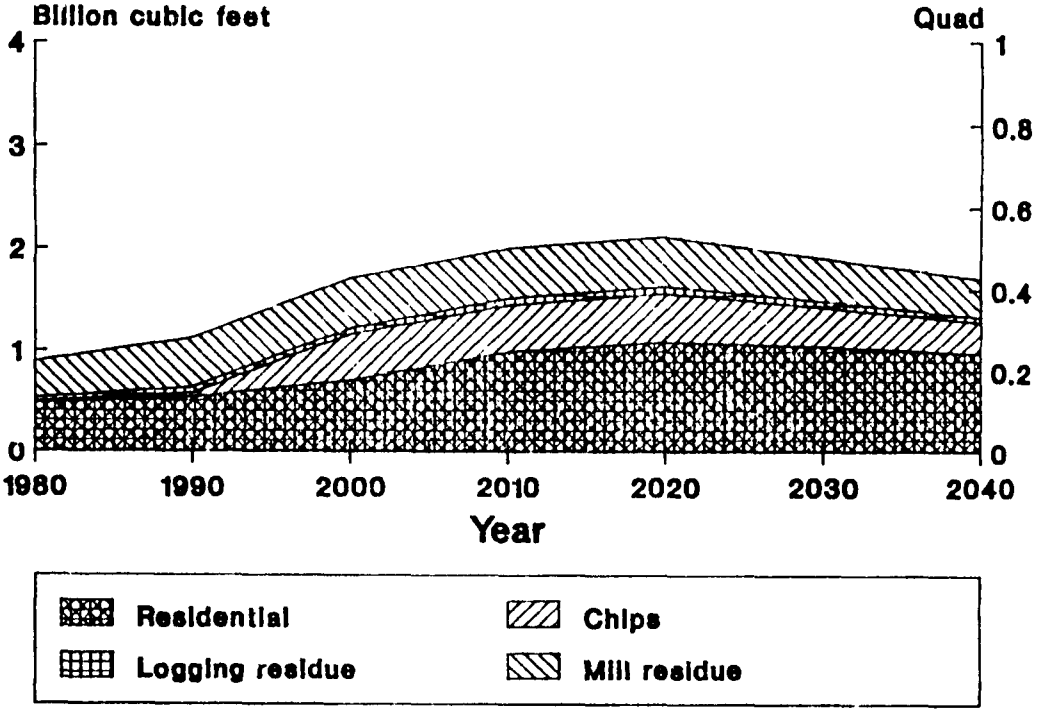

Figure 15. U.S. West fuelwood consumption projected to 2040.
Source: USFS projections.

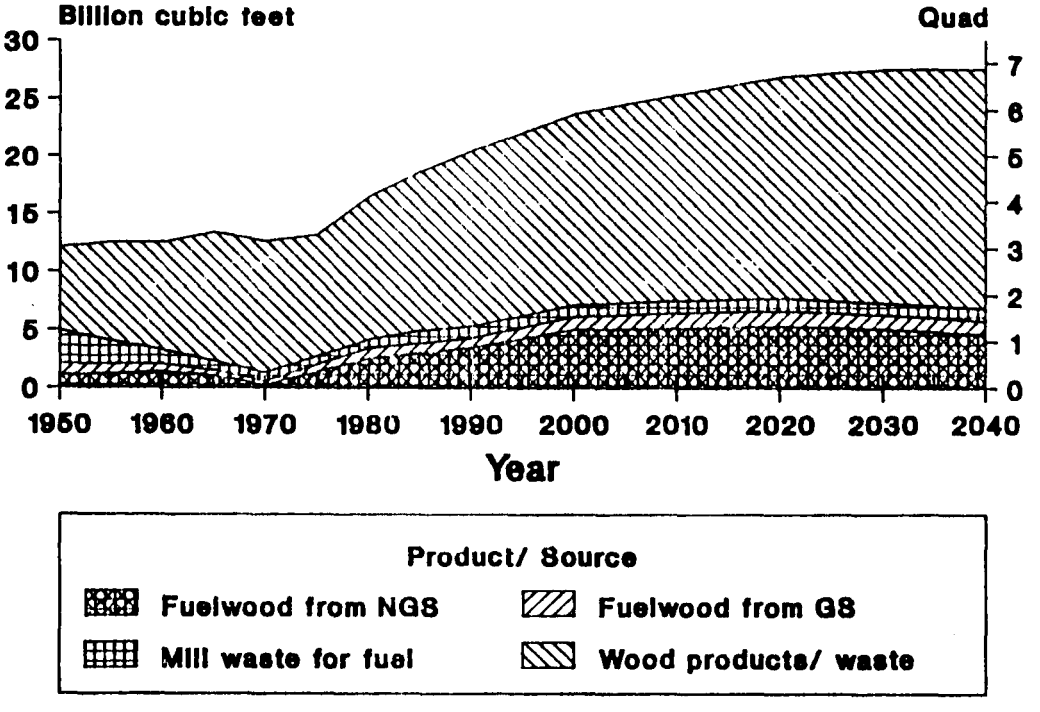

Figure 16. U.S. roundwood consumption by wood fuel and wood product categories projected to 2040.
Sources: USFS reports and projections.

Table 3. Wood energy use by type of material and region, 1986, with projections to 2040

Year	Solid wood and bark material[a]						Pulp Liquor[b]	Total	DOE Projection[c]
	Chips	Logging residue	Mill residue	Residential	Total (MMCF)	Total (quad)			
	million cubic feet					quad			
					United States				
1986	--	--	2055	--	5167	1.29	0.90	2.19	2.52
1990	250	372	1939	2959	5520	1.38			2.58
2000	511	822	1920	3742	6995	1.75			3.10
2010	571	941	1998	4995	8505	2.13			3.66
2020	593	998	2084	5123	8798	2.20			
2030	572	967	1932	4801	8272	2.07			
2040	548	671	2070	4544	7833	1.96			
					North				
1986	--	--	213	--	2037	0.51	0.10	0.61	
1990	116	176	357	1469	2118	0.53			
2000	199	276	434	1887	2796	0.70			
2010	226	330	454	2498	3508	0.88			
2020	231	361	496	2459	3547	0.89			
2030	234	352	475	2190	3251	0.81			
2040	229	255	531	1984	2999	0.75			
					South				
1986	--	--	1145	--	1892	0.47	0.65	1.12	
1990	91	132	1105	950	2278	0.57			
2000	267	484	996	1143	2890	0.72			
2010	299	545	1063	1502	3409	0.85			
2020	314	566	1110	1574	3564	0.89			
2030	299	558	1037	1574	3468	0.87			
2040	288	368	1162	1590	3408	0.85			
					West				
1986	--	--	697	--	1240	0.31	0.15	0.46	
1990	43	64	477	540	1124	0.28			
2000	45	62	490	712	1309	0.33			
2010	46	66	481	994	1587	0.40			
2020	48	71	478	1090	1687	0.42			
2030	39	57	420	1036	1552	0.39			
2040	31	48	377	970	1426	0.36			

[a] Sources: For 1986, Ref. 13, tables 3.30 and 3.31. This source does not have separate estimates of roundwood burned by industry (chips and logging residue) and households. For 2000 to 2040, USDA Forest Service projections are made using the CHIPS and WOODSTOV III models. Excludes secondary mill residue and waste wood products used for fuel.

[b] Source: Ref. 2.

[c] Source: Ref. 17, Table B-1. 1986 value is from Table 1.

To more closely describe the impact of fuelwood use on timber sources used for sawlogs, veneer logs, and pulpwood we must further subdivide total. roundwood used for fuel. First, we deduct all logging residue that is used for fuel. This is a category of material that will be a drain on timber resources regardless of whether or not it is used for fuel (Table 4). Material that is now logging residue will be removed for fuel in integrated operations when sawlogs and veneer logs are removed or in secandary operations. Second, we deduct material coming from non-growing stock sources. For residential fuelwood use, two sources indicate non-growing stock use is 75-80% (9,13). The (Ion-growing stock portion is higher for hardwoods and lower for softwoods. *For* industrial and commercial use, most fuelwood which is not logging residue will be taken by whole tree chipping If whole tree chipping harvests wood from average stand~ on timberland, the average proportions of non-growing stock would be 50% and 30% for hardwood and softwood stands, respectively (11). However, the proportion of fuel chips that is non-growing stock will be higher than these figures for two reasons. First, whole tree chipping for fuel will tend to use stands with a higher proportion of non-growing stock because they will be cheaper. This may include some land with trees that is not classified as timberland. Second, harvest of chips for fuel will often be combined with harvest of chips for pulp mills. Pulp chips will more often be from clean growing stock (main stem) parts of trees whereas fuel chips wil 1 more often he from non-growing stock parts (Tops, braches) with more bark and dirt content.

The overall proportion of roundwood (excluding logging residue) from non-growing stock will be largely determined by residential use. Although overall industrial/commercial use is projected to increase, so does residential use, and industrial use does not exceed 14% of total use.

The estimated 1986 proportion of roundwood from non-growing stock was taken from Forest Service estimates (13). It is assumed to remain high over the projection period since residential use of non-growing stock sources is expected to remain high, and expanded use of whole tree chipping operations for industrial/commercial fuel will provide fuel chips with a high proportion of non-growing stock similar to current levels using the chipping practices mentioned above.

Growing stock use for fuel is projected to increase from 0.80 BCF in 1986 (5% of all roundwood use), to a high of 1.35 BCF in 2010 (5%), then decline to 1.14 BCF in 2040 (4%) (Table 4). Even though 25-30% of all roundwood may be used for fuel over the projection period, only 4-5% is projected to come from growing stock.

Table 4. Roundwood fuelwood consumed in the United States by species, growing stock source, and end user, 1986, with projections to 2040[a]

Year	All roundwood Total	All roundwood Hard-woods	All roundwood Soft-woods	Growing stock[b] Total	Growing stock[b] Hard-woods	Growing stock[b] Soft-woods	Industrial /commercial use	Residential use
	---billion cubic feet---							
				United States total				
1986	3.11	2.57	0.55	0.80	0.59	0.21	--	--
2000	4.26	3.38	0.88	1.11	0.85	0.26	0.52	3.74
2010	5.60	4.39	1.21	1.35	1.02	0.33	0.60	5.00
2020	5.73	4.42	1.31	1.33	1.00	0.33	0.61	5.12
2030	5.38	4.11	1.27	1.23	0.94	0.29	0.59	4.80
2040	5.09	3.88	1.22	1.14	0.88	0.26	0.55	4.54
				North				
1986	1.82	1.70	0.13	0.24	0.22	0.02	--	--
2000	2.09	1.81	0.28	0.21	0.19	0.02	0.21	1.88
2010	2.74	2.37	0.37	0.23	0.19	0.03	0.24	2.50
2020	2.70	2.31	0.39	0.20	0.16	0.03	0.24	2.46
2030	2.43	2.05	0.39	0.18	0.15	0.03	0.25	2.19
2040	2.22	1.85	0.37	0.16	0.13	0.03	0.24	1.98
				South				
1986	0.75	0.69	0.05	0.32	0.29	0.03	--	--
2000	1.41	1.31	0.09	0.58	0.53	0.05	0.26	1.14
2010	1.81	1.69	0.12	0.72	0.66	0.06	0.31	1.50
2020	1.90	1.78	0.12	0.73	0.67	0.06	0.32	1.57
2030	1.88	1.77	0.12	0.70	0.64	0.06	0.31	1.57
2040	1.88	1.76	0.12	0.68	0.61	0.06	0.29	1.59
				West				
1986	0.54	0.18	0.36	0.23	0.08	0.15	--	--
2000	0.77	0.25	0.51	0.32	0.13	0.18	0.05	0.71
2010	1.05	0.33	0.72	0.40	0.17	0.23	0.06	1.00
2020	1.13	0.33	0.80	0.40	0.17	0.23	0.04	1.09
2030	1.07	0.30	0.77	0.35	0.15	0.20	0.03	1.04
2040	1.00	0.27	0.73	0.30	0.14	0.17	0.03	0.97

[a] Projections exclude logging residue used for fuel.

[b] Growing stock is the main stem portion of live trees 5 inches dbh or larger of commercial species meeting standards for quality and vigor. Excludes cull trees.

Sources: For 1986, Ref. 13, Table 3.30. This source does not have separate estimates of roundwood burned by industry and households.
For 2000 to 2040, USDA Forest Service projections made using the CHIPS and WOODSTOV III models and estimates of the split between growing stock (GS) and other sources.

CONCLUSIONS AND RESERVATIONS

The general conclusion that we draw from these modeling studies is that fuelwood use, after a rapid increase in the 1970s and early 1980s, IS expected to grow steadily through 2020 at an average rate slightly greater than that for all other timber products. Although there are important regional variations in projected fuelwood use patterns, the national picture is one of steady growth in both residential and industrial fuelwood use through 2020, with a decline in both from 2020 to 2040. These projections suggest fuelwood's share of total roundwood harvest is set and fuelwood will become a fairly permanent feature of the forest products economy. This may have important implications for forest management in the long term.

A second and not at all surprising conclusion is that the demand for fuelwood is *very* dependent on the price of competing fuels. Any marked rise in real prices of oil, gas, or to some extent electric power can be expected to cause fuelwood use to rise in both the residential and industrial sectors, with the residential sector probably liable to more rapid responce especially in some regions. These projections have used DOE energy price projections, which shows moderate increases in oil and gas prices through 2010. Other energy price projections would produce very different responses in the fuelwood market. To the extent that uncertainty exists in oil Price projections, uncertainty will necessarily exist in fuelwood demand projections as well.

Finally, we should note that national and international energy policies may have to be reviewed in the next decade as we gain a better unders.canding of the greenhouse effect. The costs of our present heavy reliance on fossil fuels may be determined to be unacceptable, and in consequence, national policy may restrict increased use of fossil fuels and could even encourage large scale reforestation to support wood fuel production. This would clearly produce very significant changes in the projections that we have made. To a large extent, these projections are based on a business as usual view of the next fifty years, which may very well turn out to not be the case.

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