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PREFACE

The main objective of this paper was to collect information about the “state-of-art” of harvesting and use of forestry biomass for energy production on North-America, and, after that, to divulgate this technology to the Brazilian forestry sector. The work has been carried out based on literature from the USA and other countries, and also with the help of some study tours. This paper was written during a sabbatical period at the Forest Operations Unit – Southern Research Station (USDA Forest Service), under the supervision of Dr. Robert Rummer, project leader of that unit.

The Forest Operations Unit is located in Auburn, Alabama, and deals, on national level, with the analyses of technologies to manage the forest stand and evaluate and manage the economical and ecological effects of the reduction of forest biomass fuel, available for a forest fire, and the process of forest restoration. Its action strategy is defined by a high level of collaboration and coordination with researchers from other institutions, enlarging its capacity to develop research projects in engineer and forestry operations areas.

This unit has been involved in biomass-related research since the late 1970's. They have nine primary research topic areas related to biomass: biomass harvesting systems; economic analysis; bundling; individual machines; proto-type machines; energy wood chipping systems; environmental considerations; short rotation woody crop production; and drying, storing, transporting and roll splitting.

I am deeply thankful to Dr. Rummer for his great support on my work at the USDA Forest Service, and also to the help, and friendship of other members of the Forest Operations Unit, specially John Klepac, Dana Mitchell, James Dowdell, Shellia Jenkins, and Juliana Canto. My work was also easier because of the friendship of Preston Steele, Emily Carter, Jason Thompson, and Johnny Grace. For all of them, thank you very much for making me feel as a member of the Unit. I also want to express my gratitude to Capes (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior), a foundation subordinated to the Ministry of Education of Brazil, for the grant that made this work possible. Finally, my special thanks goes to my wife Iara and sons, Eduardo and Alex, for their love and support during this wonderful experience in the USA.

Auburn, January 31, 2008

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Visiting Scientist
SRS – USDA Forest Service
HARVESTING AND USE OF FORESTRY BIOMASS FOR ENERGY PRODUCTION IN THE USA

Prof. Dr. Fernando Seixas

1. INTRODUCTION

Biomass, all plant and plant-derived materials, including animal manure, recently surpassed hydropower as the largest domestic source of renewable energy and currently provide almost 3 percent of the total energy consumption in the United States (Table 1). Its use as a renewable energy source became a very important issue in the U.S., as a way to reduce the need for oil and gas imports. As part of this effort, the Biomass R&D Technical Advisory Committee, a panel established by the Congress to guide the future direction of federally funded biomass R&D, envisioned a 30 percent replacement of the current U.S. petroleum consumption with biofuels by 2030. Accomplishing this goal would require approximately 1 billion dry tons of biomass feedstock per year (Perlack et al., 2005).

Looking at just forestland and agricultural land, the two largest potential biomass sources, the study of Perlack et al. (2005) found over 1.3 billion dry tons per year of biomass potential, enough to produce biofuels to meet more than one-third of the current demand for transportation fuels. The full resource potential could be available roughly around mid-21st century when large-scale bioenergy and biorefinery industries are likely to exist. This annual potential is based on a more than seven-fold increase in production from the amount of biomass currently consumed for bioenergy and biobased products. Currently, slightly more than 75 percent of biomass consumption in the United States (about 142 million dry tons) comes from forestlands. The remainder (about 48 million dry tons), which includes biobased products, biofuels and some residue biomass, comes from cropland.

The industrial sector is the most important consumer of wood for energy, with 73 percent of the total energy production from wood, but the wood consumption was 12 percent lower on 2004 than was on 2000 year (Table 2). But, this situation can change in a near future, because the energy value of logs is rising at a far greater pace than the log (and lumber) price itself (Figure 1). Even so, the wood market conditions in the South of US, with the biggest forest area in the country, are still not improving so much, with all products except pine pulpwood going down year over year (Figure 2).

The processing of harvested forest products, such as sawlogs and pulpwood, generates significant quantities of mill residues and pulping liquors, being the majority of biomass in use today. Secondary residues generated in the processing of forest products account for 50 percent of current biomass energy consumption. These materials are used by the forest products industry to manage residue streams, produce energy, and recover important chemicals. Fuelwood extracted from forestlands for residential and commercial use and electric utility use accounts for about 35 million dry tons of current consumption.
Table 1. Energy consumption by source in the United States – 2005

<table>
<thead>
<tr>
<th>Source</th>
<th>Amount (Billion Btu)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fossil Fuels</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>22,830,007</td>
<td>22.8</td>
</tr>
<tr>
<td>Coal Coke Net Imports</td>
<td>44,194</td>
<td>0.1</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>22,640,052</td>
<td>22.6</td>
</tr>
<tr>
<td>Petroleum</td>
<td>40,441,181</td>
<td>40.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>85,955,434</td>
<td>85.8</td>
</tr>
<tr>
<td><strong>Nuclear Electric Power</strong></td>
<td>8,133,222</td>
<td>8.1</td>
</tr>
<tr>
<td><strong>Renewable Energy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydro-electric Power</td>
<td>2,714,661</td>
<td>2.7</td>
</tr>
<tr>
<td>Biomass</td>
<td>2,780,760</td>
<td>2.8</td>
</tr>
<tr>
<td>Geothermal</td>
<td>351,671</td>
<td>0.4</td>
</tr>
<tr>
<td>Solar</td>
<td>64,467</td>
<td>0.1</td>
</tr>
<tr>
<td>Wind</td>
<td>149,490</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>6,061,049</td>
<td>6.1</td>
</tr>
<tr>
<td>Electricity Net Imports</td>
<td>84,360</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>99,894,296</td>
<td>100.0</td>
</tr>
</tbody>
</table>

1Beginning in 1993, ethanol blended into motor gasoline is included in both “Petroleum” and “Biomass”, but is counted only once in total consumption. 


![Figure 1. Estimated energy value of lumber vs. U.S. lumber prices (Wegner, 2006)](image)
Figure 2. South-wide average wood stumpage prices from 1997 to 2007 (Timber Mart-South, 2007).

Table 2. Historical renewable energy consumption by energy use sector and biomass and wood as energy source, 2000-2004 (Quadrillion Btu) (EIA a, 2005)

<table>
<thead>
<tr>
<th>Sector and Energy Source</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>6.158</td>
<td>5.328</td>
<td>5.835</td>
<td>6.082</td>
<td>6.117</td>
</tr>
<tr>
<td>Biomass</td>
<td>2.907</td>
<td>2.640</td>
<td>2.648</td>
<td>2.740</td>
<td>2.845</td>
</tr>
<tr>
<td>Wood</td>
<td>2.257</td>
<td>1.980</td>
<td>1.899</td>
<td>1.929</td>
<td>1.989</td>
</tr>
<tr>
<td>Residential</td>
<td>0.503</td>
<td>0.439</td>
<td>0.382</td>
<td>0.434</td>
<td>0.408</td>
</tr>
<tr>
<td>Biomass</td>
<td>0.433</td>
<td>0.370</td>
<td>0.313</td>
<td>0.359</td>
<td>0.332</td>
</tr>
<tr>
<td>Wood</td>
<td>0.433</td>
<td>0.370</td>
<td>0.313</td>
<td>0.359</td>
<td>0.332</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.109</td>
<td>0.089</td>
<td>0.090</td>
<td>0.102</td>
<td>0.106</td>
</tr>
<tr>
<td>Biomass</td>
<td>0.100</td>
<td>0.080</td>
<td>0.081</td>
<td>0.087</td>
<td>0.089</td>
</tr>
<tr>
<td>Wood</td>
<td>0.053</td>
<td>0.040</td>
<td>0.039</td>
<td>0.040</td>
<td>0.041</td>
</tr>
<tr>
<td>Industrial</td>
<td>1.828</td>
<td>1.630</td>
<td>1.608</td>
<td>1.581</td>
<td>1.676</td>
</tr>
<tr>
<td>Biomass</td>
<td>1.781</td>
<td>1.593</td>
<td>1.565</td>
<td>1.533</td>
<td>1.620</td>
</tr>
<tr>
<td>Wood</td>
<td>1.636</td>
<td>1.443</td>
<td>1.396</td>
<td>1.363</td>
<td>1.448</td>
</tr>
<tr>
<td>Transportation</td>
<td>0.139</td>
<td>0.147</td>
<td>0.174</td>
<td>0.239</td>
<td>0.296</td>
</tr>
<tr>
<td>Biomass</td>
<td>0.021</td>
<td>0.019</td>
<td>0.049</td>
<td>0.036</td>
<td>0.029</td>
</tr>
<tr>
<td>Wood</td>
<td>0.007</td>
<td>0.006</td>
<td>0.011</td>
<td>0.017</td>
<td>0.012</td>
</tr>
<tr>
<td>Independent Power Producer</td>
<td>0.972</td>
<td>0.956</td>
<td>1.036</td>
<td>1.103</td>
<td>1.127</td>
</tr>
<tr>
<td>Biomass</td>
<td>0.432</td>
<td>0.432</td>
<td>0.467</td>
<td>0.485</td>
<td>0.479</td>
</tr>
<tr>
<td>Wood</td>
<td>0.127</td>
<td>0.121</td>
<td>0.140</td>
<td>0.151</td>
<td>0.155</td>
</tr>
</tbody>
</table>
Kirby et al. (2003) listed items identified as the most important screening criteria (in order of importance) for biomass:

1. Sustainable biomass resource is available; biomass power plant must within 50 miles of the fuel source.
2. Site must be within 50 miles of a population center with a skilled labor force.
3. Proximity of communities in “at risk” regions identified by the National Fire Plan is known and favors biomass power.

The following items were also identified, but not as the most important screening criteria: a) a water supply is needed.; b) land slope is 7%-12% or less; c) the visual impact is an issue; d) landscape changes caused by harvesting must be considered; e) invasive species control is a consideration; f) livestock protection is possible at the site; g) forest thinning and municipal solid waste applications are good potential sites; h) full cost of competing power (production, T&D, environmental costs etc.) is known and favorable to biomass.

Data from Watson et al. (1987) reinforced the importance of power plant proximity of the fuel source. They concluded that transportation of the wood 50 miles requires three times as much fuel as does the conventional logging operations, being the most costly aspect in terms of fuel consumed.

The total industrial biomass energy consumption in the U.S. was 1,532,947 Trillion Btus on 2003, with 75% for useful thermal output and 25% for electricity. The net generation was 29,001 Million kWh. Paper and allied products industries used 75% of the total biomass energy consumption, but 53% came from self-produced black liquor, and they generated 93% of the net production of energy (EIA b, 2005). The majority of the wood fuelled power plants in forest industry are cogeneration plants, which produce both heat and electricity. The power-to-heat production ratio for a conventional back-pressure turbine cogeneration system ranges from 42.63 kWh/293 kWh, which is relatively matched to the steam and electricity needs at older craft mills. The wood electricity production capacity in the pulp and paper industry is about 5000 MW. There are also a lot of power plants in forest industry producing only heat and process steam without electricity production. The number of boilers was about 2393 in pulp and paper industry. Most of them are wood fired power boilers (Leinonen, 2004).

2. BIOMASS AS FEEDSTOCK FOR A BIOENERGY AND BIOPRODUCTS INDUSTRY: THE TECHNICAL FEASIBILITY OF A BILLION-TON ANNUAL SUPPLY

This document was prepared on 2005 by Robert D. Perlack, Lynn L. Wright, Anthony F. Turhollow, Robin L. Graham, Bryce J. Stokes, and Donald C. Erbach, and its purpose was to determine whether the land resources of the United States are capable of producing a sustainable supply of biomass sufficient to displace 30 percent or more of the country’s present petroleum consumption. Accomplishing this goal would require approximately 1 billion dry tons of biomass feedstock per year. The document has two parts: A – Forest-derived biomass resource assessment; and B – Agriculture-derived
biomass resources. Only the first one, with few modifications, is included here, to give a good idea about the biomass perspective of the U.S. over the next years.

2.1. Introduction

Biomass is already making key energy contributions in the United States, having supplied nearly 2.9 quadrillion Btu (quad) of energy in 2003, over 3 percent of the total energy consumption in the United States. Biomass is also particularly attractive because it is the only current renewable source of liquid transportation fuel.

The Biomass Research and Development Act of 2000 created the Biomass R&D Technical Advisory Committee to provide advice to the Secretaries of Agriculture and Energy on program priorities and to facilitate cooperation among various federal and state agencies, and private interests. The Technical Advisory Committee also established the setting of a very challenging goal: biomass will supply 5 percent of the nation’s power, 20 percent of its transportation fuels, and 25 percent of its chemicals by 2030. The goal is equivalent to 30 percent of current petroleum consumption and will require more than approximately one billion dry tons of biomass feedstock annually — a fivefold increase over the current consumption (DOE, 2003).

2.2. The biomass feedstock resource base

The land base of the United States encompasses nearly 2,263 million acres, including the 369 million acres of land in Alaska and Hawaii. About 33 percent of the land area is classified as forest land, 26 percent as grassland pasture and range, 20 percent as cropland, 8 percent as special uses (e.g., public facilities), and 13 percent as miscellaneous uses such as urban areas, swamps, and deserts (Vesterby and Krupa, 2001; Alig et al., 2003). About one-half of this land has some potential for growing biomass.

The biomass resource base is composed of a wide variety of forestry and agricultural resources, industrial processing residues, and municipal solid and urban wood residues (Figure 2). Currently, slightly more than 75 percent of biomass consumption in the United States (about 142 million dry tons) comes from forestlands. The remainder (about 48 million dry tons), which includes biobased products, biofuels and some residue biomass, comes from cropland. More than 50 percent of this biomass comes from wood residues and pulping liquors generated by the forest products industry. Currently, biomass accounts for approximately:

- 13 percent of renewably generated electricity,
- nearly all (97 percent) the industrial renewable energy use,
- nearly all the renewable energy consumption in the residential and commercial sectors (84 percent and 90 percent, respectively), and
- 2.5 percent of transport fuel use.
2.3. Forest derived biomass resource assessment

The total forestland in the United States is approximately 749 million acres — about one-third of the nation’s total land area. Most of this land is owned by private individuals or by the forest industry (Figure 3). Two-thirds of the forestland (504 million acres) is classified as timberland which, according to the Forest Service, is land capable of growing more than 20 ft\(^3\) per acre of wood annually (Smith et al., 2004). In addition, there are 168 million acres of forestland that the Forest Service classifies as “other”, generally incapable of growing 20 ft\(^3\) per acre of wood annually. The remaining 77 million acres of forestland are reserved from harvesting and are intended for a variety of non-timber uses, such as parks and wilderness. The total forestland base considered for this resource analysis includes the 504 million acres of timberland and the 168 million acres of other forestland.

<table>
<thead>
<tr>
<th>Forest Resources</th>
<th>Agricultural Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Primary</td>
</tr>
<tr>
<td>• Logging residues from conventional</td>
<td>• Crop residues from major crops — corn stover,</td>
</tr>
<tr>
<td>harvest operations and residues from</td>
<td>small grain straw, and others</td>
</tr>
<tr>
<td>forest management and land clearing</td>
<td>• Grains (corn and soybeans) used for</td>
</tr>
<tr>
<td>operations</td>
<td>ethanol, biodiesel, and bioproducts</td>
</tr>
<tr>
<td>• Removal of excess biomass (fuel</td>
<td>• Perennial grasses</td>
</tr>
<tr>
<td>treatments) from timberlands and</td>
<td>• Perennial woody crops</td>
</tr>
<tr>
<td>other forestlands</td>
<td></td>
</tr>
<tr>
<td>• Fuelwood extracted from forestlands</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td>Secondary</td>
</tr>
<tr>
<td>• Primary wood processing mill residues</td>
<td>• Animal manures</td>
</tr>
<tr>
<td>• Secondary wood processing mill</td>
<td>• Food/feed processing residues</td>
</tr>
<tr>
<td>residues</td>
<td></td>
</tr>
<tr>
<td>• Pulping liquors (black liquor)</td>
<td>Tertiary</td>
</tr>
<tr>
<td>Tertiary</td>
<td>• MSW (Municipal solid waste) and post-</td>
</tr>
<tr>
<td>• Urban wood residues — construction</td>
<td>consumer residues and landfill gases</td>
</tr>
<tr>
<td>and demolition debris, tree</td>
<td></td>
</tr>
<tr>
<td>trimmings, packaging wastes</td>
<td></td>
</tr>
<tr>
<td>and consumer durables</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. The biomass resource base
Of the 504 million acres of U.S. timberland, about 29% is publicly owned, 13% is owned by the forest industry, and the remaining 58% is privately owned. Timberland ownership varies considerably among regions of the country. The East United States tends to be dominated by private ownership and the West by public land ownership (Alig et al., 2003).

2.3.1. Forest resources

The processing of harvested forest products, such as saw logs and pulpwood, generates significant quantities of mill residues and pulping liquors, which constitute the majority of biomass in use today (Figure 2). These materials are used by the forest products industry to manage residue streams, produce energy, and recover important chemicals. Fuelwood extracted from forestlands for residential and commercial use and electric utility use accounts for about 35 million dry tons of current consumption. In total, the amount of harvested wood products from timberlands in the United States is less than the annual forest growth and considerably less than the total forest inventory (Figure 4), suggesting substantial scope for expanding biomass resource base from forestlands.

In addition to these existing uses, forestlands have considerable potential to provide biomass from two primary sources: residues associated with the harvesting and management of commercial timberlands for the extraction of saw logs, pulpwood, veneer logs, and other conventional products; and currently non-merchantable biomass associated with the standing forest inventory. This latter source is more difficult to define, but generally would include rough and rotten wood not suitable for conventional forest products and excess quantities of smaller-diameter trees in overstocked forests.
These two categories of forest resources constitute what is defined as the primary source of forest residue biomass in addition to the fuelwood that is extracted for space heating applications in the residential and commercial sectors and for some feedstocks by electric utilities.

There is also a relatively large tertiary, or residue, source of forest biomass in the form of urban wood residues — a generic category that includes yard trimmings, packaging residues, discarded durable products, and construction and demolition debris.

All of these forest resources can contribute an additional 226 million dry tons to the current forest biomass consumption (approximately 142 million dry tons) – an amount still only a small fraction of the total biomass timberlands inventory of more than 20 billion dry tons (Figure 5). Specifically, these forest resources include the following:

- The recovered residues generated by traditional logging activities and residues generated from forest cultural operations or clearing of timberlands.
- The recovered residues generated from fuel treatment operations on timberland and other forestland.
- The direct conversion of roundwood to energy (fuelwood) in the residential, commercial, and electric utility sectors.
- Forest products industry residues and urban wood residues.
- Forest growth and increase in the demand for forest products.
A summary of the amounts of biomass available annually and on a sustainable basis from forest resources is summarized in Figure 6. The approximate total quantity is 368 million dry tons annually. As noted, this includes about 142 million dry tons of biomass currently being used primarily by the forest products industry, as well as the 89 million dry tons that could result annually from a continuation of demand and supply trends in the forest products industry.
2.3.2 Increasing biomass resources from forests

2.3.2.1 Logging residues and other removals from the forest inventory

A recent analysis shows that the annual removals from the forest inventory totaled nearly 20.2 billion ft$^3$ (572 million m$^3$). Of this volume, 78 percent was for roundwood products, 16 percent was logging residue, and slightly more than 6 percent was classified as “other removals” (Smith et al., 2004). The total annual removals constitute about 2.2 percent of the forest inventory of timberland and are less than net annual forest growth (Figure 4). The logging residue fraction is biomass removed from the forest inventory as a direct result of conventional forest harvesting operations. This biomass material is largely tree tops and small branches left on site because these materials are currently uneconomical to recover either for product or energy uses (Figure 7). The remaining fraction, other removals, consists of timber cut and is burned in the process of land conversion or cut as a result of cultural operations such as precommercial thinnings and timberland clearing.

For the United States, total logging residue and other removals currently amount to nearly 67 million dry tons annually: 49 million dry tons of logging residue and 18 million dry tons of other removal residue (Table 3).

Table 3. Current availability of logging residue and other removals

<table>
<thead>
<tr>
<th>Forest Resource</th>
<th>National Forest</th>
<th>Other Public</th>
<th>Private Lands</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logging residues</td>
<td>1.1</td>
<td>3.2</td>
<td>44.4</td>
<td>48.8</td>
</tr>
<tr>
<td>Other removals</td>
<td>0.5</td>
<td>0.7</td>
<td>17.1</td>
<td>18.3</td>
</tr>
<tr>
<td>Total</td>
<td>1.6</td>
<td>3.9</td>
<td>61.5</td>
<td>67.1</td>
</tr>
</tbody>
</table>

Note: Conversion of volumetric data assumes an average density of 30 dry lbs/ft$^3$ (Timber Product Output database)
Source: Timber Product Output database (USDA-FS, 2004a)

Not all of this resource is potentially available for bioenergy and biobased products (Figure 7). Stokes reported a wide range of recovery percentages, with an average of about 60 percent potential recovery behind conventional forest harvesting systems (Stokes, 1992). With newer technology, it is estimated that the current recovery is about 65 percent. Other removals, especially from land-clearing operations, usually produce different forms of residues and are not generally as feasible or as economical to recover. It is expected that only half of the residues from other removals can be recovered. Of course, not all of this material should be recovered. Some portion of this material, especially the leaves and parts of tree crown mass, should be left on site to replenish nutrients and maintain soil productivity.
Figure 7. Forest utilization relationship

Limiting the recoverability of logging and other removal residue reduces the size of this forest resource from about 67 million to 41 million dry tons. About three-fourths of this material would come from the logging residue. Further, because of ownership patterns most of the logging residue and nearly all residues from other sources (e.g., land clearing operations) would come from privately owned land (Figure 8).

Figure 8. Logging and other removal residues
2.3.2.2 Forest Residues from Fuel Treatment Thinning

Vast areas of U.S. forestland are overstocked with relatively large amounts of woody materials. This excess material has built up over years as a result of forest growth and alterations in natural fire cycles. Over the last ten years, federal agencies have spent more than $8.2 billion fighting forest fires, which have consumed over 49 million acres (Figure 9). The cost of fighting fires does not include the costs of personal property losses, ecological damage, loss of valuable forest products, or the loss of human life.

The FTE (Fuel Treatment Evaluator) identified nationwide about 7.8 billion dry tons of treatable biomass on timberland and another 0.6 billion dry tons of treatable biomass on other forestland (Table 4). Only a fraction of these approximately 8.4 billion dry tons is considered potentially available for bioenergy and biobased products on a sustainable annual basis. Many factors reduce the size of this primary biomass resource (USDA-FS, 2003).

<table>
<thead>
<tr>
<th>Forest Resource</th>
<th>National Forest</th>
<th>Other Public</th>
<th>Private Lands</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timberland</td>
<td>1,849</td>
<td>770</td>
<td>5,175</td>
<td>7,794</td>
</tr>
<tr>
<td>Other forest land</td>
<td>147</td>
<td>158</td>
<td>310</td>
<td>616</td>
</tr>
<tr>
<td>Total</td>
<td>1,996</td>
<td>928</td>
<td>5,486</td>
<td>8,410</td>
</tr>
</tbody>
</table>

Note: Conversion of volumetric Forest Inventory Analysis data assumes 30 dry lbs/ft³. Tree volumes were partitioned into two utilization groups - trees greater than 7 inches taken to a 4 inch minimum top diameter and the remaining smaller material (tops, limbs, small diameter trees). The larger-sized material was assumed merchantable for high-value products and the smaller-sized material suitable for bioenergy and biobased products.

Source: Fuel Treatment Evaluator (USDA-FS, 2004c)

The first of these limiting factors is accessibility to the material from the standpoint of having roads to transport the material and operate logging/collection systems. This is rarely a technology-limited factor since there is equipment for nearly any type of terrain and for removing wood a long distance, even without roads (e.g., via helicopters, two-stage hauling, or long-distance cableways). However, there are usually economic and political constraints that inhibit working in roadless areas and more difficult terrain. Estimates of operational accessibility assume conventional types of operations by limiting the areas for consideration to roaded forestland. About 60 percent of the North American temperate forest is considered accessible (not reserved or high-elevation and within 15 miles of major transportation infrastructure) (FAO, 2001). The Forest Service’s final environmental impact statement for roadless area conservation indicates that about 65 percent of Forest Service acreage falls within roaded or nonrestricted designations.
Road density is much higher in the eastern United States, and in most cases, the topography is more accessible.

A more significant restriction is economic feasibility. Operating in steep terrain, in unroaded areas, or with very low-impact equipment is expensive. The value of the biomass (in its broad sense, meaning a combination of product value and treatment value) has to be weighed against the cost of removing the material. For example, May and LeDoux (1992) compared FIA data for hardwood inventory with economic modeling of the cost of harvest and concluded that only 40 percent of the inventory volume in Tennessee was economically available. Biomass, with a lower product value, would be even less available if the biomass has to cover the entire cost of the operation. If the biomass were to be produced as part of an integrated operation, it would be at most 40 percent available in the eastern hardwood example. The primary economic factor is the cost of transportation to processing mills.

The recoverability (i.e., the fraction of standing biomass removed offsite) of wood for bioenergy and biobased products is a function of tree form, technology, and timing of the removal of the biomass from the forests. In most cases, merchantable wood is removed, and the forest residues — in the form of limbs and tops, and small non-merchantable trees — remain scattered across the harvest area. This practice reduces recoverability when the biomass is removed in a second pass. However, when all biomass is harvested and processed using an integrated system, recovery is usually greatly improved, even greater than 90 percent. For example, a study by Stokes and Watson (1991) found that 94 percent of the standing biomass could be recovered when using a system to recover multiple products if the biomass from in-woods processing was actually utilized for bioenergy.
There is a concern about removal of large quantities of biomass from stands because of reduced long-term site productivity and loss of diversity and habitat associated with down-wood debris. Although the consequences are very site-specific, most negative impacts can be eliminated or minimized by leaving leaves, needles, and a portion of the woody biomass on site (Burger 2002). The 8.4 billion dry tons of treatable biomass that is potentially available for bioenergy and biobased products was reduced by the following factors:

- To allay any concerns about site impacts, recovered material using an integrated system is limited to 85 percent.
- Only 60 percent of the identified treatable areas are assumed to be accessible.
- Fuel treatment material is recovered on a 30-year cycle before any sites are re-entered.
- Harvested fuel treatment biomass is allocated into two utilization groups: (1) merchantable trees suitable for conventional or higher-value forest products as well as rotten trees, brush and understory, small saplings, and polewood trees; (2) the residues (e.g., tops, limbs, and branches) from the harvested larger trees suitable for bioenergy and biobased product uses. The conventional forest products fraction assumed is 70 percent, and the residue or bioenergy and biobased product fraction is 30 percent (USDA-FS, 2003).

The combination of these factors significantly reduces the amount of fuel treatment biomass that can be sustainably removed on an annual basis. About 49 million dry tons can potentially be removed annually from timberlands, and about 11 million dry tons can be removed annually from other forestlands (Table 5). Most of the fuel treatment biomass from timberlands would come from privately owned lands; slightly less than 20 percent of the material would come from national forests. In contrast, proportionately more of the fuel treatment biomass allocated to bioenergy and biobased products on other forestlands would come from publicly held lands. The 60 million dry tons of fuel treatment biomass assumes that a relatively large percentage (70 percent) goes to higher-valued products. If feedstock prices for biomass were to increase relative to conventional forest products, the amount of biomass available for bioenergy and biobased products could increase substantially.

Table 5. Availability of fuel treatment thinnings

<table>
<thead>
<tr>
<th>Forest Resource</th>
<th>National Forest</th>
<th>Other Public</th>
<th>Private Lands</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>million dry tons</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timberland</td>
<td>9.4</td>
<td>3.9</td>
<td>35.2</td>
<td>48.6</td>
</tr>
<tr>
<td>Other forest land</td>
<td>2.2</td>
<td>2.4</td>
<td>6.3</td>
<td>11.0</td>
</tr>
<tr>
<td>Total</td>
<td>11.7</td>
<td>6.3</td>
<td>41.5</td>
<td>59.6</td>
</tr>
</tbody>
</table>
2.3.2.3 Forest products industry processing residues

Primary wood processing mills

The Forest Service classifies primary mill residues into three categories — bark, coarse residues (chunks and slabs), and fine residues (shavings and sawdust). In each of these categories, residues are further segmented into hardwoods and softwoods. Primary mill residues are desirable for energy and other purposes because they tend to be clean, uniform, and concentrated and have low moisture content (< 20 percent). These desirable physical properties, however, mean that nearly all of these materials are currently used as inputs in the manufacture of products or as boiler fuel. Very little of this resource is currently unused. According to Forest Service estimates, about 80 percent of bark is used as fuel and about 18 percent is used in low-value products such as mulch (USDA-FS, 2004a). For coarse residues, about 85 percent is used in the manufacture of fiber products and about 13 percent is used for fuel. About 55 percent of the fine residues are used as fuel and 42 percent used in products.

Primary timber processing mills (facilities that convert roundwood into products such as lumber, plywood, and wood pulp) produced 91 million dry tons of residues in the form of bark, sawmill slabs and edgings, sawdust, and peeler log cores in 2002 (USDA-FS, 2004a). Nearly all of this material is recovered or burned, leaving slightly less than 2 million dry tons available for other bioenergy and biobased product uses (Table 6).

Table 6. Forest products industry processing residues

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy</th>
<th>Product And Other Uses</th>
<th>Unused</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mill Residue Byproducts (million dry tons)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary wood processing mills</td>
<td>39.4</td>
<td>50.3</td>
<td>1.7</td>
<td>91.3</td>
</tr>
<tr>
<td>Secondary wood processing mills</td>
<td>____</td>
<td>9.5</td>
<td>6.1</td>
<td>15.6</td>
</tr>
<tr>
<td>Pulp and paper mills</td>
<td>52.1</td>
<td>____</td>
<td>____</td>
<td>52.1</td>
</tr>
</tbody>
</table>

Notes: Primary wood processing mills account for 91.3 million dry tons split among bark, coarse wood, and fine wood in the following proportions - 26.5%, 42.9%, and 30.7%, respectively. Mill residues are projected to increase by about 30% and somewhat less for black liquor generated at pulp and paper mills. Source: Timber Product Output database (USDA-FS, 2004a)
Secondary Wood Processing Mills

Residues are also generated at secondary processing facilities — mills utilizing primary mill products. Examples of secondary wood processing mill products include millwork, containers and pallets, buildings and mobile homes, furniture, flooring, and paper and paper products. Since these industries use an already processed product, they generate smaller quantities of residues. In total, the secondary mill residue resource is considerably smaller than the primary mill resource (Rooney, 1998; McKeever, 1998). The types of residues generated at secondary mills include sawdust and sander dust, wood chips and shavings, board and cut-offs, and miscellaneous scrap wood.

At the larger secondary mills, most of the residue produced is used on site to meet energy needs (such as heat for drying operations) or is recycled into other products. This is in contrast to practices at the smaller mills where much of the residue material goes unused (Bugelin and Young, 2002). The recovery of residue at smaller mills is more constrained because it may be generated seasonally and may be more dispersed.

One of the few estimates of the amount of secondary mill residue available is provided by Fehrs (1999). He estimates that 15.6 million dry tons is generated annually, with about 40 percent of this potentially available and recoverable. The remaining fraction is used to make higher-valued products and is not available (Table 6).

Pulp and Paper Mills

In the manufacture of paper products, wood is converted into fiber using a variety of chemical and mechanical pulping process technologies. Kraft (or sulfate) pulping is the most common processing technology, accounting for over 80 percent of all U.S.-produced pulp. In Kraft pulping, about half the wood is converted into fiber. The other half becomes black liquor, a by-product containing unutilized wood fiber and valuable chemicals.

Pulp and paper facilities combust black liquor in recovery boilers to produce energy (i.e., steam), and, more importantly, to recover the valuable chemicals present in the liquor. The amount of black liquor generated in the pulp and paper industry is the equivalent of 52 million dry tons of biomass (Table 6). Because the amount of black liquor generated is insufficient to meet all mill needs, recovery boilers are usually supplemented with fossil and wood residue–fired boilers. The pulp and paper industry utilizes enough black liquor, bark, and other wood residues to meet nearly 60 percent of its energy requirements. Currently, the forest products industry along with DOE are looking at black liquor gasification to convert pulping liquors and other biomass into gases that can be combusted much more efficiently.
2.3.2.4. Urban Wood Residues

There are two principal sources of urban wood residues: MSW (Municipal Solid Waste) and construction and demolition debris. MSW consists of a variety of items ranging from organic food scraps to discarded furniture and appliances. In 2001, nearly 230 million tons of MSW was generated (EPA, 2003). Wood and yard and tree trimmings are the two sources within this residue stream that are potentially recoverable for bioenergy and biobased product applications. The wood component includes discarded furniture, pallets, containers, packaging materials, lumber scraps (other than new construction and demolition), and wood residuals from manufacturing. McKeever (2004) estimates the total wood component of the MSW stream at slightly more than 13 million dry tons (Table 7). About 55 percent of this material is either recycled as compost, burned for power production, or unavailable for recovery because of excessive contamination. In total, about 6 million dry tons of MSW wood is potentially available for recovery for bioenergy and biobased products. The other component of the MSW stream — yard and tree trimmings — is estimated at 9.8 million dry tons. However, only 1.7 million dry tons is considered potentially available for recovery after accounting for what is currently used and what is unusable.

Table 7. Summary of availability of urban wood residues

<table>
<thead>
<tr>
<th>Urban Wood Residue Source</th>
<th>Generated</th>
<th>Recovered, Combusted For Energy &amp; Unusable</th>
<th>Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction residue</td>
<td>11.6</td>
<td>3.0</td>
<td>8.6</td>
</tr>
<tr>
<td>Demolition debris</td>
<td>2.77</td>
<td>1.61</td>
<td>11.7</td>
</tr>
<tr>
<td>Woody yard trimmings</td>
<td>9.3</td>
<td>8.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Wood (MSW)</td>
<td>13.2</td>
<td>7.3</td>
<td>6.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>62.3</strong></td>
<td><strong>34.4</strong></td>
<td><strong>28.0</strong></td>
</tr>
</tbody>
</table>

Notes: Woody yard trimmings were converted to dry tons based on 40% moisture content. The amount of urban wood residue generated is estimated to increase by about 30%. This estimate is based on trends associated with residential and nonresidential construction, demolition, and remodeling, as well as in the disposal of curables and packaging residues. Source: McKeever (2004)

The other principal source of urban wood residue is construction and demolition debris. These materials are considered separately from MSW since they come from much different sources. These debris materials are correlated with economic activity (e.g.,
housing starts), population, demolition activity, and the extent of recycling and reuse programs. McKeever (2004) estimates annual generation of construction and demolition debris at 11.6 and 27.7 million dry tons, respectively. About 8.6 million dry tons of construction debris and 11.7 million dry tons of demolition debris are considered potentially available for bioenergy and biobased products (Table 7). Unlike construction debris, which tends to be relatively clean and can be more easily source-separated, demolition debris is often contaminated, making recovery much more difficult and expensive.

All these sources of urban wood residue total 28 million dry tons. As noted by McKeever (1998), many factors affect the availability of urban wood residues, such as size and condition of the material, extent of commingling with other materials, contamination, location and concentration, and, of course, costs associated with acquisition, transport, and processing.

2.3.2.5 Forest Growth and Increase in the Demand for Forest Products

The Fifth Resources Planning Act Timber Assessment projects the continued expansion of the standing forest inventory despite the estimated conversion of about 23 million acres of timberland into more developed uses (Haynes, 2003). The size of the standing forest inventory will increase because annual forest growth will continue to exceed annual harvests and other removals from the inventory. The forest products industry will continue to become more efficient in the way it harvests and processes wood products. The demand for forest products are also projected to increase. However, the increase will be less than historical growth owing to a general declining trend in the use of paper and paperboard products relative to GNP and the relatively stable forecast of housing starts (Haynes, 2003). The increase in the consumption of forest products will be met by an increase in timber harvests; an increase in log, chip, and product imports; and an increase in the use of recovered paper. Further, consumers will become more efficient in the use of wood products by generating fewer wood residues and increasing recycling rates.

These changes and trends will affect the availability of forest residues for bioenergy and biobased products. An overall increase in the amount of biomass available due to changes in the demand and supply of forest products will increase the availability and use of forest residues by about 89 million dry tons annually by mid-21st century. Specifically, the availability of logging and other removal residues could increase by about 23 million dry tons over the current annual resource estimate of 41 million dry tons. Fuelwood harvested for space- and process-heat applications could increase by another 16 million dry tons over current levels. Wood residues and pulping liquors generated by the forest products industry could increase by about 16 and 22 million dry tons, respectively. And, the amount of urban wood waste generated could increase by 11 million dry tons over currently available amounts.
2.3.3 Forest Resources Summary

Biomass derived from forestlands currently contributes about 142 million dry tons to the total annual consumption in the United States of 190 million dry tons. Based on the assumptions and conditions outlined in this analysis, the amount of forestland-derived biomass that can be sustainably produced is approximately 368 million dry tons annually — more than 2.5 times the current consumption (Figure 10). This estimate includes the current annual consumption of 35 million dry tons of fuelwood extracted from forestland for residential, commercial and electric utility purposes, 96 million dry tons of residues generated and used by the forest products industry, and 11 million dry tons of urban wood residues. As already discussed, there are relatively large amounts of forest residue produced by logging and land clearing operations that goes uncollected (41 million dry tons per year) and significant quantities of forest residues that can be collected from fuel treatments to reduce fire hazards (60 million dry tons per year). Additionally, there are some unutilized residues from wood processing mills and unutilized urban wood. These sources total about 36 million dry tons annually. About 48 percent of these resources are derived directly from forestlands (primary resources). About 39 percent are secondary sources of biomass from the forest products industry. The remaining fraction would come from tertiary or collectively from a variety of urban sources.

Figure 10. Summary of potentially available forest resources
2.4. Potential Concerns and Impacts

Forestland and cropland resources have the potential to provide for a seven-fold increase in the amount of biomass currently consumed for bioenergy and biobased products. This annual potential exceeds 1.3 billion dry tons — the equivalent of more than one-third of the current demand for transportation fuels. More than 25 percent of this potential would come from extensively managed forestlands and about 75 percent from intensively managed croplands. The major primary resources would be logging residues and fuel treatments from forestland, and crop residues and perennial crops from agricultural land. Some additional quantities of biomass would be available from secondary sources; however, most of this biomass would be expected to be used by the forest products industry and food processing industries. Tertiary or residue sources of biomass are small relative to the primary sources. A sizeable fraction of this potential would be captive to existing uses. Examples are most of the biomass resource generated by the forest products industry, fuelwood extracted from forestlands, some urban wood residues, grains used in the production of biofuels, and some agricultural residues. Excluding these captive uses of biomass from the total resource potential still shows 220 million dry tons of forestland biomass (logging residue, fuel treatments, urban wood residues) and, depending on crop yield improvements, 450 to nearly 850 million dry tons of cropland biomass (agricultural residues, perennial crops, and most process residues) as potentially available for new bioenergy and biobased product uses (Figure 11).

Producing one billion tons or more of feedstock annually will require technologies that can increase the utilization of currently available and underutilized feedstocks, such as agricultural residues and forest residues. It will require the development of perennial crops as an energy resource on a relatively large scale. It will require changes in agricultural and silvicultural crop management systems. Production yields from these systems will need to be increased and costs lowered. Changes in the way biomass feedstocks are collected or harvested, stored and transported, and preprocessed will also have to be made. Accomplishing these changes will obviously require investments and policy initiatives as well as the coordinated involvement of numerous stakeholder groups to gain broad public acceptance.

The utilization of a significant amount of these biomass resources would also require a concerted R&D effort to develop technologies to overcome a host of technical, market, and cost barriers. Demonstration projects and incentives (e.g., tax credits, price supports, and subsidies) would be required. Additional analyses would be required to discern the potential impact that large-scale forest and crop residue collection and production of perennial crops could have on traditional markets for agricultural and forest products.

Forest-Derived Biomass Resources

The three key forest resources identified for this assessment are residues from logging and other removals, fuel treatments, and urban wood residues. There are particular issues associated with the utilization of each of these resources.
Accessibility, terrain (e.g., steep slopes), and environmentally sensitive areas limit fuel treatment operations. Where treatment operations are appropriate, costs associated with the removal of the excess biomass may be prohibitive. Separating and marketing larger-diameter trees for conventional (higher-valued) forest products would be necessary to help defray the costs of dealing with large numbers of small-diameter material (USDAFS, 2003). Removing large trees, however, can create unfavorable public opinion and opposition to fuel treatment operations.

Transportation costs, usually in the range of $0.20 to $0.60 per dry ton-mile, could severely limit haul distances, if based solely on bioenergy and biobased product values. The availability of markets within viable transport distances may limit the practicality of removing fuel treatment biomass for bioenergy and biobased products.

Labor availability may be a key constraint in fuel treatment operations. The strategic fuel treatment assessment for the western states notes that there is a disparity between the distribution of skilled forestry workers and the forestlands requiring fuel treatments (USDA-FS, 2003). Mobilizing forestry workers and equipment across large distances can increase costs and reduce competition for contracted projects.

Fuel treatment operations have the potential to create environmental impacts, especially if sites are severely disturbed. The impact of erosion and consequent movement of sediments into surface waters is a particular concern. However, studies suggest that there is often a much higher flow of sediments into surface waters as a consequence of wildfires than as a consequence of fuel treatment thinning operations (USDA-FS, 2003).

More cost-effective fuel treatment operations and recovery of logging and other removal residue will require the development of more efficient and specialized equipment that can accommodate small-diameter trees. The availability of more efficient equipment will make the recovery of biomass for bioenergy and biobased products much more cost-effective.

Federal funding for forestry programs for such activities as private tree planting, forest stand management, and technical assistance are a small fraction (<0.5 percent) of direct agricultural payments to farmers (Alig et al., 2003). Given the size of private forestland ownership, well-crafted policies aimed at providing incentives for landowners to manage their holdings could attract large quantities of biomass.

The availability of urban wood residues is largely governed by the size of tipping fees. Where such fees are high (due in part to the lack of land for landfills), recycling is often higher. Also, high tipping fees provide economic incentives to utilize these resources.

Some urban wood residues are highly dispersed, making economical recovery potentially costly. Seasonality of the generated residue can also affect the viability of this source.
- Contamination and commingling of urban wood residues with non-wood products, especially demolition residues and some construction residues, can limit uses. Contamination with dirt and rocks is also a potential issue with yard and tree trimmings.

Figure 11. Summary of potential forest and agricultural resources
2.5. Summarized Findings

The purpose of this analysis was to determine if the land resources of the United States are sufficient to support a large-scale biorefinery industry capable of displacing a significant fraction of our nation’s petroleum consumption. This study found that the combined forest and agriculture land resources have the potential of sustainably supplying much more than one-third of the nation’s current petroleum consumption.

Forest lands, and in particular, timberlands, have the potential to sustainably produce close to 370 million dry tons of biomass annually. This estimate includes the residues generated in the manufacture of various forest products and the residues generated in the use of manufactured forest products. It also includes the harvest of wood for various residential and commercial space-heating applications. With the exception of urban wood residues, most of these sources of forest biomass are currently being utilized and there are significant efforts under way to use these resources much more efficiently. Two potentially large sources of forest biomass not currently being used are logging and other removal residues, and fuel treatment thinnings. These sources can sustainably contribute over 120 million dry tons annually. The logging and other removal residues can easily be recovered following commercial harvest and land clearing operations. Fuel treatment thinnings can also be recovered concomitantly with efforts to reduce forest fire hazards and otherwise improve the health of our nation’s forests.

In the context of the time required to scale up to a large-scale biorefinery industry, an annual biomass supply of more than 1.3 billion dry tons can be accomplished with relatively modest changes in land use and agricultural and forestry practices.

2.6. References


3. HOW WOOD IS USED FOR ENERGY

There are several environmental advantages, compared with fossil fuels, when using wood biomass for energy. There is little net production (~5%) of carbon dioxide (CO₂), the major greenhouse gas, because the CO₂ generated during combustion of wood equals the CO₂ consumed during the lifecycle of the tree. Wood fuels contain minimal heavy metals and extremely low levels of sulfur, and, under controlled burning process, produces minimal ash, which can be used as fertilizer (Bergman & Zerbe, 2004).

Wood fuels is usually less expensive than competing fossil fuels, but transportation and large volumes of fuel (~1,360 green kg (~1.5 tons) per hour per megawatt of power generated) available nearby the wood-processing units are the key factors for the success of forest biomass use for energy. Considering small scale operations, an average delivered costs of chips would be $33/1000 green kg ($30/ton) or the equivalent of $1.95/GJ ($2.05/million Btu) assuming roughly $16.5-$22/1000 green kg ($15-$20 per ton) transportations costs. On 2003, the average price of fossil fuels and natural gas at utility plants was $2.13/GJ ($2.25/million BTU) and $5.31/GJ ($5.60/million Btu), respectively. Another aspect to consider is the capital cost necessary to build a biomass-fired generating plant, which is still higher than other several traditional sources (Figure 12). In general, wood combustion system costs are $50,000 to $15 0,000 for a 0.6 MW (2 million Btu/h) system, $ 100,000 to $350,000 for a 0. 6 to 1. 5 MW (2 to 5 million Btu/h) system, and $250,000 to $500,000 for a 1.5 to 3 MW (5 to 10 million Btu/h) system. Cost of installation is extremely variable because of the different types and capacities of equipment as well as whether equipment is new, used, or in-place and can be converted to burn wood (Bergman & Zerbe, 2004). Even so, 4.9 full-time jobs per megawatt of net plant generating capacity are created, associated with biomass power plants (Morris, 1999).

Zerbe (2004) provides a didactical explanation about the several possible ways of using wood for energy. The first one is called chunkwood, fairly uniform particles, about the size of an average fist. Chunkwood can be readily dried since there are openings for air to circulate when it is piled for storage. Drying green wood to lower moisture contents makes it easier to burn with less smoldering and smoking and gives the wood a higher heating value. Chunkwood is rarely used now, but it will probably become more popular in the future.

Chips and sawdust are more common types of particulate wood fuel. Chips are dried in special dryers that may use wood or fossil fuels to generate heat. Sometimes dry sawdust
and chips are available at secondary wood manufacturing plants such as furniture plants. Dry sawdust can be a very desirable fuel for use in special combustors that burn particles in suspension. In such cases grates are not necessary. Chips are advantageous for handling and storing. They can be used effectively in automated stoker applications.

![Figure 12. Cost of new central station electricity generation technologies (Energy Information Administration, 2006).](image)

Shavings are produced when lumber is planed or molded or spun off from logs that are peeled. Since shavings are usually produced in the processing of dry lumber they make good fuel. Green shavings from applications such as rounding logs for log home construction may be further processed by chipping and drying.

Wood pellets are made by compression milling small wood particles such as sawdust. Pellets are sold at retail outlets in 18 kg (40 pound) sacks. They handle and store easily. They should be kept dry to prevent disintegration, and to avoid risk of mold and decay. The most common use of pellet fuel is for heating with modern and convenient pellet stoves. Some of these stoves burn pellets with 85% efficiency and have automatic ignition, feed, and control systems.

Manufactured fireplace logs (firelogs) are made from waste wood to provide open-hearth warmth and ambience with clean fuel. Wood briquettes are similar products of smaller length that are used as barbecue fuel or industrial stoker fuel. There are two types of firelogs or fuel logs; one type is made with the addition of around 50% wax. The other type is all wood. In the USA wax-type logs are more popular, but the all-wood type is more popular throughout the rest of the world. All-wood logs are made in machines that apply pressure with screws or pistons. The heat developed in the process is sufficient to
cause the lignin in the wood to flow and act as a binder for the particulate wood waste. Briquettes are made in the same ways as all-wood logs, but the log lengths from the machines are cut into thin disks.

In developing countries charcoal is much more commonly used as a fuel. This is an advance from use of solid wood fuel for use in domestic or light institutional or industrial (e.g., baking) applications. Charcoal is more easily stored and transported than wood, and it is more durable in the presence of moisture.

Industrial use of wood fuels today is a typical practice in primary and secondary forest products manufacturing plants. Unseasoned wood and bark fuel is typically used in sawmills and plywood and particleboard manufacturing plants. Pulp and paper mills burn green manufacturing waste, and, sometimes, forest harvesting waste. The black liquor that pulp mills use is a high percentage of total overall wood fuel usage. Furniture plants often have premium dry wood fuels available.

Charcoal is only one of several different forms of advanced products that may be obtained through pyrolyzing wood in the presence of insufficient oxygen to cause complete combustion. Depending on pyrolysis temperature there may be different proportions of char, tar, liquids, and gases. With high temperatures and proportionately low oxygenation, mostly gas is formed. Wood gasification results in gaseous products composed of mainly hydrogen and carbon monoxide and some hydrocarbons that include methane.

The wood distillation through heating in a retort without introducing oxygen can produce methanol for fuel along with other chemicals and charcoal. However, for producing methanol from wood it is more efficient to use a synthesis process similar to that used for making methanol from natural gas. Little alcohol fuel is made from wood today, but the promise for the future, with continuous development of cost-lowering technology, appears better. Nevertheless, the quantity of fossil fuel energy needed to deliver 1,000,000 Btu to the automobile gas tank is far lower than for the same product made from agricultural crops. Cellulosic ethanol production from wood will require only about 10,000 Btu of fossil fuel per 1,000,000 Btu delivered to the fuel tank, while cellulosic ethanol production from corn will require almost 50% (Table 8).

Table 8. Energy required to deliver 1,000,000 Btu to a vehicle fuel tank

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Total Energy Required (Btu)</th>
<th>Fossil Energy Required (Btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>1,241,000</td>
<td>1,241,000</td>
</tr>
<tr>
<td>Ethanol (corn-starch)</td>
<td>1,587,000</td>
<td>600,000</td>
</tr>
<tr>
<td>Ethanol (corn-cellulose)</td>
<td>1,250,000</td>
<td>230,000</td>
</tr>
<tr>
<td>Ethanol (wood)</td>
<td>2,600,000</td>
<td>10,000</td>
</tr>
</tbody>
</table>

The kraft paper manufacturing process is popular throughout the world. It can produce high-quality paper with less pollution than with the sulfite process. In the kraft process recovery of papermaking chemicals is important. These chemicals are contained in the large amounts of liquid waste known as ‘black liquor’ from the process. Therefore the overall process includes a large recovery boiler that produces much energy in using the black liquor as fuel.

Wood fuel can also be fired together with other fuels, like coal and gas (Figure 13). It is co-fired with coal in some power plants where the primary coal fuel has high sulfur content. Wood is low in sulfur so that the mixture of coal and wood facilitates meeting sulfur emission requirements. According to Sénéchal (2007), biomass coal co-firing is the most economic way to produce “green power” because of its high efficiency (~40%), and also requires a small supplementary investment (~100€/KWe). But it is also presents more complex combustion chemistry, and a necessity of homogeneous biomass feedstock supply to not perturb the boiler operation and plant efficiency;

![Figure 13. Example of a co-firing power plant (Sénéchal, 2007).](image)

Gas is co-fired with wood to overcome difficulties when wood is at a higher moisture content than that at which it can readily be combusted. With co-firing gas it is fired through one or more burners mounted above wood fuel feeders. The gas burners can also be fired to maintain up to 100% of the heat delivery load for start-up and as a back-up during fuel supply shortages. Table 9 shows the power plants that were co-firing with biomass, on a commercial basis, at the beginning of this century in U.S.
Table 9. U.S. power plants co-firing with biomass (Haq, no date)

<table>
<thead>
<tr>
<th>Facility Name</th>
<th>Company Name</th>
<th>State</th>
<th>Capacity (Megawatts)</th>
<th>Heat Input from Biomass (Percent of Total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6th Street</td>
<td>Alliant Energy</td>
<td>IA</td>
<td>85</td>
<td>7.7</td>
</tr>
<tr>
<td>Bay Front</td>
<td>Xcel Energy, Inc.</td>
<td>WI</td>
<td>76</td>
<td>40.3</td>
</tr>
<tr>
<td>Colbert</td>
<td>TVA</td>
<td>AL</td>
<td>190</td>
<td>1.5</td>
</tr>
<tr>
<td>Gadsden 2</td>
<td>Alabama Power Co.</td>
<td>AL</td>
<td>70</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Greenridge</td>
<td>AES</td>
<td>NY</td>
<td>161</td>
<td>6.8</td>
</tr>
<tr>
<td>C. D. McIntosh, Jr.</td>
<td>City of Lakeland</td>
<td>FL</td>
<td>350</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Tacoma Steam Plant</td>
<td>Tacoma Public Utilities</td>
<td>WA</td>
<td>35</td>
<td>44.0</td>
</tr>
<tr>
<td>Willow Island 2</td>
<td>Allegheny Power</td>
<td>WV</td>
<td>188</td>
<td>1.2</td>
</tr>
<tr>
<td>Yates 6 and 7</td>
<td>Georgia Power</td>
<td>GA</td>
<td>150</td>
<td>&lt;1.0</td>
</tr>
</tbody>
</table>

As an example, van Ree (2007) states that with advanced biomass conversion technology, it is possible, through gasification and Fischer-Tropsch Synthesis, to produce 210 L of “green diesel” from 1 ton of wood, with 69% of total energetic efficiency (Figure 14).

![Sequence of "green diesel" production from wood biomass (van Ree, 2007).](image)

Figure 14. Sequence of “green diesel” production from wood biomass (van Ree, 2007).

**Scales of Operation**

The micro scale can be considered for space heat use, with wood-burning facilities using less than 1 MW (3.4 million Btu/h) of electrical or thermal energy, on residences or small institutions. Each year in the United States, the equivalent of 52,700 million oven-dry kg (58 million tons) of wood are used for residential and small institutional space heating. Small gasifiers coupled to internal combustion engines and generators can produce up to
20 kW$_e$ (68,300 Btu/h) of electricity for decentralized use. Micro-scale cogeneration should be capable of operating at electrical power levels as low as 2 kW$_e$ (6,830 Btu/h) and could be used in domestic/household applications. One small generating plant might use 454 oven-dry kg (0.5 ton) of wood fuel per day or 0.164 million oven-dry kg (180 tons) per year.

The small scale use for space and/or process heat is located in the range of 1 to 5 MW (3.41 to 17.1 million Btu/h). Types of fuel used are whole tree and mill chips, pellets, and briquettes. The typical heating medium is hot water instead of steam. High-pressure steam may require additional operator attention and maintenance that could make wood heat not economical. Small-scale electrical generation with wood fuel is mainly located at forest products manufacturing plants. A few Vermont schools use boilers with close-coupled gasifiers (cogeneration) at the 1- to 3-MWth (3.41- to 10.2-million Btu/h) level to generate hot water for space heating. If configured to produce both heat and electricity, these units could produce between 500 kW$_e$ and 1.5 MW$_e$ (1.71 and 5.12 million Btu/h).

A few educational facilities in the United States (e.g., Massachusetts, Minnesota, Mississippi) use wood for space heating in the medium scale category. Known capacity at educational institutions is a total of about 31.2 MW (106 million Btu/h). This is the equivalent of about 136,000 oven-dry kg (150 tons) of wood per day or 50 million oven-dry kg (55,000 tons) per year. Forest products manufacturing plants also have medium-scale generating electricity facilities. California has medium-sized power generating plants in Mount Lassen Power, Rio Bravo, and Hayfork (Figure 15). Medium-scale cogeneration plants would be suitable for producing electricity and processing steam for dry kilns at a lumber manufacturing plant. Total power-generating capacity in the 5- to 15-MW (17.1- to 51.2-million Btu/h) range from wood in the United States is about 1,160 MW (3,960 million Btu/h). This is the equivalent of about 5.0 million oven-dry kg (5,500 tons) of wood per day or 1,830 million oven-dry kg (2 million tons) per year.

Large-scale plants using wood fuel are common in forest products manufacturing plants. At Fort James Corp. in Green Bay, Wisconsin, a combustor boiler produces 27.8 MW (95 million Btu/h) of electricity using fuel from the paper mill and deinking sludge. An educational institute in Moscow, Idaho, operates a hogged wood fuel burning facility with a capacity of about 25.8 MW (88 million Btu/h). The average size of biomass-fueled power plants is 20 MW$_e$ (68.3 million Btu/h). Larger plants are up to 50 MW$_e$ (171 million Btu/h) and more. The most viable fuel source is whole-tree chips that cost $12.66 to $21.10 per 1,000 green kg ($12 to $20 per ton). Transportation is the highest variable cost due to the distances that the chips travel to the plant. Typically, the majority of wood chips are transported within an 86.6-km (50-mile) radius of the plant. Therefore, location of a new plant requires much foresight to ensure the plant would have a continuous supply available for the years of plant operation. The installed capacity of wood power plants capable of generating more than 15 MW (51.2 million Btu/h) in the United States was about 6,310 MW (21,500 million Btu/h) as of October 1999, but some of these plants are not currently operating (Bergman & Zerbe, 2004).
Another example is the Craven County Wood Energy Biomass plant, located near New Bern, North Carolina, a 50 megawatt wood waste-fueled power plant, being in service since November 1990. It consumes approximately 530,000 tons of wood waste each year, or 1650 green t / day. The wood waste consists of: mill residues (20%); whole-tree wood chips (40%); clean waste wood from landfills (30%); and others (10% - railroad ties, agricultural waste, etc.). The equivalent energy of the woody biomass is 5,000 BTUs / t, and the thirty suppliers, are paid by weight. The economical distance of biomass transportation is 50 miles, but can reach 100 miles in case of a special material offer. The mill has a 40,000 t chip stock, and each chip pile goes through an air dry process during 3-5 weeks.

Biomass delivery is done 5 days a week, from 7h00 a.m. to 7h00 p.m., during summer time, and from 7h00 a.m. to 5h00 p.m., during winter time. Trucks are unloaded with help of two elevated platforms, and chips are transported on belts to the yard (Figure 16). During the transportation, metal parts are collected by a magnet, and non standard chips, in terms of higher size, can be destined to a grinder for another process (Figure 17). The plant consumes one million gallons of water per day, and produces 40 t of ashes each day. Flyash produced by the plant is used by area farmers as a soil enhancement, and bottom ash is used as ground cover on landfills. But these destinations still don’t represent any source of economical revenue.
4. WOOD PELLETS

Wood pellets are a type of wood fuel, generally made from compacted sawdust. They are usually produced as a byproduct of sawmilling and other wood transformation activities. The pellets are extremely dense and can be produced with a low humidity content (below 10%) that allows them to be burned with a very high combustion efficiency. Their high density also permits compact storage and rational transport over long distance. Pellet heating systems provide a low-net-CO$_2$ solution, because the quantity of CO$_2$ emitted during combustion is equal to the CO$_2$ absorbed by the tree during its growth. With the high efficiency burners developed in recent years, other emissions such as NO$_x$ and volatile organic compounds are very low, making this one of the most non-polluting heating options available. One remaining problem is emission of fine dust in urban areas due to a high concentration of pellet heating systems. Electrostatic particle filters for pellet heaters have however been developed and considerably reduce the problem when installed as standard. The energy content of wood pellets is approximately 4.8 MWh/ton (or about 17 MBTU/ton) (Wikipedia, 2007), equivalent to 2.8 barrels of oil (Pellet Fuels Institute, n.d.).
According to the Pellet Fuels Institute, there are more than 80 U.S. and Canadian active pellet plants, producing in excess of 1.3 million tons of fuel per year, with 1450 jobs on pellet manufacturing and more 2566 industry-related jobs. Most of the North-America pellet production is destined to the European market, which estimated consumption on 2006 was near 5 million metric tons, but the internal market is also growing, as it is possible to see by the 118,000 free standing pellet stove installations during 2005/06 period and more 185,000 projected for 2006/07 (Swaan, 2006). There are approximately 800,000 homes in the U.S. using wood pellets for heat, in freestanding stoves, fireplace inserts and even furnaces (Pellet Fuels Institute, n.d.). The use of wood pellets is widespread among population in the Scandinavian countries (Figure 18), and estimated 60% of new homes in Europe rely on wood pellet furnaces rather than electricity or natural gas (Timber Mart-South, 2007). Swaan (2006) reports a wood pellet estimated production over 7.5 million metric tons by North-America on 2010, with a 3 million metric tons consumption. Most part of that excess is suppose to be sold in the European market, with a projected deficit of 4 million metric tons (8 million metric tons production vs. 12 million metric tons consumption).

![Figure 18. Pellet fuel consumption in tons per 10000 people in 2003 (Pellet Fuels Institute, n.d.).](image)

The basic process to manufacture wood pellets starts pulverizing the waste sawdust to a uniform size and then dried to a specific moisture level (Figure 19). It is then forced through a press under very high pressure to produce the pellet. Since there are no artificial additives or binders used in this process it is very important to store this fuel in a cool dry place. Moisture will cause the pellet fuel to lose its form and will greatly reduce its heating and burning capabilities. Another problem is the excess of handling, which may cause the pellets to break, and as the pellets break a small amount of loose sawdust is produced. This loose sawdust is called fines and in excess can cause difficulty with some fuel feed systems (Energex, 2007).
The heating value of pellets and its efficiency make them a viable energy option for house heating. Table 10 shows a comparison among different fuel sources according data for Northeast United States, and similar comparison was also made with 2005 data for England (Table 11). The cost of wood pellets considered in the US example was $250.00 per ton with an 83% efficiency, and $177 and $238 per ton in England with 85% efficiency.

Table 10. Heating value and burning efficiency of different energy sources (modified from Wood Pellet Info, 2007).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Heating Value</th>
<th>Efficiency</th>
<th>$ per kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood Pellets</td>
<td>16.4 million BTU/ton</td>
<td>83%</td>
<td>0.063</td>
</tr>
<tr>
<td>Firewood</td>
<td>20 million BTU/cord</td>
<td>77%</td>
<td>0.055</td>
</tr>
<tr>
<td>Coal – Anthracite</td>
<td>25 million BTU/ton</td>
<td>80%</td>
<td>0.034</td>
</tr>
<tr>
<td>Fuel Oil #2</td>
<td>134,500 BTU/gallon</td>
<td>83%</td>
<td>0.076</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>1.03 million BTU's/MCF</td>
<td>80%</td>
<td>0.089</td>
</tr>
<tr>
<td>Propane</td>
<td>91,200 BTUs/gallon</td>
<td>80%</td>
<td>0.140</td>
</tr>
<tr>
<td>Electricity</td>
<td>3413 BTU/kWh</td>
<td>100%</td>
<td>0.140</td>
</tr>
</tbody>
</table>

(1) $250.00/ton; (2) $250.00/cord; (3) $200.00/ton; (4) $0.66/L; (5) $2.16/ccf; (6) $0.79/L.
Table 11. Cost of delivered energy in England with 2005 data (modified from The Log Pile Website, 2007).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>$ per kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0.053 to 0.103</td>
</tr>
<tr>
<td>Heating Oil (in condensing boiler)</td>
<td>0.057&lt;sup&gt;(1)&lt;/sup&gt;</td>
</tr>
<tr>
<td>LPG (in condensing boiler)</td>
<td>0.064&lt;sup&gt;(2)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Coal (anthracite grains)</td>
<td>0.041&lt;sup&gt;(3)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0.038</td>
</tr>
<tr>
<td>Logs in Stove</td>
<td>0 to 0.069&lt;sup&gt;(4)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Wood Chip</td>
<td>0.020 to 0.029&lt;sup&gt;(5)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Wood Pellets</td>
<td>0.041 to 0.048&lt;sup&gt;(6)&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>(1)</sup> $0.48/L;  <sup>(2)</sup> $0.41/L;  <sup>(3)</sup> $251.87/ton;  <sup>(4)</sup> $204.00/ton;  <sup>(5)</sup> $61.20/ton (25% moisture), and $81.60/ton (30% moisture);  <sup>(6)</sup> $177.00/ton and $238.00/ton.

The Pellet Fuels Institute (PFI, 2007) has established fuel standards that must be met by pellet mills in US. The Institute recommends that manufacturers conduct both in-plant and independent laboratory tests of their product on a regular basis. PFI-graded fuel must meet tests for:

- **Density**: consistent hardness and energy content (minimum 40 pounds/cubic foot).
- **Dimensions**: length (1 ½” maximum) and diameter (1/4” x 5 1/16”) to assure predictable fuel amounts and to prevent jamming.
- **Fines**: limited amount of sawdust from pellet breakdown to avoid dust while loading and problems with pellet flow during operation (amount of fines passing through 1/8” screen no more than .5 percent by weight).
- **Chlorides**: limited salt content (no more than 300 parts per million) to avoid stove and vent rusting.
- **Ash content**: important factor in maintenance frequency.

Pellet mills produce two grades of fuel – Premium and Standard. The only difference between the two is ash content. Standard grade fuel is usually up to 3% ash content, while premium grade is less than 1 percent. This difference is a result of the pellet contents. Standard pellets are derived from materials that produce more residual ash, such as tree bark or agricultural residues. Premium pellets are usually produced from hardwood or softwood sawdust containing no tree bark. Premium pellets make up 95 percent of current pellet production and can be burned in all appliances. Standard pellets should only be burned in appliances designed to burn the higher ash content pellets.
5. BIOREFINERY

Gasification technology enables low-quality solid fuels like biomass to be converted with low pollution into a fuel gas (synthesis gas or “syngas”) consisting largely of hydrogen (H2) and carbon monoxide (CO). Syngas can be burned cleanly and efficiently in a gas turbine to generate electricity. It can be passed over appropriate catalysts to synthesize clean liquid transportation fuels or chemicals. It can also be converted efficiently into pure H2 fuel. While most pulp and paper manufacturing facilities in the United States today do not export electricity and none export transportation fuels, their established infrastructure for collecting and processing biomass resources provides a strong foundation for future gasification-based “biorefineries” that might produce a variety of renewable fuels, electricity, and chemicals in conjunction with pulp and paper products (Figure 20).

Figure 20. Future “biorefinery” concept based at a pulp and paper manufacturing facility (Larson et al., 2006)

Larson et al. (2006) did a substantial study about the possibilities of such technology, and the potential gain as a result of replacing the aging fleet of Tomlinson recovery boilers used today to recover energy and pulping chemicals from black liquor. The majority of Tomlinson boilers operating in the United States were built beginning in the late 1960s through the 1970s. With serviceable lifetimes of 30 to 40 years, the Tomlinson fleet began undergoing a wave of life-extension rebuilds in the mid-1980s (Figure 21). Within the next 10 to 20 years, rebuilt boilers will be approaching the age at which they will need to be replaced, the capital investment for which at a typical mill is between $100
and $200 million. Concerted efforts are ongoing in the United States and Sweden to develop commercial black liquor gasification technologies.

Figure 21. Age distribution of Tomlinson recovery boilers in the United States.

Compared to installing a new Tomlinson power/recovery system, a biorefinery would require larger capital investment. However, because the biorefinery would have higher energy efficiencies, lower air emissions, and a more diverse product slate (including transportation fuel), the internal rates of return (IRR) on the incremental capital investments would be attractive under many circumstances, between 14% and 18%. In addition to the economic benefits to kraft pulp/paper producers, biorefineries widely implemented at pulp mills in the U.S. would result in nationally-significant liquid fuel production levels, petroleum savings, greenhouse gas emissions reductions, and criteria-pollutant reductions. A fully-developed pulpmill biorefinery industry could be double or more the size of the current corn-ethanol industry in the United States in terms of annual liquid fuel production. Forest biomass resources are sufficient in the United States to sustainably support such a scale of forest biorefining in addition to the projected growth in pulp and paper production (Larson et al., 2006).

At the end, the pulp and paper industry could diversified its products, utilizing forestry biomass, already a well-known feedstock, to reach another potential market with good growing perspectives (Figure 22).
6. HARVESTING SMALL TREES AND FOREST RESIDUES

There are three main logging methods in the USA: whole-tree, tree-length and cut-to-length systems (Figure 23). McCary (1991) reported that, in 1986, the main logging systems were whole-tree and tree-length, being responsible by 94% of the total transported wood. According to Leinonen (2004), the main method is still the whole-tree method, with a share of 80%. The share of cut-to-length method is 15% and the share of tree-length method is 5%.

In the whole-tree logging method the trees are felled at the stump and skidded beside the road for delimbing and/or processing and stocking. In tree-length logging method trees are felled, delimbed and topped at the stump and the stems are transported to the landing or roadside. In both methods the cross-cutting of the stems takes place at the landing or at the mill. In cut-to-length logging method the trees are felled, delimbed and cross-cut at the stump and the products are hauled to the roadside where they are stocked.

These logging methods harvest forests where wood volume varies from about 1 250 cubic feet per acre (88 m³/ha) in South region to about 2 500 cubic feet per acre (175 m³/ha) in the West region. In the North region the volume is about 1 400 cubic feet per acre (98 m³/ha). If we assume that the average dry wood density (29.6 lb/cubic feet, 473 kg/m³) is valid, the volume (stem mass) on timberland varies from 18.5 dry short tons per acre (South) to 37 dry short tons per acre (West) (USDA Forest Service, 2002, apud Leinonen, 2004).

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Figure 22. Markets and values for potential biorefinery products (Larson et al., 2006)
6.1. Whole-Tree Method

The whole-tree method, sometimes called full-tree method, uses a feller-buncher to fell and bunch timber, which is then transported to landing or roadside by a skidder, generally a rubber-tired grapple skidder, where processing equipment such as delimiters, slashers and whole tree chippers can prepare the logs to the final transportation. General advantages of whole-tree harvesting systems are (Leinonen, 2004):

- It is suitable for thinning and regeneration fellings,
- it can efficiently handle a variety of tree sizes,
- it is well suited for operations on steep slopes,
- the individual machines are mechanically simpler, which leads to less down time and higher mechanical availability, requires less skilled operators, less training and quicker attainment of maximum productivity,
- investment and operating costs are generally lowest on a per unit basis and
- because less labor is required per unit of production, overall production levels are high.
6.2. Tree-Length Method

In tree-length logging trees are felled and delimbed at the stump, and the stems are transported to the landing or roadside. The slash is distributed over the harvesting site. In softwoods, trees can be topped down to 2 in (5 cm) top. However, topping generally occurs at a 2.8 in (7 cm) to 3.9 in (10 cm) top. Trees are most often skidded to roadside with grapple skidders. The tree-lengths are bucked to pulpwood and logs at roadside, or can be left as tree-lengths for tree-length hauling to the mill. The tree-length method is most applicable to final felling, and can be used in partial cutting (Pulkki 2002). The tree-length system consists of chain saw fellers or feller bunchers, delimiters/toppers, skidders and slashers. General advantages of this method are much the same as for full-tree systems with the following additional advantages (Leinonen, 2004):

- Limbs and tops are left in the stump area, reducing nutrient removal,
- it is well-suited to clearcutting and
- it may be applied during partial cutting where skid trails are wide and straight enough because trees are delimbed and topped at the stump.

6.3. Cut-to-Length Method

In this system, the trees are felled and processed at the stump into defined log lengths by a harvester machine, and then transported to roadside on a forwarder, a machine that carries rather than drags wood. General advantages of the CTL system are:

- It is suitable for thinning and generation fellings,
- it can work efficiently in small tracts because there are only two machines to move between stands,
- minimal landing space is required,
- it is well-suited to thinning because it processes the harvested trees to shortwood lengths at the stump, minimizing damage to the residual stand and reducing nutrient removal,
- skid trails do not have to be created and the trails used can be narrow and meandering,
- the equipment work well in wet areas and on sensitive sites because of its capability to work on a slash mat it produces as it moves through the stand,
- forwarders can work economically over longer distances because of the longer loads they can carry, reducing the needed road network, and
- the system facilitates product sorting and merchandising (Leinonen, 2004).
6.4. Harvesting Small Trees

Conventional forestry equipments and systems are been used in the U.S. to harvest small trees. These operations are highly mechanized with the most common utilizing feller/bunchers, grapple skidders, a chain flail delimer/debarker/chipper and chip vans. Another replaces the flail/chipper and vans with irongate delimers, log trucks and a drum debarker. But, those machines sometimes are not economical when used in thinning systems, where the number of trees per area is high, but the percentage of the volume of trees is low. Another problem is the economical situation of the logging businesses in US. According to Stuart et al. (2005), logging costs have increased 35% over the period 1995-2004, but prices paid for logging services have decreased by 10%. There are also economic differences according to the harvest system utilized. Hartsough et al. (1997) found that stump-to-mill costs for CTL system were about 25 percent higher than for a whole-tree system in a plantation, and 50 percent higher in a natural stand.

A study done by Watson et al. (1986) tested two harvesting methods for utilization of understory biomass against a conventional harvesting method, all of them using feller-buncher and skidder on pine plantation and natural stand. The conventional harvesting method tested removed all pine 6 inches DBH and larger and hardwood sawlogs as tree length logs. The two intensive harvesting methods were a one-pass and a two-pass method. In the one-pass method, all material 1 inch DBH and larger was simultaneously harvested. Pines 1 to 6 inches DBH and hardwoods 11 inches DBH and less were chipped for energy wood and all other stems were logged tree length. With the two-pass method, the energy wood was harvested in a first pass through the stand, and the commercial size wood being removed as tree length logs was harvested in a second pass. The conventional harvesting system recovery averaged 52 percent of the standing biomass while the one-pass and two-pass methods recovery averaged 85 percent and 76 percent of the standing biomass, respectively. The one-pass method did not recover as much of the total stand as roundwood, because the tops being sent to the chipper included more of the bole to facilitate feeding the chipper. In the two-pass system, the felling costs for the energy wood were significantly higher, but there were no significant differences in skidding costs among the treatments in the plantations. It demonstrates that skidding costs do not change by stem size if the feller-bunchers can build full-capacity loads for the skidders. The conventional system had an average harvesting cost of $8.75 per green ton onto the log truck while the one-pass and two-pass methods had average costs onto log trucks and chip vans of $7.60 and $8.85 per green ton.

A one-pass and two-pass methods were also evaluated by Miller et al. (1985) in slash pine plantations, ranged in age from 17 to 23 years, with an average of 27 tons per acre of energywood and 32 tons per acre of pulpwood. The feller-buncher was the only machine that was significantly affected by the tonnage of energywood present on the two-pass blocks. As the energywood tonnage decreased, the feller-buncher productivity decreased. The one-pass system had lower costs per ton and utilized more of the energywood than the two-pass system. But, the two-pass system has the benefit of allowing the felled energywood to dry, thus increasing the BTU value.
Hartsough et al. (1994) studied three harvesting systems for thinning pine plantations and naturally regenerated stands, producing small sawlogs and fuel chips. The whole tree system consisted of a feller-buncher, skidder, stroke processor (Figure 24), loader and chipper. The cut-to-length system included a harvester, forwarder, loader and chipper. A hybrid system combined a feller-buncher and harvester to produce bunches of small whole trees for fuel, and bunches of long delimbed sawlogs. The cut-to-length system had higher costs per unit of material and yielded less fuel than the other systems, but damaged fewer trees in the natural stands than the other systems. Nevertheless, damage levels were low for all systems.

Figure 24. Treeking PowerStroke processor head (Photo: Treeking)

A cut-to-length (CTL) system, consisting of a harvester and a forwarder, may be an option to use when fuel prices do not cover the costs of comminution and transport the residues, leaving them on the site. Hartsough and Cooper (1999) tested a CTL system, consisting of a Bell TH120 harvester, a Bell T12B 12-ton forwarder, and a Morbark 27 chipper, to clearcut a 7-year-old plantation of *Eucalyptus viminalis*, with 1225 stems per hectare and average trees with 5.62 in. (14.3 cm) DBH and 3.31 ft$^3$ (0.094 m$^3$) (inside bark) volume. Production rates are shown in Figure 25. For trees in the 5- to 11-inch DBH range, a reasonably balanced system would include three harvesters, two forwarders, and one chipper. The conclusion was that system may be cost competitive with whole-tree systems.
With the objective to implement fuel reduction treatment on the Coconino National Forest in Arizona, Klepac et al. (2006) evaluated a cut-to-length system comprised of a Timberjack 1270 harvester and Timberjack 1010B 10-ton forwarder. The prescriptions called for removal of 105 trees per acre of trees less than 16 inches DBH, with a removed volume of 3.98 hundred cubic feet (11.3 m$^3$) per acre, for one stand, and to remove 450 trees per acre with a 56 percent reduction in basal area, a removed volume of 8.03 hundred cubic feet (22.7 m$^3$) per acre, for the other stand. The harvester produced 10.31 m$^3$/PMH while harvesting sawlogs and 0.93 m$^3$/PMH while harvesting biomass. Forwarder productivity averaged 19.54 m$^3$/PMH while transporting sawlogs and 4.53 m$^3$/PMH while transporting biomass. The final conclusion was about the inefficiency of using a single-grip harvester to handle small trees for a biomass product.

Economics is a central issue in choosing a harvesting system, and depends on several site-specific factors such as values of delivered products, transportation distances, tree sizes, topographic conditions etc. There are some general trends related to the systems, like harvester-forwarder systems are generally more expensive per unit harvested than feller-buncher/skidder systems. Systems that involve fewer pieces of equipment require less capital, fewer people and have lower move-in costs than other options. Forwarding eliminates the log breakage that results from skidding, especially of long whole trees (Table 12).

A simulation model was used in New Zealand to identify promising delivery systems (including harvesting, storage, transportation and processing) of logging residues to an energy plant and the associated costs. The cheapest system identified for all three sites considered was to chip the residues in the power plant, after being forwarded to landing, stored there for 3 months, and transported to power plant by truck. The cheapest option tended to be the simplest system because each time the material was handled, extra costs were added (Hall et al., 2001).
Table 12. Summary of selection criteria for the harvesting systems (Hartsough et al., 1995)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost per unit Volume</td>
<td>Lower</td>
<td>Lower</td>
<td>Intermediate</td>
<td>Higher, especially for fuel</td>
<td>Higher</td>
</tr>
<tr>
<td>Capital cost</td>
<td>Intermediate</td>
<td>Higher</td>
<td>Higher</td>
<td>Intermediate</td>
<td>Lower</td>
</tr>
<tr>
<td>Harvest unit Volume</td>
<td>High chippable volume and percentage required</td>
<td>High total and chippable volume required</td>
<td>High total and chippable volume required</td>
<td>High chippable volume required</td>
<td>Can be low</td>
</tr>
<tr>
<td>Product considerations</td>
<td>Can produce long logs, limited to low % of sawlogs</td>
<td>Can produce long logs, maximum fuel recovery</td>
<td>Can produce long logs, low level of sawlog breakage, high fuel recovery</td>
<td>Short logs only, less fuel produced no sawlog breakage during transport</td>
<td>Short logs only, no sawlog breakage during transport</td>
</tr>
<tr>
<td>Tree size Limitations</td>
<td>F/B diam limit</td>
<td>F/B diam limit</td>
<td>F/B diam limit, harvester diam &amp; branch size limits</td>
<td>Harvester diam &amp; branch size limits</td>
<td>Harvester diam &amp; branch size limits</td>
</tr>
<tr>
<td>Wood Extraction Distance</td>
<td>Distance impacts skidding cost</td>
<td>Distance impacts skidding cost</td>
<td>Distance impacts skidding cost</td>
<td>Less sensitive to distance</td>
<td>Less sensitive to distance</td>
</tr>
<tr>
<td>Roading considerations</td>
<td>Need large radius curves</td>
<td>Need large radius curves</td>
<td>Need large radius curves</td>
<td>Low roading density, need large radius curves</td>
<td>Low roading density</td>
</tr>
<tr>
<td>Slope limits</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
<td>30%</td>
<td>30%</td>
</tr>
<tr>
<td>Soil strength requirements</td>
<td>Intermediate</td>
<td>Intermediate</td>
<td>Intermediate</td>
<td>Less than for skidders</td>
<td>Less than for skidders</td>
</tr>
<tr>
<td>Soil surface disturbance</td>
<td>Intermediate to High</td>
<td>Intermediate to High</td>
<td>Intermediate to High</td>
<td>Minimal</td>
<td>Minimal</td>
</tr>
<tr>
<td>Damage to Reserve stand</td>
<td>Low to high</td>
<td>Low to high</td>
<td>Low to intermediate</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Residual fuel Loading</td>
<td>Least</td>
<td>Least</td>
<td>Very low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Residues at Landing</td>
<td>Can be substantial</td>
<td>Negligible</td>
<td>Negligible</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td>Visual impact</td>
<td>Low to intermediate</td>
<td>Low to intermediate</td>
<td>Low to intermediate</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

Brunberg and Svenson (1990) considered the multitree-handling (MTH) as a good solution to achieve higher productivity with single-grip harvesters in thinning operation, without sacrificing the opportunities afforded by single-tree handling. Another line of development is the use of MTH processing following mechanized felling-bunching. But, this is going against the current trend in forestry to use fewer machines, and the drawback
that feller-bunchers are sensitive to terrain conditions. In a study with a Valmet 892/955 single-grip harvester, in a denser pine stand, a large proportion of the trees were thinned using MTH, with a sharp rise of 16-37% in productivity. The machine could work more quickly because of a reduction in boom manipulation and the fact that trees could be processed simultaneously. Productivity gains can be achieved when up to at least four trees can be handled at a time, although it is not often that such a high number can be achieved. As shown by the example in Figure 26, this number can really only be attained when the smallest trees are being handled. In the dense pine stand study, no fewer than 25% of the trees were felled in felling handling three trees at a time. In the more usual stand, the corresponding figure was 10%. The main time saving, however, was achieved when two trees instead of one tree were handled at a time. In the pine stand, the time taken per tree fell by the following amounts: 32% with two trees being handled, 40% with three, and 46% with four trees.

Figure 26. Time taken per tree in MTH felling and processing using single-grip harvester (Brunberg and Svenson, 1990).

After three tests conducted in Canada with the multi-stem harvester head Waratah HTH-470HD (Figure 27), mounted on a Timberjack 608L tracked carrier (2 sites) and on a Timberjack 1270B harvester (1 site), Gingras (2004) concluded that the ability to handle more than one stem at a time increased productivity by an average of 21 to 33% compared with harvesting similar stems one at a time. The average volume in the stands was 14 m$^3$/ha, and the machine productivity was 15.5 m$^3$/PMH. But, as mean diameter increases, the advantage offered by multi-stem processing decreases, being none around 20 cm DBH. Overall, the greater productivity of multi-tree handling compared with single-tree handling in small trees makes it an attractive concept for commercial thinning or other partial cuts.
Kärhä et al. (2005) evaluated a Naarva-Grip 1600-40, an energy wood felling, bunching and bucking head equipped with a multi-tree-processing function and three guillotine blades (Figure 28). The felling head can cut a 50 cm-thick tree bunch, in which the biggest individual stem is 32 cm in diameter. They concluded that the average density and volume of removal had the greatest effect on the productivity of felling-bunching work, and other factors (e.g. number of trees in the bunch, and the proportion of multi-tree processing) had no significant influence on productivity in their research. The authors also pointed that mechanized harvesting is expensive on sites where the average size of the stems to be removed is under 30 dm$^3$ and the energy wood volume is less than 30 m$^3$/ha.
Two Timberjack’s energy harvester heads, the 720 (Figure 29) and the 730 models, were tested by Spinelli et al. (2007) in three small tree resources of Europe, namely: Finnish young conifer forests, French hornbeam coppice and Italian sycamore plantations. The maximum cutting diameter of the TJ720 felling head is 20 cm and 30 cm for the TJ730. Depending on site characteristics, the energy harvester reached an average productivity between 4 and 8 green tons per net working hour. Best results were obtained in single-row plantations, where the machine could maneuver with ease.

A time study was done by McDonald and Stokes (1994) with a harvest system consisted of three HydroAx 411B feller-bunchers with 40 cm shears, two Timberjack 450B grapple skidders, and a Morbark model 30 (76 diameter disk, 600 kW) chipper. The equipment operated in 6-year-old, short-rotation sycamore plantations, with 7.6 cm diameter trees planted on a 1.5 x 3.0 m spacing, and a yield of 14.3 green t/ha/year. The feller-buncher productivity was 15.5 green t/PMH, the skidder was 37.5 green t/PMH, the chipper was 57 green t/PMH, and the final cost per green t was $8.71. When pilling 2 accumulations per bunch (apb), comparing to 4 apb (one skidder turn), the feller-buncher had higher productivity, but this gain was more than offset in loss of productivity for skidding.

A 216 kW biomass harvester, modified from a John Deere silage harvester, was developed and tested by Felker et al. (1999) to examine the productivity and cost of harvesting shrubs and small trees for energy purposes (Figure 30). While the harvester severed and chipped a few individual 20-cm basal diameter trees, the harvester was much more efficient harvesting dense stands of small trees that were less than 10-cm in basal diameter, reaching a production rate of 0.95 ha h⁻¹ with a fresh weight harvest production of 7050 kg h⁻¹. Using $70 h⁻¹ operating cost data for similar commercial equipment, they estimated an energy cost of $1.00 kJ⁻¹, concluding that an annual demand for about 12000 Mg of biomass at $9 per green Mg would be necessary to justify the purchase of the first harvester.
First thinnings are not economically feasible, most of the time, mainly because of harvesting costs. Kärhä et al. (2004) studied the productivity and cost of the four most widely used thinning harvesters in Finland. Those small and cheaper harvesters were: Nokka Profi (95 kW), Timberjack 770 (82 kW), Sampo-Rosenlew 1046X (73.5 kW) and Valtra Forest 120 (88 kW) (Figure 31). The productivity per operating hour (E₁₅ including delay times shorter than 15 minutes) of the thinning harvesters was found to be 5.6-10.3 m³/ E₁₅ (stem size 50-100 dm³) in first thinnings and 9.1-12.7 m³/ E₁₅ (100-150 m³) in second thinnings. The average wood removal was 52 m³/ha in the first thinnings and 58 m³/ha in the second thinnings. According to the authors, it would appear that thinning harvesters can operate at the same productivity level as medium-sized harvesters in thinnings and, consequently, they could be operated to achieve cutting costs lower than those of medium-sized harvesters.
Bolding (2002) incorporated a smaller chipper (250 HP engine) into a traditional cut-to-length harvest operation to remove traditional wood products and energywood. Energywood was felled but not processed by a Timbco T-415 harvester, and forwarded in full tree form to the chipper. The addition of the small chipper increased the utilization of the non-merchantable portion of merchantable stems, and reduced fire hazards, but the delivered cost of energywood was higher than the market rate for it.

A small Conehead 565 chipper was introduced to a mechanized tree-length system to also harvest tops, limbs, and understory biomass on a 33 year-old slash pine (P. elliottii) plantation. The system had a Tigercat 718 feller-buncher, a John Deere 640D grapple skidder, and a Prentice 280 loader with a pull-through delimber. Three treatments compared the conventional ground-based tree-length harvesting system (A), the addition of the Conehead chipper to chip all limbs and tops (B), and also the chipping of non-merchantable woody biomass of all species that were between one and four inches at DBH that could be harvested by the feller-buncher and skidder (C). Roundwood production averaged 65.8 tons per acre, and treatments B e C chip production were 3.8 tons per acre and 10.8 tons per acre, respectively. Both conventional logging and the chip treatments consumed an average of 0.43 gallons of diesel per ton of wood produced for felling, skidding, and loading activities, plus 0.40 gallons for chipping. Chips were produced from limbs and tops at costs ranging $11 per ton and up, and also pursuing understory for use in making chips was approximately $1 per ton more expensive. Cost projections suggested that the method of producing chips can be competitive if no more
than 10 loads of roundwood are harvested to produce a load of chips (Figure 32) (Westbrook Jr. et al., 2006).

Figure 32. Estimates of delivered chip costs for treatments B (limbs and tops) and C (limb/top/understory) as the number of loads of roundwood required to produce one load of chips varies (Westbrook Jr. et al., 2006)

A study from Baughman et al. (1990) incorporated a tub grinder (Barkbuster 1100) into an in-woods chipping operation to process flail delimber residue into energywood. The trial was conducted with the machine as a part of an integrated system of tree processing, but it is possible to follow the flail/chipping operation with the fuel machine as a separate function, which could be valuable on limited landing spaces. Production rates were acceptable to keep pace with the equipment mix, and processing turned the residues into a positive cash flow.

Watson et al. (1992) compared the costs of transportation, harvest operations, and woodyard handling and chipping between long wood operations and in-woods chipping operations. Costs favored the long wood method when processing larger stems from mature stands. When biomass utilization is considered, woodland chippers would be more favorable because they can more efficiently utilize small stems.

A case study was used by Gingras and Favreau (1996) to estimate delivered costs of roundwood and chips to primary wood-using industries, and to compare these costs with costs for various scenarios of integrated or second-pass biomass harvesting and delivery. Two site types were selected: a) boreal softwood, with dense stands, small tree size, long extraction distances and haul distances to the mill also lengthy; b) Acadian mixedwood, with larger stems and shorter extraction and haul distances. Three harvesting systems were compared:

**Full tree to roadside** (system 1) – the feller-buncher fells and bunches full trees destined for fiber production, while sorting out undersize and unmerchantable species into separate bunches. Grapple skidders bring the full-tree bunches to roadside, where a stroke delimber delims and tops the trees. The grapple skidder also skids the unmerchantable trees to roadside. A mobile full-tree chipper is used to process this material, plus the roadside debris from the delimbing operation (Figure 33).
The cut-to-length system integrated with full-tree chipping (system 2) – It incorporates mechanized felling with a two-way sawlog/pulpwood sort by the feller-buncher, and sawlog processing at the stump followed by roadside debarking and chipping of pulpwood. The sawlog-quality trees are delimbed and merchandized into sawlogs by a single-grip processor, which creates trailside piles of slash. The logs are brought to roadside by a forwarder and unloaded directly onto a trailer. Tops and material too small to produce sawlogs are placed on the pulpwood bunches by the processor. The pulpwood bunches are grapple skidded to roadside and processed by a chain flail delimber-debarker-chipper (DDC). Pulp-quality chips are blown directly into a B-train chip van. Biomass is produced during processing at the stump (delimming slash) and at the DDC (flail debris). A tub grinder comminutes the DDC debris in a continuous process, and loads the material directly into a B-train chip van. The forwarder retrieves delimming residues from the processor operation in the stump area and brings this additional material to the tub grinder (Figure 33).
Figure 33. Machines and material flow in system 2 (Gingras and Favreau, 1996).

**Cut-to-length (system 3)** – In the first pass, the harvester produces sawlogs and pulpwood. Residues are left on or beside the trails and the forwarder extracts the logs to roadside. Once the roundwood material has been extracted, the forwarder extracts the residues to roadside. A full-tree chipper then comminutes the material and blows it into a chip van (Figure 35).

System 3 was the simplest in terms of logistics, but presented high biomass costs and the highest roundwood costs. In system 2, biomass cost on the boreal site ($36.17/gmt – green metric ton) was cheaper than with the conventional module in system 1 ($41.15/gmt) because the tub grinder is cheaper to use than a mobile chipper, and the slash was more concentrated than in delimber piles. On the Acadian site, the high cost of forwarding slash to the grinder was not completely offset by the tub grinder’s lower operating cost versus the full-tree chipper, which made the biomass cost of this system ($28.31/gmt) less attractive than the traditional delimber system ($25.80/gmt). The factors that most affected forest biomass costs were the type of harvesting system, the transportation distances, the level of moisture in the residues and the utilization rates of the biomass comminution\(^1\) machines (Gingras and Favreau, 1996).

---

\(^1\) The reduction of a material into smaller particles (Pottie and Guimier, 1985).
Another valuable approach in this energy procurement process is the reduction of fuel consumption by forestry machines (Figure 36). Fuel consumption in Sweden (per cubic meter of timber harvested) has fallen with 30% since 1985: from 5.4 liters of diesel to just 3.7 liters today (Löfroth, 2006).

The current and estimated future (1996 to 2015) energy efficiency in the production and transportation of short-rotation forest (Salix) and logging residues in Sweden was analyzed by Börjesson (1996), as well as the change in energy efficiency resulting from a transition from fossil-fuel-based energy systems to biomass-based systems (Table 13). According to the author, new dedicated energy crops, such as Salix and energy grasses,
are assumed to have a large yield increase potential, mainly because of weed control, clonal adaptation and better disease resistance. Higher energy yields from logging residues of about 30% are assumed to occur due to improved harvesting technology together with decreased harvest losses, shorter rotation periods for the stands, and stands with higher productivity than today. In a biomass based energy system around 2015, it is assumed that fossil liquid fuels and natural gas (NG) are replaced by methanol and hydrogen produced through gasification from woody biomass, with conversion efficiencies of 60% and 65%, respectively. It was also assumed that the higher demand of nutrients from increased biomass yields to 20 to 30% will be satisfied by increased use of organic fertilizers, such as organic wastes and residues. Salix chips can be transported by truck about 250 km before the transportation energy is equal to the production energy. Corresponding distances for tractor, train and boat (coastal shipping) are about 100 km, 500 km and 1000 km, respectively. A transition from a fossil-fuel-based energy system to a CO₂-neutral biomass-based system around the year 2015 is estimated to increase the energy input in biomass production and transportation by about 30 to 45%, resulting in a decreased net energy output of about 4%.

Table 13. Energy yields, primary energy inputs, net energy yields, and energy output/input ratio for present production conditions (1996) and future production conditions (2015) for Salix and logging residues in Sweden (Börjesson, 1996)

<table>
<thead>
<tr>
<th>Biomass Resource</th>
<th>Year</th>
<th>Energy yield (GJ ha⁻¹ year⁻¹)</th>
<th>Primary energy input (GJ ha⁻¹ year⁻¹)</th>
<th>Net energy yield (GJ ha⁻¹ year⁻¹)</th>
<th>Energy output/input ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salix</td>
<td>1996</td>
<td>180</td>
<td>8.4</td>
<td>172</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>330</td>
<td>9.1</td>
<td>321 (317)</td>
<td>36 (26)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(12.1)</td>
</tr>
<tr>
<td>Logging residues</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After final felling</td>
<td>1996</td>
<td>5.4</td>
<td>0.21</td>
<td>5.19</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>7.9</td>
<td>0.21</td>
<td>7.69 (7.60)</td>
<td>38 (26)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.30)</td>
</tr>
<tr>
<td>After first thinning</td>
<td>1996</td>
<td>10</td>
<td>0.47</td>
<td>9.53</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>13</td>
<td>0.42</td>
<td>12.6 (12.4)</td>
<td>31 (21)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.61)</td>
</tr>
</tbody>
</table>

Comparing a Caterpillar 950F front-end loader (Figure 37) with a Caterpillar 528 grapple skidder, used to extract bunched whole trees to a landing in a short rotation Eucalyptus plantation, Spinelli and Hartsough (2001) concluded that the loader was 40–60% more productive than the grapple skidder, depending on extraction distance. On flat, solid terrains, the loader performed better than the skidder, extracting more wood and handling landing activities as well. The loader benefits from a much larger payload, which it can move over reasonably long distances at an acceptable speed, and also couples the advantage of forwarding versus skidding, i.e. reduced contamination. But, when the slope
gets steep or the ground soft, the loader is penalized by its high center of gravity and its low flotation. The loader is also more expensive than skidders and produces more soil compaction. Finally, the loader must be adapted to wood extraction, mainly with an appropriate guarding to protect both the machine and the operator.

6.5. Harvesting Forest Residues

Gan and Smith (2006) assessed the amount of logging residues and their potential for electricity generation and CO$_2$ emission displacement in all states in the USA. A minimum viable power plant capacity of 10MW was considered, and the annually recoverable logging residues in the USA were estimated at 13.9 million dry t from growing stock and 36.2 million dry t from both growing stock and other sources (net of wet rot or advanced dry rot and excluded old punky logs; consisted of material sound enough to chip; included downed dead and cull trees, tops above a 10.16 cm growing-stock top, and smaller than 12.7 cm d.b.h.). The recoverable residues from both growing stock and other sources could generate 67.5TWh electricity annually. This would displace 17.6 million t carbon emitted from coal-fueled power plants (about 3% of total carbon emissions from the US electricity sector in 1997) at a cost ranging from US$60 to 80 t$^{-1}$ C. The authors considered some constraints in logging residue procurement, like the low spatial distribution density of some logging residues, and accessibility constraints and loss in the procurement process. They imposed a minimum spatial density constraint and assumed that only a fraction of the residues that meet the minimum spatial density requirement could be recovered. They determined the minimum required spatial density ($M_{\text{min}}$) of logging residues with the following formula:

$$
M_{\text{min}} = 0.4669 \frac{n \tau^2 P_{\text{min}}}{\phi R^2},
$$

(1)
where \( P_{\text{min}} \) is the minimum viable power plant scale (dry t day\(^{-1}\)); \( \tau \) the tortuosity factor, i.e. ratio of actual travel distance to line of sight distance; \( n \) the number of "slices" to complete a circular geometry (assuming a "pie slice" shape for the harvest area with the power plant at the apex); \( \phi \) the fraction of timberland in the area; and \( \bar{R} \) the average biomass delivery distance (km). They postulated the energy content of logging residues to be 19.19 GJ dry t\(^{-1}\) and the energy efficiency of the power plant to be 35%, and set \( \tau = 1.35, \, n = 1, \, \phi = 0.65 \). Equation (1) also implied that the plant would operate for 330 days annually (i.e. capacity factor = 0.904). The minimum required spatial density was then compared with the spatial density (\( M \)) of logging residues for each state calculated by:

\[
M = \eta \, \frac{LR}{A},
\]

(2)

where LR is the amount of logging residues left at harvest sites at the state level; \( \eta \) the recovery rate of logging residues (assumed 70%); and \( A \) the total timberland area for each state. In computing the biomass spatial distribution density, the authors assumed that logging residues were evenly distributed throughout the whole timberland area in a given state. If \( M < M_{\text{min}} \), it would not be feasible to recover logging residues for electricity production in the specific state. Otherwise, it was considered feasible, and the amount of recoverable logging residues in that state was computed by \( \eta \, LR \).

Another study done by Gan and Smith (in press) evaluated the co-benefits associated with the utilization of logging residues for bioenergy production in the eastern Texas, with 48,000 km\(^2\) of timberlands. Annual average logging residues in eastern Texas were estimated at 1.3 million dry tons. The authors assumed a 70% biomass procurement rate, and concluded that these logging residues, if used for electricity production, would displace about 2.44 million tons of CO\(_2\) (1.6% of CO\(_2\) emissions from coal-fueled electricity production in the state). This amount would valued about $9.0 million at the CO\(_2\) price traded at the Chicago Climate Exchange (3.65 $ t\(^{-1}\) CO\(_2\), May 2006), accounting for about 2% of the stumpage value. In addition, removing logging residues would save $200-250/ha in site preparation costs. The most important social impact would be the 260 new jobs to the logging industry in the 43 counties, with an additional 300 jobs created in other sectors due to the indirect and induced impacts. Moreover, electricity generation and distribution would generate another 150 jobs directly and 780 employment opportunities overall. Together, residue procurement and power generation would generate nearly 1,340 jobs, accounting for almost one third of the total current employment in the logging sector in the study region.

It is also important to know the properties of the logging residues. According to Hakkila (1998), branches, compared to the pure stem wood of pine (\( P\)inus \( s\)yl\( v\)estris) and spruce (\( P\)icea \( a\)bies), have the following characteristics:

- high bark content,
- the share of lignin is high and the share of cellulose low, and also have more terpenes, tannins, resins, waxes and fatty substances, thus increasing the heating value compared to stem wood,
• higher content of mineral substances or ash, especially in the needles, which lowers the heating value and may cause extra handling costs,

• denser than stem wood substances, which means that the heating value is higher than in stem wood,

• lower moisture content.

Alakangas et al. (1999, apud Kallio and Leinonen, 2005) described the advantages and disadvantages of harvest logging residues, in terms of forestry aspects:

ADVANTAGES

• nutrient leaching to waterways is decreased,

• soil preparation can be accomplished with less radical means,

• more natural develop in regeneration areas,

• because planting can be done earlier, regeneration areas are not covered with grass and there is less need for fighting against grass,

• planting is easier,

• forest regeneration costs less, is faster and results are expected to be better.

DISADVANTAGES

• organic material is removed from the nutrient cycle,

• the amount of humus protecting the soil is decreased,

• some nutrients are removed from the ecosystem,

• risk of acidification is increased and

• danger of growth losses.

To reduce the impact of logging residue recovery in Swedish forests, in terms of nutrient exportation, on average, about 70% of the branches and 30% of the needles are harvested (Börjesson, 2000).

Moisture content is an important wood fuel characteristic and can be measured on a green or dry basis. The maximum moisture content permissible for wood to be used as a fuel is in the range of 65 to 68 percent. Above this moisture content, the energy required to evaporate the moisture is greater than the energy in the dry matter of wood, and combustion cannot be sustained without a supply of external energy. Vaporization consumes 0.7 kWh heat energy per kilogram of water. If the moisture content of fresh softwood is reduced from 55 % to 40 %, the initial amount of water is reduced by half, and the effective heating value increases 8 % (Hakkila, 2004).

A special paper (WalkiWisa), on a 4 meters wide roll format, can be used to avoid rain and snow to wet the energy wood piles (Figure 38). Covering operation can be done using forest machine crane, costing 0.35 – 0.5 €/MWh, with paper representing 80% of the costs and work 20%. This alternative reduces moisture content of full trees on average 6% (5 –8%), residue bundles on 9%, and results better with logging residues (10-
15%). About 5% reduction in moisture covers the covering costs. At the end of storage period, paper is chipped with residues (Tahvanainen and Asikainen, 2006).

Figure 38. Covering of logging residue piles with special paper (WalkiWisa) to avoid rain and snow to wet them (Tahvanainen and Asikainen, 2006).

For all systems, excessive fuel moisture can cause corrosion and blockages of the fuel handling and feed system, and a reduction in combustion efficiency. Wood contains acids, and with sufficient moisture, can be quite corrosive (Badger, 2002).

Forest residues include low-value materials resulting from harvesting, thinning, and land-clearing operations for replanting from commercial logging and silvicultural operations. Wood waste harvested during commercial logging and silvicultural operations may include tops, limbs, bark, and whole trees. The whole trees may result from thinning, unmerchantable timber, or land clearing for replanting. The moisture content ranges from 40 to 60 percent, with higher moisture contents in actively growing plants and lower levels in dormant plants (Badger, 2002).

Chipping is the primary method for harvesting forest residues for fuel. This process economically converts low quality wood like rough, rotten and salvageable trees, logging residues and excess growth into easily handled wood fuel. Wood chips are produced at the logging site by running unmerchantable timber through a disk chipper. The chips, which are nominally 25 mm by 25 mm by 6 mm, are blown into a trailer for transport to the wood energy facility. Most leaves and dirt debris are removed from the chips by differences in particle density when the chips are blown into the transport trailer (Badger, 2002).

Three types of chips are commonly produced: whole-tree chips produced primarily from unmerchantable timber, round-wood chips, and clean chips. Whole-tree chips are made in the forest by feeding the entire tree (trunks, limbs and branches) into the chipper. Round-
wood chips are made from tree trunks, after the limbs and branches have been removed. Clean chips are made from tree trunks that have had their bark removed, and are usually sold for pulp markets. Clean chips, which are bark free, typically have ash contents of less than 0.05 percent. Since bark has a high ash content, which may be augmented by soil particles, whole-tree and round-wood chips have higher ash contents, typically in the range of approximately one percent (Badger, 2002).

In the production of whole-tree chips, small branches and limbs are not reduced to sizes comparable with standard chips. Long slivers and splinters may become mixed with the wood chips and may jam material handling equipment. For this reason, it is recommended that whole-tree chips be screened before they are introduced into a wood energy handling system. Round-wood and clean chips are more consistent in size and may not require screening (Badger, 2002).

The recovery enhancing effect of three single-grip harvester work techniques on the productivity of logging residue recovery for energy was studied by Nurmi (2007). The three harvesting methods used were: $M_1$) felling and delimbing on one side of the strip road; $M_2$) felling and delimbing on both sides of the strip road; $M_C$) felling and delimbing in a conventional manner, where felling is done from one side of the machine, and delimbing and bucking take place in front of the machine over the strip road (Figure 39). Roundwood harvest was carried out with a single-grip harvester in a Norway spruce ($P. abies$) stand, and the residue recovery was carried out with a heavy Kockums 850 forwarder. Its nominal weight was 13,500 kg and had a maximum load rating of 12,000 kg. The load space had been lengthened by 80 cm to accommodate a larger, 22m$^3$ load space. Harvesting method, forwarding distance, load weight, driving speed and the residue density are among the major factors affecting forwarding productivity. The load weight was a more significant variable than the forwarding distance, and the author concluded that the size of load space and the carrying capacity of the forwarder is of vital importance when forwarding logging residues. The residue yield was also important to consider, and was higher with $M_1$ (14.4%) and $M_2$ (34.8%) alternative methods compared to the conventional one. Grasping, collection phase and the whole procurement operation were more effective when the harvester operator had used either one of the two alternative methods where residues are accumulated in heaps along the strip road.
Figure 39. Single-grip harvester work methods: \( M_1 \) felling and delimbing on one side of the strip road; \( M_2 \) felling and delimbing on both sides of the strip road; \( M_C \) felling and delimbing in a conventional manner (Nurmi, 2007).

### 6.5.1. Energy Production Process

The fuel preparation steps must change the characteristics inherent in the feedstocks into the characteristics needed for the conversion device, thus the feedstock requirements for the conversion device must be known. Badger (2002) discussed about three conversion devices: direct combustion, gasification, and small modular biomass (SMB) systems.

*Direct combustion systems* commonly used for combustion of biomass fuels can be classified into pile, suspension, and fluidized bed combustion (FBC) systems. *Pile combustion systems* burn the wood fuel in either a heaped pile supported on a grate (used for smaller scale systems) which are horizontal or inclined, or in a thinly spread pile spread across a grate which may be traveling or stationary.
Pile burners are noted for being relatively simple to design, low capital and operating costs, ability to take a fairly wide range of wood particles and moisture contents, and difficulty to control due to the large mass of burning fuel. Moisture contents up to 65 percent can be burned in pile burners. Minimum particle sizes depend on the grate openings while the maximum particle size depends on the fuel feed opening into the combustion chamber. In general, large chunks or stringy bark, or particles down to sawdust size may be used in these systems.

Underfeed stokers are another version of a pile burner. Underfeed stoker systems push fuel into the combustion chamber from beneath the burning pile. Usually an auger is used to push the fuel into the combustion chamber. Particles must be small enough to flow with the auger, and not too fine, stringy, or green to cause packing and blockage problems. The optimal particle size range is dependent on the auger size.

Suspension combustion systems are of two types, with both requiring fuel moisture contents less than 15 percent and uniform particle sizes with maximum dimensions less than 6 mm. Suspension burners include cyclonic burners and pneumatic spreader-stoker systems that burn fuel particles suspended in a turbulent air stream.

Fluidized bed combustion (FBC) systems burn the wood fuel on a high-temperature bed of finely divided inert material, such as sand, that is agitated by air blown from beneath the bed. Solid fuel is introduced into the chamber via an airlock, where the fuel particles burn while suspended in the bed. FBC systems are particularly suited for burning fuels that contain high levels of ash, or consist of irregularly shaped particles, or have high moisture contents. The sizing of fuel is important. Small particles can pass through the unit and may not be caught by the cyclone for recycling back to the bed. Too large of particles can be too heavy to float in the fluidized bed, and cause problems.

Thermochemical gasification of biomass fuels involves the use of heat to decompose a feedstock under oxygen-limiting conditions. Gasification removes ash, including most alkali metals, and with gas-cleanup, removes particulates from the fuel stream. The gaseous form facilitates its use in a wider range of energy applications than solid fuels. The most common types of gasifiers are upright and downdraft fixed bed systems and fluidized bed systems. Fixed bed gasifiers require fairly uniform particles of sufficient size to allow airflow through the bed. Standard 25 mm by 25 mm by 6 mm pulpwood chips have good physical dimensions for most gasifiers. Feedstock moisture contents of up to 20 percent moisture content are acceptable for gasification systems, and moisture contents in the range of 15-25 percent actually increase gas production due to the conversion of the hydrogen in the water. Fluidized bed gasifiers (FBG) work similarly to FBCs, except that oxygen in the gasification chamber is limited to minimize its combustion. Fuel requirements for FBGs are similar to FBCs. A major advantage of FBGs over fixed bed gasifiers is their ability to handle a wider variety of particle sizes and types of fuels at one time, and fuels with moisture contents up to 65 percent.

Small Modular Biomass (SMB) Systems refers to a broad range of biopower systems of 1-5 MWe in size. Generally, the feedstock requirements are highly dependent on the conversion technology, and the conversion technology is usually designed for a particular feedstock.
Table 14. Summary of wood fuel specifications by burner type (Badger, 2002)

<table>
<thead>
<tr>
<th>Device size range</th>
<th>Pile Burners (wet cells)</th>
<th>Thin-pile spreader stoker</th>
<th>Underfiring Stokers</th>
<th>Suspension cyclonic</th>
<th>Suspension, air Spreader-stoker</th>
<th>FBCs</th>
<th>Gasifiers, Fixed-bed</th>
<th>Gasifiers, FBG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applicable fuel type</td>
<td>Virtually any kind except wood flour</td>
<td>Sawdust, non-stringy bark, shavings, end cuts, chips and chip rejects, hog fuel</td>
<td>Sawdust, non-stringy bark, shavings, flour, sander dust, hog fuel</td>
<td>Virtually any kind except wood flour and stringy materials</td>
<td>Chips, hog fuel</td>
<td>Virtually any kind except wood flour and stringy materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle size</td>
<td>Limited by grate size and feed opening</td>
<td>6-50 mm</td>
<td>6-38 mm</td>
<td>6 mm max</td>
<td>6 mm max</td>
<td>50 mm max</td>
<td>6-100 mm</td>
<td>6-50 mm</td>
</tr>
<tr>
<td>Moisture content</td>
<td>&lt;65%</td>
<td>10-50%</td>
<td>10-30%</td>
<td>&lt;15%</td>
<td>10%</td>
<td>&lt;60%</td>
<td>&lt;20%</td>
<td>15-65%</td>
</tr>
</tbody>
</table>

6.5.2. Wood and forest residue processing

Residual trees, cull material, limbs, and tops must be reduced to a form that will allow for an easy and economically feasible form of removal, transport, and handling. The most common form of primary reduction is whole-tree chipping, but shredding, grinding, and chunking may also be used (Sirois and Stokes, 1985). When the trees or residual material are chipped, with limbs, tops, and bark attached, the chips have limited use for making paper pulp and composite panel products. Usually material with such high bark content is only suitable as energywood to produce electricity and steam. Clean chips for pulping can be produced in the woods by delimbing and debarking before chipping (Stokes and Sirois, 1989).

Chipping

Chippers are machines that cut or shear wood with high speed rotating knives against stationary anvils, to produce a material (chips) with relatively smooth surfaces and uniform shape and size. There are three basic types of chippers: disk, drum and V-drum (Pottie and Guimier, 1985). A disk chipper (Figure 40) is composed of knife blades inserted in a heavy disk which usually rotates at speeds between 400 and 600 rpm. Logs, whole trees or residues are fed endwise and are supported by a bed knife. As the wood comes in contact with the knife blades, pieces are sheared of and pass through the chip slots. The material is chipped across the grain at an angle of about 30°. Material can be fed horizontally with feed rolls or by gravity. Chips are either blown through a spout by centrifugal force and a fan on the rotating disk, or fall through the bottom of the chipper
Disk type chippers are commonly used to chip debarked logs or mill trimmings to produce pulp chips.

Figure 40. Disk chipper principle (Pottie and Guimier, 1985).

A drum chipper consists of a rotating drum fitted with knife assemblies on its surface. The wood is fed towards the drum where pieces are sheared off by the knives, usually against an anvil. The knives may be large and mounted parallel to the axis of the drum (Figure 41-a) or they may be small individual–chip knives mounted in a spiral around the drum (Figure 41-b). Once cut, the chips can exit into the inside of the drum through slots located in front of the knives or they can be temporarily accumulated in a “drum pocket” and discharged through a sizing screen. Drum chippers can be fed vertically, horizontally or at an angle. If fed vertically or at an angle, it usually relies on gravity to advance the wood. If fed horizontally the wood may be pulled in by the drum or, for more positive feed, feed rolls may be used (Pottie and Guimier, 1985).

Figure 41. Drum chipper principle: a) large knives mounted parallel to the axis of the drum; b) small knives mounted in a spiral around the drum (Pottie and Guimier, 1985).
A V-drum chipper combines drum and disk chipper designs (Figure 42). Two truncated conical drums equipped with knives are assembled on the same shaft and form an angle of about 90°. Logs or whole trees are fed horizontally or by gravity into the V formed by the two drums and perpendicularly to the rotation axis. Once cut, the chips pass through openings in the drums and fall onto a conveyor or are blown through a spout (Pottie and Guimier, 1985).

![Figure 42. V-drum chipper principle (Pottie and Guimier, 1985).](image)

There are two basic types of in-woods chippers: portable and mobile. Portable chippers are confined to the landing or deck area, where all the material to be processed is brought, usually by skidding and in the form of whole trees. Portable chippers (Figure 43) are generally high-production, high-cost machines and thus require highly efficient felling and skidding systems in order to utilize their capacity (Sirois and Stokes, 1985).

![Figure 43. Vermeer BC2000XL brush chipper capable to handle limbs and logs up to 20" (51 cm) in diameter](image)
Mobile chippers travel to the stump in order to process whole trees and residues, and are available in three types: chipper forwarders (Figure 44), chip harvesters and chip harvester forwarders. Chipper forwarders travel to the felled tree, self-load all usable material, chip it, and transport the resulting product for eventual unloading at the landing. Mobile chip harvesters are not only capable of loading and chipping, but they also fell the material to be processed utilizing a “swath-felling” technique. The resulting chips are not forwarded by the same machine, but are discharged into another vehicle for forwarding. Chip harvester forwarders accomplish all the tasks of the mobile chip harvester while also forwarding all chipped material to a convenient unloading point (Sirois and Stokes, 1985).

![Figure 44. Chipper forwarder model DPM (Photo: Demuth)](image)

**Grinding**

Grinders reduce particles in size by repeatedly pounding them into smaller and smaller pieces through a combination of tensile, shear and compressive forces. Nearly all grinders, including tub and horizontal feed grinders, rely on a hammermill as the pounding device. A hammermill has club-like projections - hammers - attached to a rapidly rotating drum (rotor). The high rotational speed (more than 1,000 revolutions per minute (rpm)) gives the hammers enough inertia to shred the material. As the drum rotates, the hammers spin rapidly and smash against the material trapped inside the hammermill chamber until the pieces are small enough to pass through the discharge screen or grate. To be effective, the material being ground has to be somewhat rigid and brittle, although the hammers will eventually pulverize most anything. Particles coming out of a grinder look ragged, broken and smashed. The particles encompass a wide range of shapes and sizes (smaller than the screen opening) (Goldstein and Diaz, 2005).

The rotary hopper or tub grinder is a method of primary size reduction, presenting lower cost and the ability to process a much wider variety of raw materials than chippers. It appears that grinding may prove more economically feasible than portable chippers for the reduction of tops, limbs, and other logging slash. This reduction can be carried on simultaneously with the harvest of sawlogs or pulpwood. Despite its many uses, the
lower production rate of present grinders, compared to chippers, could prove to be a drawback in some cases (Sirois and Stokes, 1985).

The rotary tub grinder begins processing when raw material is fed into the top of its cylindrical or sloping-sided hopper (Figure 45). The slow rotation of the hopper causes the material to move down into a large hammermill located in the stationary floor. After being “sheared-off” by the hammermill, cutters, the material passes into a chamber where it is ground against sizing screens, through which the final product is passed. This reduced material can be discharged pneumatically or by a belt elevator (Sirois and Stokes, 1985).

Forest residue chipping with tub grinder in Finland, utilizing a motor power between 400 to 750 kW, considered as medium-sized chipper, produced an output from 100 to 300 loose-m$^3$/h (Leinonen et al., 2007).

![Figure 45. Vermeer TG5000 tub grinder with 402.7 kW](image)

**Chunking**

According to Pottie and Guimier (1985) the definition of chunkwood is short, thick pieces of wood where the majority of particles are produced by a specific cutting action; they have length in the fiber direction of 5 to 25 cm, but constant for particular chunkwood comminutor, and variable cross-section areas ranging from about finger size up to entire discs equal in diameter to the material being reduced. The machine, originally a helical or spiral-head chipper, has evolved into an involuted disc chunker (Figure 44). Chunking requires less energy, produces a product suitable for energywood or other limited applications, and has lower air resistance, slightly lower dry-matter losses over time, and twice the complete burnout time (Stokes and Sirois, 1989; Danielsson, 1990). Chunking also offers other potential advantages over chipping or hogging like better storing and screening characteristics (Pottie and Guimier, 1985).
Hogs

Hogs are generally composed of high-speed rotating drums with rows of knives or hammers that can reduce even large material into chip-size pieces, with a wide variation in size and shape. Hogs have a 1200 rpm limit and most of them run in 700-900 rpm range (CWC, 1997). Screens are used to control particle size so that the unacceptable large pieces are sent back through the mill (Figure 47). Because of knife wear and breakage, hogs are extremely sensitive to dirty or contaminated material, making cleaning necessary when used with certain material sources (Sirois and Stokes, 1985).

Figure 47. The principle of a hammer mill hog (Hakkila, 1989, apud Naimi et al., 2006).
Hammermills

Hammermills are generally employed after hogging when a very finely ground fuel is needed, as with suspension burners. A hammermill (Figure 48) beats and grinds the fuel against a sizing screen until the material is able to pass through. Hammermills are very moisture sensitive and usually require that the moisture content be below 14 percent (Sirois and Stokes, 1985). They are typically horizontal shaft, swing-hammer types utilizing electric motors ranging from 75 to 220 kW that operate at high torque and high speed, up to 3600 rpm. They typically produce particle sizes in the range of 25-125 mm with a grinding rate of 20-55 tones/hour; however, they are limited to use with dry wood. Hammermills may employ different hammers and screens of different sizes and configurations, depending on wood input characteristics and final product desired (Donovan, 1994, apud Badger, 2002). In many articles they use the general name of hammermills for hogs too. Hammers in hammermills and hammer hogs can be fixed hammers or swing hammers. The swing hammers can accept more contaminated feed and they are easier to maintain in comparison with the fixed hammers that can get higher energy to the work piece (Naimi et al., 2006).

Figure 48. C-17 Williams hammermill model

Shredding

The term shredder is usually reserved for machines that tear particles apart (versus smash). The word “shear” is often added as an adjective, i.e., shear shredder. Compression forces are applied to a particle in offset planes to produce a shearing action. This machine uses one or more rotating shafts, each with a set of cutting disks or knives mounted closely together on the shaft(s) that sits in a chamber at the bottom of a feed hopper. As the shaft rotates, the cutting devices pull the material down through the small spaces between the cutting disks/knives and the surrounding chamber. Many shredders use a pair of counter rotating shafts that draw the material down, forcing the pieces out between the two shafts. Particles produced by shredders tend to have an elongated shape (Goldstein and Diaz, 2005).
A shredder consists of two shafts equipped with shredding disks counter rotating at low speed (usually < 50 rpm) (Figure 49). A hopper receives the material to be comminuted and feeds it to the shredding shafts. Feeding arms are used to push the material down. Residue caught between the shredding shafts is torn and crushed and falls on a conveyor.

![Figure 49. Shredder principle (Pottie and Guimier, 1985).](image)

It may also have a horizontal disk rotor mounted on a vertical shaft powered by a motor located at the base of the machine (Figure 50). Cutting knives pinned to the rotor extend radially under the centrifugal force but can swing back into the rotor disk when contacting tramp metal or rocks. The material is cut between the rotating knives and the fixed anvils which are bolted to the periphery of the casing. Material is gravity fed at the top and discharges horizontally on the side onto the conveyor belt. Vertical shaft shredders are particularly well suited for reducing bark (Pottie and Guimier, 1985).

![Figure 50. Vertical shaft shredder principle (Pottie and Guimier, 1985).](image)
Adaptable for use either at the logging site or at the burning site, shredding has the following advantages: a) lower energy requirements than hogs or hammermills, because shredders tear, break, and crush instead of just hammer, and thus are able to accomplish a similar size reduction with less applied energy at lower tool speeds; b) uniform finished product size; and c) less possibility of jamming and breakdown due to the inclusion of foreign objects (pieces of metal, rocks etc.) in the material being processed because of its high torque and low speed. This eliminates the need for a cleaning phase of the wood prior to size reduction (Sirois and Stokes, 1985).

![Figure 51. Artech MD Series low speed, high torque, dual shaft industrial shredder](image)

A summary of the reduction device, speed, feed stock, sensitivity to contaminants and the geometry of particles produced for different size reduction machineries is presented on Table 15. The pointed low sensitivity to contaminants by hammer hogs is different than the affirmative of Sirois and Stokes (1985) that hogs are extremely sensitive to dirty or contaminated material, because of knife wear and breakage.

### Table 15. Size reduction device, speed, feed stock, sensitivity to contaminants and the geometry of particles produced for different size reduction machineries (CWC, 1997, apud Naimi et al., 2006).

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Reduction device</th>
<th>Speed</th>
<th>Feedstock</th>
<th>Sensitivity to contaminants</th>
<th>Geometry of particles produces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disk chipper</td>
<td>Replacement knives</td>
<td>High</td>
<td>Whole log</td>
<td>High</td>
<td>Clean edge/two sided</td>
</tr>
<tr>
<td>Drum chipper</td>
<td>Replacement knives</td>
<td>High</td>
<td>Whole log</td>
<td>High</td>
<td>Clean edge/two sided</td>
</tr>
<tr>
<td>Swing hammer hogs</td>
<td>Swinging hammers</td>
<td>Moderate</td>
<td>Wood waste</td>
<td>Low</td>
<td>Coarse/multi-surface</td>
</tr>
<tr>
<td>Fixed hammer hogs</td>
<td>Fixed hammers</td>
<td>Moderate</td>
<td>Wood waste</td>
<td>Low</td>
<td>Coarse/multi-surface</td>
</tr>
<tr>
<td>Knife Hogs</td>
<td>Semi-sharp hammers</td>
<td>Moderate</td>
<td></td>
<td>Moderate</td>
<td>Semi-coarse</td>
</tr>
</tbody>
</table>
6.5.3. Forest Chip Production

According to Hakkila (2004), a forest chip production system consists of a sequence of individual operations performed to process biomass into commercial fuel and to transport it from source to plant. The main phases of chip procurement are purchase, cutting, off-road transport from stump to roadside, comminution, measurement, secondary transport from roadside to mill, and receiving and handling at the plant. The main methods used in Finland are included in that report, and they are: chipping at the roadside, at the terminal and at the mill. In minor scale is used chipping at the terrain.

Chipping at the roadside landing

The properties of logging residue influence the chipper and crusher efficiency. A logging residue chipper should have a long feeding table, which facilitates an even chipper load, avoiding peak stresses, and also needs to have forced feed but still be resistant to clogging. Alakangas et al. (1999) detail the specifications of a good logging residue chipper:

- high productivity,
- long feeding table,
- must have forced feed but be resistant to clogging,
- drum chippers are not as sensitive to impurities as disc chippers,
- drum chippers produce a more even quality of chips than crushers.

Disc chippers are best suited for whole trees. The feeding hole of a disc chipper is often too small for logging residue. Furthermore, logging residue chips made with a disc chipper contain large amounts of long splinters. This is why drum chippers are usually employed for chipping logging residue. They make it possible to produce more evenly sized chips than disc chippers or crushers. Drum chippers are also not as sensitive to impurities as disc chippers (Alakangas et al., 1999, apud Kallio and Leinonen, 2005).

The productivity of chipping is influenced by the raw material, the storage and working site arrangements and the specifications of the chipper and crushers. For chipping logging residue the productivity varies between 40 and 80 m$^3$ loose of logging residue chips/effective hour. Fresh logging residue is usually faster to be chipped than drier logging residue. A chipper operation analysis indicated that the chipper’s relative productivity is increased when the working site exceeds the limit of 400 m$^3$ loose of logging residue chips and the pile 200 m$^3$ loose of logging residue chips. The form of intermediate store, purity of raw material and moisture does effect in the productivity of chipping. Moisture of the forest residue has minor influence on the effectivity of the crusher (Kallio and Leinonen, 2005).

Limited available space and narrow roads on mountainous terrain are main constraints on chipping operations, requiring good planning and cooperation among yarding, chipping and transportation crews. One of the problems is chip discharge. Blowing the chip
directly into a truck is an alternative, saving space and additional loading costs, but also
requires very careful organization to avoid waiting times for chipper and truck. To avoid
the problem, one may discharge directly onto the ground, building up large heaps.
Besides, subsequent reloading into a truck may take less time than direct discharge -
especially if the chipper is comparably small. But, heaps take a lot of space, which may
be prohibitive at a yarder landing. Spinelli et al. (2001) reported data from 15 case studies
where in-woods chipping followed cable extraction (Table 16).

Table 16. Summary of chipping operations - cases in conjunction with cable yarding
(Spinelli et al., 2001)

<table>
<thead>
<tr>
<th>Stand type</th>
<th>Material</th>
<th>Average size (kg)</th>
<th>Layout</th>
<th>Machine</th>
<th>Power (kW)</th>
<th>Crew No.</th>
<th>Feed</th>
<th>gt/PMH*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coppice</td>
<td>Slash</td>
<td>21</td>
<td>stacked</td>
<td>Pezzolato</td>
<td>205</td>
<td>2</td>
<td>Crane</td>
<td>4.5</td>
</tr>
<tr>
<td>Coppice clear-cut</td>
<td>Slash</td>
<td>30</td>
<td>bunched</td>
<td>Bruks CT1200</td>
<td>313</td>
<td>1</td>
<td>Crane</td>
<td>7.6</td>
</tr>
<tr>
<td>Coppice</td>
<td>Logs</td>
<td>15</td>
<td>stacked</td>
<td>Pezzolato 300</td>
<td>205</td>
<td>1</td>
<td>Crane</td>
<td>10.8</td>
</tr>
<tr>
<td>Selection cut</td>
<td>Logs</td>
<td>125</td>
<td>loads</td>
<td>Eschlböck Biber 8</td>
<td>239</td>
<td>1</td>
<td>Crane</td>
<td>19.0</td>
</tr>
<tr>
<td>Thinning</td>
<td>Logs</td>
<td>65</td>
<td>stacked</td>
<td>Rudnick and Enners</td>
<td>328</td>
<td>1</td>
<td>Crane</td>
<td>20.5</td>
</tr>
<tr>
<td>Coppice clear-cut</td>
<td>Tops</td>
<td>60</td>
<td>stacked</td>
<td>Bruks CT1200</td>
<td>313</td>
<td>1</td>
<td>Crane</td>
<td>22.4</td>
</tr>
<tr>
<td>Coppice</td>
<td>Slash</td>
<td>8</td>
<td>loads</td>
<td>Morbark</td>
<td>45</td>
<td>2</td>
<td>Hand</td>
<td>1.0</td>
</tr>
<tr>
<td>Conversion cope</td>
<td>Whole</td>
<td>27</td>
<td>loads</td>
<td>Gandini</td>
<td>73</td>
<td>2</td>
<td>Hand</td>
<td>2.4</td>
</tr>
<tr>
<td>Coppice</td>
<td>Logs</td>
<td>2</td>
<td>stacked</td>
<td>Pezzolato</td>
<td>46</td>
<td>2</td>
<td>Hand</td>
<td>2.5</td>
</tr>
<tr>
<td>Coppice</td>
<td>Slash</td>
<td>13</td>
<td>loads</td>
<td>Pezzolato</td>
<td>46</td>
<td>2</td>
<td>Hand</td>
<td>2.8</td>
</tr>
<tr>
<td>Thinning</td>
<td>Tops</td>
<td>25</td>
<td>stacked</td>
<td>Pezzolato</td>
<td>224</td>
<td>2</td>
<td>Crane</td>
<td>4.8</td>
</tr>
<tr>
<td>Thinning</td>
<td>Tops</td>
<td>28</td>
<td>stacked</td>
<td>Pezzolato</td>
<td>224</td>
<td>2</td>
<td>Crane</td>
<td>5.5</td>
</tr>
<tr>
<td>Coppice</td>
<td>Logs</td>
<td>69</td>
<td>bunched</td>
<td>Morbark 550</td>
<td>232</td>
<td>1</td>
<td>Crane</td>
<td>8.5</td>
</tr>
<tr>
<td>Thinning</td>
<td>Tops</td>
<td>77</td>
<td>stacked</td>
<td>Pezzolato</td>
<td>224</td>
<td>2</td>
<td>Crane</td>
<td>12.9</td>
</tr>
</tbody>
</table>

* Green tons per Productive Machine Hour

Data of chipper productivity in relation to various raw material options is stated by
Stampfer and Kanzian (2006). In total, 118 hours (PSH15 – including breaks up to 15
minutes) of chipping were recorded, and a total of 9,246 m³ of chips was produced.
Chipping productivity from logging residues and roundwood varied between 52 and 134
m³/PSH15, respectively (Figure 52). Figure 52 also shows the increased potential with
reduced operational delays. The chipper spent 20% of the total work time for waiting on the truck. 90% of the waiting times ranged between 9 and 16 minutes, with an average of 12.6 per loaded truck.

Figure 52. Chipper productivity in relation to various raw material options with and without operational delays (Stampfer and Kanzian, 2006).

Mitchell (2005) made a review of a few residue processing production studies and concluded that direct comparisons are difficult, because the description of residues and methods of documenting productivity can vary widely (Table 17).

Table 17. Production and cost estimates for comminution of forest residues (Mitchell, 2005).

<table>
<thead>
<tr>
<th>Reference, Year</th>
<th>Communion Device</th>
<th>Type</th>
<th>Description of Forest Residues</th>
<th>Productivitya ($) (US$ 2002)</th>
<th>Cost (PMH) ($) (US$ 2002)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boldt, 2002</td>
<td>Bandit 1850 Whole Tree Chipper</td>
<td>M</td>
<td>Limbs and tops from merchantable pine and hardwood thinning; and non-merchantable trees 0.5 – 4.0 inches DBH.</td>
<td>20.24 ft³/cm³ (11.54 bdt³/m³)</td>
<td>$1.73/gt ($3.04/bdt³)</td>
</tr>
<tr>
<td>Asikainen and Pulliainen, 1998</td>
<td>Evolution 910R Drum Chipper</td>
<td>M</td>
<td>Logging residues from spruce-dominated final fellings in Finland</td>
<td>11.5 × 10³ kg/cm³ (dried mass)</td>
<td>$11.38/bdt³</td>
</tr>
<tr>
<td>Morbark, 1994</td>
<td>Morbark 60/36 Drum Chipper</td>
<td>M</td>
<td>Logging residues, piled tops and larger limbs, trees &lt;10-inches dbh</td>
<td>NA</td>
<td>$5.46/bdt³</td>
</tr>
</tbody>
</table>

a M = Mobile, S = Self-propelled
b PMH = Productive machine hour; SHM = Scheduled machine hour
b g = green tons
c bdt = bone dry ton
d conversions made by author for ‘00 to US(2002); PMH to PMH; and 10³ kg to tons (US-short).
In 1984, the Logging Residue Processor (LRP with 240 kW) (Figure 53) was developed by the Forest Engineering Research Institute of Canada (FERIC), including a Jeffrey 45WB hammer mill. Novak (1986) evaluated that machine processing spruce and jack pine roadside residues. The volume residues in the roadside piles was approximately 3500 m$^3$/ha and their bulk density was just over 200 kg/m$^3$. Approximately 80% of all the woody material was comprised of pieces no longer than 2 cm in diameter, and the moisture content (oven-dry bases) varied from 100% to 275%, depending on its location (depth) within the residue pile and material (woody or foliage). The tests results of the LRP demonstrated a potential productivity of 26 green tones per productivity machine hour (PMH).

A Maxigrinding 425 grinder (Figure 54) producing fuel chips from roadside delimbing residues was evaluated by Desrochers (1998). The grinder was powered by a 313 kW motor, and worked together with a Michigan L-90 front-end loader. The chips were dropped directly into the front-end loader’s scoop, and once the loader was full, it unloaded the chips directly into the chip vans. The average productivity was 8.7 oven-dry tones (odt) per PMH (including delays of less than 15 minutes), but could reach 11.3 odt/PMH using a chip blower to load the chips directly into the chip vans, avoiding the delays due to the front-end loader (23% of PMH). The Maxigrind did not appear to be an ideal machine for grinding delimbing residues, and its production cost was $20.63/odt.
Chipping at the standing

The terrain chipper must be suited for efficient chipping of logging residue so what when chipping is done on terrain the operator does not need to wait for the chipper to finish its work before loading the next bundle. For terrain chipping the productivity of the work at forest haulage of 200 m is 15 to 20 m³ loose/cross hour. In the case of terrain chipping the logging residue is mostly processed when it is still fresh. When chips are stored the moisture content decreases no more, but remains high, and dry matter losses will lower the profitability of storage (Laurila and Vesisenaho, 1997, apud Kallio and Leinonen, 2005).

Richardson (1986) provides information about two Bruks mobile off-road chip harvesters models (Figure 55), 1001 CT (approx 200-250 kW) and a prototype 800 CT (approx 145 kW), under different forestry systems conditions in Canada. The maximum log diameter for the 1001 CT model was 40 cm for softwood and 30 cm for other hardwood, and 30 cm for the 800 CT model. Long-term studies on the Bruks 1001 CT found productions data from 3.5 to 3.9 o.d.t./PMH. Short-term studies on the Bruks 800 CT model got productions from 2.9 to 4.4 o.d.t./PMH. The main comparisons between different systems considered in this report were: a) roadside chipping has higher productivity (but not necessarily lower costs) than off-road chipping; b) full-tree chipping is more productive than chipping logging residue; c) chipping logging residue, off-road, in conjunction with a forwarder or a shuttle has higher productivity (but not necessarily lower costs) than when working autonomously. The author details that the off-road chipping is applicable in areas where chipper travel distance is less than 300 m, using a forwarder-mounted transfer bin (shuttle) in greater distances. Where long extraction distances are involved, forwarders or skidders may be used to gather the biomass and carry it close to the chippers or to roadside, but skidded trees or logging slash may carry on sand and stones, causing rapid wear-and-tear to the knives. Important factors affecting the productivity of Bruks mobile chip harvesters included: operator skill, biomass density, extraction distance, felling pattern (e.g., manual non-directional, manual directional or feller-buncher), terrain conditions, species type and maintenance.
The grapple of the terrain chipper crane needs to be designed for logging residue, much like in forest haulage of logging residue (Figure 56). Using a fingered grapple significantly reduces the risk of introducing impurities into the chipper, but a wide grapple is not suited for terrain chipping because it is difficult to feed logging residue into the chipper.

The advantage of terrain chipping, compared to roadside chipping, is that less machinery is required for harvesting, which remarkably improves the organization of the work. Additionally, less space is required for terrain chipping than for roadside chipping, and the chipping and lorry transportation do not function as a hot chain, as in case of roadside chipping. Since the produced chips are immediately tipped on a container platform, the chips will be less contaminated with impurities than in the case of roadside chipping (Hakkila, 1989, apud Kallio and Leinonen, 2005).
The disadvantages of terrain chipping include a fairly poor off road capability and a difficulty of achieving a satisfactory chip quality throughout the year. The cost competitiveness of a terrain chipper is not very good for long distance forest haulage either. In addition, the chain of terrain chipping requires even storage space for the containers and a sufficient amount of containers depending on the long distance transportation (Hakkila, 1989, apud Kallio and Leinonen, 2005).

Researchers from North Carolina State University were studying a so-called bio-harvester, composed by a FTX 440 track carrier (440 HP) from Fecon, an Ahwi mulcher attachment, and an agricultural wagon (Figure 57). The objective of the machine was to harvest the underbrush material (D.B.H. < 8.0”), make chips, and blow them directly inside the wagon (Figure 58). Tests conducted on December 2007 showed the wagon inadequacy, in terms of size and structure, as also the specie influence, causing problems to cut the trees and process the chips (Figure 59). The presence of felled trees was also a problem, and the machine had a low mobility inside the stand. The chip load was dumped inside containers at the end of each cycle (Figure 60).

Figure 57. Bio-harvester with mulcher attachment (Left), and wagon (Right).

Figure 58. Chip production and discharge on wagon.
Chipping at the terminal

Chipping at a terminal is a compromise between comminution at a landing and at the plant. Biomass is hauled uncomminuted to the terminal for size reduction, and then transported to the plant as chips. The haulage distance is about 100-500 m to roadside landing while it is less than 10 km to fuel terminal. For the terrain haulage of forest residues Vapo Oy has developed an operation pattern where the farm tractor-driven HavuHukka trailer is used first for off-road transport from logging site to road and, subsequently, for on-road transport to a terminal (Figure 61) (Hakkila, 2004). The trailer has closed sides that compact logging residue. The sides are open during loading, and hydraulic cylinders press the sides in when the load is full. With the sides pressed in, the frame volume of the trailer is about 45 m³ with the capacity to contain 8-12 m³ of fresh logging residue. The maximum profitable distance between the forest terrains to a terminal is 10 km. The method enables for logging residue to be harvested at work sites smaller than usual if they are located close to the terminal.
Hydraulic compacting devices increase costs, so they are more suitable for bigger forest entrepreneurs. Figure 62 presents an agricultural tractor-based combination, in which the loading width of the trailer can be hydraulically adjusted from 2.0 m to 4.2 m. The capacity of the load increases from 15 m$^3$ to 30 m$^3$, respectively. The narrowing of the load space allows forest haulage across growing stands (Mutikainen, 1999, apud Kallio and Leinonen, 2005).

Another option is the Brush Transport System (BTS-1) (Figure 63), from Continental Biomass Industries, which is supposed to be assembled in a forwarder with a load capacity around 31000 lbs (14 metric tons). The BTS-1 has a load capacity of 9 metric tons of forest residues, equivalent to 30-35 m$^3$. With adjustable sides that open to 37° for loading, and closing to 10° compressing the load for transport, the BTS allows the operator to off-load a full load of material in less than a minute, and allows two loads to be dumped one atop the other (CBI, 2006).
When chipping at the fuel terminal, it is possible to chip forest residues either onto the ground or directly to the truck trailer. There are some advantages to use fuel terminal – harvesting chain. Forest residues dry very well at open fuel terminals. Also the harmful impurities like stones are easily avoided in this harvesting chain. By using terminal chipping of logging residues it is possible to produce high quality chips, the properties of which include homogenous chip size and low moisture content (Kallio and Leinonen, 2005).

Sinclair (1985) tested a prototype model of a container system (Figure 64) used to recover roadside biomass in mountainous terrain. The system recovered 82 m$^3$ of biomass, with 0.54 m$^3$ per piece, per eight-hour shift. Load size averaged 20.5 m$^3$ with a cycle time of 1.99 hour, and its cost was lower than the conventional system (logging truck and choker skidder).
Hammer and plate crushers are also suited for processing logging residue due to their construction. Crushers tolerate impurities, such as rock and metal, much better than chippers. A problem is presented by the low quality of the resulting chips since crushing produces in fairly long splinters. This is why chips made by a crusher can only be used at large end use facilities where even long splinters cause no conveyor malfunctions (Alakangas et al., 1999, apud Kallio and Leinonen, 2005).

The power requirements of crushing are significantly higher than those of chipping. In crushing the raw material is comminute by tearing and in chipping by cutting. Crushers are usually heavy units, which are difficult to transfer. Consequently, they are better suited for processing logging residue at the end use facility or terminal than for operation at a roadside landing. For crushing logging residue the effective hourly output is in the range of 60 to 100 m$^3$ loose of logging residue chips (Pulkkinen, 1996, apud Kallio and Leinonen, 2005). Advantages and disadvantages of using a crusher are:

- crushers tolerate impurities better than chippers,
- low quality of crush because of splinters,
- crusher produced chips can be used at large end use facilities only,
- crushers are heavy and difficult to transport.

**Chipping at the power plant**

Over short distance, it may still be economical to transport logging residues to the plant as unprocessed loose material (Figure 65). The stationary crushers currently in use are capable of comminuting loose logging residues, although the productivity is not as high as for bundled material. From the point of view of long distance transportation with a lorry and trailer, transporting unchipped, incompact logging residue is problematic because its low density. While the solid volume content of chips is 35 to 40% it is only 15 to 20% for whole logging residue (Alakangas et al., 1999, apud Kallio and Leinonen, 2005).

![Figure 65. Loading unprocessed logging residues into a biomass truck (Hakkila, 2004)](image)
In order to achieve maximum loads with a full trailer combination (110 m$^3$ loose), the density would need to be as high as 336 kg/m$^3$ loose. The profitability of transportation can be improved compacting the load or by extending the load space. VTT has developed compacting technology for truck transport of forest residues from forest to power plant. By using the VTT’s compacting technology it is possible to increase the net load of the truck by 50% (Kallio and Leinonen, 2005). According to Alakangas et al. (1999), the characteristics of chipping/crushing logging residue at the end use facility are:

- hot chain problems are avoided,
- chipping/crushing can be done more economically than in terrain or by the roadside,
- productivity is 20% better than for roadside chipping,
- chipping at the end use facility is the most economical option when the transportation distance is less than 55 km,
- lorry transport of logging residue is not economical without compacting,
- the profitability of transportation can be improved either by compacting the load or extending the load space,
- heavy crane must be used.

Another option to deal with the low forest residue density is to use a type of distillation method known as fast pyrolysis process, capable of converting various woody materials into a BioOil that has the advantage of increasing the energy density of the material, from roughly 100,000 Btu/ft$^3$ to 600,000 Btu/ft$^3$. According to the Renewable Oil International Company (Florence, AL), a mobile plant could be transported to the woods, and 1 dry ton of wood per day could produce roughly 120 gallons (1200 lb) of liquid (BioOil), 500 lb of charcoal, and 300 lb of combustible gas (Figure 66). Considering the increase of the energy density, one tank truck could transport the same amount of energy in the form of BioOil as two chip trailers (Badger, 2006).

![Figure 66. ROI mobile plant for fast pyrolysis process of woody biomass (Badger, 2006).](image-url)
Crushers and heavy power chippers are best suited for end site processing of logging residue because they require little maintenance and can easily be automated. In addition, crushers tolerate impurities well. Consequently, idle time for knife maintenance can be minimized. In contrast, using chippers for end site processing would tie up significantly more operational and maintenance resources (Alakangas et al., 1999, apud Kallio and Leinonen, 2005).

End site crushing of logging residue is the most efficient if logging residue loads can be unloaded directly on the feed conveyor of the crusher with the unloading/loading equipment of the transportation lorry. Thus no additional storage or feeding of the raw material would be required and crushing cost below 2 €/m³ could be achieved (Rinne, 1998, apud Kallio and Leinonen, 2005).

Fixed installations of electric powered crushers are suited for end site crushing of logging residue. Crushers can be either plate or hammer crushers. High speed crushers are probably the best for crushing logging residue. The problems of end site crushing include noise and dust. The sound intensity level produced by crushers may reach 100 to 110 dB. The dust problem can be mitigated for example with water spray (Kallio and Leinonen, 2005).

Scherpenzeel (1999) presents the characteristics, costs and capacities of three mechanized wood chip harvesting methods, as used in the Italian forestry industry on a commercial basis. The first case, chip production from residues (tops and branches) of a poplar plantation, produced 105 tons of chips per hectare, utilizing a self-propelled tracked chipper (Gandini 45 MSS 245 kW) into the stand, followed by the chip truck. Chip was blown directly into the chip truck, with a chipping productivity of 19.5 tons/hour. The second case was residues chipping (tops and branches) of a pine stand after the first thinning. The tops were left on access paths, and picked up by a self-propelled chipper (Gandini 60 MSS 307 kW) followed by a chip truck. The chipping productivity was 22.0 tons/hour, with a final production of 30 tons/ha. The last case was a mixed coppice for industrial chip production, with chips being produced by a tractor-mounted chipper (Pezzolato H1320/400 on Fiat 1880 - 132 kW), from trees skidded to a landing, where valuable logs were crosscut before chipping. The chipping productivity in that case was 8.0 tons/hour, resulting in a final production of 70 tons/ha.

Rawlings et al. (2004) studied the use of roll-off containers for transporting slash. They incorporated roll/off containers in active logging operations, as part of whole tree log processing, deliming and loading slash directly into them. A hook truck picked up one container and drove it to a centralized location, where a grinder produced “hog fuel” directly into chip van (Figure 67). The roll on/off containers had a capacity of 48 cubic yards each. They also utilized roll-off containers at sites which slash had already been created and piled, taking it to be processed by a grinder in a centralized location. The results indicated that the roll on/off container system was not cost competitive with a regular highway chip van, unless access presents a problem for the chip van.
Figure 67. Sequence of operations (clock wise) for slash removal and transport using roll on/off container technology: a) Daewoo DH280 with Denis strokeboom delimber loading slash into roll on/off container; b) Loading tilted roll on/off container while on truck; c) Universal Refiner PDR-80-63, 475-hp grinder with conveyor belt, converted to radio control and set on tracks; d) A Daewoo Model 220LL Log loader loading slash into the grinder (Rawlings et al., 2004).

The Moha chipper truck (Figure 68), considered by Asikainen and Pulkkinen (1998) as new technology, is also able to chip, forward, and transport the chips to the mill, if the transport distance is shorter than 30 to 40 km. It has some considerable advantages compared to chippers operating at the landing; e.g., it can move in difficult terrain, there is no interaction between machines (because there is only one machine operating), and one operator can handle the entire system. Its engine (type 800 CT) has maximum output of 229 kW, and an estimated productivity of 29 m$^3$ loose/PMH.
Chipping costs may be affected by a number of variables including species, wood basic density, material size, moisture content, machine costs and usage. 6 chipper machines were chosen for time study trials, working with roundwood from different feedstock, including: feedstock type (oak poles, shortwood and branchwood); moisture content (dry oak vs. wet oak); product diameter (5 cm vs. 15 cm); feed speed (fast v slow); wood basic density (oak vs. pine) (Table 18). The highest overall output of 6.3 m$^3$ per scheduled hour was achieved by the Jenz chipping lime at West Dean, and the types of material did give different outputs but it was difficult to identify the reasons. The feedstock diameter appears to be significant in terms of to optimize the use and capabilities of a machine. The optimum size appears to be that which allows the chipper to operate fully to the point just prior to the need to use the reverse feed or the automatic 'no stress' system. Machine choice should be based on expected feed material diameter (Technical Development Branch - TDB, 1998).

Table 18. Output data for chipper machines studied (TDB, 1998).

<table>
<thead>
<tr>
<th>Material Processed at Cannock</th>
<th>Material Processed at West Dean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sesmo HP25</td>
</tr>
<tr>
<td>Material</td>
<td>Dry Oak</td>
</tr>
<tr>
<td>Moisture content (% wet basis)</td>
<td>36%</td>
</tr>
<tr>
<td>Throughput (m$^3$/hr)</td>
<td>5.69</td>
</tr>
<tr>
<td>Chip output (m$^3$/hr)</td>
<td>15.41</td>
</tr>
<tr>
<td>Volume : weight (m$^3$/tonne)</td>
<td>1.096</td>
</tr>
<tr>
<td>Solid volume : Chip volume</td>
<td>1:2.71</td>
</tr>
<tr>
<td>Solid volume : Chip volume (settled)</td>
<td>1:2.58</td>
</tr>
</tbody>
</table>
6.5.4. Forest Residues Bundling Project

One technical option to harvest logging residues was developed in Scandinavia, based on cut-to-length systems. An integrated bundling unit is mounted on the rear frame of an 8-wheeled forwarder, and collects, compresses and wraps forest residues, producing cylindrical bundlers with around 60 cm diameter and 3 m length. The biomass handling becomes real simple when compacting and aggregating forest residues like log forms (Figure 69).

![Figure 69. The Timberjack 1490D Slash Bundler](image)

In spring of 2005, there were nearly 30 slash bundlers in use in Finnish forests, and in 2003 more than 0.7 million slash bundles were produced. In the study done by Kärhä and Vartiamäki (2006), the average productivity was 18.1 bundles $E_{15}^{-1}$ (approximately 8–10 solid m$^3$ $E_{15}^{-1}$) with the Timberjack bundlers ($E_{15}$ operating hour, including delayed times shorter than 15 min). The operator had the most significant effect on the bundling productivity, and the recovering conditions also significantly affected the bundling productivity, especially the quality and location of the residues piles, which should be stacked on one side of the strip road, particularly when there is not much residue removal at the bundling site. The better the piles and windrows and the fresher the residues, the higher was the residue removal. When the quality of piles and windrows was good, the residue removal was, on the average, 68 solid m$^3$ ha$^{-1}$ on the bundling sites, against 50 solid m$^3$ ha$^{-1}$ in poor or average conditions. The average bundle length was 302 cm and the diameter 72 cm, the mean volume of the bundle was 0.50 solid m$^3$ and the average weight was 418 kg. The average energy content of a bundle was 1.02MWh when the mean moisture content (w.b.) was 45%.

While biomass bundling is proven technology in Europe, its performance in North American conditions needed to be evaluated and compared to alternative fuel treatments. One of the studies was developed by Rummer et al. (2004), which objective was to examine the operational performance of the Timberjack 1490D Slash Bundler across a wide range of conditions found on typical western US forests (Table 19). They worked in eight different forestry sites, but collected bundles in seven, sometimes because of residues were too scattered, short, or rotten, or at some locations, there was also a requirement to leave a certain amount of slash volume or specific coarse woody debris.
In Europe, the bundle standard length is about 10 ft (3 m). Bundles ranged in length from 8 to 16 feet (2.4 to 4.8 m) during the course of this study, trying to make the bundles more compatible with conventional trailers. The shortest bundles were intended for cross-wise stacking on flatbed transport, while the longer bundles were expected to fit the rack spacing on a standard doublebunk trailer (Figure 70). Bundled green material had a density that was similar to the dry density of roundwood (about 22 lb/ft$^3$, or 360 kg m$^{-3}$), while bundles with dry residues had an average density of 16 lb/ft$^3$. (265 kg m$^{-3}$) This highlights the problem of getting a full payload on a conventional logging trailer, particularly with dry residue.

Table 19. Key demonstration site descriptors (Rummer et al., 2004)

<table>
<thead>
<tr>
<th>Site</th>
<th>Forest Type</th>
<th>Slash Type</th>
<th>Residual Trees/ac</th>
<th>Median DBH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonner’s Ferry, ID</td>
<td>Mixed conifer</td>
<td>4-yr old slash</td>
<td>142</td>
<td>8”</td>
</tr>
<tr>
<td>LaGrande, OR</td>
<td>lodgepole pine</td>
<td>small whole trees</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Idaho City, ID</td>
<td>ponderosa pine</td>
<td>whole trees</td>
<td>54</td>
<td>12”</td>
</tr>
<tr>
<td>Stevensville, MT</td>
<td>ponderosa pine</td>
<td>CTL slash</td>
<td>61</td>
<td>14”</td>
</tr>
<tr>
<td>Medford, OR</td>
<td>Mixed conifer, westside stand</td>
<td>heavy limbs, tops</td>
<td>70</td>
<td>6”</td>
</tr>
<tr>
<td>Georgetown, CA</td>
<td>Pine thinning, landing piles</td>
<td>limbs and tops</td>
<td>56</td>
<td>*</td>
</tr>
<tr>
<td>Bend, OR</td>
<td>Lodgepole pine</td>
<td>small whole trees</td>
<td>137</td>
<td>6”</td>
</tr>
<tr>
<td>Prineville, OR</td>
<td>Juniper treatment in grassland</td>
<td>whole junipers</td>
<td>Few</td>
<td>*</td>
</tr>
</tbody>
</table>

Figure 70. Quad bunk shortlog trailer (Rummer et al., 2004)
Another problem was the bundle stability. Solid, rigid bundles were produced when the residues had some pieces that were 10 to 20 feet long and at least 3 inches in diameter. Without some longer material in the mix, bundles could become flexible or even fail (Figure 71). Large, short material like butt cuts doesn’t bundle well. Large diameter pieces introduce discontinuities into the bundle that can produce weak points. The bundler can adjust to more difficult material by increasing the number of twine wraps and reducing the wrap spacing, but this affects productivity and cost.

![Figure 71. Failed bundle due to breakage (Rummer et al., 2004)](image1)

Technical specifications for the 1490D list productivity as 10-30 bundles/hour. In this study were found productivities between 5-24 bundles/hour, with the lowest production due to worse slash arrangement, requiring more time aligning, bunching and feeding stems. At the sites where the bundler was handling whole trees, it was necessary for the operator to properly align longer pieces, which could be improved if the residues were properly presented for bundling by the previous operation.

Assuming a potential production rate of 20 bundles per machine hour (8 bdt), the cost of collecting biomass and creating bundles would be about US$16 per bdt. Forwarding is estimated to cost $5 per bdt based on 4 loads per productive hour. With a hauling cost of $0.10 to $0.20/ton-mile, a 50-mile haul would add $5 to $10 per bdt. Finally, chipping at the energy facility may incur an additional $3 per bdt. Thus, the total cost to deliver chipped hog fuel from CRL’s would be about $29 to $34 per bdt. Nearly half the total delivered cost is due to the bundling function. This value is not competitive when compared with other fuel sources, like coal (US$24.74/ton), but could be if the value of the forest management treatment is considered, like slash treatments and fuel reduction operations.

![Figure 72. A bundle pile of approximately 60 bdt of biomass (Rummer et al., 2004)](image2)
One alternative also been considered is the use of “cutter-shredder-baler” machines, initially developed for short-rotation woody crops, to harvest understory biomass. A Canadian prototype was developed including a New Holland BR 740 baler, an Orsi model WHO 1550 shredder, basically a 1.5 m long rotor with 12 hammers, an adjustable shear bar (Figure 73), and a cutter head attached in front of the shredder (Figure 74). An agricultural tractor must be used to pull it and to provide power through PTO (Lavoie et al., 2007).

Figure 73. Canadian prototype: cross-section of cutting and shredding mechanisms (Lavoie et al., 2007)

In one test conducted on pine stand, with 8.0 green tons per acre of understory biomass, mainly composed of palmetto, gall berry, and wax myrtle, the time to produce one bale by the Canadian prototype was 13.5 minutes. Each bale had an average volume of 75.0 cubic feet and weighed 1,180.4 green pounds (Figure 75).

Figure 74. Canadian prototype: front view of cutter head (Lavoie et al., 2007)

Figure 75. Canadian cutter-shredder-baler prototype, and produced bale.
7. MANAGING THE CHIP PILE

Chips are the most common form of fuelwood for combustion, and their greatest disadvantage is that they deteriorate and lose quality fairly rapidly if not managed carefully. Most wood energy facilities maintain on site a 30 to 45 working-day supply of feedstock in outside storage, being prepared for possible problems with chip production.

Wood chip piles are constructed using two methods: a labor-intensive method with bulldozers, and a more automated system involving gravity feed. Wood chips in piles constructed by bulldozers suffer from reduced quality caused by a pile design that is necessitated by this equipment. Wood chip piles built using gravity feed systems, such as conveyor belts and pneumatic blowers, produce conical piles, which maintain better wood chip quality and be more economical (Figure 76). The two major factors involved are temperature and moisture. These create a pile environment that, along with the ambient environment, either encourages or discourages the growth of fungi and bacteria. This, in turn, controls the deterioration of fuelwood quality (Christopherson et al.; 1993).

![Figure 76. Conical pile made of Eucalyptus chips completing 360°.](image)

7.1. Moisture

Soon after a wood chip pile is constructed, two distinct moisture regions develop: a) the exterior region of the pile is moist; b) the interior region of the pile is dry. The exterior region moisture comes from two sources. One is from water in the warm air rising from the interior of the pile and condensing in the cooler exterior region of the pile; the other is from rain. The interior of the pile will lose 20-25 percent of its original moisture during the first 60 days after pile construction. The moisture in the exterior of the pile will increase 50 percent or more during the same period, but that layer will protect the interior from increasing moisture during precipitation. When the exterior layer becomes saturated, water will run off the pile. Over time, moisture will eventually percolate into the pile as the pile interior cools.

The effect of storage on the fuelwood moisture content of Norway spruce logging residue were studied by Nurmi (1999). Storages included uncomminuted residue piles on the clear-cut left by single grip harvester, uncomminuted residue in large windrows at road
side landing and as a third alternative a comminuted, compacted and non-compacted residue piles at a terminal. The initial moisture content of fresh residue was 56% on green weight basis. After one-year storage the residue at the clear-cut had reached an average moisture content of 28.5 and 42.2% at the landing. The moisture content of comminuted material had risen to 65.3% during nine-month storage. Compaction did decrease pile temperature indicating lower dry matter losses in the compacted pile (Christopherson et al.; 1993).

7.2. Pile temperature

The temperature in a chip pile follows in a predictable pattern under normal circumstances. The exterior, moist-layer temperature lags behind the ambient air temperature by 8 to 24 hours. The interior of the pile has high temperatures. There is a rapid increase in interior pile temperature because of the respiration of living cells in the wood chips. These initial temperatures range from 40-60 degrees C (Figure 77). Piles built with clear chips are cooler than whole tree chip piles because the living cells in the cambium have been removed. Interior pile temperatures are maintained by the respiration of bacteria and fungi living off the free sugars and cellulose in the wood chips. If the interior temperature of the pile reaches approximately 65 degrees C, the fungi will cease to function. After the fungi and bacteria are killed by temperature or starvation, the interior wood chip pile temperature will gradually decrease. As the interior temperature decreases additional moisture will move into the pile (Christopherson et al.; 1993).

Figure 77. Chip pile moisture and temperature dynamics (Curtis, 1980, apud Christopherson et al., 1993)

Under some circumstances the temperature in a chip pile will increase to a level where spontaneous combustion can occur (Figure 78). When air does not circulate freely through the pile because of chip compaction during construction, or a layer of some kind, heat pockets will develop. In these heat pockets, acetic acid produced by the fungi and bacteria can build up, and, at sufficient concentrations, will oxidize wood. Chemical oxidation will create temperatures of 80-100°C. If the wood chips are exposed to these temperatures for 60-90 days, then exposed to the oxygen in air, spontaneous combustion is likely to occur (Christopherson et al.; 1993).
7.3. Bacteria and fungi

Bacteria and fungi can cause loss in wood biomass and a reduction in feedstock quality. Most of the various microorganisms found in wood chip piles use free sugars and do not decay wood. Some organisms produce by-products that stain the wood and compromise quality for use in bleached pulps. Other fungi and bacteria break down the cellulose, hemicellulose, and lignin into food and nutrients to support growth, compromising the structure of wood.

There are two major groups of fungi endemic in temperate and tropical regions that cause the deterioration of wood. White rot fungi use all the macro-molecules in the wood. Brown rot fungi use the cellulose and hemicellulose. These fungi grow best in temperatures from 30 to 45 degrees C and at moisture levels from 40 to 100 percent. A general rule of thumb employed by many woodyard managers is a 1 percent per month reduction in wood biomass resulting from fungal activity. The rate of decay in wood chip piles varies with the season, approximately 1.5 percent in the summer and 0.5 percent in winter. The better method of control involves manipulating the wood chip pile environment, by creating a hot dry environment. The effect of bacteria that decompose wood is inconsequential when compared to the rate and amount of woody material deteriorated by wood rot fungi (Christopherson et al.; 1993).

7.4. Preventing chip decay

Wood chip size can have an impact on pile construction, chip quality, and handling. Larger wood chips and wood chunks allow for better air flow into the pile. There is less wood area exposed to fungi and the pile dries better. Many wood combustion facilities are using wood chunks and larger wood chips to improve combustion quality. Unfortunately, the tradeoff is that in rainy environments, water can percolate deeper into the pile increasing percent moisture and reducing quality.
The standard wood chip has dimensions of approximately 1 ½ x ½ x ¼ inches plus or minus 30 percent. Wood chunks vary greatly in size, from 2 to 5 ½ inches long. Research on drying rates indicates that chunks in that size range dry at comparable rates. Chunks generally dry twice as fast as wood chips for the first 60 days of storage. Eventually, both wood chunks and wood chips reach moisture equilibrium. Disadvantages of using wood chunks are that they require a 33 percent larger area for storage than the same weight in wood chips, and they can not be stacked in piles with sides as steep as wood chip piles.

Wood chip piles should be constructed on clean, well-drained hard surfaces. All old wood chips should be removed before a new pile is started, because they can serve as an inoculum for wood rot fungi. Placing the pile on concrete not only facilitates good drainage, it helps keep a higher percentage of the base free of dirt, gravel, and other contaminants. After concrete, the best surfaces to use are asphalt, compacted soil and gravel, in that order.

During wood chip pile construction, precautions should be taken to prevent situations that can result in spontaneous combustion or promote wood rot fungal growth. Layers of fines and bark should not be allowed to develop and restrict air movement. Sections of the pile containing large amounts of bark and fine material will also create pockets of fungal activity. Fungus is often introduced into the interior of the pile on the bark. The bark and the fines tend to hold moisture and provide an ideal environment for the beginning of fungal growth.

Piles constructed with gravity feed systems will tend to be of a conical shape. Conical piles 40 feet and less in height are less prone to spontaneous combustion than taller piles and piles constructed by bulldozers. Piles constructed by bulldozers have broad flat tops that collect moisture and promote the growth of fungi (Figure 79). Bulldozers also compact the pile, causing restrictions in air movement that can result in spontaneous combustion. The large conical pile and the wind row derivation maximize the volume of chips located in the hot dry interior portion of the pile where fungal activity is lowest. The dry wood chips have higher available energy than green wood chips, making them of better quality for combustion.
To optimize the beneficial effects of storage, wood chips should not remain in the pile longer than 30-60 days, depending on the environment. The most popular storage operating system is first in/first out. That method uses the oldest wood chip piles first. Under normal circumstances the wood chip would be stored from 6-8 weeks. This duration of storage is long enough to facilitate drying but not long enough to allow significant biomass losses. Some studies (Thornqvist and Jirjis, 1990; Fredholm and Jirjis, 1998) have observed dry matter loss in stored woody biomass. Green chips stored in a large pile for seven months lost approximately 12 percent of their dry matter and bark stored in a large pile for six months lost approximately 26% of their dry matter. The dry-matter loss in the bark pile resulted in a 20 percent decrease in energy content.

Another approach to storage is the standby pile. A standby pile is built and maintained for a long period while the wood energy facility requirements are met by fresh material. When fresh wood chips are not available or a surge of wood chips are required, chips are reclaimed from the standby pile. In some instances the standby pile is small enough to be kept under covered storage which allows chip quality to be maintained. In general, the standby pile is in the open and the wood chips are low quality, and are to be used only until the normal flow of fresh wood chips is resumed (Christopherson et al., 1993).

8. HARVESTING SHORT-ROTATION WOODY CROPS (SRWC) FOR ENERGY

Perennial woody crops (also referred to as short-rotation woody crops) are also a potential primary biomass resource. Eucalyptus species constitute about 38% of all short-rotation plantations worldwide and hardwoods in general make up about 63% of all plantations. In temperate regions, poplar, willow, and black locust predominate (Perlack et al., 1995). According to Wright (2006), short-rotation woody crops (SRWC) established in Brazil, New Zealand, and Australia over the past 25 years equal about 50,000 km$^2$. SRWC plantings in China may be in the range of 70,000–100,000 km$^2$. SRWC and other energy crops planted in the US and EU amount to less than 1000 km$^2$.

One more specific definition of short-rotation woody crops could be specialized energy forests, grown according to the "grassland" concept, in extremely dense stands, harvested at 3-4 years intervals and regenerated from the stools, which are expected to survive 5 rotations at least.

In an estimative of 10 million ha classified as short-rotation plantations in the U.S., Ranney (1994, apud Perlack et al., 1995) noted that less than half of this planted area could be termed as successful or commercially viable. Ranney's technical criteria for successful plantations for energy use are described as follows:

- more than 80% survival of planted materials;
- annual productivity greater than 10-12 dry tonnes/ha of harvested wood and bark;
- uniformity in diameter, height and straightness;
- less than $50/dry tonne in delivered cost;
- and less than 2 tonnes/ha in erosion each year.
Gallagher et al. (2006) developed a model to summarize all the costs, and completed a break-even analysis to determine the delivered cost for plantations of eastern cottonwood (*Populus deltoides* Bartr.) from a hypothetical fiber farm in 2003. Using current yield from an experimental fiber farm, short-rotation cottonwood plantations were not cost effective, as delivered cost to a pulp mill, located 50 km away, averaged $78.00 t\(^{-1}\). According to the authors, if yield could be increased by 40%, over the 20 t ha\(^{-1}\) year of green fiber considered here, through improvements in genetics and silvicultural practices, delivered cost could be reduced to $60.00 t\(^{-1}\) for roundwood, crucial to the cost feasibility of intensively managed, short-rotation hardwood plantations.

Working with willow (*Salix* spp.), Volk et al. (2006) pointed out that despite technological viability and associated environmental and local economic benefits, the high price of willow biomass relative to coal has been a barrier to wide-scale deployment of this system. The cost of willow biomass was $3.00 GJ\(^{-1}\) ($57.30 Odt\(^{-1}\) - oven dry ton) compared to $1.40-1.90 GJ\(^{-1}\) for coal.

### 8.1. The willow example

Willow has several characteristics that make it ideal for woody crop systems, including high yields obtained in a few years, ease of vegetative propagation, a broad genetic base, a short breeding cycle, and the ability to resprout after multiple harvests. There are about 450 species of willow worldwide, ranging from prostrate, dwarf species to trees that are over 40 m high. The willows used in woody crop systems are primarily drawn from the subgenus *Caprisalix*, which includes over 125 species worldwide (Volk et al., 2004). Willow crop cultivation occurs on agricultural or open fallow land and requires both forestry and agronomy knowledge. A double-row configuration is used, with a density of 10 000–20 000 plants per hectare (Figure 80), depending on soil conditions, rotation length, and desired dimensions of the end product. Unrooted cuttings are planted following agricultural-type site preparation and complete weed control that is begun in the fall prior to planting. Planting machinery cuts 12–24-cm long sections from 100–200 cm dormant whips, then plants them flush with the soil surface. Each willow plant will develop multiple 6–15 stems.

![Figure 80. Willow biomass crops planted in the typical double-row configuration. Plants have just sprouted in the spring, after being cut back to ground level (coppiced) during the winter. Arrows indicate the recommended spacing for willow biomass crops, resulting in a plant density of just over 14 000 per hectare (Volk et al., 2004).](image)
Willow is typically harvested on a 3–4-year cycle, using modified agricultural equipment that cuts and chips the biomass in a single operation. At the end of the first three-year rotation willow aboveground biomass can reach up to 37.5 Odt ha\(^{-1}\). Willow plants resprout vigorously after each harvest. Seven to eight harvests are possible from a single planting (Figure 81). Spinelli and Kofman (1996) report that an average butt diameter for willow crops in Europe at harvest is 15-30 mm and average height is 3.5-5.0 m.

Figure 81. Willow biomass crop growth cycle. Once the crop is established, seven to eight harvests at 3–4-year intervals are possible (indicated by the cycle of green arrows) before the crop needs to be replanted. After each harvest, the willow resprouts the following spring and develops rapidly (Volk et al., 2004).

8.2. Harvesting machines

Conventional forestry equipments and systems are been used in the U.S. to harvest SRWC. These operations are highly mechanized with the most common utilizing feller/bunchers, grapple skidders, a chain flail delimber/debarker/chipper and chip vans. Another replaces the flail/chipper and vans with irongate delimiters, log trucks and a drum debarker. But the conditions in SRWC plantations - flat, obstacle-free ground, small trees of uniform size growing in straight rows, uniform road spacing (in many cases), short transportation distances to the mill (in some cases), small branches and bark characteristics which differ from those of conifers - all suggest that SRWC harvesting, processing and transportation can be carried out in different and cheaper ways (Hartsough and Yomogida, 1996).

One problem of using conventional machines is the tree size, because, generally, costs are less for larger trees. For example, Stokes et al (1986) found that the minimum economic tree diameter for one SRWC plantation situation was about 15 cm when utilizing conventional feller-bunchers and skidders.

According to Hartsough and Yomogida (1996) the best machines, mainly from Scandinavia, are based on well-developed harvesters for traditional crops such as corn or
sugar cane, and involve relatively minor developments, such as headers specifically designed for harvesting small diameter hardwoods (Figure 82). For small trees, harvesting concepts may be classified as cut-and-chip by one machine, cut-only, or cut-and-forward. Cut-and-chip appears to be the best option, because the bulk chips are cheaper to handle than whole trees, and because the harvester is smaller and has less idle time than a combination harvester-forwarder.

![Figure 82. New Holland FX45 forage harvester with modified Kemper corn head (Photo by Abrahamson, L.P.).](image)

A list of “ideal” harvesting/processing/transportation systems for large SWRC might include the following two examples: a) continuous-travel feller/chipper, combined primary/secondary chip transport, and separation of clean chips from residues; b) continuous-travel feller/loader, combined primary/secondary transport of whole trees, delimbing/debarking, and chipping. Both systems could be used to produce either pulp chips or, by eliminating the separation step, whole-tree chips for energy.

**Feller-bunchers**

Tricycle or articulated rubber-tired drive-to-tree feller-bunchers (Figure 83) are by far the cheapest commercially available machines for felling and bunching trees in the 13 to 25 cm DBH range, to be followed by skidding, whole-tree forwarding or woods-mobile chipping. They cause more soil disturbance than other felling methods, and can’t load forwarders or trailers. Rubber-tired or tracked limited-area (excavator-style) feller-bunchers are more expensive than drive-to-tree machines, but they can travel in a single track, causing very little surface disturbance.

![Figure 83. Tricycle feller-buncher from Bell](image)
Harvesters

Harvesters are much more expensive than feller/bunchers, but are used in many countries or regions where it is desirable to leave residues on site rather than accumulating them at roadside or using them for fuel. They also cause almost no site disturbance, and can create a mat of slash that is traveled on by the forwarders which transport the log lengths to roadside. They have been used to simultaneously delimb and debark eucalyptus. The disadvantages include the extra cost of processing trees into shorter lengths, and the extra downstream costs of handling the multiple smaller pieces (Hartsough and Yomogida, 1996). Another recently option is the “harwarder” (“harvester-forwarder”), a machine combination of a harvester with a forwarder (Figure 84). The “harwarder” may compete with the harvester + forwarder system if the forwarding distance is short, with lower traffic movements.

Figure 84. “Harwarder” Valmet 801 Combi/330 Duo.

A study from Sirén (2003) compared one “harwarder” model Pika 828 (Figure 85) with three other small harvesters especially developed for thinning: Sampo 1046X, Nokka Profi e Assa 810. Table 20 shows machine prices, excluding taxes, and costs by operational hour ($E_{15}$ – includes interruptions lower than 15 minutes).

Figure 85. “Harwarder” Pika 828.
Table 20. Machine prices (€) and operational costs (€ by E₁₅ hour)

<table>
<thead>
<tr>
<th>Machine</th>
<th>Price (€)</th>
<th>Operational cost (€ / E₁₅)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampo 1046X</td>
<td>140 496</td>
<td>54.0</td>
</tr>
<tr>
<td>Nokka Profi</td>
<td>223 784</td>
<td>61.5</td>
</tr>
<tr>
<td>Assa 810</td>
<td>168 259</td>
<td>56.9</td>
</tr>
<tr>
<td>Pika 828 “harwarder”</td>
<td>269 215</td>
<td>62.1</td>
</tr>
<tr>
<td>“Forwarder”</td>
<td>172 465</td>
<td>51.2</td>
</tr>
</tbody>
</table>

The net effective time (E₁₅) was 84.6% for the “harwarders” and 81.6% for the “thinning” harvesters. The technical availability was 79.1% for the “harwarders” and 84.5% for the harvesters. The “harwarder” productivity was calculated for a 250 m distance and is presented in Table 21. The small harvesters’ productions, in different felling systems, are listed in Table 22. The “harwarder” costs in this study were higher than the other systems with harvester and forwarder.

Table 21. “Harwarder” productivity (m³/E₁₅) in different felling systems

<table>
<thead>
<tr>
<th>Productivity</th>
<th>Log average size</th>
<th>Average removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m³/E₁₅)</td>
<td>(dm³)</td>
<td>(m³/ha)</td>
</tr>
<tr>
<td>First thinning</td>
<td>3,81</td>
<td>89,4</td>
</tr>
<tr>
<td>Last thinning</td>
<td>4,41</td>
<td>137,0</td>
</tr>
<tr>
<td>Clear cut</td>
<td>7,48</td>
<td>264,6</td>
</tr>
</tbody>
</table>

Table 22. The harvesters’ productivity (m³/E₁₅) in different felling systems. The average log size (dm³) is between parentheses.

<table>
<thead>
<tr>
<th>Harvester</th>
<th>1º Thinning (m³/E₁₅)</th>
<th>Last Thinning (m³/E₁₅)</th>
<th>Clear Cut (m³/E₁₅)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nokka Profi</td>
<td>8,81 (131,1)</td>
<td>10,28 (129,5)</td>
<td>12,07 (168,4)</td>
</tr>
<tr>
<td>Sampo 1046X</td>
<td>6,26 (94,6)</td>
<td>7,76 (121,7)</td>
<td>12,97 (302,6)</td>
</tr>
<tr>
<td>Assa 810</td>
<td>7,65 (112,0)</td>
<td>10,43 (177,5)</td>
<td>19,47 (465,3)</td>
</tr>
<tr>
<td>Total (average)</td>
<td>6,92 (103,6)</td>
<td>9,20 (140,3)</td>
<td>16,18 (336,8)</td>
</tr>
</tbody>
</table>
Skidders

Rubber-tired grapple skidders are obviously overbuilt for most SRWC plantations; the heavy guarding for machine protection, extreme axle or frame oscillation capabilities for rough terrain, low gearing for handling slopes, and decking blade may have little or no utility. Because trees are dragged on the ground, skidding disturbs the soil surface and requires more tractive effort than does forwarding.

Forwarders

The use of a log-length forwarder causes less damage to the stand and has been shown to cause less soil compaction and disturbance than a skidder. Also, the use of forwarders may cause less damage to stumps than do skidders. However, stump damage is not currently a major consideration when harvesting SRWC plantations for pulp material, since replanting is considered to be more economically attractive than coppice regeneration for pulp production. As noted before, the cut-to-length harvester and forwarder system is generally more expensive than whole tree systems because of the extra handling of the multiple short pieces (Hartsough and Yomogida, 1996).

8.3. SRWC harvesting machines (for DBH less than 8 cm)

Trees with DBH values less than 8 cm are generally not suitable for pulp production; hence, this harvested woody material is usually used for biomass fuel. Two general schemes are currently employed for the harvesting of SRWC with DBH values less than 8 cm. One scheme is the “cut-only” process (Figure 86a), and the other is the “cut-and-chip” process (Figure 86b). According to Culshaw (1993, apud Hartsough and Yomogida, 1996), recent tests have shown that the cost of harvesting is minimized by using machinery which produces chips in an one-pass operation (“cut-and-chip” process).
Hartsough and Yomogida (1996) describe several different models of cut-and-chip and cut-only harvesters tested on SRWC. Three models of cut-and-chip and two models of cut-only harvesters, with better results under different situations, are included here.

8.3.1. Cut-and-chip harvesters

Austoft Sugar Cane Harvester

The Austoft harvests two rows of stems per pass (Figure 87). Two augers, at the front of the machine, feed the stems into either circular saws or bush disks for cutting; bush disks are preferred over circular saws in stony soil conditions. The severed stems are then picked up at the butts by a lifting roller and are then transferred to a series of rollers which convey the stems to a swinging knife billeting mechanism at the back of the harvester. The 4 to 6 cm billets are then transferred by a conveyor to a trailer. As an alternative, 1 cubic meter of chips may be stored on the conveyor until a trailer arrives. In January 1994, a series of twelve harvesting runs were carried out with the Austoft in the U.K.. The machine could average 0.4 hectare/standard (std) hour or 9.2 Odt/std hour, assuming twin row planting and two-way working (a standard hour includes allowances for servicing and personal breaks, but does not include downtime for unscheduled repairs; two-way operation involves the machine cutting while moving through the plantation, turning, then cutting on the return pass). Average travel speeds while cutting two rows spaced at 1 meter ranged from 2.1 to 3.9 km/h in stands averaging 19.2 to 32.5 Odt/ha. In these tests, the Austoft was run on both uphill and downhill conditions. Productivity was not affected by travel direction.

Figure 87. Austoft “cut-and-chip” harvester in 2 year Poplar crop

Trials in Scandinavia and Europe indicate average productivities of around 20 green tonnes per hour (range: 10 to 30) for the Austoft (Spinelli, 1996, apud Hartsough and Yomogida, 1996). The machine is robust and in its current configuration is likely to have high availability when harvesting SRWC. The tracked undercarriage gives it high
mobility on soft soils, and it is capable of operating on slopes. Spinelli and Kofman (1996) made a comparison among the productivities recorded for the Austoft harvester in Sweden, Britain, Italy and Denmark (Table 23).

Table 23. Comparison among the productivities recorded for the Austoft harvester in Sweden, Britain, Italy and Denmark (Spinelli and Kofman, 1996).

<table>
<thead>
<tr>
<th>Place</th>
<th>Sweden</th>
<th>Sweden</th>
<th>Britain</th>
<th>Italy</th>
<th>Denmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
<td>Willow</td>
<td>Willow</td>
<td>Willow Poplar</td>
<td>Poplar</td>
<td>Willow</td>
</tr>
<tr>
<td>Age (years)</td>
<td>N.A.</td>
<td>N.A.</td>
<td>3</td>
<td>1-2</td>
<td>4-5</td>
</tr>
<tr>
<td>Row system (row)</td>
<td>twin</td>
<td>twin</td>
<td>single</td>
<td>single</td>
<td>twin</td>
</tr>
<tr>
<td>Butt diameter (mm)</td>
<td>16-25</td>
<td>18-25</td>
<td>N.A.</td>
<td>23-61</td>
<td>14-22</td>
</tr>
<tr>
<td>Stocking (Ton/ha)</td>
<td>37-42</td>
<td>29-63</td>
<td>37-80</td>
<td>11-34</td>
<td>28-50</td>
</tr>
<tr>
<td>Harvesting speed (km/h)</td>
<td>3.3-4.5</td>
<td>2.6-5.1</td>
<td>2.1-3.8</td>
<td>5.1-8.8</td>
<td>3.3-6.0</td>
</tr>
<tr>
<td>Productivity (Ton/Wph)</td>
<td>19-26</td>
<td>21-32</td>
<td>9-25</td>
<td>18-22</td>
<td>14-23</td>
</tr>
</tbody>
</table>

**The Claas (695) Jaguar Harvester**

The Claas Jaguar is a multi-purpose “cut-and-chip” harvester (Figure 88), which blows chips into a chip forwarder which travels behind the harvester. Two forwarders are matched with one harvester so the harvester can operate continuously. In December 1994, a series of tests were carried out in the U.K.. Travel speeds while cutting twin rows averaged 4.0 to 6.9 km/h in stands averaging 7.5 to 17.5 Odt/ha. Assuming twin row harvesting, calculations indicated that the Claas 695 could achieve a two-way output of 8.6 Odt/std h, assuming a yield of 19.2 Odt/ha (Hartsough and Yomogida, 1996).

Figure 88. The Claas Jaguar “cut-and-chip” harvester
It should be noted that the Claas base machine, designed for forage harvesting, may have high maintenance requirements when fed a steady diet of SRWC. It works well on gentle slopes and frozen ground, but is not as capable on very soft soils or steep terrain. Spinelli and Kofman (1996) also made a comparison among the productivities recorded for the Claas harvester in Sweden, Britain, Italy and Denmark (Table 24).

Table 24. Comparison among the productivities recorded for the Claas harvester in Sweden, Britain, Italy and Denmark (Spinelli and Kofman, 1996).

<table>
<thead>
<tr>
<th>Place</th>
<th>Sweden</th>
<th>Sweden</th>
<th>Britain</th>
<th>Italy</th>
<th>Denmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
<td>Willow</td>
<td>Willow</td>
<td>Willow</td>
<td>Poplar</td>
<td>Willow</td>
</tr>
<tr>
<td>Age (years)</td>
<td>N.A.</td>
<td>N.A.</td>
<td>3</td>
<td>1-2</td>
<td>4-5</td>
</tr>
<tr>
<td>Row system (row)</td>
<td>twin</td>
<td>twin</td>
<td>single</td>
<td>single</td>
<td>twin</td>
</tr>
<tr>
<td>Butt diameter (mm)</td>
<td>16-34</td>
<td>16-22</td>
<td>N.A.</td>
<td>17-56</td>
<td>N.A.</td>
</tr>
<tr>
<td>Stocking (Ton/ha)</td>
<td>21-53</td>
<td>27-54</td>
<td>12-32</td>
<td>14-48</td>
<td>31-60</td>
</tr>
<tr>
<td>Harvesting speed (km/h)</td>
<td>4.7-9.1</td>
<td>5.5-9.2</td>
<td>3.5-6.9</td>
<td>5.2-7.3</td>
<td>5.1-7.1</td>
</tr>
<tr>
<td>Productivity (Ton/Wph)</td>
<td>22-35</td>
<td>26-42</td>
<td>7-13</td>
<td>8-21</td>
<td>12-31</td>
</tr>
</tbody>
</table>

Spinelli and Kofman (1996) concluded that the Austoft and the Claas are good harvesters, working fine and achieving high harvesting productivity. The Austoft is sturdier and enjoys better off-road mobility, whereas the Claas can travel on-road and inflicts less damage to the stools. They pointed some problems to be solved like machine design, off-road mobility and crop spacing. The Austoft is the only harvester that can negotiate soft soil, but its capability has no use if the support fleet will eventually get stuck. Then the point is the careful selection of the sites where one will plant short rotation crops. Either one refrains from planting in the wettest spots or new machinery will have to be designed. Irrational spacing is detrimental to work efficiency. It will slow down most machines and stop some of them. More thought must be given to correct field design. The double-row system works fine for most harvesters, even if it is not the best for all of them. The Claas cannot harvest effectively single rows, if the inter-row is smaller than 1.5 m. Even so, the productivity will be greatly reduced.

**New Holland FX45**

Volk et al. (2007) reported that a head made by Coppice Resources Ltd. (CRL) in Doncaster, U.K. was probably the most robust for the size of willow produced in the U.S.
Two large diameter saw blades, with a hydraulic drive mechanism, mounted on a New Holland FX45 forage harvester, run at about 1200 rpm to cut the willow stems and feed them into the forage harvester to be chipped. After field trials during summer of 2006, the authors concluded that the chipped material produced was consistent and high quality, but there were problems in the flow of material through the harvester. This problem was complicated by the foliage, which caused the cut willow stems to hang up rather than fall down and feed into the harvester. Field trials during the dormant season in the late fall of 2006 (Figure 89) indicated that material flow was improved, but was still not optimal. The harvester was able to operate at ground speeds of 3-4 miles/hour (1.9-2.5 acres/hour with 70% field efficiency) if stem diameters were less than 3 inches.

![Figure 89. Harvesting willow biomass crops with a New Holland FX45 forage harvester and a specially designed Coppice Resources Ltd. (CRL) willow cutting head and a close up view of the CRL willow cutting head (Volk et al., 2007).](image)

### 8.3.2. Cut-only harvesters

**Frobbesta harvester**

The Frobbesta Harvester is a Swedish machine which was designed to simultaneously cut two 76 cm spaced rows of 2 to 5 year old willow coppice with 122 cm between pairs of rows (Figure 90). When cutting, the coppice is fed in by two counter-rotating paddle wheels and then gripped between a long inclined metal auger. The stems are then severed by two circular saws. The inclined auger then lifts and tilts the stems over a metal guide box, and the stems are released and fall horizontally into a rear trailer platform. When the platform is full, the bundle of stems is pushed off.
In January 1994, a series of 8 tests were carried out on the Frobbesta in the U.K. (Hartsough and Yomogida, 1996). The harvester was found to have a productivity of 1.97 Odt/std h, assuming twin row planting and two-way working. The test results are summarized in Table 25.

**Table 25. Frobbesta harvester study results (Hartsough and Yomogida, 1996)**

<table>
<thead>
<tr>
<th>Site</th>
<th>Working Method</th>
<th>Average Run (ft)</th>
<th>Spacing</th>
<th>Output (acres/std hr)</th>
<th>Output (ODT/std hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Actual</td>
<td>Without Blockage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.11</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.24</td>
<td>0.97</td>
</tr>
<tr>
<td>Dunstall Court</td>
<td>2 Way</td>
<td>500</td>
<td>3 ft + 3 ft</td>
<td>0.11</td>
<td>0.14</td>
</tr>
<tr>
<td>(8.92 ODT/acre)</td>
<td></td>
<td>600</td>
<td>5 ft + 2 ft</td>
<td>-----</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5 ft + 3 ft</td>
<td>-----</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.36</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.12</td>
<td>1.63</td>
</tr>
<tr>
<td>Swanbourne</td>
<td>1 Way</td>
<td>400</td>
<td>5 ft + 5 ft</td>
<td>0.14</td>
<td>0.200</td>
</tr>
<tr>
<td>(8.16 ODT/acre)</td>
<td>Reverse</td>
<td>400</td>
<td>5 ft + 2 ft</td>
<td>-----</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.22</td>
<td>-----</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.12</td>
<td>1.63</td>
</tr>
</tbody>
</table>

**Empire 2000**

Another self-propelled “cut-only” machine is the Empire 2000 which was built in Sweden (Figure 91). Front augers gather stems before they are cut by 2 circular saws and transferred into a conveyor which passes them to the rear of the harvester. After the stems are delivered horizontally to the collection chamber, they may either be transferred directly to a tractor and trailer or stored in the collection chamber for discharge at the end of the row.
In December 1995, a series of fourteen tests were carried out on the Empire 2000 in the U.K. (Hartsough and Yomogida, 1996); the machine achieved an overall average productivity of 6.7 Odt/std h. Test results are summarized in Table 26.

### Table 26. Empire 2000 study results (Hartsough and Yomogida, 1996)

<table>
<thead>
<tr>
<th>Site</th>
<th>Working Method</th>
<th>Average Run (ft)</th>
<th>Spacing</th>
<th>Output (acre/std hr) Actual</th>
<th>Output (acre/std hr) Without Blockage</th>
<th>Output (ODT/std hr) Actual</th>
<th>Output (ODT/std hr) Without Blockage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Castle Archdale</td>
<td>1 Way</td>
<td>140</td>
<td>3 ft + 3 ft</td>
<td>0.32</td>
<td>0.40</td>
<td>4.64</td>
<td>5.71</td>
</tr>
<tr>
<td>(14.4 ODT/acre)</td>
<td>Reverse</td>
<td>140</td>
<td>2 ft + 5 ft</td>
<td></td>
<td>0.47</td>
<td></td>
<td>6.43</td>
</tr>
<tr>
<td>Castle Archdale &amp; Swanbourne</td>
<td>2 Way</td>
<td>650</td>
<td>5 ft + 5 ft</td>
<td>0.47</td>
<td>0.59</td>
<td>4.23</td>
<td>5.34</td>
</tr>
<tr>
<td>(9.01 ODT/acre)</td>
<td></td>
<td>650</td>
<td>2 ft + 5 ft</td>
<td></td>
<td>0.86</td>
<td></td>
<td>7.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>660</td>
<td>2 ft + 5 ft</td>
<td></td>
<td>0.94</td>
<td></td>
<td>8.46</td>
</tr>
<tr>
<td>Swanbourne</td>
<td>Round Robin</td>
<td>720</td>
<td>5 ft + 5 ft</td>
<td>0.79</td>
<td>1.2</td>
<td>5.43</td>
<td>7.98</td>
</tr>
<tr>
<td>(6.88 ODT/acre)</td>
<td></td>
<td>660</td>
<td>2 ft + 5 ft</td>
<td></td>
<td>1.8</td>
<td></td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>660</td>
<td>2 ft + 5 ft</td>
<td></td>
<td>1.7</td>
<td></td>
<td>11.9</td>
</tr>
</tbody>
</table>

#### 8.4. Processing – Chipping

Chippers can be classified by type, which indicates the device on which the knives are mounted (disk or drum), size, and power source (electric motor or internal combustion engine) (Figure 92). Essentially any chipper will produce material that is acceptable for the direct combustion energy market. The ideal pulp chip, however, has relatively tight size tolerances, and larger disk chippers are generally considered to produce the highest quality chips. The blade and anvil on a disk chipper can be set to control chip thickness, and bigger chippers with higher inertia travel at more uniform speeds. Large chippers at fixed installations are powered by synchronous motors and turn at essentially constant speed. Knives on chippers at fixed installations are probably less susceptible to damage from rocks and can be replaced at more uniform intervals. All these factors result in
better chips from large fixed chippers than from small mobile chippers, so, from the standpoint of chip quality, it would be optimal if trees were transported to a central yard or a mill for processing. A large percentage of pulpwood is handled this way, but the remainder is chipped at landings after delimbing and debarking (Hartsough and Yomogida, 1996).

Figure 92. Whole tree chipper model 2090 from Bandit Industries.

Drum chippers can process larger and less-uniform material than an equivalent-sized disk chipper. Knives on drum chippers are less susceptible to damage by rocks and dirt, and can be sharpened many times without removing the knives; therefore drum chippers are commonly used to produce biomass fuel.

8.5. Conclusions

The use of conventional forestry equipments is probably not optimal for SRWC plantations, but the amount of such kind of plantation didn’t justify, until now, the full-cycle development of specialized equipments for smaller trees, i.e., lower than 8 cm DBH. But, the conditions in SRWC plantations, quite similar to agricultural crops, suggest that harvesting, processing and transportation can be carried out in different and cheaper ways.

The best machines are based on well-developed harvesters for traditional crops such as corn or sugar cane, and involve relatively minor developments, such as headers specifically designed for harvesting small diameter hardwoods. For small trees, harvesting concepts may be classified as cut-and-chip by one machine, cut-only, or cut-and-forward. Cut-and-chip appears to be the best option, because the bulk chips are cheaper to handle than whole trees, and because the harvester is smaller and has less idle time than a combination harvester-forwarder. Other possible ways are the smaller forestry machines developed for earlier thinning or multipurpose machines like the “harwarder”. The economical feasibility of the SRWC plantations for energy production will depend on higher crop production, lower price harvesting machines and the price of other energy sources.
9. REFERENCES


