Swedish University of Agricultural Sciences
Faculty of Natural Resources and Agricultural Sciences
Department of Economics

Competition for forest fuels in Sweden

- Exploring the possibilities of modeling forest fuel markets in a regional partial equilibrium framework

Dag Lestander

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Dag Lestander

Supervisor:	Ing-Marie Gren, Swedish University of Agricultural Sciences, Department of Economics
Examiner:	Rob Hart, Swedish University of Agricultural Sciences, Department of Economics

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Summary

This thesis project focuses on the need for better tools for analyzing competition for forest fuels in Sweden, in particular how policy measures may influence the market and involved actors in different regions of Sweden. Raw materials from the forest have for long constituted important inputs in the Swedish forest industry. Today some of these raw materials are increasingly used as inputs also in bioenergy production, largely driven by bioenergy promoting policies, and there are signs of increased competition for forest fuels which may have various and uncertain effects on the industries in question.

The thesis project explores the possibilities to adapt previously used forest sector equilibrium models into a new model suitable for analysis of Swedish forest fuel markets, called the Swedish Forest Sector Trade Model (SFSTM). The approach takes into account regional differences in supply and demand for 23 types of products produced and/or used by eight types of producers, plus consumers, in five different regions (four Swedish and one international). The project contributes with the novelty of an economic partial equilibrium model of the Swedish forest sector that includes regional trade and bioenergy production.

After extensive data collection and fitting of the model setup according to Swedish circumstances, the model is programmed and solved in GAMS software. The model is calibrated and then tested as a tool for analysis by implementing scenarios that imply shifts in energy demand and introduction of a tax on forest fuels used in bioenergy production.

The project results are primarily of interest in understanding the models functionality in a Swedish context, in particular with regards to the availability of regionalized data and related implications for the model setup. The thesis concludes in several key issues and recommendations on further steps to be taken if this type of model should continue to be developed in Sweden, such as; the need for better data on extraction and processing cost of logging residues, the need for better data on exogenous input costs in forest industries, and how the model results are affected by the choice of geographic scale of (trading) regions and related assumptions on transport cost functions.

Key terms: forest industry, bioenergy, forest fuels, energy policy, regionalized partial equilibrium trade model

Sammanfattning

Detta uppsatsprojekt har focus på behovet av batter verktyg för analys av konkurrens om skogsbränsle i Sverige, särskilt hur styrmedel kan påverka marknaden och dess aktörer i olika delar av Sverige. Råmaterial från skogen har länge varit viktiga insatsvaror i den Svenska skogsindustrin. Idag används i ökande grad dessa råmaterial även för produktion av bioenergi vilket har främjats av politiska beslut och styrmedel. Det finns tecken på ökad konkurrens om skogsbränslen vilket kan få många och svårbedömda effekter på berörda industrier.

Uppsatsprojektet utforskar möjligheterna att utifrån tidigare utvecklade jämviktsmodeller för skogssektorn utveckla en modell som fungerar för analys av den Svenska skogsbränslemarknaden, här kallad SFSTM. Modellen omfattar regionala skillnader i tillgång och efterfrågan på 23 produkttyper som produceras och/eller används av åtta olika producenter, plus konsumenter, i fem olika regioner varav fyra Svenska. Projektet är nyskapande genom att en ekonomisk partiell jämviktsmodell av den Svenska skogssektorn utvecklas som dessutom inkluderar regional handel och bioenergiproduktion.

Efter omfattande datainsamling och anpassning av modelluppsättningen efter Svenska förhållanden programmeras och körs modellen i programvaran GAMS. Modellen kalibreras och testas som analysverktyg genom olika scenarion om ändrad efterfrågan på energi samt introduktion av skatt på skogsbränslen som används i bioenergiproduktion.

Projektets resultat är framförallt intressanta för att förstå modellens funktion i en Svensk kontext, särskilt med avseende på tillgängligheten av regionaliserbara data och hur detta påverkar modelluppsättningen. I slutsatserna sammanfattas flera viktiga frågor och rekommendationer om modellen skulle vidareutvecklas i Sverige, bl.a. behovet av bättre data på mängd och kostnad för uttag av avverkningsrester som skogsbränsle, behovet av bättre data på exogena insatskostnader i skogsindustrin, och hur modellresultaten påverkas av den geografisk skalan för regioner som tillåts idka handel i modellen liksom vilka antaganden som görs kring transportkostnadsfunktioner.

Nyckelord: skogsindustri, bioenergi, skogsbränsle, energipolitik, regionaliserad partiell jämviktsmodell

List of abbreviatons

CHP	Combined Heat and Power (or cogeneration) is a process by which a power station generates electricity and heat simultaneously and higher efficiency can thus be achieved compared to plants producing only heat (or electricity).
Coniferous / Non-coniferous	Conifer trees have needles and are also called softwood species. Here non-coniferous trees refer to broad leaved trees, also called hardwood species.
GAMS	General Algebraic Modelling System.
EFI-GTM	European Forest Institute Global Trade Model
FAOSTAT	The FAO Corporate Statistical Database, administered by the United nations Food and Agriculture Organization.
Fibre boards	Similar to particle boards but more dense and stronger. Several different varieties exist.
KWh / MWh /GWh	Energy units where Wh refers to Watt hours, i.e. the product of power in Watts multiplied by time in hours. K, M and G refer to Kilo (thousand), Mega (million) and Giga (billion).
Logging residues	Tree tops and branches, small and weak trees, and other types of wood materials that are usually by-products from logging activities.
m^3 ub	Cubic meter under bark (including bark)
m^3 sub	Solid cubic meter under bark (solid material as opposed to loose in e.g. piles)
m^3 solid	Solid cubic meter
NTM	the Norwegian Trade Model
Particle boards	A composite material made from wood particles such as wood chps, sawmill shavings and sawdust. Particle boards are more dense than conventional wood, but less

	dense and weaker than fiberboard.
SF-GTM	The spatial partial equilibrium model for the Finnish forest sector
SVO	The Swedish Forest Agency, the Swedish Government's expert authority on forests and forest policy.
tDM	ton Dry Matter, as opposed to ton wet matter which includes regular water content in humid material.
VMR	Previously called Virkesmätningsrådet, a subdivision of SDC (Skogsnäringens IT-företag) that deals with measuring and accounting of Swedish roundwood.

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1. Introduction

1.1. Problem background

During the last few decades different types of biofuels have become more important in Swedish energy production, particularly in district heating plants but also increasingly so in electricity generation. The use of biofuels has the advantages of lower emissions of greenhouse gases while at the same time easing domestic dependence on imported fossil fuels that have become more costly. The Swedish government, along with many other countries primarily in Europe, has implemented various types of policies in order to promote the use of biofuels. Some examples of such policies are tax exemptions, subsidies and minimum requirements. The Swedish policies on bioenergy have caused fast growth in the number and scale of energy production facilities capable of utilizing biofuels. This development has accelerated during the 1990's and continues to progress today.

Some of the most important types of biofuels in Sweden are forest fuels derived originating from forestry or forest industries. Pulpwood, logging residues and forest industry by-products may be used directly in combustion or refined into wood pellets, briquettes or wood powder to facilitate long distance transports. Forest fuels are used in wood and pellet stoves to heat single family homes as well as in large scale district heating plants serving more densely populated areas. For a period of time the cost of producing energy based on forest fuels has been relatively low compared to using traditional fossil fuels, mostly because of economic policies. The increasing use of forest fuels in energy production has also given rise to new market demand alongside more traditional forest industries' demand for forest biomass. There may now be buyer's competition for particular raw materials and this competition is expected to increase in the future.

The future developments within the market for wooden biomass are hard to predict much due to the complex flows and interconnections that characterize actors in the market. There are split views on how the Swedish forest industry cluster may be affected by the new market circumstances. Considering the economic importance of forest industries in Sweden there is reason to investigate the effects of competition on forest biomass markets more closely. Forest industry organizations, public authorities and researchers have struggled to develop tools and models that may be used to understand the development in the sector. The government also requests better knowledge that could guide energy- and environmental policy reforms that have been repeatedly under discussion during recent years.

Previous studies on the Swedish forest industry's relation to the energy market have applied various methods and models to analyze possible effects from policy changes. One of the most notable limitations of those studies has been the availability of reliable statistics much due to the somewhat immature character of bioenergy production. Another drawback is that the study perspecitive has mostly been on the national level and thus regional effects have not been clearly displayed. Considering the differences in supply and demand for wood based biomass in different parts of Sweden as well as the importance of transport economics, a regionalized analysis could likely improve the understanding of allocation and use of wood materials. The inspiration for the study presented in this paper is thus the possibility of developing such a model that may include regional aspects of supply and demand as well as the allocation of forest fuels via regional trade.

1.2. Aim and purpose

The purpose of this study is to develop a model that may be used to analyze how changed market conditions for bioenergy producers could affect Swedish forest industries through the markets for roundwood and other forestry products. The aim is to adapt previously used equilibrium models into a model suitable for analysis of Swedish forest fuel markets. Differences in supply and demand across regions are of central interest as well as potential effects in different parts of Sweden. The ultimate goal is to successfully apply the model in analysis of effects from changes in energy demand and taxes on bioenergy. The focus will be on raw material supply, forest industry activities, bioenergy production based on forest fuels and demand for forest raw material. A secondary goal is also to identify what shortcomings in data availability that are most notable in relation to regional analysis of forest fuel markets in Sweden.

1.3. Method

Literature on markets for and production of bioenergy and forest industry products in Sweden and Scandinavia is studied to get an overview of Swedish biomass market developments in recent years. A regional partial equilibrium model is developed based on existing economic forest sector models. The model is programmed in a modeling software called General Algebraic Modeling System (GAMS). Swedish data from a chosen base year is gathered, analyzed and prepared before using it in calibration of the model. The possibility of using the model in scenario analysis is then explored. Data issues are of important concern in the evaluation of model behavior and the results found.

1.4. Delimitation

The study is based on existing data and previous estimates of demand- and supply curve characteristics such as price elasticities, and thus there are no additional estimation procedures included in the study. The partial equilibrium model only includes forestry production, forest industries and bioenergy production based on forest fuels (unrefined and refined solid forest fuels). Possible interactions with other markets in Sweden and abroad are disregarded and inputs stemming from other sectors of the economy are assumed to be exogenous to the model. No environmental effects are considered in the model. The time perspective for the study is short term, i.e. between 5-10 years, and does not take into account dynamic changes over time. The focus of the study is on developing a basic model and particularly some parts of the data used in the model should be regarded as preliminary and in need of further development before reliable model results may be achieved.

The types of forest fuels that are considered in this study are logging residues, by-products from forest industries and roundwood. Other types of wood fuels such as recycled wood and energy forest fuels are not included, and likewise no particular attention is given to biofuels from agriculture, recycled paper or black liquor. Nor is the possibility of using forest fuels to produce biofuel for transports considered.

1.5. Outline of the thesis

Chapter 1 introduces the background, aim and purpose, method, delimitations and the outline of the paper. ***Chapter 2*** gives a background on energy policies relevant to forest fuels, the Swedish forest industry cluster, the use of forest fuels in energy production and an overview of availability and prices for forest fuels in Sweden. ***Chapter 3*** gives a brief theoretical perspective on competition for forest fuels between forest industries and energy producers, and describes some economic models of the forest sector that constitute the inspiration and methodological foundation for the model developed in this thesis. ***Chapter 4*** explains the model that is developed in terms of model components and mathematical formulation. ***Chapter 5*** *briefly* describes sources, computations and assumptions related to the model input data. ***Chapter 6*** describes calibration and sensitivity analysis followed by results from various model scenarios ***Chapter 7*** is devoted to discussing and analyzing the results and possible improvements of the model.

2. Background

This thesis project is aimed primarily at adapting existing forest sector models to a Swedish context and to explore the possibilities of modelling bioenergy and forest industry production at a regional level in Sweden. In order for the reader to understand the setup and functioning of the model some knowledge of the Swedish forest industry cluster and the use of forest fuels is needed. This chapter will provide a broad overview of the Swedish forest industry cluster, the use of forest fuels in energy production, and energy policies that influence the use of forest fuels. The text is aimed at describing the development of forest industry production as well as the supply and use of forest fuels over the last few decades, and little attention is paid to the various industries' production techniques.

2.1. Energy policies influencing the use of forest fuels

The use of forest fuels in Sweden has to a large extent been driven by domestic energy and environmental policies, primarily by energy taxation favouring bioenergy. Policies and measures at the EU-level have become increasingly important in later years and the use of biofuels such as forest fuels will likely continue to be stimulated in coming years.

EU directives and policies affect the use of forest fuels in Sweden, either directly or via national policies. The European Commission white paper on renewable energy (COM(97) 599) and the following green paper on the security of energy supply (COM(2000) 769) set out strategies for increased production of renewable energy, and great potential was said to exist in heat and electricity from biomass. A number of EU-directives agreed upon in recent years have set out ambitious targets, in terms of renewable energy production, for the EU as well as for individual countries. For example the so called *RES-E-directive* (Directive 2001/77/EC) defined a target of increasing renewable electricity in Sweden from 49% in 1997 to 60% in 2010. The directive 2003/87/EC on greenhouse gas emission allowance trading leading to the initialization of the European trading system in 2005 has favoured renewable electricity production. According to Fagernäs et al. (2006) in the long run emissions trading is planned to replace most national incentives for promotion of renewable energy sources.

Several types of national energy policies and instruments are used to steer energy production and consumption in Sweden towards goals defined in energy and climate politics. The goals that relate most to the production and use of forest fuels are those targeted at increasing renewable energy production and lowering carbon dioxide emissions. Overall energy taxation is the most important policy instrument used which includes taxes on energy, carbon dioxide and sulphur. By being exempt from such taxes forest fuels have been made relatively less costly to use as input in heat and electricity production. The Swedish electricity certificate system that was introduced in 2003 provides additional support to electricity producers that use biofuels such as forest fuels. Together these measures have spurred the use of forest fuels in both small and large scale heat production as well as in combined heat and power plants (Swedish Energy Agency, 2005).

The general energy tax is levied on most fuels except biofuels and peat. The primary purpose of the tax is fiscal but it is also used as a policy instrument aimed at dampening energy use. The carbon dioxide tax acts as an environmental fee and is paid in proportion to emissions of carbon dioxide from all fuels except biofuels and peat. The taxes on energy and carbon dioxide emissions do not apply on electricity production, instead a tax is levied on the use of electricity (differentiated between geographic regions and users). The reverse applies for heat, where usage is untaxed but production is taxed with energy tax, carbon dioxide tax, sulphur tax and nitrogen oxide tax. Combined heat and power plants with sufficiently high efficiency (in terms of electricity produced) are exempt from the energy tax and pay a reduced carbon dioxide tax of 21% of normal rates. (Wetterlund, 2007). Manufacturing industries, green house farming, agriculture, forestry and aquaculture are exempt from energy taxes on fossil fuels and also have the carbon dioxide tax reduced to 21 percent. Energy intensive industries may also enjoy reduced carbon dioxide tax if certain requirements (related to energy intensity) are fulfilled (Swedish Energy Agency, 2009).

The electricity certificate system was introduced in may 2003 and is aimed at stimulating renewable electricity production, e.g. electricity produced with forest fuels in combined heat and power plants. The system is organized so that producers of renewable electricity receive a certificate for each MWh of produced electricity, and the certificate may then be sold to generate additional revenue on top of electricity sales. On the demand side binding quotas are set for distributors of electricity who must thus purchase a number of certificates proportional to their annual production and use of electricity. The nationwide certificate quota will increase gradually from 8,1% of total electricity use in 2003 to 17,9% in 2010. The goal is to increase renewable electricity production by 17 TWh from 2002 to 2016. (Wetterlund, 2007)

2.2. The Swedish forest industry cluster

Forestry and forest industrial activities have played important roles in Sweden historically and still make considerable contributions in terms of employment, exports and industrial production value. Sweden is recognized as one of the world's leading exporters of sawnwood, pulp and paper products, much owing to the relative abundance of roundwood in Swedish forests. In 2005 the value of Swedish forest sector production was around 201 billion SEK, and forest industry value added constituted about 11,8% of total value added in Swedish industries. Forestry and forest industry total value added was about 3.1% of GNP in the same year. The export value of forestry and forest industry products reached 114 billion SEK, which made up 11,6% of total commodity exports in 2005. In 2007 around 101200 people worked in forestry and forest industries (Swedish Forest Agency, 2009).

There are three main types of forest industries presently active in Sweden; sawmills, wood board industries, and pulp and paper industries. A brief description of each of these industries follows, with focus on the development of production and prices over the last 10-15 years.

2.2.1. Sawmill industries

The Swedish sawmill industry has undergone great changes over the past few decades. A general tendency is that sawmills have become larger and fewer, mainly as a result of closing-down of many small sawmills. In 1984 there were 179 sawmills of scale between 1000-5000 m3 production per year, but in 2000 there were only 71 left in the same group. During the same period the number of sawmills producing 100 000 m3/year or more increased from 23 to 49 (Navrén, Nylinder & Gustavsson, 2000). Increasing market competition, economies of scale and high investment costs are likely some of the factors causing the shift from small to large scale sawmilling.

Sawlogs of primarily spruce and pine are used in sawnwood production and the cost of production depends much on sawlog availability and prices. Sawnwood products require roundwood material of higher fiber quality than pulpwood and thus sawmills do not currently compete directly with pulp and paper industries for raw material.

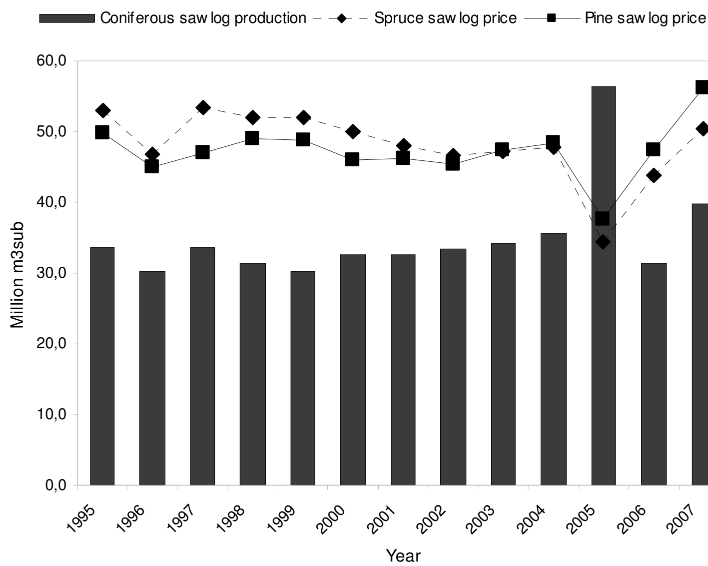


Figure 1: Production of coniferous sawlogs (delivery logs) and sawlog prices for spruce and pine (CPI adjusted prices with base year 2004).
Source: Swedish Forest Agency, 2009

The figure above shows Swedish production of coniferous sawlogs and prices for delivery logs from 1995 to 2007. Sawlog prices have fluctuated considerably in the past but have been quite stable during the last 12 years. Harvested quantities of sawlogs have also remained quite stable with the exception for 2005 when harvest peaked and prices slumped due damages from the storm Gudrun in southern Sweden.

In addition to domestically produced roundwood, imported sawlogs constituted about 1.1% of total roundwood used in sawmills in 1995, but increased to 7.9% in 2000 (Navrén, Nylinder & Gustavsson, 2000). In 2004 imported sawlogs made up about 3.8% of total sawlogs used in Sweden, and imports were greatest in the southern wood balance region (VMR, 2008). Most imported sawlogs originate from Finland, Norway and Russia (Swedish Forest Agency, 2009).

Production of sawnwood has increased from about 11 million m3 in 1980 to around 18 million m3 in 2007. The average real export price of sawnwood decreased from around 2571 in 1980 to 1863 SEK per m3 in 2006, but then turned upward again in 2007 (Swedish Forest Agency, 2009). The figure below shows the development of production, exports and real export prices of coniferous sawnwood from 1990 to 2007. As can be seen in the diagram exports of sawnwood constitute a great share of total production and the sawmilling industry is thus largely dependent on demand from abroad.

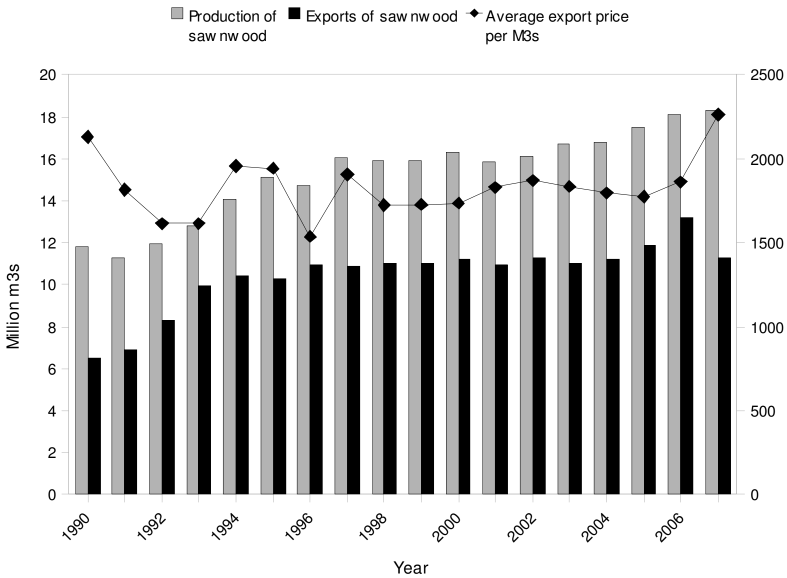


Figure 2: Production and exports of coniferous sawnwood, and real average export price. Source: Swedish Forest Agency, 2009

The production of sawnwood results in large quantities of by-products, primarily sawdust, planer shavings, wood chips and bark. Some of these by-products are used by internally at the sawmills but the larger part is sold to other forest industries, refined wood fuel producers and heating/electricity plants. According to the sawmill inventory study from 2002 final output of sawnwood constituted about 47% of the total roundwood quantity used in sawmills. The exchange of sawnwood as a share of roundwood input varies between regions and individual sawmills and also differs depending on the wood species used in production (Navrén, Nylinder & Gustavsson, 2002). The figure below shows sawnwood and by-products as approximate shares of total output measured as the sum of sawnwood and by-products in m3.

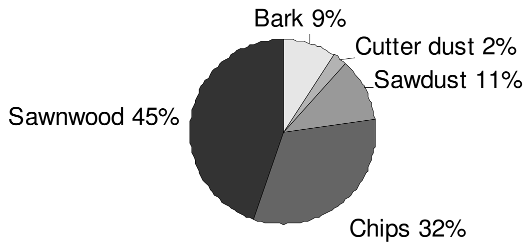


Figure 3: Approximate shares of total output for sawnwood and by-products.
Based on production figures from 2004.
Source: Own computation based on VMR, 2008

In 2001 sawmill production resulted in about 4,5 million solid m^3 of sawdust (including planer shavings). The figure below shows the allocation to different users as percentages of total sawdust from sawmills. In addition to sawdust used in forest industries and for energy purposes, marginal quantities are used as bedding in stables and farming.

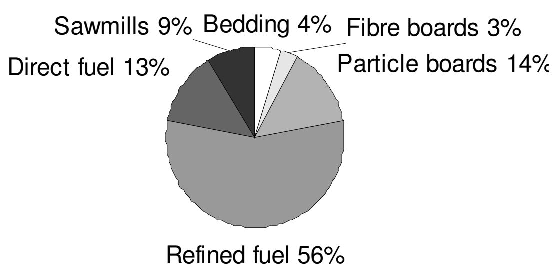


Figure 4: Sawdust end usage as shares of total sawdust available from sawmill production in 2001.
Source: Swedish Energy Agency, 2003

The use of sawdust in the energy sector and refined wood fuel production has increased rapidly since 1990, especially the share of sawdust allocated to refined wood fuels, and sawdust use in wood board manufacturing has decreased somewhat (Swedish Energy Agency, 2003). The below figure shows sawdust prices between 1990 to 2002. Note however that these prices correspond to prices at sawmills, and thus the price paid by users would usually be higher due to transport costs and service fees. There are also variations in price depending on the type of user (Lundmark & Söderholm, 2004). The downward price trend from 1990 to 2000 is likely a result of increased sawmill production (see Figure 2) which increased supply of by-products relative to demand. In lack of more recent figures on sawdust prices it is difficult to tell current prices, though there is reason to believe that price levels have gone up significantly during the last few years.

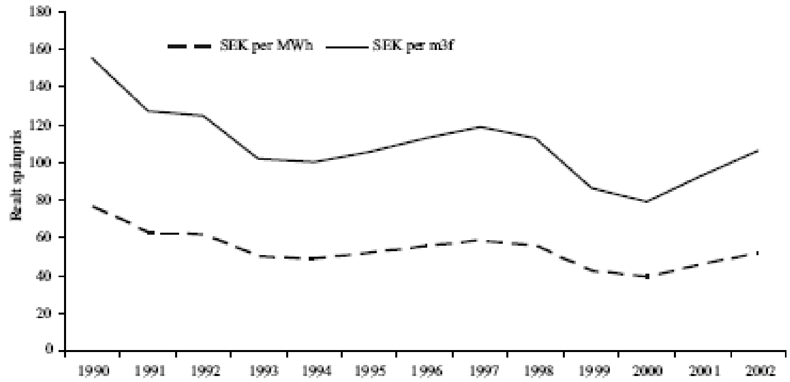


Figure 5: Real average price of sawdust at sawmills (CPI adjusted prices with base year 2001).
Source: Lundmark & Söderholm, 2004

Wood chips constitute the bulk of by-products from sawmills and most of it is used in pulp and paper manufacturing. In 2007 about 3.1% of woodchips from sawmills were used internally by sawmills, 90.5% was sold to other forest industries (primarily pulp and paper industries) and about 6.4% was sold as wood fuel (VMR, 2008). As can be seen in the diagram below, real wood chip prices went from levels around 500 SEK/m3s during the mid 80's to slightly more than 200 SEK/m3s after year 2000. The agreement on woodchip price between seller and buyer varies in terms of contract time, volume or weight measures, transport, quantity etc. Additional details on pricing is provided by the regional sawmill associations.

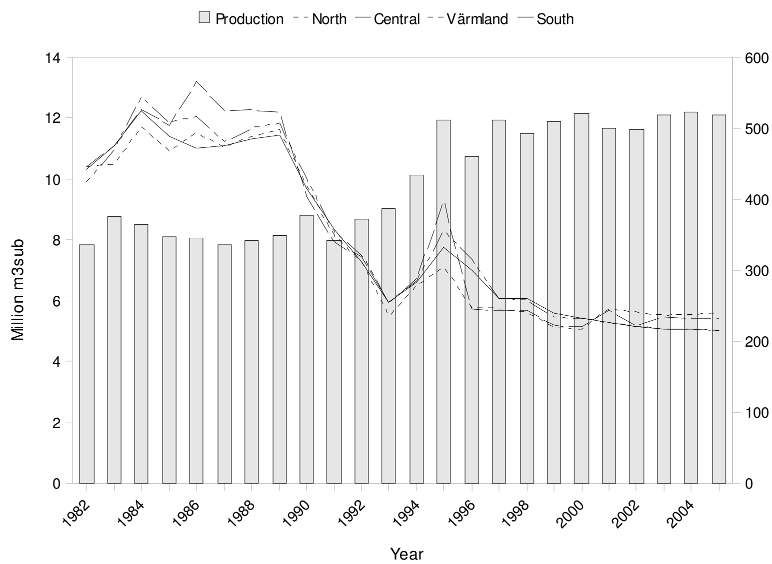


Figure 6: Estimated production of wood chips and regional real prices.
Note that woodchip production in 1982 to 1997 have been approximated by assuming woodchip to be 35% of total sawlog production, based on by-product exchange rates in sawmills.
Source: Swedish Forest agency and VMR (various years)

Overall the supply of by-products from sawmills by definition is not produced and supplied in the market as a response to demand, but instead depends on the production of the main sawmill product (sawnwood). In other words increased demand for by-products should lead to higher prices unless production of sawnwood (and therefor also by-products) increases simultaneously. The quantity of by-products available in the market may also be affected by technological changes in sawmills, e.g. that the capacity to utilize by-products for energy increase or that sawnwood exchange rates (as a share of roundwood input) is improved by installing more efficient machinery.

2.2.2. Wood board industries

The Swedish wood board production has decreased significantly over the last decades (both in numbers of producers and output quantity), and Sweden as a whole has gone from being a net exporter of wood boards in the 1970 to being a net importer in recent years. The expansion of new and more efficient production in other parts of Europe has made Swedish producers less competitive both in terms of product quality and production costs (Swedish Energy Agency, 2003). Most of produced quantities are now used domestically. The two diagrams below show the development of production and import prices since 1980. However it should be noted that the underlying figures (FAOSTAT, 2009) are imperfect due to e.g. classification issues related to different qualities of wood boards. For example there are many types of fibre boards with varying density and physical characteristics that make them suitable for different building purposes. Particle boards are often referred to as low-density fibreboard and there may be difficulties in making clear distinctions between the two main categories.

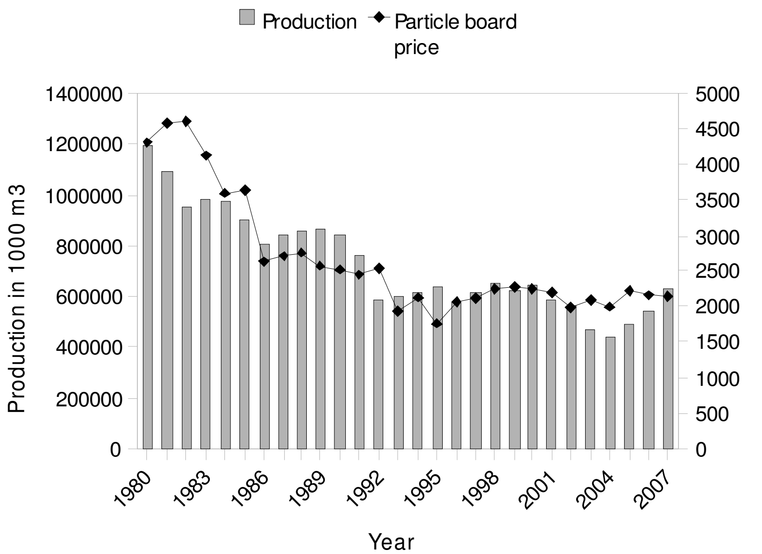


Figure 7: Particle board production in Sweden and real import price.
Source: FAO, 2009

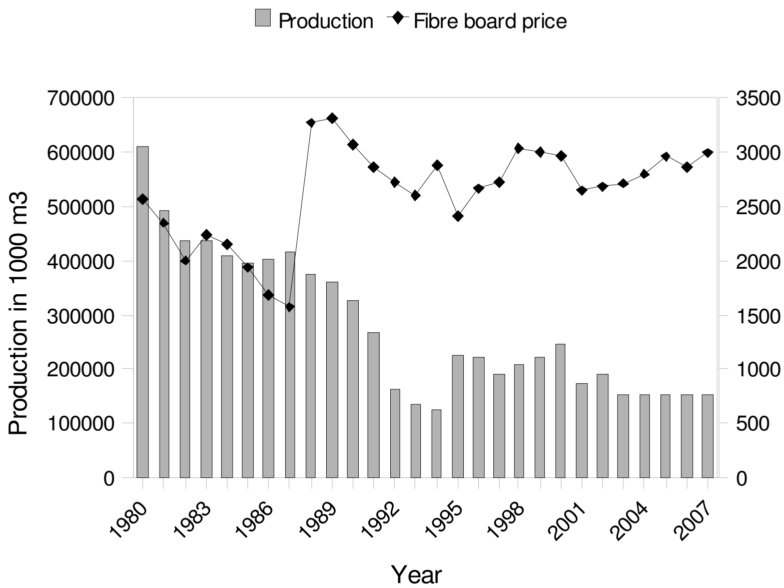


Figure 8: Fibre board production in Sweden and real import prices.
Source: FAO, 2009

Sawdust is used in production of both particle boards and fibre boards. In 2001 about 651 000 m^3s of sawdust were used in manufacturing of particle boards. An additional 120 000 m^3s of wood chips and other types of wood fibre were also used as raw material or for heating purposes. Fibre board industries used around 147 000 m^3s sawdust and 211000 m^3s of other wood fibre in the same year, thus making other wood fibre than sawdust the main input. The substitutability between different types of raw material depends on the type of wood board being produced. Some wood board manufacturers produce their own sawdust from wood chips or other wood material, but such processes are usually costly. In general raw materials constitute around 20-30 percent of production costs (Swedish Energy Agency, 2003), and the Swedish association for wood and furniture manufacturers has raised concerns about increasing raw material prices and its effects on wood board industries (TMF, 2009).

2.2.3. Pulp and paper industries

The Swedish pulp and paper industry is characterized by large and capital intensive production plants that produce paper and pulp mainly for export markets. Production (and production capacity) in paper mills has increased quite steadily over the last 25 years, while market pulp production (pulp sold in the market and not used internally) has remained more stable. Paper and pulp is exported mainly to other European countries, but also to Asia and North

America. In 2006 the 12 largest paper mills constituted about 65% of total production capacity in Sweden, and a similar pattern is found among market pulp producers. The structure of individual producers varies in terms of integration of pulp and paper production. In 2006 there were 12 non-integrated paper mills, 18 mills with integrated pulp and paper, and 13 mills producing market pulp solely. In the same year there were 16 paper mills using recycled paper as raw material (Skogsindustrierna, 2009).

Pulp and paper mills are spread out throughout the country, but most of them are situated near the Baltic Sea coast or other waterways which enable affordable transports by sea to export markets. The demand for paper products is expected to grow in the future, especially in Asian countries, and likewise new production capacity in those countries is growing. In a global perspective, the production of pulp has gradually shifted southward in recent years, especially to Latin America where relatively cheap wood fibre is found in abundance. Swedish pulp producers are thus facing harder competition which puts pressure on cost reductions and efficiency measures (SOU 2006:81). The diagram below shows the development of pulp production and prices since 1980.

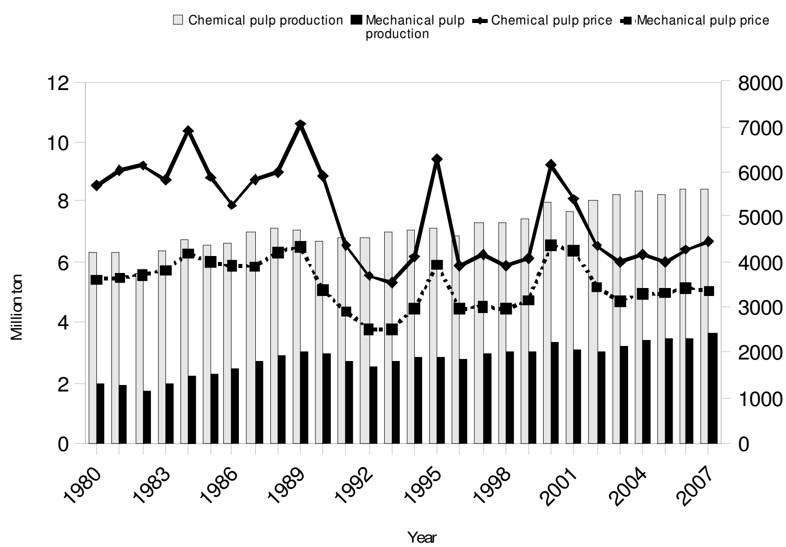


Figure 9: Production of pulp (mechanical and chemical) and real export prices.
Source: FAO, 2009

The industry is heavily dependent on the supply of wood raw material. Spruce, pine and non-coniferous pulpwood is used in varying ratios depending on the type of pulp or paper being produced. Considerable quantities of primarily pine and non-coniferous pulpwood are imported, mostly from Finland, Norway, the Baltic countries and Russia. Domestic supply of pulpwood nevertheless remains the most important source of raw materials for the industry. The diagram below shows production of pulpwood and prices (for different species) from 1995 to 2007. Pulpwood prices are relatively low today compared to price levels in the mid 70's and 80's.

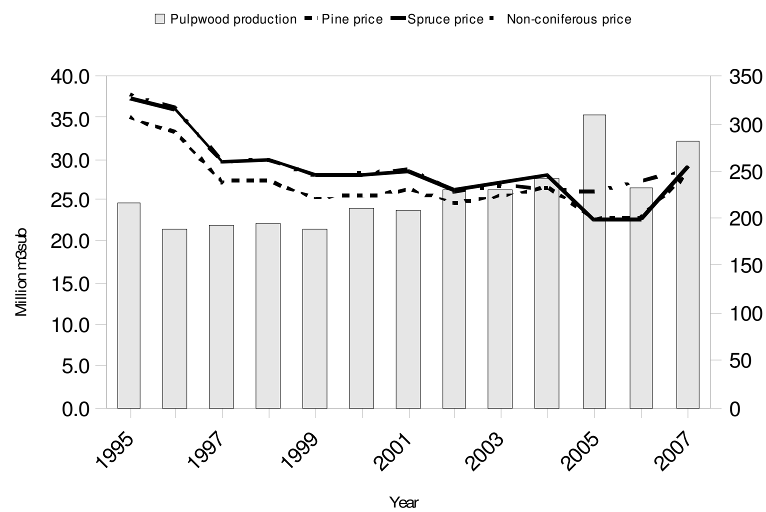


Figure 10: Pulpwood production and real pulpwood prices by species.
Source: Swedish Forest Agency, 2009

In addition to virgin pulpwood large quantities of wood chips from sawmills are also used in pulp production. In 2007 11.6 million m^3s of wood chips, of which 1.1 million m^3s imported, were used in the pulp and paper industries (VMR, 2008). The substitutability between virgin pulpwood and wood chips depend on quality requirements and it is not possible to determine the type, i.e. species, of wood chips used based on official statistics.

2.3. Swedish bioenergy – growing production and use of forest fuels

Energy supplied in Sweden reached a total of 624 TWh (excluding net import of electricity of 1.3 TWh) in 2007. Energy based on oil and nuclear power was most important, followed by biofuels and hydro power. The composition of different types of energy supply has changed over the last 30 years, mainly due to the expansion of nuclear power and a drop in oil based energy. The supplying of biofuels has increased by 179% from 1970 to 2007, much as a result of expansion of municipal district heating plants using various types of biofuels. In 2004 supplied renewable energy (including hydro power, wind power and biofuels) constituted 30% of total energy supply in Sweden (Swedish Energy Agency, 2008).

The industrial sector (mainly forest industries) makes an important contribution to total renewable energy production in Sweden. Around 60 TWh of biofuels (of which the bulk was black liquor in pulp industries) were used in this sector in 2007 (Swedish Energy Agency, 2008).

Forest fuels are used primarily in district heating and combined heat and power generation, but also in private homes in the form of e.g. firewood, wood pellets and briquettes. Energy used in residential and non-industrial premises heating amounted to 94,7 TWh in 2003, of which 42% was used in small houses, 31% in multiple apartment buildings and 25% in office and business premises. Around 5% of small houses relied on biofuels only, but biofuels were also used in combined heating (using a combination of biofuels and electricity or oil). In multiple apartment buildings as well as in office and business premises district heating constituted the dominant type of heat supplied (Swedish Energy Agency, 2005).

Combustion based electricity generation reached 13.6 TWh in 2007, and biofuels represented about 65% of total fuels used. The share of biofuels of total fuels used in power generation has increased gradually over the last 30 years and the use of oil has diminished (Swedish Energy Agency, 2005).

2.3.1. Production and use of energy in forest industries

Forest industries use large amounts of biofuels, primarily black liquors and wood by-products, to produce heat and electricity needed in industrial processes. Most heat and electricity generated in forest industries is used internally and is thus not available in the market. Pulp and paper industries are especially energy intensive in terms of both heat and electricity required in production, and black liquors constitute the bulk of total fuels used. The diagram below shows the development of biofuel utilization in forest industries (and other industrial sectors) since 1980. As can be seen by comparing the below diagram with Figure 9 (which shows pulp production) there is an obvious correlation between the use of biofuels and production in pulp and paper industries.

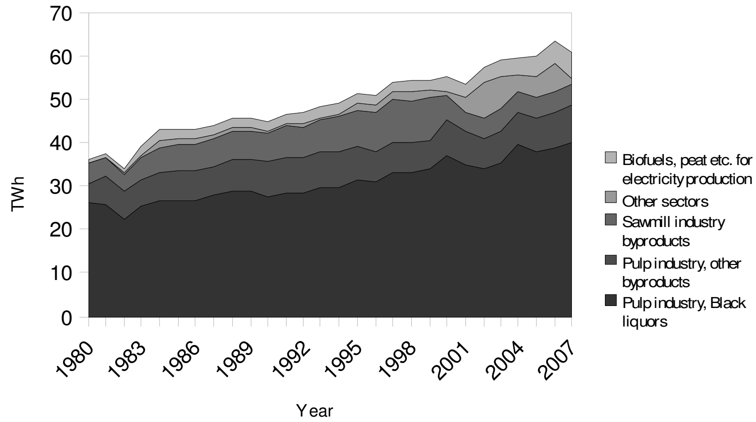


Figure 11: The use of biofuels in Swedish industries in 1980 to 2007.
Source: Swedish Energy Agency, 2008

In 2007 internal fuels accounted for 78% of total fuel inputs used in producing heat and electricity in Swedish pulp and paper mills. External fuels, i.e. purchased fuels, constituted around 22% of of total fuels used. Some mills sell bark and other types of wood residues to other users, but overall the industry is a net consumer of wood fuels. In addition to bark from sawmills, logging residues are also used in pulp and paper mills as heating fuels. The share of internal fuels as well as the share of purchased biofuels has increased from 2000 to 2007 as a result of new technology and more efficient use of biofuels (Wiberg, 2008).

2.3.2. District heating and combined heat and power generation

District heating is defined as centralized production of hot water that is distributed in piping to provide heating in buildings. District heating was introduced in Sweden in the 1950's and has expanded gradually since then, now being the dominant type of heating in chief towns in most Swedish municipalities. The production capacity in district heating plants increased rapidly particularly between 1975 to 1985 when rising oil prices made district heating more attractive owing to its flexibility in potential fuel inputs. District heating may also provide a basis for power generation in combined heat and power plants, and this type of cogeneration has become more profitable in later years because of energy and environmental policies favouring the use of biofuels in electricity production. The flexibility in choice of fuel input in district heating has enabled diversification of fuels and a shift from oil products to renewable alternatives, primarily biofuels, household waste, peat etc. (Swedish Energy Agency, 2005). The share of biofuels (including waste and peat) increased from 2% in the 1970's to 25% in 1990. The introduction of the carbon dioxide tax in 1991 spurred further increases in the use of biofuels, and in 2003 the introduction of the electricity certificate system (which set mandates for purchases of certain types of renewable electricity), together with other policies such as the ban of waste depony, resulted in yet more rapid expansion of biofuel use in district heating and combined heat and power plants (Swedish Energy Agency, 2008). The diagram below shows the use of different types of biofuels in heat and power generation from 1980 to 2007.

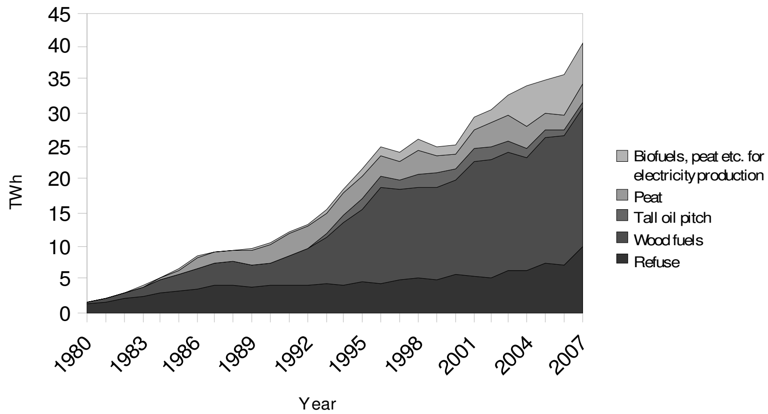


Figure 12: The use of biofuels in district heating and combined heat and power plants in 1980 to 2007.
Source: Swedish Energy Agency, 2008

In 2004 the Swedish district heating association predicted that district heating would likely grow by 2-3 percent per year until 2010, implying an additional 10 TWh of heat delivery. Predictions of future development patterns after 2010 are more uncertain, but district heating could potentially grow to around 80 TWh depending on growth of demand, energy policies etc. Increased demand for heat may also make further expansion of electricity generation possible. The amount of electricity that can be produced in combined heat and power plants depends on the type of fuel used, e.g. using solid wood material as input in electricity generation normally limits the share of electricity of total energy produced to around 30%. Future developments in new technologies may improve the power to heat ratio, for example by gasification of biofuels, which could in increases potential electricity production (Svensk Fjärrvärme, 2004). Forest fuels already constitute the bulk of fuels used in district heating and combined plants, and further increases are expected.

2.3.3. Small scale heating

In 2006 11.2 TWh of biofuels, mainly firewood, were used in small houses for heating. Firewood is most common among those who have access to forests, e.g. farmers and people living in the countryside. Wood chips are used to a lesser extent and the use of wood pellets and briquettes has grown gradually over the past few years. According to pellets industry figures the use of wood pellets has increased by more than 700% from 2000 to 2007 (Swedish Energy Agency, 2008).

There is great potential for additional increases in the use of wood pellets in small houses, mainly by conversion of existing oil burners and electric heating. The cost of installing pellet burners or stoves depend on which type of heating system that is currently in place, e.g. if a house already has water borne heating system or not. Pellet burners may often replace oil burners and pellets stoves are good alternatives for converting direct electricity heating (Svebio, 2004). According to estimates presented by the Swedish Energy Agency in 2008 the use of wood pellets could potentially increase from 1,8 TWh in 2005 to around 8.2 TWh within the next 10-20 years. There is also potential, although more limited, for increased use of pellets in multiple apartment buildings and other buildings but district heating will likely be the main type of heat supply there (Swedish Energy Agency, 2008).

2.4. Forest fuels – development of production and prices

Several different types of forest fuels are used in energy production, either in the form of unrefined fuels such as sawdust, wood chips and bark, or refined wood fuels such as wood pellets, briquettes and wood powder. Different types of forest fuels have varying characteristics in terms of energy content, weight and volume, combustion properties etc. and likewise regional availability and prices show considerable variations. Overall the types of forest fuels considered in this study may be divided into three main categories; logging residues, refined wood fuel and forest industry by-products. A brief description of each of these categories follows, and focus is aimed at fuel properties, availability and costs.

2.4.1. Logging residues

Logging residues consist of wood material such as tree tops and branches, small trees and low quality tree stems without forest industrial use. The residues may be extracted during forest thinning or at final harvest, and the supply of logging residues is thus to a high extent dependent on roundwood production. The cost of extraction of logging residues may be substantially reduced when performed jointly with roundwood harvest. Before being used as fuel logging residues are usually comminuted near the point of harvest or at the user. The quality of the resulting forest chips is mixed which makes the fuel more suitable for medium or large scale energy production plants (Lundmark & Söderholm, 2004).

As with other types of wood fuels the energy content (per volume or weight unit) in logging residues depends mainly on moisture content, the type of wood residue and tree species. When costs are estimated, or when forest chip prices are agreed, the mentioned physical characteristics are important factors. Several attempts have been made to estimate the potential availability and cost of logging residues for energy production, and the results are far from uniform.

Some examples of presented studies are summarized in a report by the Swedish Energy Agency (2007), where annual potentials range from 24 to around 70 TWh depending on assumptions regarding ecological, economic and practical restrictions.

The cost of collecting, forwarding, comminution and delivery to user depends on a number of factors and in general there are few reliable cost estimates available today. Statistics on prices paid by forest chip users are likewise of low quality. Some indicators are nevertheless found in statistics on produced quantities and prices compiled by the Swedish Forest Agency, and the diagram below shows the development since 1994. Note however that the production figures shown below include considerable shares of other types of forest fuel than logging residues. In 2006 delivered quantities of logging residues (as chips or not comminuted) reached around 6.7 TWh (Svenska Trädbränsleföreningen, 2007).

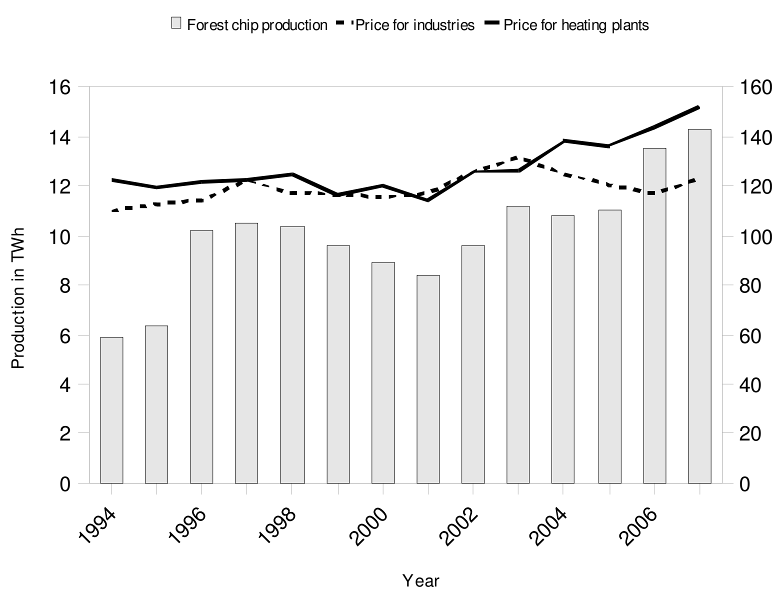


Figure 13: Production of forest fuel and real prices paid by industries and heat plants. Production figures include all forest fuels except bark, sawdust and refined wood fuels. Source: Swedish Forest Agency, 2009

2.4.2. Refined wood fuels

The most common types of refined wood fuels are wood pellets, briquettes and wood powder. Refined wood fuels possess physical characteristics that make them easier and cheaper to transport and burn. In addition the development of quality standards for refined wood fuels has made it easier for users to know what they actually purchase in terms of e.g. energy content. The relatively low transport costs of these types of fuels (owing to high density and low moisture content) facilitate distribution to large scale users as well as to single homes.

The raw materials used in manufacturing of refined wood fuels are mainly wood chips, sawdust, planer shavings and bark. Production of pellets from logging residues is usually more costly due to high raw material moisture content which makes drying required. New production techniques that may enable use of additional types of raw materials are being tested. According to the Swedish Energy Agency (2003) several producers of refined wood fuels are integrated in forest industries such as sawmills, and a considerable share of raw material in the form of by-products are thus acquired internally. About 35% of all sawdust used for refined wood fuels are purchased internally and the remaining 65% are bought in the open market. In general raw material costs constitute about 50% of total production costs for refined wood fuel, but this figure is uncertain and may vary considerably between producers. Due to high transport costs imports of raw materials are usually not a viable option for production of refined wood fuels. For sawdust the transport distance usually lies between 50-100 km, but distances have tended to increase over the last few years.

Overall the production capacity and sales of refined wood fuels have increased rapidly since the early 1990's, while prices have remained fairly stable except in the last few years. The diagram below displays the development of production and price between 1994 and 2007. The production figures are based on the assumption that sales (for which statistics are available) equal production, but stocks kept by distributors may cause sales figures to differ from actual production.

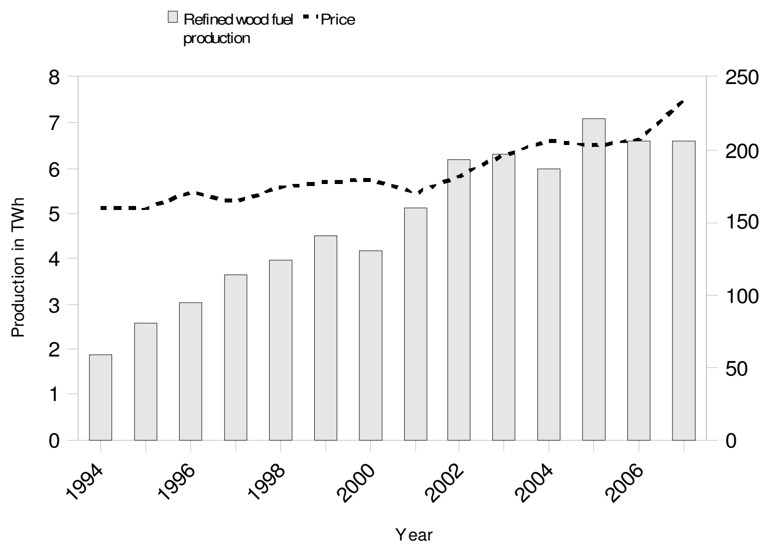


Figure 14: Production (sales) of refined wood fuels and real price at thermal power station. Source: Swedish Forest Agency, 2009

2.4.3. Forest industry by-products

Forest industry by-products originate primarily from sawmills (as is explained in 2.2.1. above) and consist of various types of potential biofuels such as wood chips, sawdust, planer shavings and bark. Unlike forest chips from logging residues, wood chips from sawmills are used in pulp and paper production but may also be used as input in energy production (Lundmark & Söderholm, 2004). The fuel properties of forest industry by-products show great variation depending on factors such as moisture content and from which type of trees they are produced. The quality of statistics on production of by-products is likewise affected by the mentioned physical characteristics, and it is often difficult to determine any precise figures due to errors in unit conversion (energy unit to/from weight or volume units).

Wood chips from sawmills have so far not been extensively used as input in energy production, but this may change as prices of other forest fuels increase. The by-products sold as fuels have thus traditionally been primarily bark and sawdust (including planer shavings). The table below describes the development of sales of these two types of by-products (when sold as fuels) and real prices for industry and energy producers. As can be seen prices remained fairly stable until 2002 but has since increased for both types of users.

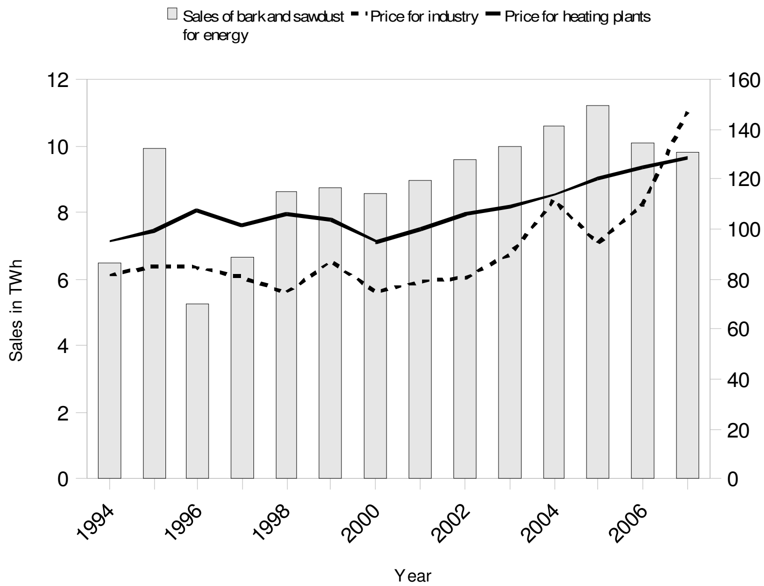


Figure 15: Sales of bark and sawdust for energy and prices at industries and heating plants. Source: Swedish Forest Agency, 2009

3. Forest fuels in a competitive market – theory and economic modelling

The above description of the Swedish forest industry cluster and bioenergy production gives some insight in the current market situation for some types of forest fuels. Certain types of forest industry by-products are (or may potentially be) used as inputs in forest industries as well as in bioenergy production. The market for forest fuels is showing signs of increasing competition between different types of users and it is thus of interest to study market interactions more closely both in theory and empirically. This chapter briefly describes the competition for forest based raw material through a simplified theoretical perspective. Next a summary of previously developed economic models of the forest sector follows, aimed at providing a methodological background for the model developed in this thesis project.

3.1. A simplified theoretical perspective on competition for forest fuels

To exemplify how competition for forest fuels could function we may start with a simplified description of two end markets (energy and forest industries) for a forest fuel in a small open economy, as shown by Lundmark & Söderholm (2004). The raw material is assumed to be homogeneous and will thus form one supply curve independent of the final user of the product. The supply curve meets two demand curves since there are two different potential users. By assuming energy price to be exogenous and determined solely by the import price of fossil energy fuels, the energy sector's demand curve becomes horizontal. Under the given circumstances competition in the market could be described as in the figure below (assuming arbitrary price levels).

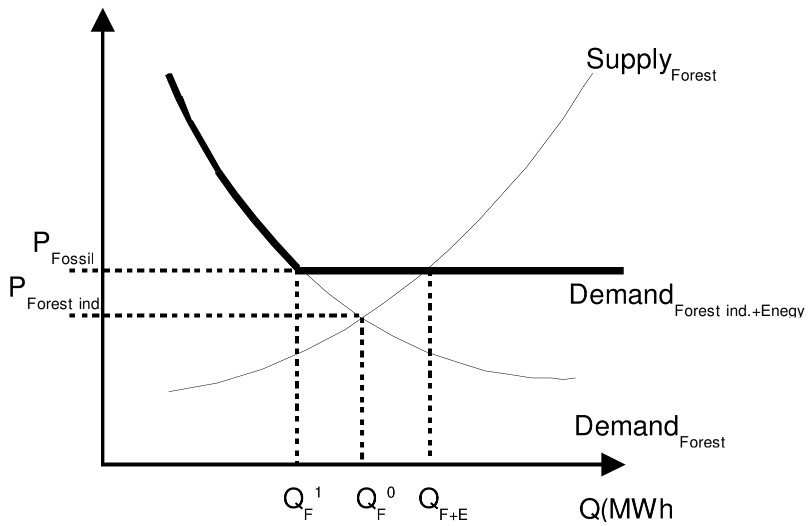


Figure 16: Market competition for raw material between forest industry and bioenergy producer.
Source: Lundmark and Söderholm, 2004

The figure illustrates how the forest industry's willingness to pay for forest raw material is higher than that of energy producers at quantities below Q^1_F along the x-axis. However quantities above Q^1_F, energy producers have higher willingness to pay than forest industries and consequently raw material supplied up to the quantity Q_{F+E} will be used in bioenergy production. At Q_{F+E} the combined demand function (fat and kinked line) is balanced by forestry supply and market equilibrium is attained. If instead forest industries would be the sole user of forest raw materials (no demand from energy producers) the equilibrium price ($P_{Forest\ ind.}$) and total quantity (Q^0_F) would be lower than in the former case where competing demand exists. In a competitive demand situation forest industries would have to pay a higher price ($P_{Fossil} > P_{Forest\ ind}$) per unit of raw material and therefore use less ($Q^1_F < Q^0_F$) of that input.

In the general example described above we assumed price insensitivity in raw material demand for energy producers. We now narrow our perspective to analyze the market situation for a specific type of forest fuel such as logging residues, wood chips, sawdust or pulpwood. Now energy producers are (also) assumed to be sensitive to raw material price as is shown by the downward sloping demand curve ($Demand_{Energy}$) in the figure below. Thus energy producers have a less elastic demand curve than in the previous case but forest industries show even less elastic demand. The substitutability between inputs is one important factor determining the shape (in this case the slope) of the demand curves. It is likely the case that forest industries such as wood board manufacturers are less able to substitute e.g. sawdust with other inputs, but energy producers may often switch to other forest fuels if the price of sawdust increases. Higher substitutability between inputs should imply more elastic (flatter) demand curves.

The figure below illustrates how a competitive situation could appear for a single type of raw material. The fat and kinked line constitutes the summed demand curve for forest industry and bioenergy producers. The vertical broken line to the right sets the maximum quantity (Q^*) of the raw material that is available in a given time period. The level of Q^* may depend on production capacity as well as ecological and/or technical factors that limit supply. The supply curve shows increasing slope as higher quantities are supplied and finally becomes near vertical. In other words the raw material price could potentially rise very rapidly as supplied quantity approaches Q^*.

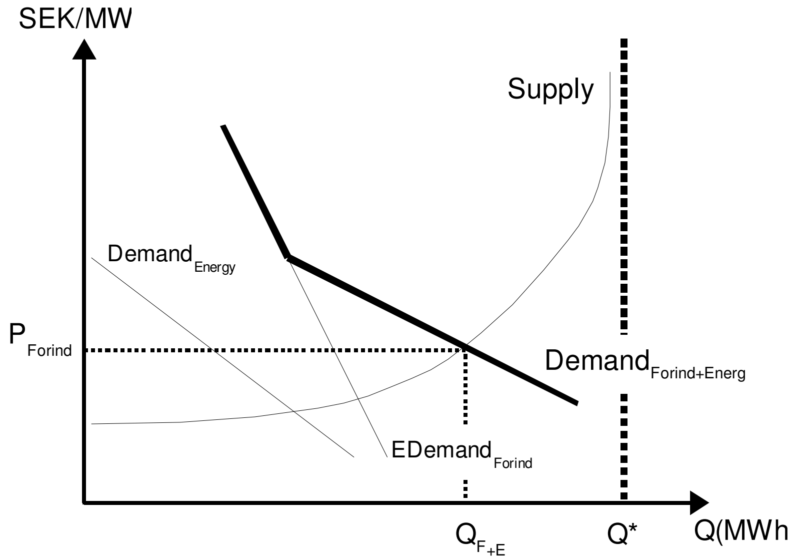


Figure 17: Supply and demand for a single raw material under buyer's competition.
Source: Lundmark and Söderholm, 2004

The figure above shows a situation where both forest industries and energy producers would adjust demanded quantities gradually in case of a shift in raw material price. As noted by Lundmark & Söderholm (2004) the input substitutability within energy industries may imply upper limits on price increases due to increased demand. This could be the case e.g. if the price of sawdust reaches the price level of pulpwood (both prices measured per MWh energy content) thus shifting energy producer's demand away from sawdust to pulpwood and thus easing further increases of sawdust price. However a following effect could be that the demand for pulpwood and thus pulpwood prices increases which could affect yet other forest industries.

The characteristics of forest fuel supply curves also differ depending on the type of forest fuel in question. The above figures are likely more relevant in the case of forest fuels that are supplied in the market as a response of demand (for example pulpwood supplied by forest owners). Other types of forest fuels such as sawdust and bark are by-products from forest industrial activities. For these by-products the maximum quantity available in the market will depend mostly on sawmill production of sawnwood, but also on how much of the by-products that are used internally at sawmills instead of being sold in the market. Similarly the potential supply of logging residues is limited by the level of roundwood harvest.

3.2. Economic models of the forest sector

In the past various types of models have been applied in analysis of the forest sector. In the following the term “forest sector models” refers to models where supply of roundwood or forest fibre (from forestry) and use of the wood material (by forest industries) are both included (Solberg et al., 2007). The study undertaken in this thesis project relates closely to forest sector models belonging to the family of generalized or partial equilibrium models and inspiration is drawn particularly from the EFI-GTM (European Forest Institute – Global Trade Model) and closely related models with national focus such as NTM (the Norwegian Trade Model), NTM II and similarly structured model for the Finnish pulp and paper industry called SF-GTM. The purpose of these models has often been to make long term projections of forest sector developments, e.g. forest resources, harvest and availability of roundwood, forest industry production levels and demand for wood products.

EFI-GTM was originally developed at IIASA (The International Institute for Applied Systems Analysis) and presented by Kallio, Dykstra & Binkley in 1987. The model has been successively developed and is presently managed by the European Forest Institute in Finland (Kallio, Moisyev & Solberg, 2004). EFI-GTM is a regional, multi-periodic partial equilibrium model aimed at analysing issues such as economic competitiveness, regional trade and production costs in the forest sector. The model currently includes 61 regions of which 30 are in Europe (primarily individual countries). The time horizon of the model is technically unlimited but uncertainties in future development, e.g. of technologies and demand, limit the practical time frame to around 20-30 years. Recursive dynamics are used to model dynamics over time in EFI-GTM, meaning that the equilibrium solution from one year is used as input data in modelling the following year, and so forth.

The endogenous variables in the model are prices and produced quantities (for each period, region and product), traded quantities between regions and total yearly use of production inputs (labor, electricity, bioenergy, fossil fuel) in each region. Various types of scenarios may be implemented in the model by changing the assumptions on the exogenous variables defined initially. Some of the most important exogenous parameters are those relating to regional economic growth, production technologies and production capacity, demand and supply elasticities, production costs, exchange rates etc. EFI-GTM comprises a rather detailed description of forestry and forest industry production, particularly in Europe. Bioenergy has so far only been included in terms of forest industry bioenergy production, but other types of bioenergy could easily be incorporated if suitable data on production costs, capacities etc. could be found (Kallio, Moisyev & Solberg, 2004). The EU-funded

EFORWOOD project (Sustainability Impact Assessment of the Forestry-Wood Chain) is aimed at including some additional types of forest fuels, e.g. refined wood fuel production, in the EFI-GTM framework (Solberger et al., 2007).

Following in the footsteps of EFI-GTM, a forest sector model called SF-GTM was developed by Ronnila in 1995. This model provided a detailed description of the Finnish pulp and paper industry (at a geographic level of counties) and focused on analysis of domestic market developments. A similar model called NTM was developed for Norway by Trömborg & Solberg in 1995, and in 2004 Bolkesjö presented an improved and updated version called NTM II. All the model mentioned above share the same basic structure but vary in regional focus and in particular model components. Bolkesjö was the first one to include a detailed description of bioenergy production and thus the demand for forest fuels in a similar framework. The efforts of modelling bioenergy in NTM II was continued by Trömborg, Bolkesjö and Solberg (2006 and 2007) and the bioenergy technology component in particular has been developed further.

4. Model description

This chapter describes the Swedish Forest Sector Trade Model (hereafter SFSTM) in terms of major theoretical foundations and mathematical model components. First a brief explanation of the fundamentals of partial equilibrium analysis in trade models is given, followed by an overview of the particular agents and products that are included in the model. Next follows a description of the mathematical functions that are assumed to model economic agent's behaviour, e.g. the appearance of supply- and demand functions in the model. The full scale model is finally formulated in which the objective function and constraint equations are defined.

4.1. General notes on partial equilibrium trade models

A partial equilibrium approach implies modelling of a selected set of variables while assuming certain parameters to be exogenous and thus determined outside and independent of the model equilibrium. In other words the partial equilibrium focuses on a subset of the economy (e.g. a particular industry or commodity) and treats all other variables (e.g. household income, prices of complements) as exogenous, and possible feedback loops with the rest of the economy are thus disregarded. The limited scope of the partial equilibrium model makes it easier to attain greater detail in the description of the industry/commodity in question, compared to general equilibrium models. In contrast general equilibrium models aim to describe the whole economic system thus accounting for impacts on other parts of the economy and feedback effects that connect back to the original market (O'Toole & Matthews, 2002).

The connection between price, production and demand may be defined by supply and demand curves that are calibrated in base year reference data. The shape of supply and demand curves may in turn be based on econometric studies and other types of studies in which price elasticities are estimated. Partial equilibrium models are often used in analysis of trade between regions, for example in studies of possible trade flow changes due to shifts in supply and/or demand in certain countries or regions (Trömborg & Solberg, 1995).

A partial equilibrium model may be constructed so that consumers and producers in different regions are brought together in a mathematical modelling system in which equilibrium is computed. In this type of regional model transport costs often constitute an essential component, for example defined as a constant cost per unit transported between two regions. The transport cost per unit and kilometre for a given product may be allowed to vary with distance, possibly depending on transport mode, and is thus not necessarily linearly increasing with distance (Trömborg & Solberg, 1995).

The partial equilibrium model will compute simulated equilibrium prices in all markets as well as demanded and produced quantities in all regions. Quantities exported and imported between regions, if allowed, are also computed. Samuelson (1952) describes the functioning of partial equilibrium in a simple example where a product is manufactured and consumed in two regions (markets). Beginning with two markets with different equilibrium price levels, the introduction of trade between the two regions will result in new equilibrium prices. In the new equilibrium the difference between prices in the two regions will be equal to the cost of transporting the product from the region with excess supply to the region with excess demand. It also follows that exports from one region will be equal to imports to the other.

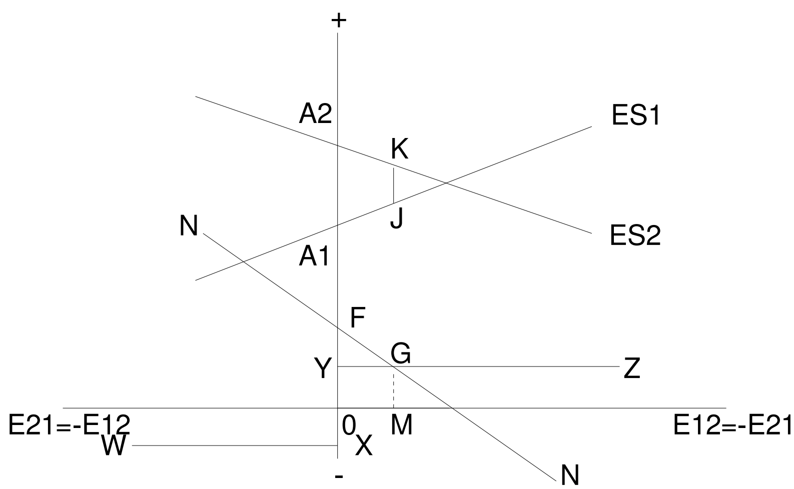


Figure 18: Equilibrium in two markets.
The transport cost is given by WXYZ. Equilibrium applies where NN (which is the result of subtracting ES1 from ES2) crosses WXYZ. Net social surplus is formed by the area YFG. Source: Samuelson, 1952

Figure 18 depicts the equilibrium solution briefly outlined above. The equilibrium prices are given in points *J* and *K*. In equilibrium the distance *JK* will be equal to transport costs *T12* and thus also equal to the difference between *ES1* and *ES2* (the excess supply curves). The vertical difference between *ES1* and *ES2* in turn defines the net surplus curve called *NN*. Equilibrium is attained in *F* where *NN* is equal to transport costs given by the line *WXYZ*. The sum of consumer and producer surplus constitutes the social pay-off in both markets, and is displayed by the NN-curve in the figure. When transport costs are subtracted from *NN* we get the net social pay-off (hereafter called NSP). *NSP* for the two markets may thus be defined as:

NSP = Social pay off in market 1 + Social pay off in market 2 – transport costs

Or mathematically:

$$NSP = -\int_{0}^{E_{12}} s_1(x)\,dx - \int_{0}^{-E_{12}} s_2(x)\,dx - t_{12}(E_{12})$$

where $s_i(E_i)$ is the excess supply function. In the figure above, the area *YFG* constitutes net social pay-off in equilibrium and the objective in the simple model described is to maximize this area.

4.2. The Swedish Forest Sector Trade Model (SFSTM)

4.2.1. SFSTM overview

The model developed in this thesis is a partial equilibrium model of the Swedish forest sector. The model includes forest owners, forest industries and energy producers that use forest fuels as inputs. The mathematical formulation and the structure of *SFTM* are based on previously developed forest sector models. Most notable among the references used in this part of the paper is the description of EFI-GTM by Kallio, Moisyev & Solberg (2004), along with the doctoral thesis *Modeling supply, demand and trade in the Norwegian forest sector* by Bolkesjö (2004).

The model is structured so that net social pay-off in the whole sector is maximized, i.e. the sum of consumer and producer surplus minus transport costs is maximized. The objective function in the model is maximized under several constraints, e.g. production capacities for the various types of industries included in the model. The optimized model results in market equilibrium conditions under the assumption of free competition. The endogenous variables that are determined within the model are equilibrium prices, produced quantities of forest industry products and bioenergy, consumption, and use of intermediate and by-products. Quantities traded between regions are also computed in the model. All the endogenous variables are computed for every product in every region in the model. Prices of inputs such as labour, capital and other variable production costs are assumed to be exogenous to the model and are thus not affected by changes in the partial equilibrium.

The figure below shows the products that are included in SFSTM. In total there are six roundwood assortments, nine forest industry final products, two types of forest industry by-products in addition to wood chips, and three types of intermediate products in the model. Note that wood chips are not modelled as separate products but are instead included in the three pulpwood categories. This means that wood chips (by-product) resulting from production of spruce sawnwood is available as spruce pulpwood in the market.

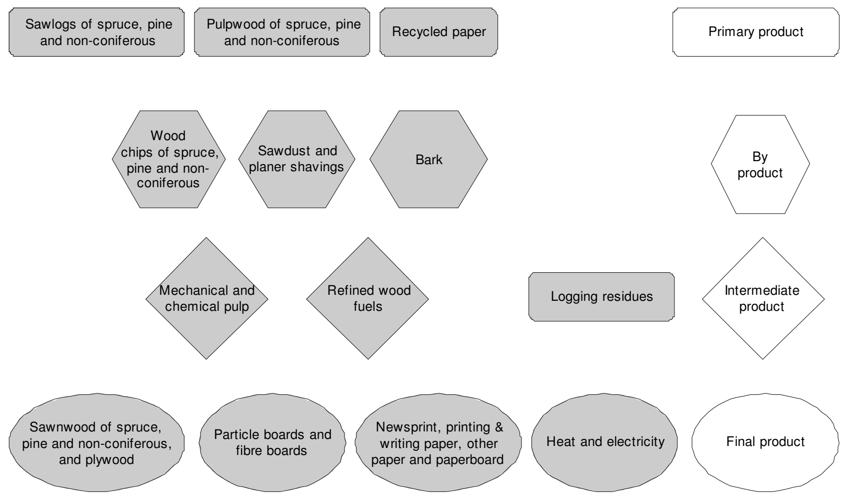


Figure 19: Products included in SFSTM.
Product category is displayed in the right hand side of the figure.

Three main categories of economic agents are defined in each region:

1. Raw material suppliers - Forest owners
2. Producers - Sawmills, pulp and paper industries, wood board industries, refined wood fuel producers and bioenergy producers
3. Retailers and/or consumers

The connections and relationships between these economic agents are described in a simplified manner in the flow diagram below.

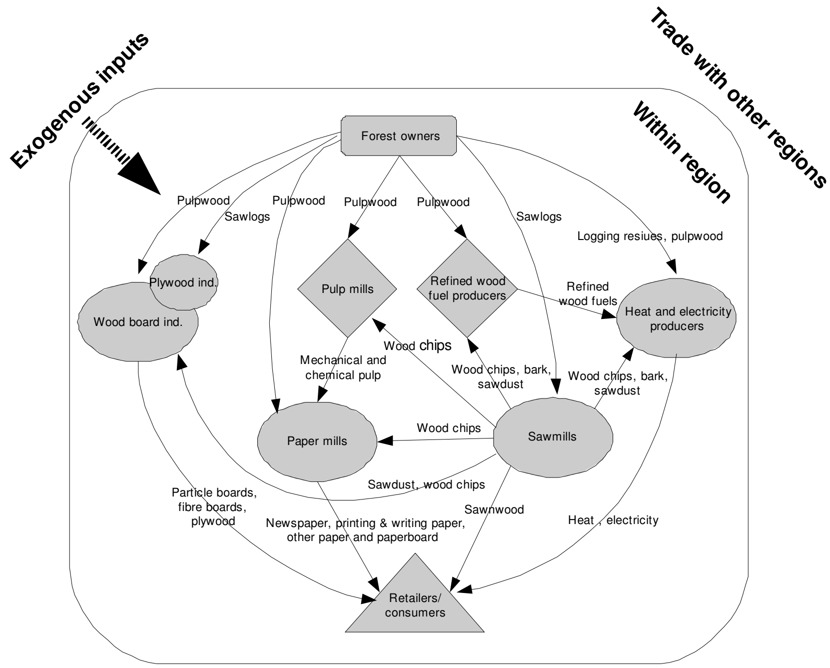


Figure 20: Flow diagram
Showing raw materials, intermediate products, by-products and final products along with economic agents on regional level in SFSTM. Note that interregional trade and exogenous inputs constitute important components in the full scale model but are not shown in detail here.
Source: Own adaption based on Bolkesjö (2004) and Lundmark & Söderholm (2004).

In the mathematical formulation of the model raw material suppliers (1) and producers (2) are assumed to be profit maximizing agents. Consumers (3) on the other hand are assumed to be welfare maximizers and price takers. When the individual regions are combined into the full scale model profit maximizing trade agents are added to the economic agents mentioned above. The trade agents thus exploit any possible profits that can be made from trading products between regions given regional price differences and transport costs. Various constraints affect each type of agent, e.g. production capacity in a given region. Balance equations are also defined so that e.g. supply and use of raw materials are balanced in each region (also taking traded quantities into account). Further details on the formulation of the mathematical functions describing the fundamental economic agents in the model are given by Lestander (2009).

Unlike EFI-GTM, NTM and SF-GTM, the model developed in this thesis project does not account for any dynamic changes over time. SFSTM is thus a static model and the time perspective is therefore more limited than in the above mentioned models.

4.2.2. *Roundwood supply*

The roundwood supply curves in SFSTM are given by non-linear functions that are increasing in roundwood price. There are in total six roundwood supply curves in each region in the model (one for each roundwood assortment and region). Previous estimates of timber price elasticities determine the slope, and observed prices and quantities harvested in the base year are used to set the level of the supply curves. The underlying rationale for the positive slope of roundwood supply curves is that the harvesting cost increases with production, e.g. driving costs go up when additional and more marginal forest stands are harvested.

The mathematical formulation of roundwood supply is based on the economic theory of a Cobb-Douglas production function. Similar to Kallio, Moisyev & Solberg (2004) the inverse supply function for sawlogs and pulpwood looks as follows:

$$\pi_w^i = d_w^i + \alpha_w^i (h_w^i)^{\beta_w^i} \tag{1}$$

where π^i_w is the price per cubic meter of a given roundwood assortment *w* in region *I*, d^i_w is an exogenously given price variable in timber price that is independent of harvest level, and h^i_w is the harvest level for roundwood assortment *w*. α^i_w is a parameter that captures shifts in roundwood supply due to other factors than timber price and β^i_w is the inverse of the estimated price elasticity for timber. The value of α^i_w is computed by substituting base year values for d^i_w, h^i_w, π^i_w, och β^i in (1).

The model also includes restrictions on the sawlogs to pulpwood ratio, i.e. all roundwood may be used as pulpwood but the share of roundwood suitable for sawnwood production is limited due to quality requirements.

4.2.3. *Forest industry production*

Forest industry production in sawmills, pulp and paper mills as well as wood board industries is modelled by linear production functions defined by input-output coefficients. This modeling technique is similar to that used by Kallio, Moisyev & Solberg (2004). The set-up of forest industries in SFSTM differs somewhat from that described by Kallio et al, mainly by which inputs and by-products that are included and in the definition of exogenous inputs. The input-output coefficients define how much raw materials or other inputs that are required to manufacture one unit of a given final product (or one unit of an intermediate product in the case of pulp). Producers are assumed to be profit maximizers in a competitive market, which implies that forest industries will produce up to the level where marginal costs are equal to marginal revenue.

A set of production technologies l are defined for forest industries in each region. The production technologies correspond to each type of producer of final or intermediate products. For each production technology l and region i input-output coefficients are defined that determine the type and quantity of inputs that are required to produce one unit of the main product m using that technology. In addition to the endogenous inputs (sawlogs, pulpwood, sawdust, bark and pulp) with coefficients a_{kl} there are also exogenous inputs with coefficients a_{nl} (k are endogenous products and n are exogenous). The exogenous inputs in forest industries in SFSTM are recycled paper and "other variable production costs" which is an aggregate of exogenous production costs such as capital, electricity, labor, chemicals and other materials etc.

A linear production cost function is formed based on the input-output coefficients, and for production activity l in region i the function will be:

$$\Gamma_l^i\left(y_l\right)=\left(c_l^i-\sum_{k\neq m}\pi_k^i a_{kl}\right)y_l^i \qquad (2)$$

where y^i_l is output of main product m from technology l, and c^i_l is the cost per unit given by exogenous inputs. For input-output coefficients it holds that $a_{kl} \leq 0$ for inputs and $a_{kl} \geq 0$ for by-products.

A unit investment cost, S^i_l, is defined for all technologies. Given assumptions on interest rates and life-time of technologies, the capital cost per unit of new capacity installed is defined as a percentage, σ^i_l, of the unit investment costs. Investment in new capacity will occur if the investment cost (per unit of additional capacity) is lower than the revenue that could be earned by producing and selling one more unit of a product.

4.2.4. Supply of logging residues

In SFSTM logging residues constitute a potential fuel input in energy production. Logging residues may consist of various types of forest materials such as tree branches and tops, thin and weak trees, left trees and stem pieces, trees from thinning and clearings etc. There is currently a lack of empirical estimates of price elasticities for logging residues. Therefor the supply curve for logging residues in each region is defined based on estimates of available and extractable quantities and driving costs for different types of residues. The supply curve will be a stepwise increasing linear function where different types of logging residues together form total supply.

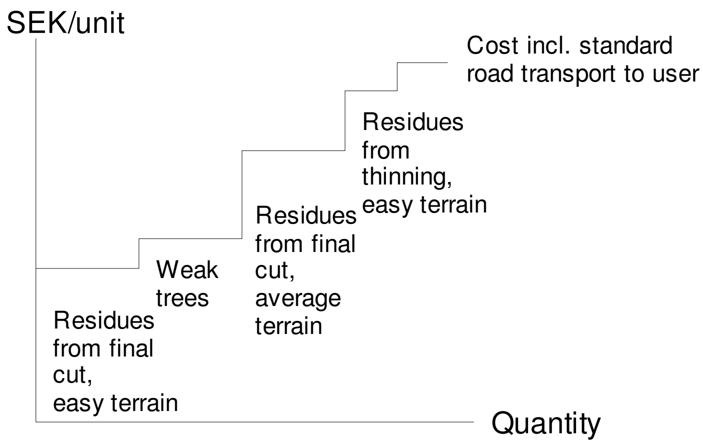


Figure 21: Illustration of a possible supply curve for logging residues in a given region. The maximum available quantity of each type of residue is limited by ecological and technical restrictions. Transport costs to users in the same region are in included in costs.

The figure above displays how a supply curve for logging residues might appear in a given region. The total quantity of logging residues supplied by forest owners and used in energy production is thus made up by several different types of logging residues, each having extraction costs and regional availability defined by data. Since logging residues may be seen as a sort of by-product it is assumed that available quantities of logging residues are proportional to regional roundwood harvest in SFSTM. In the mathematical formulation of SFSTM logging residues are defined as an intermediate product that is produced subject to a cost function as in(2). This specification is similar to that shown by Bolkesjö et al (2006).

4.2.5. Bioenergy production and refined wood fuel

Bioenergy production is modelled in the same manner as forest industries with coefficients defining input use as well as other variable production costs. Assuming profit maximizing behaviour in a competitive market bioenergy is produced up to the level where marginal costs equal the price of energy. In SFSTM the energy price is assumed to be exogenous to the model and will thus not be affected by variations in bioenergy production.

Similar to NTM II as described by Bolkesjö (2004) bioenergy production in SFSTM is divided into segments with varying number of production technologies. Production technologies differ by type of forest fuel used as input as well as in production costs (capital, operating and maintenance, efficiency rates etc).

Refined wood fuel is modeled as an intermediate product and input costs and raw material use is defined similar to forest industry production. The forest fuels that may potentially be used in direct combustion in energy production are also available for production of refined wood fuel. The resulting product is assumed to be homogeneous and independent of which raw material is used.

4.2.6. Forest industry products demand

The demand for forest products in SFSTM is modelled as a linear function decreasing in product price. The function is calibrated in consumed quantities and prices in the base year. Econometric estimates of price elasticities provide exogenous parameters that determine the slope of the demand function. Defining price as π^i_f, quantity as q^i_f and the elasticity as γ^i_f for product f in region i we get the following demand function:

$$q_f^i = \left(1-\gamma_f^i\right)\hat{q}_f^i + \left(\frac{\gamma_f^i \hat{q}_f^i}{\hat{\pi}_f^i}\right)\pi_f^i \qquad (3)$$

The inverse of function (3) is used when optimizing the model.

4.2.7. Model specification

The model components described above are all combined in the specification of the complete model. An objective function is defined along with balance equations and other constraints. Under the condition that imports from i to j are equal to exports from j to i, the global model is given by:

$$Max_{q^i, y_l^i, h_w^i, e_k^{ij}} \left[\sum_{if} \int_0^{q_f^i} P_f^i\left(q_f\right) dq_f - \sum_{iw} \int_0^{h_k^i} \left(\omega_w^i + \alpha_w^i h_w^{i\,\beta_w^i}\right) dh_w^i - \sum_{il} c_l^i y_l^i - \sum_{ijk} D_k^{ij} e_k^{ij} \right] \qquad (4)$$

where i and j refer to regions, k to products (final, intermediate and roundwood), f to final products, w to roundwood assortments and l to production activities. The first term in the objective function refers to the inverse demand function for products f in region i (note that bioenergy is included in the demand function). The second term refers to the roundwood supply function. The third term deals with production costs in forest industries, manufacturing of refined wood fuels and extraction of logging residues. The last term covers interregional trade, where D^{ij}_k is the unit cost of transport between region i and j.

The objective function is optimized under the following constraints:

$$q_f^i - \sum_l a_{fl} y_l^i + \sum_j \left(e_f^{ij} - e_f^{ji} \right) = 0 \quad \forall f, i \tag{5}$$

$$-\sum_l a_{ul} y_l^i + \sum_j \left(e_u^{ij} - e_u^{ji} \right) = 0 \quad \forall u, i \tag{6}$$

$$-\sum_l a_{wl} y_l^i - h_w^i + \sum_j \left(e_w^{ij} - e_w^{ji} \right) = 0 \quad \forall w, i \tag{7}$$

$$y_l^i \le K_l^i \quad \forall l, i \tag{8}$$

$$\sum_{il} a_{rl} y_l^i \le \sum_{if} \left(\phi_f^i \bar{q}_f^i \right) \tag{9}$$

$$q_f^i, y_l^i, h_w^i, e_k^{ij} \ge 0 \quad \forall i, j, k \tag{10}$$

Here (5) balances consumption, production and trade of final products, (6) balances production, use and trade of intermediate products (pulp, logging residues and refined wood fuel), (7)balances use, harvest and trade of roundwood assortments. Equation (8) sets maximum production capacity for each technology and region, and (9) constrains total use of recycled paper to be less than or equal to an exogenously determined share (ϕ^i_f) of total consumption in the base year. Finally (10) imposes non-negativity constraints on consumption, production, harvest and trade respectively.

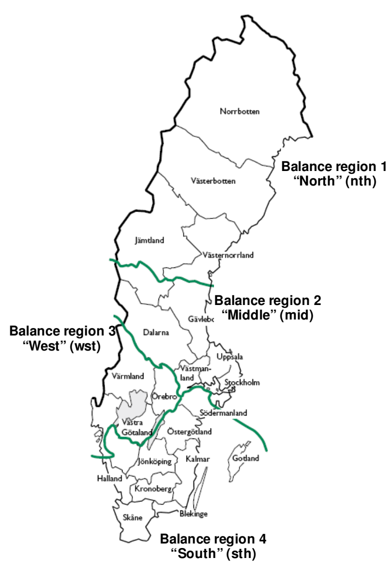
4.2.8. Programming language – GAMS

SFSTM is modelled in GAMS (General Algebraic Modeling System) programming language. GAMS is specifically designed for modelling linear, nonlinear and mixed integer optimization problems. In SFSTM follows a nonlinear programming model is optimized using the solver CONOPT (integrated in GAMSide software). The programming language is relatively user friendly and is especially useful with large complex problems. Data is entered in list and table format, and the model is described in algebraic statements.

There are many alternative programming languages and types of software that could potentially be used in implementing a model such as SFSTM. GAMS was chosen primarily because it allows easy modification of individual equations and constraints, and exceptions may also be defined rather simple. The software also specifically points out errors in execution of the model which facilitates programming. Previously developed forest sector models such as EFI-GTM and NTM II are also programmed in GAMS. The best option would therefor likely have been to reuse the programs already developed and to modify it to fit SFSTM. However, due to copyright reasons the GAMS-code for neither of the mentioned models could be made available for use in this thesis project. The program used to implement SFSTM has thus been set-up entirely from scratch based on algebraic descriptions of existing forest sector models.

5. Data

The model applied in this thesis project relies on quite comprehensive data describing the forest sector and Swedish bioenergy in the model's reference year. The year 2004 is chosen as reference year primarily since data and statistics from more recent years are likely affected by the persisting supply shock due to the storm Gudrun in 2005. The focus is on Sweden, and data are gathered (and computed) to correspond to the four wood balance regions as defined by VMR and SVO (see map below). A more detailed regional division would be preferred (similar to those found in SF-GTM and NTM II) but presently there is not sufficient data to construct the model accordingly. In order to account for foreign trade in the model a region covering "the rest of the world", also referred to as the international region, is also included. However it should be noted that the data for the international region are often rough approximations and not real statistical data.



Map 1: Swedish regions in SFSTM. Regional division is the same as for wood balance regions as defined by VMR and SVO.

Further details on data sources, assumptions and computations are provided in a separate unpublished paper (Lestander, 2009). The data description given below is meant to give an overview of the types of data used, their quality and some of the main sources used.

5.1. Roundwood supply data

There are six roundwood assortments included in SFSTM, divided into two categories (sawlogs and pulpwood) of the three wood species spruce, pine and non-conifer. Regional roundwood harvest in Sweden is computed from roundwood use statistics based on the assumption that harvest balances usage. Imports and exports are also accounted for. The method used to compute harvest is similar to that used in the report *Rundvirkes- och skogsbränslebalanser för år 2007* (Swedish Forest Agency, 2008).

Similar to Bolkesjö (2004) roundwood harvest in the international region is set to balance total roundwood use in all regions in the model. Thus roundwood harvest in that region is not based on real data but is instead determined indirectly by total consumption of roundwood in the model (total roundwood use minus Swedish harvest).

Regional roundwood prices per assortment are based on price statistics provided by the Swedish Forestry Agency (2009). The regional division of the price statistics did not correspond fully to the regions used in SFSTM and subsequently certain assumptions and computations were necessary in order to correct for mismatches. See Lestander (2009) for details on this issue. Transport costs from roadside to region centre (within regions) have been added to the original price statistics based on average transport costs reported by Skogforsk(2004). Roundwood prices in the international region are based on Swedish import prices (Swedish Forest Agency, 2009) adjusted to exclude transport costs to Sweden.

The roundwood price elasticities used in roundwood supply curves in SFSTM are similar to those used by Lundmark (2006) and Bolkesjö (2004) who in turn refer to several empirical studies of roundwood supply in Sweden, Finland and Norway. The same price elasticities are assumed to apply in all Swedish regions (but differing between sawlogs and pulpwood). Price elasticities in the international region are assumed to be somewhat higher than those in Sweden.

5.2. Regional forest industry production data

Forest industries are modelled by input-output coefficients in SFSTM. The coefficients determine the use of inputs as well as output of by-products resulting from production of one unit of a given industries main product. A number of sources have been used in order to determine input-output coefficients for each production technology in each region (except in the international region where Swedish averages are applied).

Statistics provided by VMR (2005, and personal communication Christina Lundgren) have been used to compute roundwood input coefficients (and output coefficients in the case of sawmills) as well as by-product output coefficients (bark and sawdust) for forest industries. The forest industry environmental database (Skogsindustrierna, 2005, and personal communication Katrin Heinsoo) provided complementary information that was used in determining input coefficients for paper mills. The use of market pulp (as opposed to internally produced pulp) in paper mills proved difficult to find and several different sources, e.g. corporate homepages, RISIinfo, environmental audits and annual reports, have been studied to find plausible estimates of input coefficients.

The costs of exogenous production inputs (costs of those forest industry inputs that are not endogenously modelled in SFSTM) proved to be very difficult to find. Exogenous costs may include labor, electricity, capital costs, chemicals etc., but this study has not managed to determine them separately. Such information may be available, perhaps even at individual plant level, but must be purchased from consultant firms or gathered through extensive surveying. Such expenses or efforts were not possible in this thesis project. Instead the exogenous cost components in forest industry production in SFSTM are based on very rough approximations and averages for the whole of Sweden and similar countries as described by Buongiorno et al. (2007). Overall the data used to define exogenous costs in forest industry production in SFSTM are the least reliable and are therefore subject to calibration at a later stage.

Regional forest industry production levels are set to base year values according to production figures reported by VMR (2005) and the forest industry environmental database (Skogsindustrierna, 2005, and personal communication Katrin Heinsoo). These values are primarily used to calibrate the model. Production capacity constraints (per region and production technology) are computed from the production level figures assuming average national capacity utilization rates as reported by Konjunkturinstitutet (2009). Production levels in the international region are set to balance total consumption in the model (total consumption of forest industry products minus Swedish production). The same capacity utilization rates are applied in Sweden and the international region.

Investment in new production capacity is allowed and similar to Bolkesjö (2004) an amortization factor of 0.2 is assumed. This implies that the capital cost borne by a single year is 20% of the total investment of investment in new capacity. Investment costs per additional unit of production capacity are similar to those assumed by Bolkesjö (2004).

5.3. Logging residues – regional availability and cost data

In SFSTM logging residues supplied in any of the domestic regions may be used as inputs for certain bioenergy production technologies. Logging residues are supplied and used in Sweden only (assuming no production or use in the international region). Stepwise regional supply curves are formed by data on potential availability and extraction costs as reported by Lönner et al (1998). The estimates used are dated and possibly not realistic today, but at present there appears to be no other reliable source for the kind of data required in SFSTM. There is a variety of by-products from roundwood harvest, forest care activities and land clearing, and their characteristics as fuels do vary considerably. However in SFSTM all types of logging residues are assumed to be of the same fuel quality. The cost estimates include standard transportation costs within regions. See Lönner et al (1998) for further details on the underlying computations and assumptions used in estimation of supply and costs.

5.4. Bioenergy production and refined wood fuel data

The formulation of bioenergy production in SFSTM differs somewhat from that of forest industries. Bioenergy production technologies are assumed to be the same in all Swedish regions, i.e. there are no differences in exogenous production costs and input coefficients for the same technology in different regions. What differs between regions are the endogenous input costs. In SFSTM there are five main categories of bioenergy production technologies (wood stoves, refined wood fuel stoves, district heating, CHP and forest industry bioenergy). Each of these five technologies may utilize various types of unrefined and refined wood fuels depending on their capabilities. In addition to existing production technologies new production technologies may be used in the model. The differences between existing and new production technologies are that (1) capital costs are regarded as sunk for existing production, and (2) that new production technologies are assumed to be more efficient than existing production. The categorization of production technologies is to a large extent affected by the available data and estimates of production levels, development potentials, production costs and raw material usage.

In SFSTM bioenergy production levels are defined as consumption of ditto, similar to Bolkesjö (2004). Consumption figures for the base year are thus used to set production constraints for each production technology in the model. This type of data has been gathered primarily from Ericsson & Börjesson (2008), Svensk Fjärrvärme (2005) and Wiberg (2001, 2008). Estimates by Ericsson & Börjesson (2008) are also used to define constraints on future production (consumption) of bioenergy, i.e. constraints on possible increases in energy consumption in addition to current consumption in the base year.

Production costs (defined as capital costs, operating and maintenance, and processing costs) are defined for each main technology based on various sources. Energy production efficiency rates (produced energy divided by energy input) and raw material energy content estimates together determine how much raw material that is needed to produce one unit of energy in each type of production technology. There are currently no studies providing fully comprehensive estimates of the abovementioned production costs and efficiency rates. The figures that are assumed to apply in SFSTM are the result of extensive surveying of the existing literature on the subject. Some of the main information sources are Svensk Fjärrvärme (2007), Profu (2008), Andersson & Werner (2005), De Visser (2002), and Trömborg, Bolkesjö & Solberg (2007).

The raw materials used as inputs in bioenergy production consist of unrefined wood fuels (pulpwood, logging residues, bark and sawdust) and refined wood fuel (assumed to be similar to wood pellets in fuel characteristics). All unrefined wood fuels are available directly in the market as products (or by-products) from forestry and forest industries. Refined wood fuel on the other hand is produced bearing a production cost while at the same time using unrefined wood fuel as raw material input. Production costs for refined wood fuels are based on Zakrisson (2002) who has calculated generalized production costs for wood pellets in Sweden. Regional production capacity constraints for refined wood fuel are set based on statistics reported by the European Pellet Centre (the Pellets@las website).

5.5. Energy demand

The energy demand curve in SFSTM is flat (fully elastic) and its level determined by exogenous energy prices, i.e. the level of the demand curve is not affected by the model outcome. The limited scope of the partial equilibrium model makes it plausible that factors outside of the model such as general industrial activity, electricity production, world prices of fossil fuels etc. determine energy price levels, thus making energy prices exogenous to the model.

There are two separate demand curves defined for (1) household heat and (2) electricity produced in CHP plants respectively. Household heat derived from bioenergy production is assumed to compete with heating based on electricity and oil. The price level of the energy demand curve for household heat is set based on a common household electricity price in the reference year. The total electricity price is composed of an average electricity price, electricity transfer costs and the energy tax on consumption of electricity, all as reported by the Swedish Energy Agency (2004). Value added tax is not included. Heat produced in CHP plants meets the same energy demand curve as described above, but a different demand curve applies for electricity from CHP plants. The demand curve for electricity from CHP plants is assumed to be flat at the level of the electricity spot price plus electricity certificate price as they are reported by the Swedish Energy Agency (2005).

Bioenergy produced in forest industries is assumed to be used for internal purposes only (pulp and paper manufacturing) and is thus not available in the market. Therefore there is no demand curve for forest industry bioenergy, and the production of such energy is instead determined indirectly by the demand for- and production of forest industry products. This means that the production of bioenergy in forest industries will increase (decrease) if total production of pulp and paper increases (decreases).

5.6. Demand for forest industry final products

Forest product demand is defined by linear demand functions in SFSTM. The demand functions are calibrated in base year data on consumed quantities, prices and estimated demand elasticities. Similar to Bolkesjö (2004) the consumption of forest industry products in Sweden is defined as domestic production plus imports minus exports. Production figures are based on VMR (2005) and traded quantities are taken from statistics reported by the Swedish Forest Agency (2009). The total Swedish consumption is then distributed between the four regions based on Statistics Sweden's (2009) population statistics (assuming consumption to be proportional to population). Consumed quantities in the international region are based on FAO (2009) statistics, including EU-25 plus Norway and subtracting Swedish consumption.

Product prices in the reference year are defined as export prices per unit (ton or m^3), again similar to Bolkesjö (2004). Export prices are computed from trade statistics as reported by the Swedish Forest Agency (2009) complemented by figures from UNECE (2009) in the case of coniferous sawnwood. For fibre boards and particle boards import prices are assumed to apply instead of export prices (based on the direction and size of trade of those products).

The slopes of forest product demand curves are set by previously estimated demand elasticities. The elasticities that are assumed to apply in SFSTM are the same as those used by Buongiorno et al. (2003) in the *Global forest product model* (more specifically reference is made to elasticities applied in high income countries in that study). These elasticity figures are the result of mainly two comprehensive studies (FAO, 1997, and Zhu et al., 1998) and the subjective assessment by Buongiorno et al., but they nevertheless appear to be some of the more reliable estimates available as of today.

5.7. Transport costs – cost functions and transport distances

The transport cost component in SFSTM is made up by transport cost functions and distance matrices that differ between the products being traded between regions as well as between transport modes (lorry, train or ship). Each transport cost function has a positive constant parameter defined by start costs, i.e. the initial cost of a transport job such as loading and unloading, administrative fees etc. Transport costs also depend on distance through a distance dependent cost parameter (SEK/kilometre). For each type of tradable product there are three linear transport cost functions (lorry, train and ship) that together form break even points in terms of total transport cost for different distances.

The constant cost parameters and variable transport costs for different products and transport modes have been compiled from various sources. Cost parameters for lorry transports are based primarily on advice and recommendations from logistics experts at Skogforsk (personal communication, Gert Andersson & Rolf Björheden) and head of transports at Stora Enso Skog, Jörgen Ologsson (personal communication). For train and ship transports figures have been gathered primarily from Lönner et al. (1998), Bolkesjö (2004) and Suurs (2002). Overall the estimates of lorry transport costs appear to be fairly realistic, but the assumed transport cost functions for railway and particularly transport by sea are much less reliable. See later discussion on sensitivity analysis with respect to the above mentioned cost parameters.

Transport distances between regions are formed by the shortest possible route (which differs between road, railway and sea) between region centres. The centres of each Swedish region are chosen based on geographical location of primarily forest industries as shown by the Swedish Forest Agency (2009) and presence of main transport nodes. Actual distances have been measured using Google Maps (maps.google.com, 05-01-2009), Skogsindustrierna (2009b) and a web-based calculator for distances between sea ports (www.distances.com, 05-01-2009). The region centre for the international region is chosen based on trade flow statistics (Swedish Forest Agency, 2009). Swedish exports of forest sector products are on average transported longer distances (to Germany, Great Britain, the Netherlands, Norway, Denmark, Italy and France) than imports (primarily from countries around the Baltic Sea). Therefore the distance for exports from Swedish regions to the international region is set higher than for imports. In addition it is assumed that all international transport work is made by sea, i.e. no lorry or train transports are allowed to/from Sweden.

6. Results

6.1. Calibration

After inserting all necessary data into the GAMS programme, trial runs produced equilibrium solutions that deviated considerably from base year data. The assumed production costs in forest industries in particular resulted in large deviations in regional production levels compared to the reference data. The trial runs also showed that bioenergy production costs were far lower than the price of energy (as defined in the energy demand curve). Bioenergy production (and thus consumption) was thus limited by assumed production constraints only and marginal revenues remained large and positive even at extreme relaxation of the consumption constraints.

The above observations paired with the initial uncertainty in (1) exogenous production costs in forest industries and (2) the production cost compared to energy price in the case of bioenergy, guided the decision to conduct targeted calibration of the model. The first step in the calibration process was to constrain roundwood harvest, forest industry production and consumption to base year values, thus forcing the model outcome towards the reference data. Based on the belief that perfect competition applies in the market for forest industry products, the data on exogenous production costs was then calibrated so that marginal revenues became zero for all producers. The imposed constraints were then relaxed to initial values and the model results now showed much closer resemblance to the reference data.

A somewhat similar procedure was implemented with respect to bioenergy production, but instead of calibrating production costs the level of the flat energy demand curve was adjusted in each region. The levels of the regional demand curves wer adjusted downwards so that the (existing) technology with highest production costs (including capital costs) showed zero marginal revenue at base year production levels. This calibration technique is imperfect and does not remove the binding effect of the assumed production constraints. The model results are thus still highly dependent on the assumptions made with regards to possible expansion of production (consumption) of bioenergy.

6.2. Scenario analysis

The primary aim of this thesis project is to develop a regional partial equilibrium model of the Swedish forest sector and to use this model in analysis of changing conditions for bioenergy production. In order to make assessment about the model's suitability for analysing such issues a simple set of scenarios are defined and implemented in

SFSTM. The scenarios are formulated so that the initially posed research questions may be analysed, and thus focus is on (1) changes in energy demand and (2) changes in energy taxation on forest fuels. The scenarios are used to study both how the model behaves (so that possible improvements may be identified) and what potential conclusions we may draw from using the model in actual policy analysis.

The model's result from each scenario is compared to business as usual (hereafter *BAU*). In *BAU* the basic model is run with relaxed constraints on bioenergy production, i.e. production is allowed to expand to 50% of the estimated future potential as described in the data. This potential expansion is assumed to be a reasonable constraint on bioenergy production expansion given a time horizon of 5-10 years from the base year 2004. Any increases in bioenergy production will occur in new facilities, i.e. existing production capacity will remain unchanged (as long as it is profitable) and can not grow.

Note that the diagrams that are used to display model results are only simplified representations of the actual underlying solution, and in most cases variables are presented at an aggregated level for Sweden as a whole.

6.2.1. Shifts in energy demand

The first two scenarios are defined as (A1) a downward shift in energy demand and (A2) an upward shift in energy demand. The shifts in energy demand are implemented by changing the electricity spot market price by 50% (up and down). By doing so the flat demand curve for energy is shifted up and down, thus changing the revenue potentially earned by bioenergy producers. Note however that the electricity tax, the cost of electricity transfers and the price of electricity certificates remain unchanged.

The results are displayed in the figures below where the bars show outcomes from each scenario. A downward (upward) shift in energy demand decreases (increases) regional net surpluses, but the effect appears to be smaller in the western region.

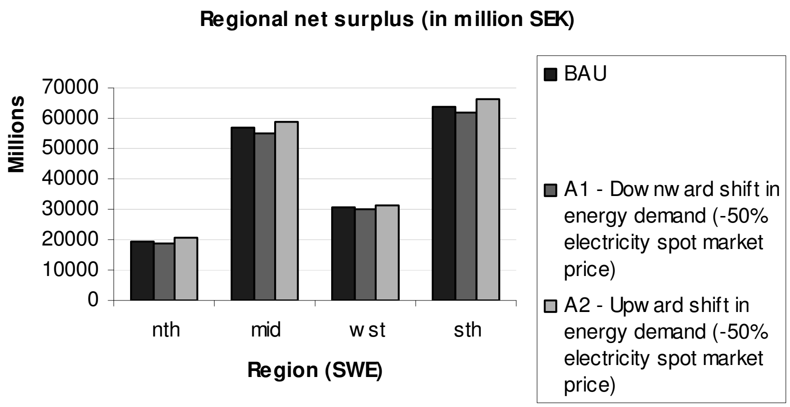


Figure 22: Scenario results (regional net surplus); shifts in energy demand.

The main reason why regional net surpluses change is that revenues in bioenergy production change following the shifts in demand. However by looking at the below diagram which describes bioenergy production per main technology in Sweden, it is clear that threshold effects play an important role in the model's solution. In this particular case (*A1*) woodstoves, small scale heating and CHP production are all reduced to base year levels (no new production capacity is installed). The upward shift in energy demand (*A2*) on the other hand does only increase the marginal revenue earned by energy producers, and total production can not expand more than in *BAU* due to the assumed constraints on potential expansion.

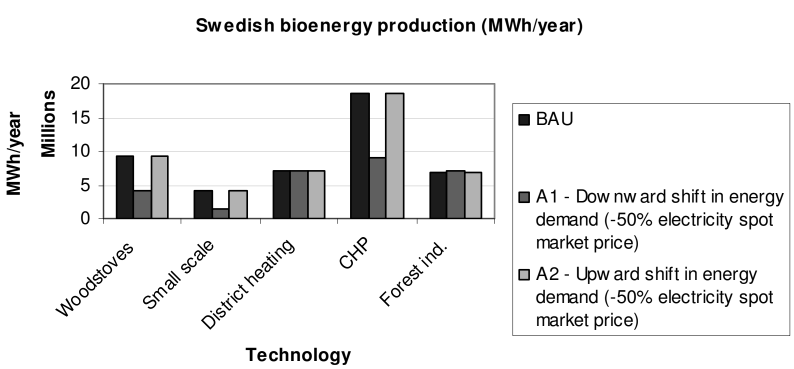


Figure 23: Scenario results (Swedish bioenergy production); shifts in energy demand.

Overall roundwood prices are adjusted downwards following a downward shift in energy demand, and certain types of forest industrial production (paper manufacturing) in Sweden thus become more profitable and show increased production levels. In *A1* particle board production shows the greatest change in relative terms, and production increases by roughly 240% (see diagram below). This effect is primarily a result of lower prices of inputs (bark and sawdust) that are used by both particle board producers and bioenergy producers.

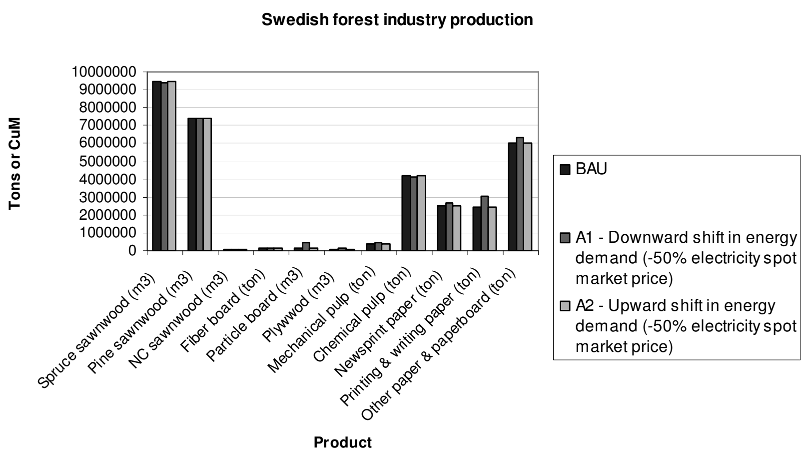


Figure 24: Scenario results (Swedish forest industry production); shifts in energy demand.

The abovementioned effect on particle board production is primarily a result of lower prices of inputs (bark and sawdust) that are used by both particle board producers and bioenergy producers. Figure 25 shows forest fuel prices (Swedish average prices weighted by regional used quantities) in each scenario.

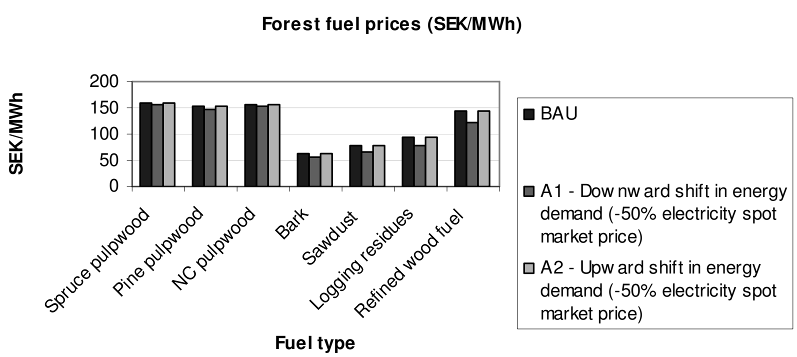


Figure 25: Scenario results (Swedish forest fuel prices); shifts in energy demand.

6.2.2. *Energy tax on forest fuels*

A scenario called *B* introduces an energy tax on forest fuels used in bioenergy production. As was explained in the background chapter forest fuels are currently exempt from energy taxes which in practice functions as a tax subsidy to bioenergy producers who utilize such fuels instead of e.g. fossil fuels. In scenario *B* the energy tax is leveled so that forest fuels are taxed equally compared to heating oil. The level of the tax depends on the energy content of the fuel and is set to 77 SEK/MWh. This implies that a forest fuel that has an energy content of 2 MWh per m^3s will bear a tax of 154 (2*77) SEK/m^3s. The tax is thus applied on the raw material input and not on actual bioenergy production. Note also that bioenergy produced in forest industries is still exempt from forest fuel taxes based on the fact that they primarily utilize internal fuels that are not bought in the market.

The model's results in scenario *B* are very similar to those found in scenario *A1* (downward shift in energy demand), but the magnitude of observed changes is smaller. The most notable difference compared to *A1* is that CHP production remains unchanged. Overall bioenergy production technologies with higher efficiency rates, such as CHP and district heating, are less negatively affected than e.g. bioenergy production in woodstoves where efficiency rates are comparably low. This effect is seen by comparing Figure 26 and Figure 23. Another difference compared to *A1* is that particle board production remains unchanged in scenario *B*.

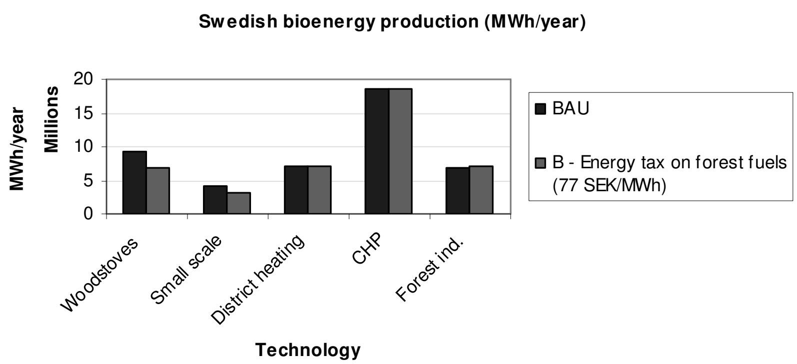


Figure 26: Scenario results (Swedish bioenergy production); introducing energy tax on forest fuels.

6.2.3. Shifts in energy demand <u>and</u> energy tax on forest fuels

The scenarios described above are finally combined, i.e. that energy demand shifts down (or up) and an energy tax is levied on forest fuels simultaneously. The two combinations of scenarios are now:

- *A1+B*, and
- *A2+B*.

Not surprisingly these scenarios do not deviate much from the previous ones. By combining lower energy demand with an energy tax on forest fuels we simply strengthen the tendency towards lower marginal revenues in bioenergy production. The most notable difference in the result is that bioenergy production in woodstoves is reduced to zero in scenario *A1+B* (see Figure 27). This outcome logically causes pulpwood prices to go down which subsequently makes certain types of Swedish forest industries more competitive compared to foreign producers.

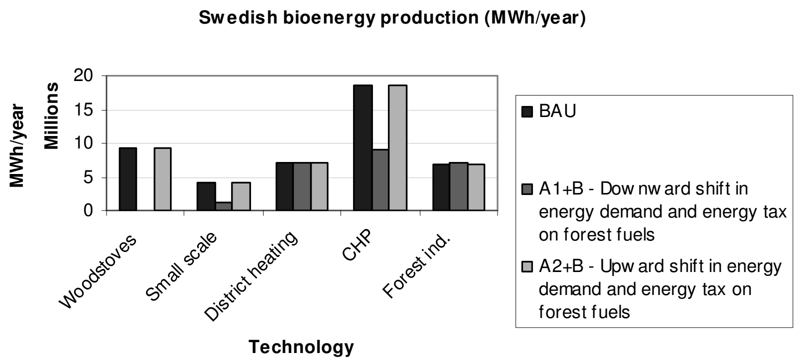


Figure 27: Scenario results (Swedish bioenergy production); shifts in energy demand and introduction of energy tax on forest fuels combined

6.2.4. Summary of results

The scenario results described above provide some examples of the model's functionality. To summarize; with regards to regional social pay-off the effect of lower (higher) energy demand is negative (positive), and the effect of introducing an energy tax on forest fuels is negative. Bioenergy production levels do change as a consequence of changing demand and energy taxation, but the changes do not occur in a smooth manner. Changes in production levels seem to happen when certain thresholds are reached in terms of production costs relative to energy price. It is clear that new combined heat and power generation is more competitive than new district heating plants and expansion of production occurs in the former only. The introduction of an energy tax on forest fuels used in bioenergy production has larger negative impact on less efficient production technologies (e.g. woodstoves) compared to more efficient ones (e.g. CHP).

The prices of forest fuels, except pulpwood, are raised due to increased bioenergy production (as in scenario *A2*), but the effect is not very strong. There is sizable difference between prices of pulpwood and unrefined forest fuels. It appears as if quite extreme increases in bioenergy production would be required to push prices of bark, sawdust and logging residues up to the level of pulpwood prices (thus making bioenergy producers de facto competitors with forest industries for pulpwood).

Measured in terms of social pay-off the four Swedish regions appear to fare about equally good or bad in each scenario. However there are minor differences that may be explained by the varying importance of e.g. forest industries and the actual effect upon them.

Furthermore the results indicate that Swedish forest industries are favoured by reduced demand for energy and energy taxes on forest fuels. Such positive effects on forest industries are likely the result of changed raw material prices which make forest industry production in Sweden relatively more competitive compared to production abroad.

6.3. Sensitivity analysis

Sensitivity analysis was performed with respect to:

- Logging residue costs
- Transport costs

A detailed explanation of the sensitivity analysis and some results is given in the appendix.

In brief the sensitivity analysis showed that changes in the parameter values defining logging residue costs had minor effects on the model outcome (in terms of regional surplus). Prices of other forest fuels were largely affected which indicates that the cost of logging residues may act as an important determinant of forest fuel prices other than pulpwood. The current set-up of the model implies that pulp and paper producers are affected by changes in forest fuel prices, and the cost of logging residues may thus change the conditions for those industries as well.

The model's sensitivity to changed parameter values in the transport cost functions was more notable. Regional net surpluses increased (decreased) with lower (higher) transport costs, and trade patterns were strengthened (weakened). Exporting industries in Sweden were favoured by lower transport costs. The production and prices of roundwood were also affected to a great extent.

7. Discussion and conclusions

This chapter is devoted primarily to discussing potential improvements of SFSTM based on the experience from model calibration, sensitivity analysis and scenario runs. The following sub-chapters briefly describe some of the main observed problem issues with regards to the model structure and data. Possible improvements are also suggested for further development of the model.

7.1. General implications of the model results

The scenario analysis as reported in the previous chapter does provide some interesting results that indicate the usefulness of SFSTM. However the current status of the model appears to be quite far from mature. The model results may perhaps be interpreted as indicators of the direction of change in certain variables, but it would certainly not be wise to take changes in magnitude seriously. It is therefore hard to draw any certain conclusions with regards to quantifiable effects from energy demand changes or implementation of energy taxes on forest fuels. I therefore defer from any policy recommendations at this stage.

Overall it is nevertheless interesting to see how SFSTM behaves when used in scenario analysis. The most important merit of the model is primarily that it appears to be the first partial equilibrium model of the Swedish forest sector that takes into account both regional trade and bioenergy production. However both these components of SFSTM may need further assessment and improvements.

It is also important to remember the model's basic structure, i.e. the underlying economic theory such as the assumption that perfect competition applies in the forest sector. These assumptions are not closely discussed or critically analyzed in this thesis project, but it would probably be worthwhile to take another look at these issues if the model is to be developed further.

7.2. Bioenergy production – data issues and desirable improvements

The set-up of bioenergy production and energy demand in SFSTM appears to imperfect and additional work is likely required before these model components may function properly. Most notably the currently assumed production costs are in need of further assessment. The model's solution in terms of bioenergy production levels and fuel usage is very much dependent on e.g. the relative size of processing costs for different forest fuels (used in the same production technology). Such cost differences must be studied closer as well as possible differences in production costs across regions.

The lack of information on bioenergy production in other European countries also constitutes a limitation in the model. It would certainly be preferable to include bioenergy producers outside Sweden especially since trade in forest fuels (refined wood fuels in particular) is becoming more important. Another issue that needs attention is the potential influence of other biofuels such as household waste. The simplified energy demand curve in the model does only consider the influence of the general energy price and the model does not take into account other competing energy inputs.

In order to make the model more credible with regards to future developments in the energy sector it would likely be necessary to further assess potential expansion of heat production and demand over time. In particular in would be interesting to have some sort of representation of coming generations of e.g. production of transport biofuels from forest biomass in the model.

The data on availability and cost of logging residues also has considerable impact on the model results, certainly with respect to bioenergy production but potentially also on forest industry production. The extraction costs for logging residues may be considerably different than assumed, and this would cause other forest fuel prices in the model to shift accordingly. If the aim is to use SFSTM in analysis of e.g. thresholds where competition for pulpwood between forest industries and bioenergy producers would occur, then it would be advisable to examine the above mentioned cost parameters further.

7.3. Poor data on exogenous input costs in forest industries

The exogenous production costs defined in the model input data need to be revised. Already when this thesis project began the mentioned type of data was identified as a likely problem since such information is often known only by the industries themselves. The current model configuration is partly able to deal with the problem by means of calibration, but in order to make the model function better and produce more reliable results it would likely be a good idea to find improved data and estimates.

One notable problem is that the exogenous production cost parameter (for a given region and product) is an aggregate of several production inputs such as electricity, labour, chemicals, capital, etc. By not defining electricity as a separate input the model is incapable of modelling changes in competitiveness and production costs for forest industries due to changes in e.g. electricity demand or energy taxation. This feature would certainly be desirable if the goal is to use the model in analysis of energy policies and other energy related scenarios.

The possibility of finding better data on the above mentioned production costs is mostly limited by either time or money; the data in question could perhaps be found by extensive surveying or it could be purchased from consultants who already possess similar information. A partial improvement would be to just separate out the use of electricity in forest industries and to keep the other exogenous inputs aggregated. This last option would likely be more feasible (judging from data publicly available) and the relative reward considerable in terms of model functionality.

7.4. Trade affected by regional scale and transport costs

One main difficulty during the development of SFSTM was to find relevant data and statistics at a suitable regional level in Sweden. Unlike Norway and Finland, where similar forest sector models have been developed before, Swedish forestry statistics and other necessary data are not available at the geographic level of counties or other relatively detailed scale. The overall data requirements limited the choice of regional scale to the four Swedish wood balance regions, and the model appears to be suffering from this due to the implied distances between region centres. Basically the relatively large domestic regions make transport distances large and thus also the thresholds for carrying out regional trade within Sweden. These thresholds in turn make it difficult for the model to attain a base scenario solution similar to the base year reference data, and large unrealistic price differences tend to appear instead. This issue is easily noted when looking at regional roundwood harvest and prices where data on observed trade flows in the base year are actually available and thus comparable with the model solution.

The fact that transport distances between regions are large also makes transport cost functions central determinants of regional product prices. Acknowledging the uncertainty in the assumed transport cost function parameters the current definition of domestic regions in SFSTM is thus problematic in several aspects.

It is hard to say how the above issues could be solved without redefining the whole model (in terms of regions modelled) and finding new data. One way forward could be to assess the data availability anew and to make focused efforts on finding estimates of necessary parameter values at a better regional scale. Several types of data required in the model are in fact available even t county or municipal level, but certain categories of data currently appear to be unavailable. However there should exist ways of finding such data by means of surveys or combination of different data sources (e.g.

geographical information system data).

7.5. Final remarks

The model developed in this thesis project has proven difficult to realize primarily due to data limitations. Several compromises have been made in order to achieve a model that may function in a basic sense. The modelling results so far primarily contribute to the understanding of how the model functions and how it may be improved, but it is not recommendable to rely much on the results for actual policy analysis. Yet the initially posed aims of this thesis project are mainly accomplished. This project has shown that the regional partial equilibrium approach may perhaps be a viable option for analysis of the Swedish forest sector, even if there are certain obstacles in the way of a well behaving model. Hopefully this project will provide a first step stone towards a usable economic model of the forest sector and bioenergy production in Sweden.

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9. Appendix

9.1. Sensitivity analysis

Sensitivity analysis was performed to check the model's robustness with regards to certain parameter values. Guided by the reliability of the base year data it appeared likely that the model results could potentially be flawed by certain categories of data used. As was mentioned in the data description, both (1) transports costs and (2) the extraction cost (and potential availability) of logging residues are quite uncertain. Erroneous cost parameters in the transport cost functions could potentially have important effects on the model results. If transport costs are in fact lower (higher) than assumed, the threshold for carrying out trade between regions would be lower (higher), and regional production levels, consumption, prices etc. in the model's equilibrium solution could thus be flawed. The assumed extraction costs of logging residues on the other hand could have large impact especially on prices of other forest fuels which in turn may affect other part of the model. For example, if the cost of logging residues in the model is too low bioenergy producers will subsequently be able to substitute other forest fuels by logging residues and thus fuel prices are kept down.

The effects of variations in the two types of data mentioned above were tested by sensitivity analysis. The BAU (business as usual) model was first run with logging residue extraction costs adjusted by 50% downwards and upwards relative to initial values. Overall the model results showed very minor differences with respect to regional net surpluses, but the effect on forest fuel prices was indeed considerable. As is seen in the diagram below; average Swedish prices of all types of forest fuels except pulpwood were highly affected. The magnitude of the price changes are about the same for all forest fuels to the right in the diagram, and this indicates that the assumed logging residue extraction costs act as determinants of other forest fuel prices in the model.

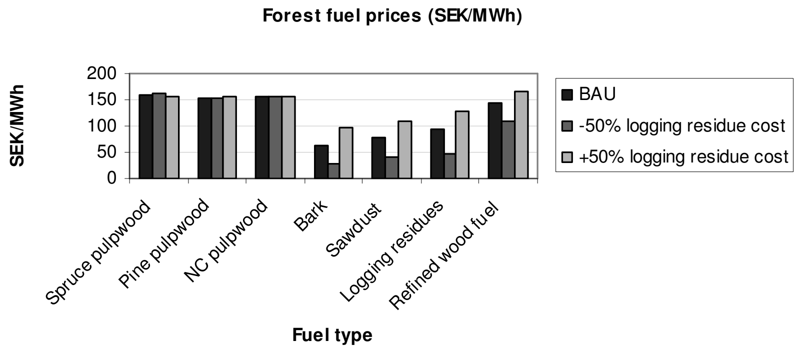

Figure 28: Sensitivity analysis of average Swedish forest fuel prices due to changes in logging residue extraction costs

The resulting changes in forest fuel prices do not imply any significant changes in bioenergy production compared to BAU, with an important exception for forest industry bioenergy. In the present set-up of the model Swedish pulp and paper manufacturers use forest fuels for energy production and their production costs are thus affected by the cost of fuels. Changes in logging residue extraction costs do therefore affect pulp and paper producers (who become more or less competitive compared to foreign producers) and thus trade patterns also change.

A similar analysis was then performed aimed at transport costs. The constant cost parameters in the transport cost functions for all transport modes (lorry, train and ship) were adjusted downwards and upwards by 50% in two separate model runs. Compared to BAU the results showed considerable changes in most aspects but in particular with respect to relative competitiveness between forest industries in different regions. The underlying effect of lower (higher) fixed transport cost parameters is that regional differences in product prices are levelled (increased). Forest industrial production is significantly affected, but the direction of production level change varies. As can be seen in the diagram below the general trend is nevertheless that Swedish production increases (decreases) in the case with lower (higher) transport costs, and this is most notable for sawnwood production.

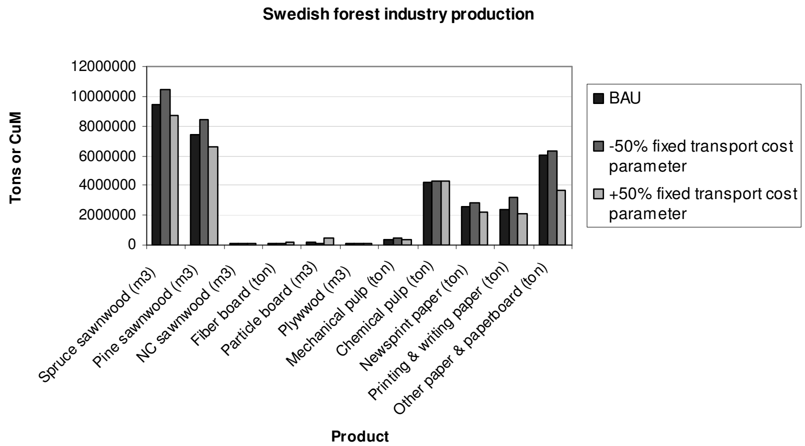

Figure 29: Sensitivity analysis of total Swedish forest industry production due to changes in transport costs

The observed changes in trade flows (to and from Sweden) seem to follow a quite clear pattern. As shown in the diagram below, lower transport costs strengthen existing trade patterns (in terms of quantities traded to/from Sweden).

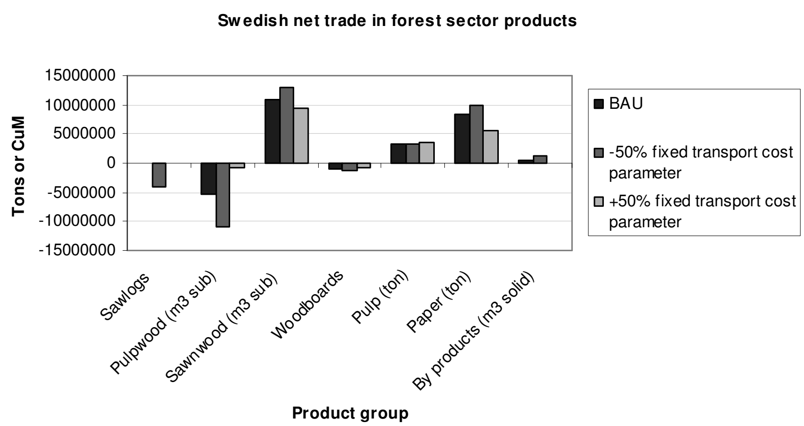

Figure 30: Sensitivity analysis of Swedish net trade by commodity group due to changes in transport costs.
Commodity groups showing positive (negative) Swedish net trade with the international region are shown by positive (negative) bars in the diagram.

The effect on regional net surpluses is also straightforward, as can be seen in the diagram below. Lower (higher) transport costs result in increased (decreased) net surpluses, but the relative change varies between regions. Bioenergy production is not affected at all except in forest industries.

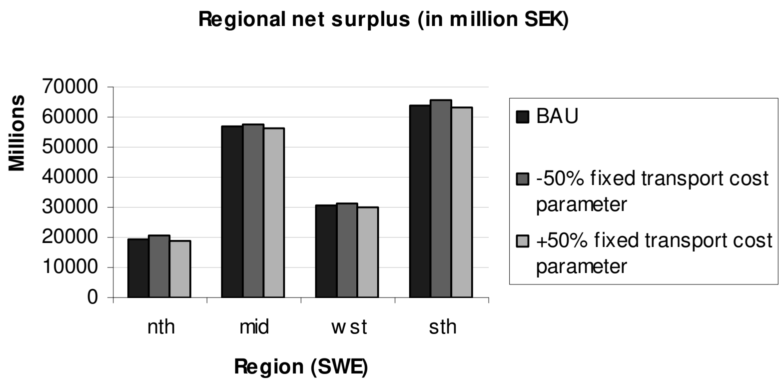

Figure 31: Sensitivity analysis of regional Swedish net surpluses due to changes in transport costs