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The Supply of Forest-based Biomass for the Energy Sector: The Case of Sweden

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Abstract

Biomass has become a popular alternative to fossil fuels in energy generation. Especially in Sweden, where vast quantities of forest resources are available, nuclear power is starting to be phased out, there are restrictions on expanding hydro power and there is the political will to “set an example” with respect to carbon dioxide emissions. These are the main drivers for the increased usage of biomass in energy generation. However, an issue often neglected is that domestic forest resources are already, to a large extent, used by the forest industries. By promoting biofuel the consequences for the forest industries need to be considered. This paper attempts to construct and analyze the supply of two types of forest resources, namely, roundwood and forest residues derived from either final harvest or commercial thinning operations. Two separate supply curves are constructed and estimated, one for *pulp usable* and the other for *pulp unusable* forest resources. The cost structure is based on an economic-engineering approach where the separate cost components are built up from the lowest cost element into aggregates for labor, capital, materials and overhead costs for each forest resource. The results indicate an untapped potential of 12 TWh of pulp unusable forest residues. However, after this 12 TWh has been recovered it becomes more profitable to use roundwood for energy purposes than to continue extracting further amounts of forest residues.

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The Supply of Forest-based Biomass for the Energy Sector: The Case of Sweden

Robert Lundmark

1 Introduction

Historically, economic growth in Sweden can, in large parts, be attributed to the expansion of industry sectors utilizing domestic raw materials such as timber and iron ore. Gradually, through technological progress and spill-over effects in and from the raw material based industries, Sweden managed to establish a foundation for a more diversified economic structure. Another notable observation regarding Sweden is that industries based on domestic raw materials still account for a significant share of manufacturing activity, although the export, production and employment shares of a more knowledge-intensive manufacturing and service sector have increased rapidly during the past few decades. The forest and metal industries together employ almost one-fifth of the industrial labor force and supply about a quarter of the total export. The continuing prominence of these sectors implies that raw material based production is not only a temporary stage in economic development but can be a sustainable element of an advanced industrial structure. This kind of long-run success requires public policies and company strategies that preserve the raw material resources and create the skills and competence that are needed to remain competitive in the face of increasing labor costs and changing technologies.

Traditionally, biomass has been used as food, as feed, as fuel and as fiber without any major conflict between the uses. Today, as a result of changing social structures and preferences, areas of conflict are emerging. The main source of conflict arises from the political willingness to increase the utilization of biomass in energy production since it is considered more environmental friendly than fossil fuels. This political willingness is often expressed in the form of subsidies for biomass use or as taxes on alternative fuels. The resulting increase in power production demand for biomass has marginally made it profitable to substitute food and feed production for energy forests and to utilize roundwood and forest residues for energy production infringing on the main feedstock for the forest industries. The reasons for increasing the utilization of biomass can broadly be explained by three causes: (1) fear of depletion of fossil fuels; (2) environmental concerns — mainly that of global warming; and (3) a surplus of agricultural land that has become available through the structural change of agriculture and “land set-aside” subsidies. Increasingly, policy makers are interested in evaluating the potential for, and implications of, large-scale production of energy using biomass as the main fuel. An integral component of evaluating this potential is an understanding of the quantities of biomass that might be available at any given price, i.e., a supply curve.

During the 1990s a number of energy policy instruments that support the utilization of forest-based biomass for energy generation were introduced. Political goals regarding renewable energy, taxes (not least on fossil fuels), subsidies, and recently trade with green certificates are some of the instruments that influence the utilization of biomass in the energy sector. Johansson *et al.* (2002) show that without existing environmental and energy taxes the life cycle cost (investment, operational and fuel costs) to produce district heating with coal or oil as the main fuel would correspond to roughly half of the cost compared to using biofuel. However, including the taxes, the cost of using coal or oil is almost twice as high as for biofuel. From an environmental perspective, the main argument for using biofuel is the fear of global warming which is associated with the emission of carbon dioxide from burning coal or oil. Domestic supply security and the political will to support a diversified energy mix are other factors influencing the strong support for biofuel utilization. Thus, the energy policy affects the production of forest resources and with that also the forest industries. If fossil fuels are taxed and highly priced as a consequence the consumer prices for energy will increase, which allows a higher price for biomass since biomass is the substitute for fossil fuels in the energy sector. For the individual forest holders it could therefore be more attractive to supply biomass to the energy sector instead of to the forest industries as the energy sector can pay a higher price. In this context the energy policy gives rise to increasing competition for the domestic forest resources. This situation has given rise to sharp protests from representatives of the forest industries who fear that the energy policy will upset the competition for the forest resources and emphasizes the fact that Sweden will lose considerable export incomes if the biomass is burned instead of used for additional refinement. On the other hand, energy sector spokesmen argue that an even more active approach in the energy policy should be conducted to support the utilization of biomass in energy generation. These representatives often argue that the energy potential from the Swedish forests is considerable and that no obvious conflict between the forest industries and the energy sector exists in the procurement of forest resources. The debate gained momentum as a consequence of the recent review of the Swedish energy taxation system. The situation described above and the following debate has been the origin to, at least, two important questions. *First*, considering the contradictory arguments, is there any conflict, or high level of competition, between the energy sector and the forest industries in their procurement of forest resources? *Second*, if not, what will it take for the energy sector to start infringing on the supply of roundwood previously exclusively available for the forest industries?

The study focuses only on the utilization of forest-based biomass in the electricity and heat sector. The future potential use of biomass to produce transportation fuel will not be considered. According to the standard definitions of biomass a number of sources can be identified. This study will be limited to only two categories namely that of biomass derived from final harvesting or commercial thinning that is either suitable for pulp production or not. The paper continues, in section 2, with a description of the current utilization of the forest resources in Sweden followed by a review of forest resource potential on a regional level in section 3. The method and model of the cost estimation is presented in section 4. Finally, the results and conclusions are presented in section 5 and 6, respectively.

2 Utilization of Forest-based Biomass in Sweden

Over 60 percent of Sweden is covered with forests. Pine and spruce are the dominant tree species with about 85 percent of the total, while birch accounts for 10–15 percent. The northern part of the country has the largest timber supplies, but growth rates are higher in the more intensively managed forests in southern Sweden. The forest inventory has been estimated at 2.8 billion m^3 standing volume. The annual increment is about 100 million m^3 standing volume, whereas felling has fluctuated between 50 and 80 million m^3 standing volume per year over the last few decades (NBF, 2003). Hence, timber supply is increasing continuously, and today it is more than twice as large as a decade ago. However, much of the increasing stock is taking place in remote and protected areas, which are uneconomical or illegal to harvest.

After a rotation period ranging between 80 and 120 years, depending on the region in Sweden, the forest stand is suitable for final harvesting. The main reason for harvesting is, of course, to access the roundwood but as a consequence harvesting residues, such as tree tops and branches, can be recovered, which are suitable for energy generation either directly or after being converted to pellets, for example.

About 17 percent of the Swedish forest areas are owned by public authorities, which is a low share compared to other European countries. The share of industrial forest holdings is 24 percent, which is higher than elsewhere in Europe. Apart from Swedish firms, only Finnish, Norwegian and Spanish industries have any significant forest holdings in Europe. The industry's forest holdings are concentrated to the largest pulp and paper companies, while most sawmills and other wood working industries do not posses any notable forest holdings. The remaining 59 percent of the total forest area are held by private owners and forest owner associations. The average size of public and industry holdings is large, above 100,000 hectares, whereas the average private forest holding is about 50 hectares. There are about 60,000 private forest owners (corresponding to a quarter of the total number of holdings) with less than 10 hectares of forests (Johansson *et al.*, 2002). The large number of small forest owners is sometimes considered to be a problem. One commonly heard argument, when the ownership structure is very fragmented, is that transaction and coordination costs are likely to be high, and the standard of forest management may be low. In particular, it is maintained that it is difficult to mechanize operations and introduce rational harvesting methods in small forest ownerships (UN, 1986). However, the ownership and size structure of Swedish forest holdings does not seem to have posed any major problem for the management of forest resources, as witnessed by the increasing total supplies. The majority of private forests are relatively well managed, partly because the forestry sector is strictly regulated and governed by law and recommendations, and partly thanks to fiscal incentives and training and extension services provided by the public sector.

Although the ownership structure has not constituted any major problem for forest management, there are some frictions in marketing. Many of the smaller private forest owners are not dependent on revenue from the forest as they also have other sources of income. Consequently, they may be unwilling to harvest when market conditions are bad and instead wait for better prices. During times of high inflation, it may also be rational for private owners to keep capital in a growing forest rather than in other forms of wealth with lower real yield. Hence, delivery volumes may fluctuate widely, depending on market conditions. To avoid this type of volatility, the pulp and paper industry, in particular, has tried to segment the market. A large share of the industry's raw material supplies is regulated through long-term contracts with individual forest owners and regional associations of forest owners. Simultaneously, there is a spot market and a substantial import to accommodate fluctuations in demand. This system has managed to stabilize the raw material flows, although the price sensitivity of small, private forest owners was illustrated by their unwillingness to harvest in the late 1970s when roundwood prices were unfavorable. However, the resulting raw material shortages mainly affected the independent sawmills whose own forest holdings are limited and forced market reorganizations and price increases (UN, 1986). To balance the market power of the large pulp and paper firms and the forest owner's associations, sawmills and other wood manufacturers have been forced to establish purchasing organizations.

2.1 Forest Industries

Table 1 summarizes some information about the structure of the two main industry groups in the Swedish forest sector: sawn wood and pulp and paper. The sawn wood product group includes sawmills and plants producing various types of wood panels, building joinery, pre-fabricated wooden houses, and wooden furniture. The pulp and paper category includes pulp and paper mills. The paper mills manufacture paper products such as paperboard and other packaging materials, stationary, tissues, wallpaper, etc. It can be seen that the pulp and paper sector was largest in terms of production values and value added, although the two sectors are roughly equal in the number of employees. The higher productivity in paper and pulp is explained by the industry's high capital intensity.

The value of the Swedish forest product exports in 2002 was 93.4 billion SEK (1 US$ ≈ 8.1 SEK), while imports amounted to 12.9 billion SEK. Thanks to large net exports, the forest sector made a larger contribution to the Swedish balance of payments than any other industry. Table 2 shows that the quantitatively most important export products were paper and paperboard, pulp and sawn wood products. In addition, it can also be noted that the categories where Sweden was a net importer were roundwood, fiber- and particle boards, and chips and particles. Imports of roundwood and chips have increased over time due to low raw material prices in, e.g., Russia and the Baltic States after the fall of the Berlin Wall. The imports of veneers consist largely of hardwoods that are not available from domestic sources.

Table 1: The Swedish forest industry, 2001. Source: SCB (2003).

	Production Value[a]		**Value Added**[a]		**Employment**[b]	
		Share of total mfg[c]		**Share of total mfg**[c]		**Share of total mfg**[c]
Sawn wood products[d]	65.0	4.9	16.2	4.3	35.9	5.2
Pulp and paper[e]	113.3	8.6	40.7	10.8	39.0	5.6
Total	178.3	13.5	56.9	15.1	74.9	10.8

[a] Billion SEK.

[b] '000 employees.

[c] Manufacturing industries (mfg) includes industry classification codes 15–36 (SNI92)

[d] Includes industry classification codes 20.1–20.5 (SNI92).

[e] Includes industry classification codes 21.1–21.2 (SNI92).

Table 2: Exports and imports of forest products, 2002. Source: FAO (2003).

	Imports[a]	**Exports**[a]
Chips and particles	0.6	0.1
Fiberboards	0.4	0.1
Particle board	0.7	0.2
Roundwood	3.9	0.8
Sawn wood	1.1	21.1
Paper and paperboard	4.6	56.9
Pulp	1.7	14.2
Total	12.9	93.4

[a] Billion SEK converted from USD using the average 2002 exchange rate of 9.7243 SEK/USD.

In aggregate terms, Sweden was among the world's largest exporter of woodpulp, paper and paperboard, and sawn wood in 2002 as shown in Table 3. The major competitors were USA, Canada, Finland, Russia, Germany and, to a somewhat lesser extent, Brazil and Austria.

Table 3: World export and production 2002. Source: FAO (2003).

	Export[a]		**Production**[a]	
Paper and paperboard				
Canada	14.3	(14.9)	20.2	(6.2)
Finland	11.5	(11.9)	12.8	(3.9)
Germany	9.7	(10.1)	18.5	(5.7)
Sweden	8.9	(9.3)	10.7	(3.3)
USA	8.2	(8.5)	81.8	(25.3)
World	96	(100)	323	(100)
Woodpulp				
Canada	11.8	(29.7)	25.7	(15.3)
USA	5.7	(14.3)	53.6	(31.9)
Sweden	3.3	(8.3)	11.4	(6.8)
Brazil	3.3	(8.3)	7.3	(4.3)
World	40	(100)	168	(100)
Sawnwood				
Canada	37.3	(32.2)	52.9	(13.6)
Sweden	11.5	(9.9)	16.6	(4.2)
Russia	9	(7.8)	22	(5.7)
Finland	8.1	(7.0)	13.4	(3.5)
Austria	6.6	(5.7)	10.4	(2.7)
USA	4.5	(3.9)	89.1	(22.9)
World	116	(100)	389	(100)

[a] Million metric ton (percent of world).

2.1.1 Price development for saw logs and pulpwood

Figure 1 depicts the price development for pulpwood of spruce, pine and birch, and for sawlogs of spruce and pine expressed at the 2001 price level. Unfortunately, in 1995/1996 the method of calculating the price series changed, making a direct comparison for the latter years difficult. Scrutinizing Figure 1 reveals three distinct features in price development. (1) The price for sawlogs lies consistently above that of woodpulp. (2) All of the price series exhibits a drastic increase during the early 1970s. A plausible explanation is the first oil crisis that increased the operation costs for harvesting, which is heavily mechanized and dependent on road transportation. (3) Fitting a simple linear trend line to the price series reveals that all prices tend to decrease over time. A reduction in the price of delivered logs would increase its demand from the power sector.

When harvesting forests not only roundwood are obtained but also large volumes of residues, i.e., tops and branches, become available. The main economic rationale behind deciding whether or not to harvest has historically been the price level of roundwood with the recovery of residues having a minor influence. In fact, even today most residues are left on the ground as economical or ecological restrictions will not permit recovery.

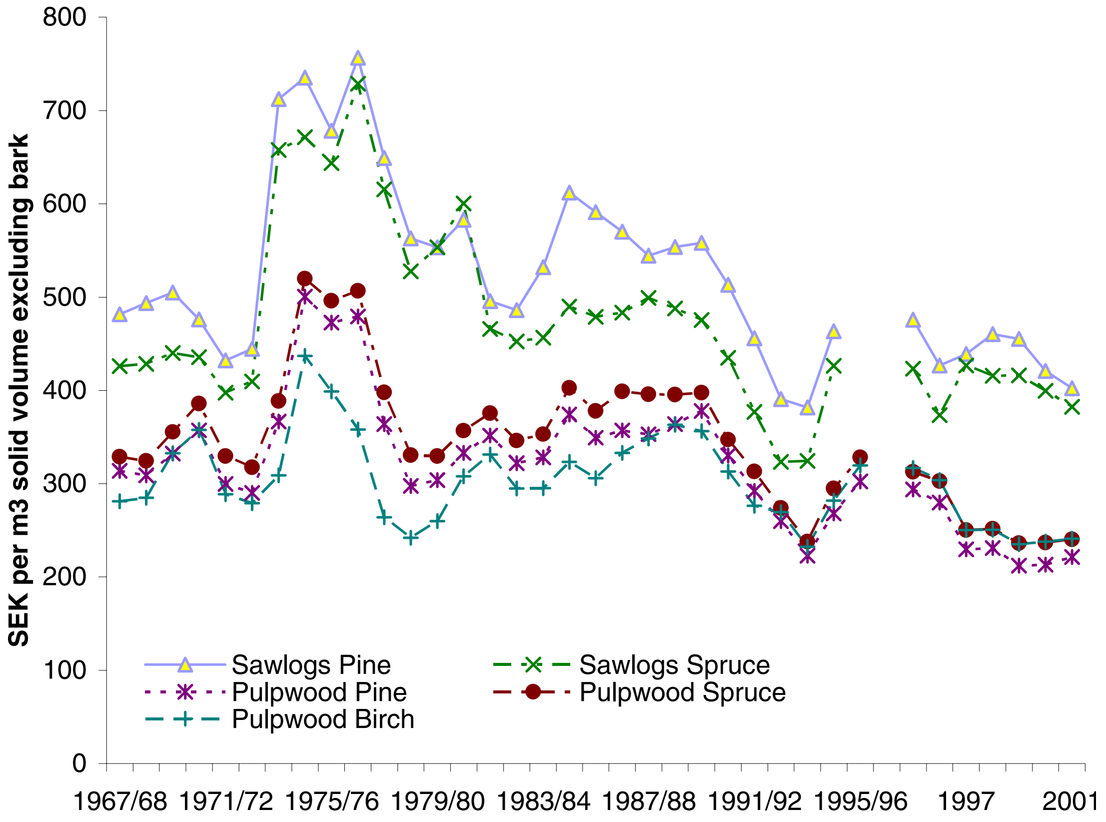

Figure 1: Average price of sawlogs and pulpwood of various species, delivery logs. Source: NBF (2003).

2.2 The Swedish Power Sector

During the period 1990 to 2001 the total energy supply in Sweden increased from 569 TWh to 616 TWh, which is a 7.6 percent increase. The contribution of biofuel, including black liquor, during the same period, increased from 65 TWh to 98 TWh, which corresponds to a 50 percent increase and constitutes almost 16 percent of the total energy supply. Today, biofuel is a larger energy source than hydro power (STEM, 2002). Table 4 presents the various energy sources contribution to the Swedish energy supply for the years 1990 and 2001.

The total energy demand in Sweden is expected to increase by 27 percent to the year 2020 (NUTEK, 1996). This expected increase in total energy demand, coupled with the decrease in energy supply due to nuclear power phase-out makes biofuel one of the most attractive alternatives to Swedish energy provision. Since further expansion of hydro power is not desirable and an increasing utilization of fossil fuels contradicts set environmental targets, renewable energy sources is expected to supply large parts of the future energy supply.

Table 4: Energy supply in Sweden in 1990 and 2001. Sources: STEM (2002) and Brunberg *et al.* (1998).

Energy Source	**1990**		**2001**	
	Supply TWh	**Share %**	**Supply TWh**	**Share %**
Oil and oil products	187	33	191	31
Nuclear power	201	35	206	33
Biofuels	65	11	98	16
Hydro power	73	13	64	10
Coal	31	5	25	4
Gas	7	1	7	1
Other	5	1	25	4
	569	100	616	100

2.2.1 Biofuel utilization in the energy sector

Biofuel is defined as fuel derived from biological material and is categorized in different groups depending on origin, manufacturing method, fraction sizes, etc. Woodfuel is such a subcategory and is defined as all biofuel where trees or part of trees are the original material and where no chemical transformation has occurred. Woodfuel can also consist of recycled wood products. Forest fuel is a category of woodfuel and includes stems, forest residues, needles and stumps as well as industrial residues such as bark, saw dust and wood chips. As the main focus of this report is on forest resources derived directly from the forests, the main emphasis from now on will be on the forest fuel category.

Biofuel is mainly used in the industry and district heating sectors. The small building sector is also an increasing user of biofuel. Within the industry, the pulp and paper industry's by-products, e.g., black liquor, constitute the single largest fraction of biofuels and generated roughly some 35 TWh in 2001. This energy supply is, however, mostly used internally and is hence not available on the energy markets. Saw mills and the wood product industry uses approximately 8 TWh of biofuels mostly also for internal energy generation. Table 5 shows the different origins and major users of biofuels together with used quantities in Sweden for the years 1990 and 2001.

Table 5: Utilization of biofuels in Sweden in 1990 and 2001. Sources: STEM (2002) and Brunberg *et al*. (1998).

Origin	**User**	**1990**		**2001**	
		Quantity TWh	**Share**	**Quantity TWh**	**Share**
Wood fuel	Pulp and paper	8.2	12.6	7.7	7.9
	Saw mills	6.4	9.8	8.3	8.6
	District heating	3.6	5.5	18.6	19.2
	Small building	10.2	15.7	9.3	9.6
Black liquor	Pulp and paper	27.6	42.5	34.5	35.6
Biofuel for electricity generation	Forest industry	0.5	0.8	2.6	2.7
	Heating sector	0.6	0.9	1.8	1.9
Other (peat, etc.)	Forest industry	0.8	1.2	0.7	0.7
	District heating	2.6	4.0	4.8	4.9
Refuse	District heating	4.0	6.2	5	5.2
Statistical uncertainty		0.5	0.8	3.7	3.8
		65		97	

The main usage of biofuel in pure energy production facilities is in district heating and in combined heat and power production (CHP) but also usage of biofuels in refined form, e.g., pellets, occurs in the small building sector equivalent to 9.8 TWh. It is in the district heating and CHP that the largest increase in biofuel usage has occurred since 1990. Approximately 29 TWh biofuels was used for heat production in district heating plants during 2001. Wood fuels accounted for 18.6 TWh, while the remaining heat was generated using a mix of tall oil, refuse, peat and other biofuels. Since 1990, the utilization of wood fuel in heat production has increased five-fold and consists chiefly of forest residues and industrial by-products.

District heating means that heat is sold to many customers in a highly urbanized area usually from a single transmission system, which encompasses the entire urbanized area. Since its inception in the 1940s, the Swedish district heating sector has grown significantly and today consists of more than 200 firms that produce and distribute heat through the system. High energy efficiency, low levels of emission and high flexibility regarding fuel choice have been the dominant factors explaining the growth. Today, district heating supplies almost 40 percent of the heat demand for dwellings and other premises in Sweden. In 2001, some 45.7 TWh of heat was supplied of which 62 percent, or 29 TWh, was generated using biofuels. This can be compared with the 1980s when roughly 90 percent of the fuel mix in the district heating sector was made out of oil. As a consequence, the district heating sector has played an important role in the development of biofuel usage. The flexibility in fuel choice is one reason that makes changes in fuel choice easier in response to changing relative prices.

There are about 1.7 million private houses in Sweden and roughly 50 TWh of fuels and electricity is used for heating and warm water supply. The prerequisite for heating in private houses varies greatly depending on the level of urbanization. The choice of heating alternatives is wide and includes different energy sources, energy carriers and transmission systems. The wood fuel that was used in private houses made up approximately 9.3 TWh in 2001, of which the main part consisted of traditional fire wood and a lesser amount of wood chips and pellets.

2.2.2 Forest fuel types

The energy sector procurement of forest fuels is primarily done by the chips of forest residues, industrial by-products and through refined forest fuels such as pellets. Forest fuels are used in many different forms. From the users perspective it is not sufficient to describe the origin of the forest fuel but also the form must be considered otherwise misinterpretations are easily made.

Forest residues include branches, tops, small trees and low quality stems that lack usage in the pulp and paper industry. Recovery of forest residues can occur either at thinning operations or at the final harvest. Forest residue recovery in connection to final harvest can create considerable synergy effects as most of the costs can be carried by the roundwood harvested. Chipping of forest residues is done either at the road side or at the heating facilities. The forest chips are most suitable for use in middle to large size facilities as these facilities have better possibilities of using chips with varying quality. However, the specific quality demand varies with combustion technique and can therefore be considered unique to the individual user. Figure 2 depicts the production and real price development for forest chips between 1993 and 2002. During this period, production increased by almost 5,000 GWh to 8,500 GWh. The real price has remained relatively constant during the period at a price level of 45 SEK per MWh for the heating sector, while the industry pays somewhat less.

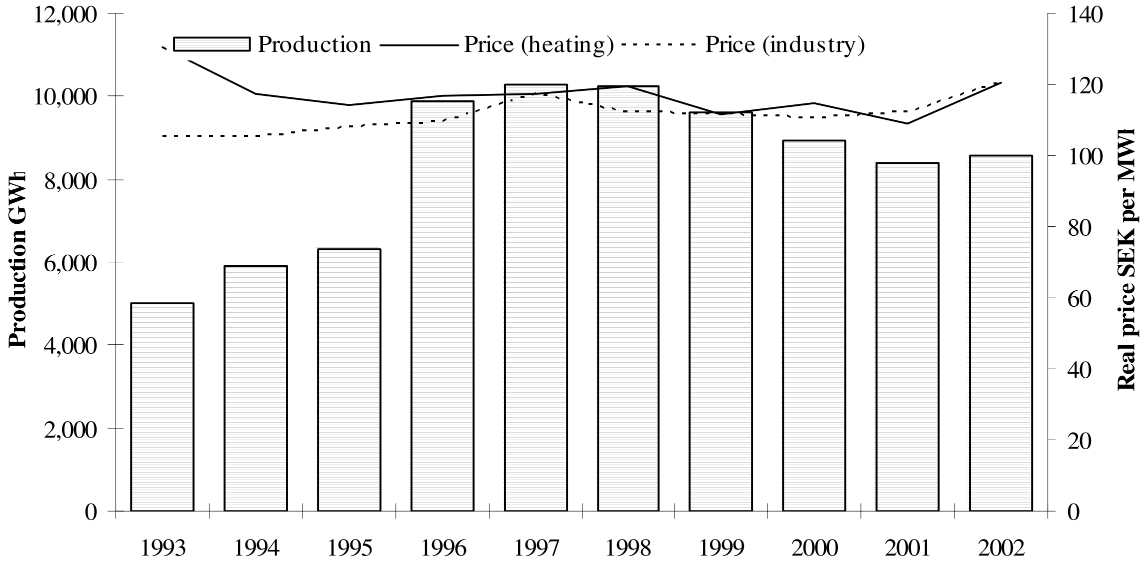

Figure 2: Production and price development of forest chips between 1993 and 2002 (2001 price level). Source: NBF (2003).

Refined forest fuels means that the forest fuel has been processed so that its properties have changed making it more suitable for its purpose. The most dominate forms of refined forest fuels are pellets, briquettes and wood powder. By refining wood fuels the combustion and transportation properties of the fuel is improved. This means, for example, that smaller furnaces or furnaces that have been converted from oil or coal burning can more easily be used with refined wood fuels. The most used raw material in the manufacturing process for refined wood fuels has traditionally been industrial by-products from the saw mills and other mechanical wood product industries. Wood chips and saw dust from saw mills dominate but also straw, peat and other energy crops can be used to a certain extent. With improved production processes and combustion technology the degree of substitution between different biofuels will increase. However, the possibility of using different biofuels in the production of refined wood fuels today is already high. The production of refined wood fuels occurs in some 30 facilities regionally dispersed in Sweden. Of the total production, pellets constitute 70 percent while wood powder and briquettes make up the remainder. Due to vertical integration with other wood related industries, approximately 35 percent of the raw material is purchased internally while the rest is purchased on the open market. Figure 3 illustrates the production and real price development of refined wood fuels in Sweden between 1993 and 2001. The production has increased from almost 1,400 GWh to more than 5,100 GWh, which is almost a four-fold increase. Despite the large production increase, the real price has not changed much. A smaller increase from 58 SEK per MWh to almost 62 SEK per MWh is the only effect.

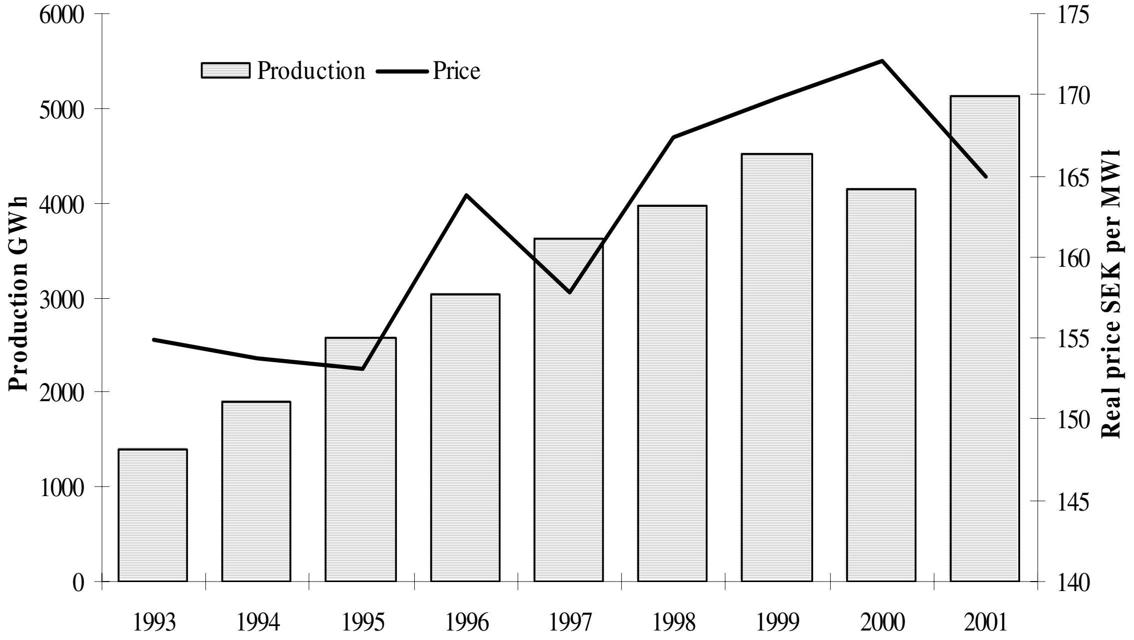

Figure 3: Production and real price development of refined wood fuels between 1993 and 2001 (2001 price level). Source: NBF (2003).

3 What Is Actually Available Out There?

During the last few decades, a number of harvesting calculations have been conducted by the Swedish National Board of Forestry. In studies evaluating the forest fuel potential the most used harvesting calculation has been the *Harvesting Calculation 1992* — AVB 92 (SOU, 1992:76). All studied reviews in the report have used AVB 92 as the base in their estimations. However, future felling levels are differently assumed in the studies, which are based on different beliefs regarding expected future demand on wood products. Thus, the reviewed studies all assume the same *physical* potential of forest fuels. The difference arises mainly due to different assumptions on the ecological, technical and economical restrictions (Table 6). The reviewed studies include:

- The Swedish Forest Industries Federation (FI) (conducted by Jaakko Pöyry, 1995);
- Biofuel Commission (BC) (SOU, 1992:90);
- Swedish University of Agricultural Sciences (SIMS/SLU) (Hektor *et al*., 1995);
- Royal Swedish Academy of Engineering Sciences (IVA) (see NBF, 1996); and
- Farmers National Association (LRF) (see NBF, 1996).

Table 6: Summary of the assumptions regarding supply restrictions. Source: SOU (1995:139).

Common assumption:

AVB 92.

The quantity of forest residues depends on the harvesting of trees for the industries' need.

Assumptions common for SIMS and BC:

Wood has no immediate interest as a fuel, except from thinnings.

Limitations due to ecological restrictions as a consequence of, for example, the redistribution of ashes.

SIMS specific assumptions:

Technological development makes it possible to recover forest residues to a larger extent.

Forest ownership borders pose no obstacle.

BC specific assumptions:

Assumptions made on patterns for technological and economical restrictions.

FI, LRF and IVA specific assumptions:

Unchanged ecological restrictions, i.e., no redistribution of ashes.

Wood from thinnings is supplied to the forest industries.

Limited economical restrictions.

Table 7 gives a more detailed account of the total potential of forest fuels categorized by fuel type. Of special interest for this study is the primary wood fuel estimates. The amounts of residues that can be extracted per tree vary with species, age and region. BC and SIMS have used the same method to calculate the gross availability of forest residues from a certain level of harvesting. Both studies assume that redistribution of ashes takes place. On the other hand, FI calculates the availability of forest residues without any distribution of ashes and concludes that forest residues are only economically viable to extract in connection with final harvesting due to the high costs involved. As a consequence, FI arrives at a potential amount of forest residues roughly 40 percent less than the SIMS and BC calculations.

Table 7: Potential availability of wood fuels by category (TWh). Source: STEM (1999).

Study	Recycled wood fuel	Primary wood fuel[a]	Industrial by-products	Sum
SIMS	4	101–109	16–17	121–129
BC	4	60–69	12–13	76–86
IVA	4	54–60	19–21	77–85
FI	4	26	17	47
LRF	4	31	20	55

[a] Wood fuel that has not had any previous use, e.g., forest residues.

Wood from thinnings can be used by the forest industries, i.e., in the pulp industry, and by the energy sector. This type of wood is, however, less suitable in the production of sawn wood products. Nonetheless, new technologies have increased the possibility for saw mills to use logs with a smaller diameter. An especially noteworthy distinction between the studies regarding wood utilization is the level of technical change that is assumed.

A considerable technical change in the forest industry is assumed in the FI study indicating, together with an increasing demand for pulp and paper products, the exclusion of wood derived from thinnings to be used as fuel. Furthermore, FI argues that the available amount of wood not harvested is best left in the forests so that any future increase in demand can be more easily meet. SIMS and BC argues, on the contrary, that the stems not used by the forest industries should be harvested and used as fuel. In addition, SIMS and BC assumes a considerable technical change in the energy sector. This is motivated by the fact that increased employment of already existing technologies will enhance the overall efficiency and larger operations gives more financial room for investments and research and development. Hence, a rapid expansion rate for utilizing wood fuel will most likely result in a faster technical development compared to the more mature forest industry sectors.

The conditions for extracting forest fuel vary considerably between the different regions in Sweden. Besides differences in ecological, biological and terrain specific properties that restricts the amount of wood fuel availability, the transportation possibilities puts further restrictions on the local supply of wood fuel. Even the profitability of using wood fuel is, to a large extent, depending on the transportation distance. The reason is that the energy content of wood fuel is less than that for fossil fuels, for example. The energy content of a ton of oil is approximately 11 MWh while for refined wood fuel it is approximately 4.6 MWh and for unrefined wood fuel about 2.8 MWh per ton. To what extent wood fuel can be transported from a region with surplus to a region with deficit depends, thus, on the transportation costs that, in turn, depend on transportation means and distance. The cheapest way of transportation is by boat followed by train and finally by truck. When it comes to domestic wood fuels, such as forest residues, it is often necessary to first transport it by truck and then reload to train or boat at a terminal. This involves increasing transportation costs for train and boat and makes trucks the most cost efficient way of transportation up to a distance of roughly 150 kilometers. For distances up to 500 kilometers train transportation becomes cheaper and for distances above that boat becomes the most cost efficient. Today, forest chips are, on average, transported some 70–80 kilometers and the transportation costs account for roughly 20–25 percent of the price (Börjesson, 2001). In a scenario where large quantities of forest chips are transported from surplus regions, such as Dalarna, Jämtland, Kronoberg and Jönköping counties, to regions with a deficit, such as Stockholm county, the transportation distance is between 300 to 600 kilometers indicating that it becomes cost efficient to reload to trains and thus the transportation costs becomes almost twice as high or between 45–55 SEK per MWh compared to 20–25 SEK per MWh without reloading.

Table 8 is recreated based on Börjesson (2001) and Lönner *et al.*, (1998) and depicts the regional differences in forest residue and wood potentials. The total forest residue potential is estimated to be approximately 22.4 million m^3ub and the stem potential to 78.3 million m^3ub per year.

Table 8: Estimation of regional forest resource potentials (1,000 m^3ub). Sources: Börjesson (2001) and Lönner *et al.* (1998).

County	Forest Residue Potential	Wood Potential
Norrbotten	1,259	5,254
Västerbotten	1,552	6,474
Jämtland	1,722	7,185
Västernorrland	1,559	6,504
Gävleborg	1,627	5,265
Dalarna	1,947	6,300
Uppsala	548	1,775
Stockholm	245	792
Västmanland	655	2,121
Värmland	1,293	4,579
Örebro	747	2,646
Västra Götaland	1,571	5,564
Östergötland	1,187	3,679
Kalmar	1,217	3,775
Blekinge	409	1,268
Skåne	1,108	3,434
Halland	452	1,402
Kronoberg	1,270	3,937
Jönköping	1,435	4,451
Södermanland	544	1,686
Gotland	76	237
Sweden	22,424	78,326

Table 8 is further broken down in Figure 4 by not only separating wood and forest residues but also the type of harvesting, i.e., final harvest or commercial thinning. As can be seen in Figure 4 the largest amount of forest resources is available in the northern and southwestern parts of Sweden, while considerable less is available around Stockholm and the southern parts of the country.

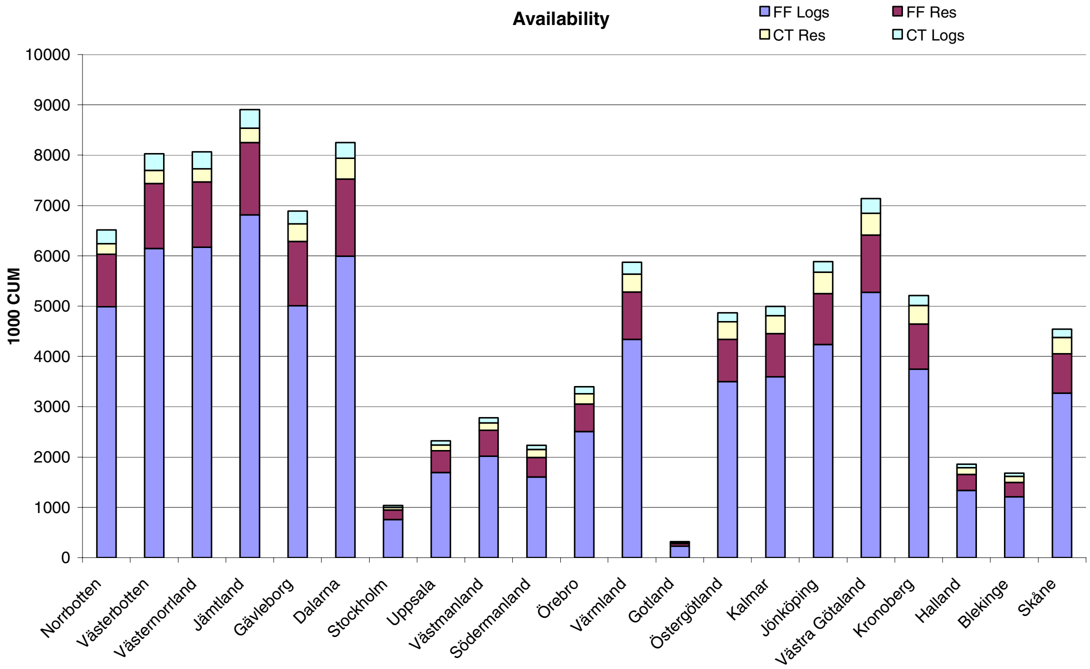

Figure 4: Regional potential of wood and forest residues by county and type of cutting. Sources: Lönner *et al*. (1998) and Börjesson (2001).

Earlier studies on the energy potential in the Swedish forests indicate that there are relatively few technical obstacles to increase the utilization of wood and forest residues. However, and this can not be stressed enough, there is an essential difference between potential and availability on the one hand and economic supply on the other. Unfortunately, the economic constraints are only elucidated from a superficial point of view in the studies reviewed. In order to clarify the economic constraints and to be able to present a clearer illustration of the real supply possibilities of wood fuel a more detailed analysis regarding the cost structure for the different categories of wood fuel is needed.

4 Cost Structure

The forest resources extraction process is a series of operations that, like many other raw material extraction processes, is relatively straightforward and does not require exceedingly complex components. Therefore, the extraction is technically feasible in a wide range of production configurations, including manual chain-saw fellings as well as sophisticated, high-volume mechanized fellings. Along with the ranging set of feasible technical configurations, the per unit production cost varies. The analysis of the cost structure was carried out through the estimation of harvesting costs using harvester-forwarder technology. For each category of forest resources, i.e., wood and forest residues from final felling and commercial thinning, the economic-engineering approach were used to develop a total cost per unit of output.

The economic-engineering approach does not strictly require the use of particular methods, however, it more generally prescribes a set of guiding principles that have come to be accepted as "standard good practice" (French, 1977). Statistical analysis is the most common alternative method to the economic-engineering approach for evaluating cost structures. One advantage of the economic-engineering approach over statistical analysis is that the economic-engineering approach can be applied when data are less available, as is often the case for costs. However, a major limitation of the economic-engineering approach is the high cost of implementing the approach. The estimation of production functions and a complete process cost function requires a significant amount of detailed technical data about each stage of the process. Following the economic-engineering approach in estimating the cost structure for each type of forest resource, a series of four procedural steps were followed. These steps include: (1) development of a description of the processing system comprising the extraction; (2) specification of the alternative production and processing stage techniques that are technically feasible, (3) estimation of the productivity functions for each stage or component in the extraction process and accumulation of the functions into a production function, and (4) synthesis of the extraction cost functions by applying input factor prices.

In general, four stages are defined in the extraction process. The stages include: (1) setting up the harvester for harvesting; (2) harvesting and separation of residues; (3) transportation of the forest resources from the harvesting site; and (4) piling and chipping the wood and forest residues in preparation for transport of the final product. The extraction and processing costs for each forest resource are synthesized from the combination of estimated productivity functions and average input factor prices. Standard economic cost procedures were used to synthesize the total cost functions including a long term fixed cost component and variable operating cost. Fixed costs include capital costs, depreciation and maintenance of machinery and equipment. Variable operating costs include labor, additive materials and overhead costs. Machinery and equipment investment costs are based on the purchase of new machinery and equipment without consideration of the cost and availability of used equipment. A straight line depreciation method is used to calculate depreciation cost of the machinery and equipment to be fully depreciated over a useful life of ten years with zero salvage value. This approach represents a maximum depreciation cost estimate since major components of machinery and equipment will have a useful life of more than ten years (or have a positive salvage value at the end of ten years). Annual maintenance cost was calculated at 2 percent of the initial machinery and equipment investment cost. Variable operating costs, including labor, materials and overhead costs, are synthesized from the component productivity.

4.1 Forest Management

The laws in forestry initially (i.e., from their institution in 1903) focused on securing sustainable raw material supplies, and the central rules stipulated that fellings should not exceed the increment, and that replanting should be undertaken after all final felling operations. Over time, the forestry laws have come to cover an increasing number of objectives. Nowadays, environmental considerations are among the most important issues, although the laws also aim to guarantee a steady flow of raw material to the forest industry. For instance, all forest owners are required to prepare a forestry plan, outlining expected thinning, felling, replanting and other operations. Thinning is mandated to increase to average log volume. One of the main challenges facing the Swedish forest industries in the early 1990s was the need to adapt forest management practices, production processes, and products to stricter environmental regulations and requirements. In the area of resource management, much of the pressure for change came from environmental organizations, which attacked commercial cultivation and harvesting methods — for instance, the practice of clear-cutting, which was perceived to destroy bio-diversity of the forests. Forest companies in Sweden were therefore more or less forced to adapt their operations, and introduced new practices that reduced the size of clear-cut areas, allowed old trees to be left standing, limit the building of logging roads, and restrict felling around river banks, lake shores, other important wildlife habitats, etc.

Thinnings are a standard silvicultural practice. In southern Sweden, nearly all economically viable stands are thinned commercially two or three times, and in northern Sweden once or twice, during the rotation period. Commercial thinnings are preceded by a pre-commercial thinning, from which timber is not harvested because of the small tree sizes. However, the short term perspective of the cost structure developed in this report makes changes in thinning practices of less importance.

Large parts of tree nutrients are contained in its branches and tops. When forest residues are removed from the harvesting area large amounts of minerals and nutrients are also removed. This removal must be compensated to ensure long run sustainability of the forest stands. An alternative to compensate for the nutrition loss that is currently widely discussed is to return the ashes that ensue from burning the forest residues. This procedure is assumed to increase the quantity of forest residues that can be extracted without harming the future productivity of the forest stands. Estimations indicate that when forest residues are removed in connection with final harvesting approximately 1–2 tons of ashes per hectare must be returned in order not to lose long term productivity. The associated costs for distributing the ashes, however, are uncertain, mainly due to rapid technical development and lack of standardized distribution methods. Nevertheless, depending on how the ashes are refined, transportation distance, and distribution method the cost of distributing the ashes is estimated to be between 600 and 1000 SEK per ton, which is equivalent to roughly 5 SEK per MWh (EPA, 1997). On the other hand, the alternative to distributing the ashes is to deposit it, which also has associated costs. For example, ashes are usually needed to be treated before being deposited. In addition, costs for handling, transport, administration, direct deposit fees and refuse deposit tax must also be included. As a consequence, returning the ashes to the forest stands does not necessarily have to be more expensive than depositing the ashes. On the contrary, it can very well be a significantly cheaper option, especially if methods for large scale redistribution systems are developed. Based on these studies, an additional cost component has been added to the total cost function to reflect the costs of returning ashes.

When the recovery of residues is included in the forest owners' optimization regarding rotation length of their stands, empirical studies indicate that the rotation length will be shorter than what is optimal if only considering a harvest of timber. However, the magnitude of the shortening is only in the range of between 2–3 years (e.g., Bjørnstad and Skonhoft, 2002). Therefore, no dramatic effects on forestry practice — in terms of rotation length — are expected as a result of jointly producing timber and recovering residues. On the other hand, including the benefits from carbon sequestration into the optimization will rapidly increase the rotation length. Thus, since accounting for CO_2 storage increases the socially optimal rotation length while accounting for the forest as a source of bioenergy shortens the rotation length, it becomes a challenge to design an appropriate forestry policy in response to climate change. Furthermore, the optimal rotation period will only decrease marginally by including the possibility to recover residues at harvesting and will hence not be considered.

4.2 Harvesting Technologies

While fossil fuel occurs in large deposits and can be produced at a fairly constant cost, forest fuels are scattered and must be collected from a large number of stands. Technical logging conditions in these stands vary widely and the variations are reflected in the productivity and cost of the work. The effects of cost factors associated with the operating environment depend on the scale of operation, the technology applied, and the source and quality requirements placed in biomass. Roundwood and forest residue production costs are calculated assuming harvester-forwarder technology. No subsequent transportation beyond road side delivery by the forwarders is included. Furthermore, the harvest of forest residues is assumed to be chipped at the road side by a mobile chipper. Again, no further transportation to the end-users is included in the model. The cost factors of wood, especially for forest chips production, are not known sufficiently. This lack of elementary knowledge has been recognized as a serious shortcoming from the view point of technology development (Hakkila, 2003). The effect of factors such as stand conditions and transportation distances should be known for a number of reasons: (1) to identify the most advantageous stands for production; (2) to estimate the change in costs when demand increases or quality requirements are tightened; (3) to focus on the key problems in machine and method development; and (4) to collect relevant material for practitioners for decision making. The cost functions indicate the driving forces behind the cost structure and emphasizes the importance of geography (terrain), the forest resources itself, technology and the management regime has on the competitiveness of the industry sectors using forest resources as a feedstock.

The integration of forest chip production with the procurement of roundwood opens up possibilities for cost savings. It is feasible to use the existing transportation equipment for forest residues whenever possible. However, due to differences in handling properties and destinations special equipment is also needed. Unfortunately, little machine compatibility has been achieved in the procurement of forest chips. The lack of compatibility is because the logging conditions vary considerably from thinnings to final harvest and because the technology is still relatively new. Several alternative production systems are in use and each system employs special equipment that is not necessarily compatible with other systems (Hakkila, 2003). Poor compatibility increases the commercial risk for contractors and users when they invest in new equipment and may result in under-employment and unnecessary shifts of harvesting machines from one site to another.

A forest fuel production system is built around the chipping component. The position of the chipper or crusher in the procurement chain largely determines the state of biomass during transportation and consequently whether subsequent machines are dependent on each other. Chipping may take place at the source, at the road side or landing, at a terminal, or at the plant where the chips are to be used. The system predominately used today is the road side or landing chipping. Landing chippers do not operate off-road and can therefore be heavier, stronger and more efficient than terrain chippers. The close linkage of chipping and trucking results in waiting and stoppages and thus reduces the operational availability. On the other hand, the landing chippers are reliable and their technical availability is rather high. The system has so far kept its position as the basic solution of large-scale procurement of forest chips.

Chipping at the road side or landing is performed in smaller operations with farm tractor-driven chippers and in large-scale operations primarily with heavy truck mounted chippers or crushers. The biomass is hauled with forwarders to the landing and bunched into piles four to five meters high. This facilitates operations in difficult terrain and in winter conditions and allows longer off-road hauling distances. The forwarder operates independently of the chipper. The chipped biomass from the chipper is blown directly into a 100 to 130 m^3 loose volume trailer truck, which delivers the chipped biomass to the user. A wider landing is required than in the alternative systems because of the large road-side inventories of biomass and the simultaneous presence of the chipper and the truck. Results from cost factors studies (Asikainen, 2003) for logging residues from final harvests indicate that:

- The cost of recovery depends on the yield of biomass per hectare. The recovery of logging residues from the final harvest of mature spruce stands is normally 20 percent of the recovery of roundwood. For pine, the corresponding figure is not much more than 10 percent. The cost of harvesting is thus lowest in spruce dominated stands and the availability of forest fuels is best in regions where spruce is the dominating species.
- The proportion of foliage in logging residues from mature stands is 30 percent for spruce and 20 percent for pine. The cost of chips increases if the residues are left to season on the site so as to improve the quality of the fuel and reduce the loss of nutrients from forest soils through defoliation. The cost increase is caused by reduced biomass recovery, the delay in the harvesting schedule, and accompanied logistical disadvantages.
- If a plant's demand for logging residues increases, the average cost of procurement increases as well, because the operations must be extended to less favorable stands and at greater distances. Considerable regional differences result from differences in the structure of forests and species dominance. Furthermore, a plant with a coastal location has to operate within a semicircular procurement area, whereas plants in the interior typically operate within a circular procurement area.

The following examples of new technology that has been developed recently illustrate the rapid progress that is being made in the field of wood fuel: (1) multi-tree handling

(MTH) felling for cost effective felling in small sized tree stands; (2) new forwarder variants for heavier payloads; (3) chippers operating on the strip road; (4) baling of logging residues, e.g., to cut transportation costs and to increase efficiency of chipping; and (5) heavy-duty chippers to meet the need for efficient, large-scale chipping at the terminal or mill/consumer plant.

Only one technology is assumed to be used within the cost calculations in the harvesting operation implying that all producers use the same technology regardless of regional differences. Ideally, different harvesting technologies should be used for different environmental conditions.

4.3 Cost Calculations

The above discussion provides the basic foundation for constructing a cost structure for harvesting wood and residues from both commercial thinnings and final harvests. When only considering the costs for harvesting wood, a cost determination approach based on Obersteiner (1998) is used and somewhat modified to reflect Swedish conditions. Total harvesting costs (*TC*) per unit of output and for road side delivery are calculated based on labor costs per unit (c_l); capital costs per unit (c_c); fuel and material costs per unit (c_m); and overhead costs per unit (c_{OH}), which are expressed as a percentage of the other costs.

$$TC = c_l + c_c + c_m + c_{OH} \quad . \tag{1}$$

Based on productivity studies conducted by Brunberg (1995) for Swedish conditions the productivity for harvesters and forwarders can be expressed as:

$$\rho^H = \frac{6000dt}{sut + 56V + 80pt} \quad , \tag{2}$$

$$\rho^F = \frac{kf * sf}{df} \quad , \tag{3}$$

where *dt* is down-time per hour; *sut* is set-up time between trees; *pt* is the share of problem trees; *V* is the average log volume; *kf* is the average rated capacity of forwarders; *sf* is average working speed of forwarders; *df* is the average terrain traveling distance; and ρ^H and ρ^F is the productivity of the harvesters and forwarders, respectively.

4.3.1 Logs

Based on Marklund's (1988) biomass functions and the actual distribution of harvested tree types the following log volume function has been constructed:

$$V^L_{Pine} = \frac{1.116}{1000} e^{11.3264\left(\frac{d_{Pine}}{d_{Pine}+13}\right)-2.3388} \quad , \tag{4}$$

$$V^{L}_{Spruce} = \frac{1.116}{1000} e^{11.3341\left(\frac{d_{Spruce}}{d_{Spruce}+14}\right)-2.0571} , \qquad [5]$$

$$V^{L}_{Birch} = \frac{1.116}{1000} e^{11.0735\left(\frac{d_{Birch}}{d_{Birch}+8}\right)-3.0932} , \qquad [6]$$

where V^L and d are the weighted average log volume and average diameter of harvested logs in the final felling of pine, spruce and birch, respectively. The first term in the volume functions transforms the unit from kilograms to m^{3}ub. Given the harvester productivity and the average volume of logs the number of trees cut per hour can be expressed as:

$$N^{T} = \frac{\rho^{H}}{V^{L}} , \qquad [7]$$

where N^T is the number of trees harvested. For simplicity, it is assumed that a sufficient number of forwarders are used to keep up with the harvesters. The number of forwarders therefore needed, can be expressed as:

$$N^{F}_{L} = \frac{\rho^{H}}{\rho^{F}} , \qquad [8]$$

where N^F is the number of forwarders needed to keep up with the harvesters in collecting logs. The subscript *L* is used to distinguish between forwarders needed to collect logs and those needed which is denoted with *R*. The labor costs for harvesting a cubic meter of stem in the final felling operation can then be expressed as:

$$C^{L}_{L} = w\left(\frac{1}{\rho^{H}}\right) + wN^{F}_{L} , \qquad [9]$$

where C^L is the unit labor cost and w is the industry specific wage rate. The unit capital cost is similarly expressed as:

$$C^{C}_{L} = \left(\frac{\delta}{8760}\right)\left(\frac{1}{\rho^{H}}K^{H} + N^{F}K^{F}\right), \qquad [10]$$

where C^C is the unit capital cost and K^H and K^F are the capital cost (purchase price) of a harvester and a forwarder, respectively. The first term in the capital cost function is the hourly depreciation of the capital equipment since the productivity variables are expressed in m^{3}ub per hour.

4.3.2 Forest residue

The biomass functions for forest residues are also estimated by Marklund (1988) and are calculated from the following functions, which have been modified to reflect that residues can only be collected from harvested trees:

$$V^R_{Pine} = \frac{3.34N^T}{1000} e^{9.1015\left(\frac{d_{Pine}}{d_{Pine}+10}\right)-2.8604} , \qquad [11]$$

$$V^R_{Spruce} = \frac{3.34N^T}{1000} e^{8.5242\left(\frac{d_{Spruce}}{d_{Spruce}+13}\right)-1.2804} , \qquad [12]$$

$$V^R_{Birch} = \frac{3.34N^T}{1000} e^{10.2806\left(\frac{d_{Birch}}{d_{Birch}+10}\right)-3.3633} , \qquad [13]$$

where the V^R indicates the volume of forest residues from pine, spruce and birch, respectively. The extra number of forwarders needed to collect the forest residues are calculated with the same principle as for log harvesting. It is assumed that a sufficient number of forwarders are used to keep up with the production of residues from the harvester.

$$N^F_R = \frac{V^R}{\rho^F} , \qquad [14]$$

where N^F is the number of forwarders needed to keep up with the harvesters in collecting forest residues. The technology assumed for forest residues is that the residues are chipped at the road side. Therefore, it is important to include the cost of chippers in the cost calculation. For simplicity, it is assumed that the productivity of the chippers is exogenous. The number of chippers needed to keep up with the volume brought back with the forwarders can be expressed as:

$$N^C = \frac{V^R}{\rho^C} , \qquad [15]$$

where N^C is the number of chippers needed and ρ^C is the productivity of the chippers. The number of chippers is calculated based on the residue volume harvested and the productivity of the chippers, which is assumed to be exogenous. The construction of the unit labor and capital cost functions for forest residue recovery follows the same principal as for harvesting logs. However, the number of chippers needed and their capital costs (purchase price) is now also included in the functions.

$$C^R_L = wN^F_R + wN^C , \qquad [16]$$

$$C^R_C = \left(\frac{\delta}{8760}\right)\left(N^F_R K^F + N^C K^C\right) . \qquad [17]$$

4.4 Results

In the above section no values were attributed to the specific parameters. The parameter values chosen for the cost calculations are obtained through various product information sheets, informal contact with machine suppliers, field-studies conducted in Sweden, and published academic papers. Overall, two sets of parameters are used. One set for the final felling operations and the other for commercial thinning operations. The specifics are presented in Table 9 together with the notation used.

Table 9: Variable specification for final felling and commercial thinning operations.

	Notation	**Final felling (FF)**	**Commercial thinning (CT)**
Down-time per hour (%)	dt	15	20
Set-up time harvester	sut	0.2	0.3
Share of problem trees (%)	pt	0.14	0.16
Capacity forwarder (m^3ub)	kf	6.22	6.22
Working speed forwarder (km/h)	sf	5	5
Terrain traveling distance	df	Road density of specific county	Road density of specific county
Gross wage including social fees (SEK per hour)	w	134.4	134.4
Depreciation rate (%)	δ	10	10
Capital cost harvester (SEK)	K^H	4,250,000	4,250,000
Capital cost forwarder (SEK)	K^F	3,187,500	3,187,500
Capital cost chipper (SEK)	K^C	585,000	585,000
Material cost wood harvesting and forwarder (SEK per m^3ub)	C_M^L	40	40
Material cost forest residue harvesting (SEK per m^3ub)	C_M^L	55	55
Overhead costs (%)	C_{OH}	20	20
Productivity chipper (m^3ub per hour)	ρ^C	35	35

Compensation to the forest owner for extracting forest residues and the cost for returning ashes to the harvested area has been added, ex ante, to the forest residue cost functions as they are based on the size of the area harvested and not the volume. On average, compensation is 1,391 SEK per hectare (Lantz, 1997) but varies between regions and the cost of returning ashes is around 1,600 SEK per hectare, which is based on the discussion in section 4.1. Assuming a volume of forest residues of 27 m^3ub per hectare (Brunberg *et al.*, 1998) would indicate an additional cost of approximately 110 SEK per m^3ub that is added to the forest residue cost functions.

Based on the parameter values presented in Table 9 the cost shares for harvesting logs and forest residues from final harvests and commercial thinnings can be estimated using the model outlined above. Figure 5 a–d depicts the cost shares for overhead cost, material cost, capital cost, and labor costs by county and forest resource category.

A few observations can be made examining the cost share figure: (1) harvesting operations in final harvests are relatively more capital intensive than in commercial thinning while the opposite is true for labor intensity; (2) extracting logs from commercial thinning is in the range of 75 SEK per m^3ub more expensive than from final fellings; (3) forest residues are, overall, less expensive if extracted in commercial thinning than in final harvests; and (4) generally, among the four categories, logs from final fellings are less expensive followed by forest residues from commercial thinnings and lastly, forest residues from final fellings and logs from commercial thinnings.

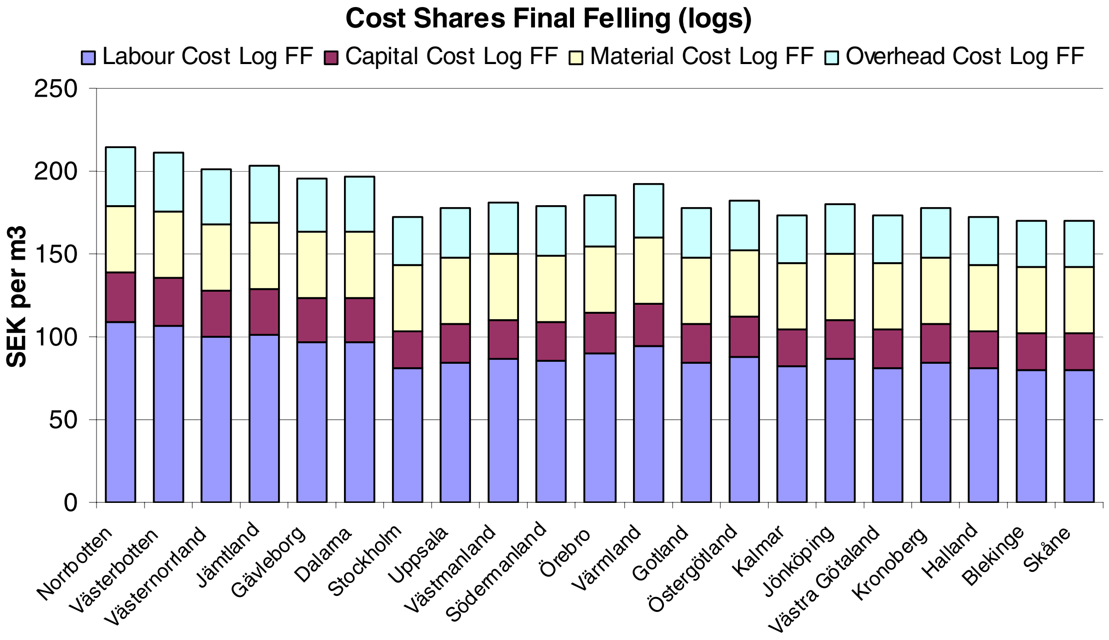

Figure 5a: Cost shares for logs in final felling by county and cost component.

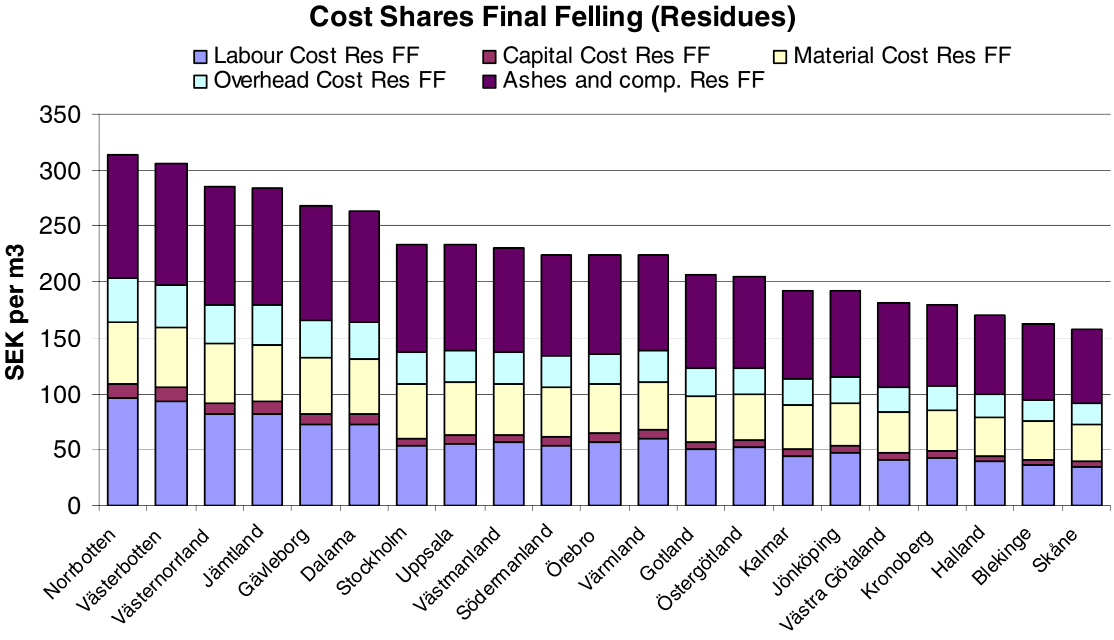

Figure 5b: Cost shares for residues in final felling by county and cost component.

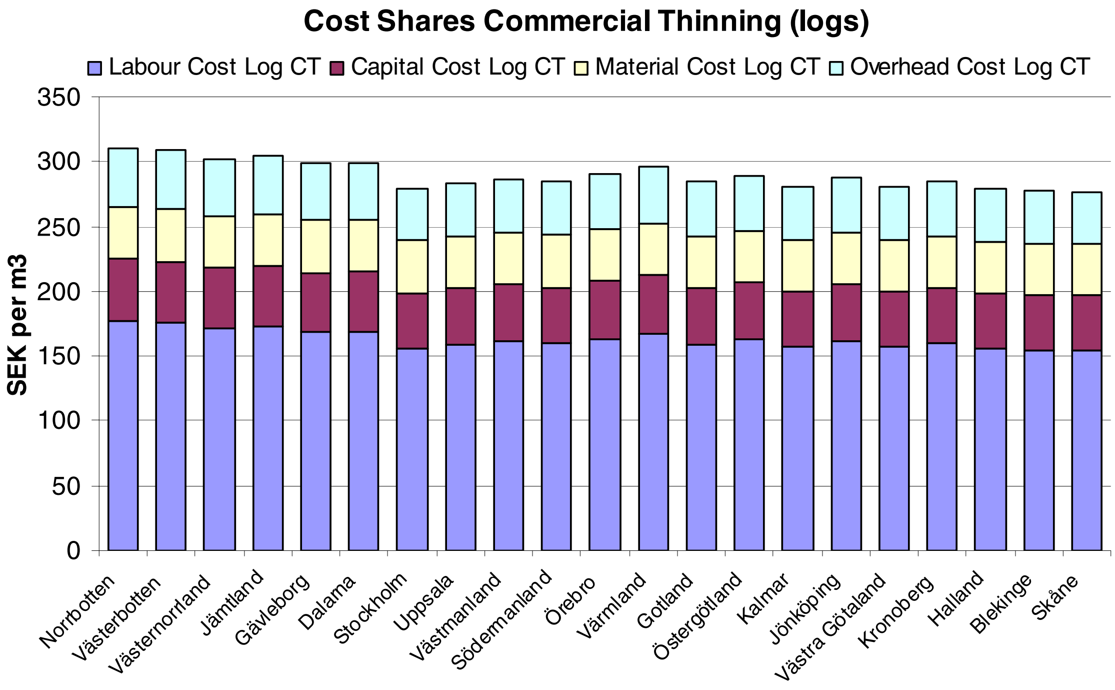

Figure 5c: Cost shares for logs in commercial thinning by county and cost component.

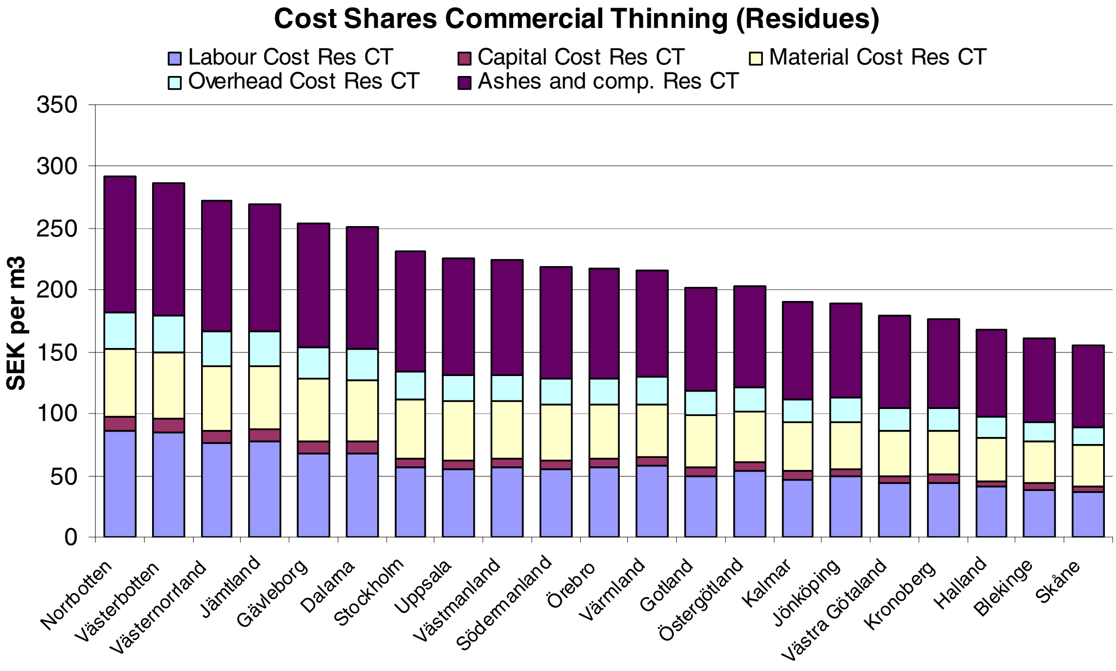

Figure 5d: Cost shares for residues in commercial thinning by county and cost component.

The total cost for logs varies between 170 SEK per m^{3}ub to 310 SEK per m^{3}ub depending on whether they are extracted in final harvests or in commercial thinnings and by county. This can be compared with the average price for pulpwood that was 221 SEK per m^{3}ub in 2002. This indicates that at the current price level it is not economical to extract pulpwood from high cost forest stands. The total cost for chipped forest residues varies between 155 SEK per m^{3}ub to 313 SEK per m^{3}ub. The average price for chipped forest residues was around 123 SEK per MWh which roughly correspond to 273 SEK per m^{3}ub.[1] Table 10 presents the actual price for wood (pulp logs) and forest residues and the estimated cost range for the same. The price and cost figures are presented both by volume and energy.

Table 10: Actual price and estimated cost for wood pulp logs and forest residues by volume and energy.

	Price/Cost in SEK per m^{3}ub		**Price/Cost in SEK per MWh**	
	Actual	**Estimated**	**Actual**	**Estimated**
Wood (pulp logs)	221	170–310	99	76–139
Chipped forest residues	273	155–313	123	69–140

5 Constructing and Analyzing the Supply Curves

By combining the regional quantities available and the regional cost estimates a supply curve can be constructed. This exercise can provide a useful tool for further analyses on numerous topics and especially for policy implications. For the purpose of this paper and in order to be able to compare the situation facing the forest industries and facing the energy sector when it comes to wood resources procurement, two separate supply functions will be constructed. One situation that faces the forest industries is the supply curve that will henceforth be called the *pulp usable* supply curve and the other situation that faces the energy sector is the supply curve that will henceforth be called the *pulp unusable* supply curve. The reason for separating the forest resources into two separate supply curves is due to: (1) the different properties of chipped forest residues and wood; (2) the forest industries are considerably more stringent in its procurement of forest resources due to quality aspects on the final product, hence they can not use forest residues as feed stock; and (3) the energy sector can use both wood and forest residues as fuel, which makes it of great interest to analyze the cost structure of the two categories from a procurement competition perspective. It should be remembered that even though two supply curves are estimated the *pulp unusable* supply curve is irrelevant without the *pulp usable* as the extraction of only forest residues is not allowed.

Figures 6 and 7 depict the supply curves for *pulp usable* and *pulp unusable*, respectively. The extraction costs are based on the cost structure presented in section 4 and the available quantities are based on the literature survey conducted in section 3. Noticeable is the sharp increase in costs in Figure 6, which is due to a substantially

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[1] 1 m^3 loose volume = 0.36 m^{3}ub; 1 m^3 loose volume = 0.85 MWh.

higher cost of extracting wood from thinning operations compared to final harvests. The amount of wood available from thinning is, however, limited. Figure 7, on the other hand, indicates a more smooth cost increase as the level of extraction increases. But the rate of increase is much higher than in Figure 6 indicating that small increases in the extraction level can only be achieved by considerable cost increases.

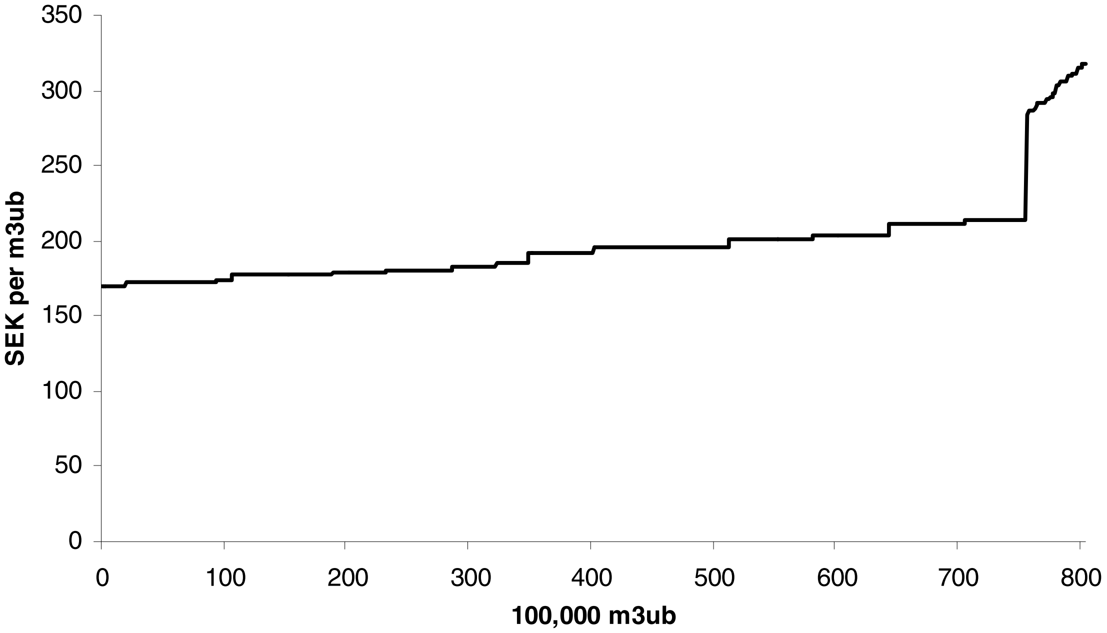

Figure 6: Supply curve for *pulp usable* forest resources.

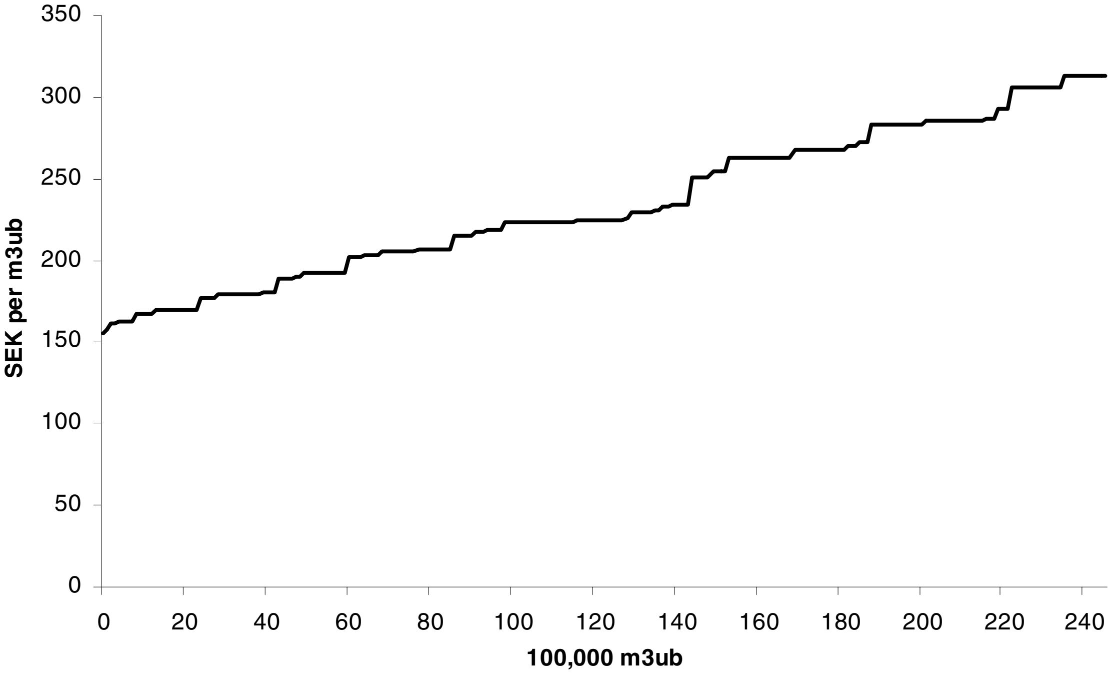

Figure 7: Supply curve for *pulp unusable* forest resources.

Combining the two supply curves can reveal interesting information that might otherwise be hard to observe. Figure 8 depicts the supply curves for *pulp usable* and a modified *pulp usable* supply curve that includes the chipping cost for wood. The reason for including the modified *pulp usable* supply curve is to facilitate a comparison between pulp unusable and pulp usable forest resources especially in light of the increased usage of forest fuel in the energy sector and the potential competition between the forest industries and the energy sector for the resource. The comparison has to be made on the same premises. As seen in Figure 8, the intercept of the *pulp usable* and *pulp unusable chipped* supply curves occurs approximately at 8.5 million m^3ub at a price level of 210 SEK per m^3ub, or at 21 TWh at a price level of 89 SEK per MWh.[2] Interestingly enough the actual harvest and use of forest residues has, however, never exceeded 9 TWh, which was harvested annually in the mid 1990s (Ericsson *et al.*, 2004).

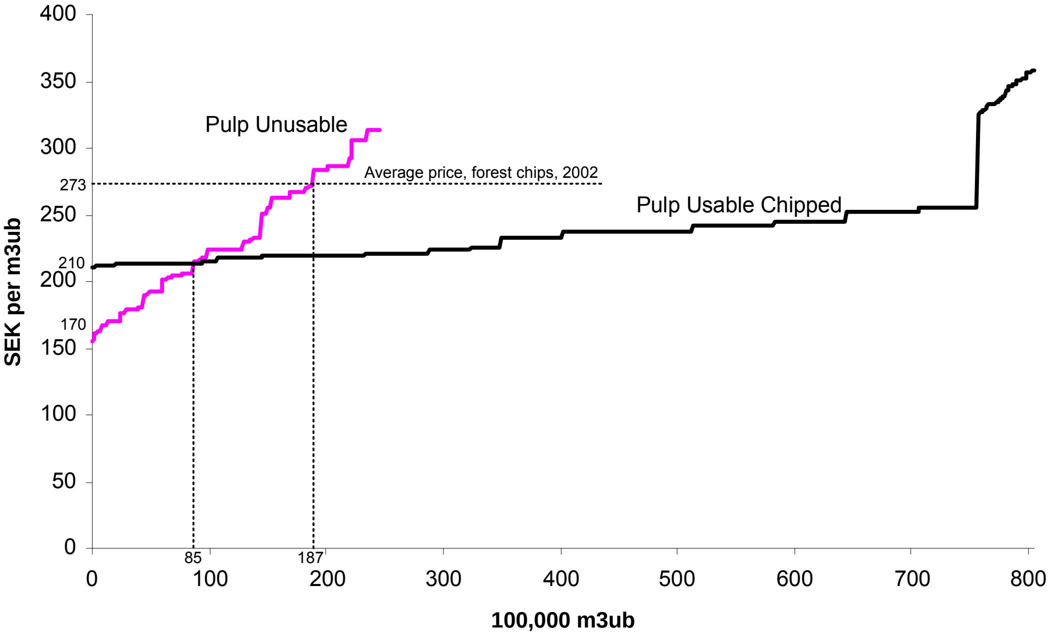

Figure 8: Supply curve for *pulp unusable* and *pulp usable* forest resources.

The interception between the *pulp usable chipped* and *pulp unusable* supply curves indicate that there is an untapped potential to extract an additional 12 TWh of forest residues, excluding the 9 TWh that are currently used, before the estimated extraction cost for forest residues matches the harvesting cost for chipped wood. Allowing for profit mark-up this potential may be reduced somewhat. Still, however, the question arises why there are not more forest residues being used in the energy sector considering the extraction cost and the prevailing price level? A number of points can help in explaining the relatively low utilization of forest residues: (1) uncertainty regarding nutrient loss and its associated cost makes forest owners unwilling to sell forest residues; (2) untested extraction technology and lacking investment willingness in the

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[2] 1 m^3ub = 2.78 m^3 loose volume; 1 m^3 loose volume = 0.85 MWh.

necessary machinery (e.g., additional forwarders and chippers in this case); (3) cheaper import of recycled wood; (4) low compensation to the forest owner; (5) regional imbalances that can not be balanced due to high transportation costs; and (6) the price level for alternative fuels makes further extraction of forest residues economically uninteresting, not least wood. A condition that needs to be satisfied before the energy sector starts purchasing forest residues to a greater extent is that the price of forest residues must be lower than that of other fuels.

5.1 The Procurement Competition for Wood

Today, the price level of chipped forest residues has reached such levels where wood could start to be used for energy purposes in large quantities. However, the price level also indicates that some additional 12 TWh worth of forest residues can be extracted before the more expensive pulpwood is starting to be profitable to use for energy generation. The price for pulpwood was on average 221 SEK per m^3ub in 2001 (depending on pine, spruce and birch and the regions) while the actual total removal of roundwood was 75,600,000 m^3 standing volume in 2001 (NBF, 2003). At this price level the pulp usable supply curve indicates that roughly 75,500,000 m^3ub, or 89,880,000 m^3 standing volume could be supplied, which corresponds very well with the estimate. For the energy sector to achieve cost efficiency, no additional forest residues will be extracted after the additional 12 TWh of forest residues is used as it is more economical to start utilizing the harvested wood instead for energy generation. However, two conditions need to be satisfied before the energy sector starts purchasing pulpwood in large quantities: (a) the price for pulpwood must be lower than for other fuels, and (b) the energy sectors willingness to pay must be higher than the forest industries willingness to pay. In other words, the forest owners must receive a higher financial dividend from delivering their forest resources to the energy sector compared to delivering it to the forest industries. A few studies exist that provide empirical estimates of the energy sectors willingness to pay for pulpwood (Parikka and Vikinge, 1994; Johansson, 2001; Wiberg, 2002; Hallberg, 2003). A summary of these studies can provide a comparison towards the price levels that is needed for larger quantities of pulpwood to be purchased by the energy sector and therefore increase competition between the energy sector and the forest industries.

Assumptions regarding moisture content, which determine the energy value in pulpwood, chipping costs and transportation distances differ between the studies with different results as a consequence. In addition to different assumptions, the studies can be divided into two conceptually distinct groups. Johansson (2001) and Hallberg (2003) emanate from answering the question to whom the forest owners would be willing to sell one cubic meter of harvested pulpwood; that is, which sector is willing to pay the most? On the contrary, Parikka and Vikinge's (1994) analyses is foremost on pulpwood from thinning operations and includes the whole production chain from harvesting to final delivery. The starting point is thus that the harvesting costs differ depending on whether pulpwood is sold to the forest industry or to the energy sector. Hence, the financial outcome for the different delivery options depends not only on the willingness to pay but also on the costs for extracting the forest resource. Another important distinction is that Parikka and Vikinge (1994) analyze a specific case, namely thinning operations in the county of Gästrikland. This means that actual compared to stereotyped transportation distances are studied. The transportation costs to the forest industries are, for example, 26 SEK per m^3 loose volume while the same is 70 SEK per m^3 loose volume to heating plants. Because of these differences and since the Parikka and Vikinge (1994) analysis is from 1994 and therefore somewhat out of date it is presented separately in Table 11. The cost estimates that are presented in Table 11 are based on moisture content around 55 percent and varying transportation distances (see above). Moreover, terrain transportation distances of 170 meters are assumed and that the price of wood fuel is 105 SEK per MWh. The results from Parikka and Vikinge (1994) indicate that a profit maximizing forest owner will sell to the pulp and paper industry because the financial outcome is more favorable.

Table 11: Costs, revenues and financial outcome of pulpwood extraction for deliverance to the pulp and paper industry (PPI) and the energy sector for pine and spruce. Source: Parikka and Vikinge (1994).

Costs[a]	**Pine**		**Spruce**	
	PPI	**Energy**	**PPI**	**Energy**
Harvesting	87	54	93	71
Forwarding or chipping/terrain transport	34	64	23	55
Transportation	26	70	26	65
Chipping at heating plant	-	29	-	28
Administration	30	30	30	30
Total Cost	177	247	172	249
Revenue at PPI and heating plant[a]				
Pulpwood	304		329	
Wood fuel		337		312
Financial outcome	127	90	157	63

[a] SEK per m^{3}ub.

The Johansson (2001) and Hallberg (2003) studies are more suitable for a direct comparison. Some difference regarding their basic assumptions exists however. Johansson (2001) assumes, for example, a moisture content of between 35–40 percent and a stereotyped transportation distance of 50 kilometers with a cost of 41 SEK per m^{3}ub, while Hallberg (2003) assumes 45 percent moisture content and no transportation costs. In order to ease the comparison Johansson's transportation cost will be added to Hallberg's results. Since Johansson (2001) solely focuses on pine and spruce and makes no attempt to separate them, only the same species from Hallberg (2003) will be analyzed even though more species are included. It is noteworthy to point out that Johansson (2001) conducted his analysis from a Northern Swedish perspective by using price information from Norrland, while Hallberg (2003) has a more Southern Swedish perspective. Table 12 summarizes the results.

Table 12: Compilation of the energy sectors willingness to pay for pulpwood based on two studies expressed in SEK per m^{3}ub.

	Johansson (2001)	Hallberg (2003)	
Total willingness to pay for energy sector	256	199	
Chipping cost at heating plant	47	All ready deducted	
Transportation cost	41	0	41
The energy sector's willingness to pay	168	199	158

The energy sector's willingness to pay for pulpwood is between 158–199 SEK per m^{3}ub for road side delivery. This can be compared to the average price for pulpwood that during the first two quarters in 2003 was around 212 SEK per m^{3}ub for pine and spruce. The results thus indicate that the energy sectors willingness to pay is below the price level for pulpwood. As a consequence, no extensive competition currently exists between the forest industries and the energy sector for pulpwood. However, this result does not contradict that individual heating plants might marginally outbid the pulp and paper industry.

5.2 The Effects of Increasing Costs for CO_2 Emissions

The overall CO_2 tax in Sweden was, at the end of 2003, 0.76 SEK per kg CO_2, which corresponds roughly to 140–210 SEK per MWh depending on the type of fuel. However, several exemptions are in place. For instance, no CO_2 tax is levied on any fuel that is used to generate electricity and the tax level is reduced to 0.19 SEK per kg CO_2 for the industry. Moreover, energy intensive industries often have special tax reductions in place. Since wood fuels are generally considered CO_2 neutral, no CO_2 tax is levied on the utilization of wood fuels. This makes wood fuels an attractive substitute for fossil fuels if the energy sector is faced with increasing tax levels. Hence, as a consequence of changing relative prices for the different fuel alternatives, due for example to the increasing CO_2 tax, the energy sector increases its use of the now relatively less expansive fuel and decrease its use of the now relatively more expensive fuel. The elasticity of substitution measures the speed at which this substitution can occur. Based on the estimated supply curves in Figure 8, Table 13 indicates the effect that the different price changes on wood fuel would have on harvesting forest residues and wood for energy purposes. Four different scenarios are considered, a reduction as well as an increase of 10 percent and 25 percent, respectively. For comparison, the status quo situation is also included in the table, i.e., the prevailing price level. The pulpwood for energy purposes indicates the quantity of pulpwood that would be purchased by the energy sector after forest residues have become too costly to extract, i.e., the difference between the quantity of forest residues supplied at the various price levels and the intersect between the *pulp usable chipped* and *pulp unusable* supply curves. For example, the average price for chipped forest residues in 2002 was roughly 273 SEK per m^{3}ub (the Status Quo scenario). At this price level, 18.7 million m^{3}ub of forest residues would theoretically be supplied, as indicated in Figure 8. However, since chipped wood becomes less costly to use after 8.5 million m^{3}ub of forest residues, some 10.2 million m^{3}ub of wood are more likely to be used. It can be seen in Table 13 that the price change on wood fuel has to decrease by 25 percent before pulpwood becomes unattractive for the energy sector. The status quo situation indicates that some 10.2 million m^{3}ub of pulpwood are an economically attractive fuel alternative for the energy sector.

Table 13: Wood fuel price changes and its affect on the supplied quantities of wood fuel.

Amount supplied (million m^{3}ub)	Price change on wood fuel				
	-25%	-10%	Status Quo	+10%	+25%
Forest residues	8.6	14.4	18.7	21.9	24.5
Pulpwood for energy purposes	0.1	5.9	10.2	13.4	16

6 Conclusions

Sweden has a long history of utilizing forest resources for economic purposes. Forest land has been considered as an economic resource and a number of legislative measures have been introduced during the last century to ensure that the forests are governed in a way to promote long-term productivity. Due to these regulations the growing stock of forest resources has grown steadily during the 1900s. However, growth has not been able to prevent the conflict of interest concerning the way the forest resources are utilized. The main focus of the conflict is whether the forest resource should be burned to generate energy or to be refined into other fibrous products. This paper set out to answer two questions that sprung from the concern raised by the conflict of interest. *First*, considering the contradictory arguments regarding the level of competition, is there any conflict, or high level of competition, between the energy sector and the forest industries in their procurement of forest resources? *Second*, if not, what will it take for the energy sector to start infringing on the supply of roundwood previously exclusively available for the forest industries?

Competition for the forest resources are *not* foremost a matter of physical availability but rather the fact that changes in demand for one user causes significant price changes for other users. In this context it is important to assess the intensity of the competition as to be able to evaluate the shape of the supply curves for the different forest resources. The results suggest that considerable additional amounts of forest residues can be extracted without any negative side effects for the forest industry because the forest industries lack the capacity for utilizing forest residues. However, the economical untapped amount of forest residues does not include all the available potential of forest residues as often used when evaluating the prospect of increasing the use of wood fuel. At a certain break point it becomes more profitable to start using wood (roundwood) for energy purposes and hence intensify the competition between the forest industries and the energy sector. According to the results, this break point occurs at roughly after an additional usage of 12 TWh of forest residues, which is considerably less than the amount assessed in other studies. Thus, it becomes important to analyze the impact of a large increase that the use of wood fuels might have on the forest industries before more promotion is put into the usage of biofuel.

Moreover, the current price level (2002) on chipped forest residues indicates that it is already today economically possible to use considerable quantities of wood for energy purposes instead of forest residues. This arises from the fact that the marginal cost of forest residues increase at a fast pace than the marginal cost for wood. Coupled with the already high price for chipped forest residues the result suggests that some 10.2 million m^3ub of wood are at risk of being diverted to the energy sector and thereby intensifying the raw material procurement competition between the forest industry and the energy sector. However, this economic potential use of wood in energy generation is based on perfect market conditions, which is not necessarily present. For instance, a number of institutional restrictions exist that limits the diversion of wood from the forest industry to the energy sector.

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