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A Partial Equilibrium Analysis of Supply Costs and Implications for the Forest Product Markets

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Abstract

As a response to policy requirements to improve energy security, and to reduce greenhouse gas emissions, the use of bioenergy in Sweden has more than doubled since 1980. In 2008 bioenergy use in Sweden amounted to 108 TWh, or 18% of the total supply of primary energy. Nearly all of this bioenergy supply originates from the domestic forest sector. There is still a desire from policy makers to continuously increase the use of renewable energy. Further increases in demand for forest based bioenergy – either as an effect of direct subsidies, renewable energy supply targets, rising fossil fuel prices, or increasing costs for carbon emissions – could, however, lead to implications for the availability of raw materials and costs, for the wood processing industries.

A static partial equilibrium model of the Swedish forest sector – based on the EFI-GTM model structure – is developed to derive supply cost curves for further increases in the use of bioenergy from the forest sector in Sweden. In addition, the implications of increased use of forest based bioenergy on the traditional wood processing industries are analyzed.

Model simulations indicate that the cost – in terms of losses in producer and consumer surplus – of an increase in the use of forest based bioenergy by 5 TWh/year in Sweden is 30 million SEK/year, while a 30 TWh/year increase would cost 620 million SEK/year. The marginal cost of increased use is estimated to be 0.011 SEK/kWh at 5 TWh/year, rising to 0.044 SEK/kWh at 30 TWh/year. The costs of reaching a target for increased forest based bioenergy use are highly dependent on the availability of pulpwood imports. An import restriction – requiring the target to be reached through domestic resources only – would increase the costs by up to five times above the unrestricted case. Policy driven increases in the demand for forest based bioenergy will have considerable effects on wood board producers, while the implications for pulp and paper producers, and sawn goods producers, are relatively small; at least as long as the increase in forest based wood fuels is less than 20 TWh/year.

Keywords: Bioenergy, energy policy, forest industry, partial equilibrium model, climate change

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Abbreviations

EFI-GTM European Forest Institute – Global Trade Model

GAMS General Algebraic Modeling System

kWh Kilowatt-hour

MWh Megawatt-hour

m^3s Cubic meter solid wood

m^3sub Cubic meter solid wood under bark

ODT Oven dry ton

ROW Region “Rest of world”

SEK Swedish krona

SFSTMII Swedish forest sector trade model version II

TWh Terrawatt-hour

1 Introduction

The management and use of forest resources are subject to a wide range of competing objectives, including: raw material supply for the wood processing industries; supply of renewable wood based fuels; and maintenance of ecosystem services, such as provision of biodiversity and carbon sequestration. Following the oil crises in the 1970s and a public referendum decision in 1980 to phase out nuclear power, bioenergy has become an increasing feature of the Swedish energy system (Kaijser 2001 & Vedung 2001). This development has been supported by a range of policy initiatives – e.g. taxes on greenhouse gas emissions and other air pollutants, renewable electricity certificates, expanded district heating infrastructure, and investment support programs – which have been motivated by environmental and energy security concerns. Since 1980 the use of bioenergy in Sweden has more than doubled, and in 2008 it amounted to 108 Terrawatt-hour (TWh), or 18% of total supply of primary energy (SEA 2010). Nearly all of this bioenergy supply originates from the domestic forest sector.

There is still a desire from policy makers to continuously increase the use of renewable energy. The European Union directive on the promotion of the use of renewable energy sources (2009/28/EC) states that 20% of energy use should be derived from renewable sources by 2020. In 2008 the renewable energy share (RES) in the EU overall was 10% (EC 2011). The directive stipulates that Sweden should have a RES of 49% by 2020, while the Swedish Government has unilaterally opted for a RES target of 50%. In 2008 the RES in Sweden was 44% (SEA 2010), and the additional renewable energy use required to meet the Swedish RES target is approximately 45-50 TWh/year, taking into account an expected overall increase in energy use (SGO 2010). Some of this increase will come from wind power and agriculturally based vehicle fuels, but it is expected that most of the additional renewable energy use will be in the form of wood based fuels in the industry and heating sectors (SEA 2009).

In a review of 17 studies of biomass in the future global energy supply, Berndes et al (2003) concluded that a refined modeling of interactions between increased bioenergy use and other competing uses (e.g. production of sawn goods and paper products) would facilitate an improved understanding of the prospects of large scale utilization of biomass for energy purposes. Spatial price equilibrium models (Takayama & Judge 1964) can be used to analyze these interrelations within the forest sector. The main objective of such numerical models is to provide consistent analysis of how and by how much production, consumption, trade and prices of primary products (e.g. saw logs, pulpwood), intermediates (e.g. pulp), and end user products (e.g. sawn goods, wood board products, paper products) from the forest sector might change as a response to changes in external factors, such as economic growth, transportation costs, energy prices, forest management, and consumer preferences (Kallio et al 2004). These models use information on producer and consumer behavior, provided by econometric studies, to develop scenarios on the future development of the forest sector.

Bolkesjø (2004) has an extensive overview of early forest sector models, while Toppinen & Kuuluvainen (2010) provide an overview over later ones. The first models were developed in the late 1970s, and they were predominantly national partial equilibrium models. An early example is the Swedish forest sector model developed by Nilsson (1980). During the 1980s the first global forest sector model, the Global Trade Model (GTM), was developed at IIASA (Kallio et al 1987). The model structure of the GTM has later formed the basis for several national models, including the SF-GTM of the Finnish forest sector (Ronnilla 1995), the Norwegian Trade Models (NTM) by Trømborg & Solberg (1995), and the Pan Siberian Forest Industry Model (PSFIM) by Obersteiner (1998). The GTM also laid the foundation for the EFI-GTM from the European Forest Institute (Kallio et al 2004). Another global partial equilibrium model is the Global Forest Products Model (GFPM), which is largely similar to the GTM (Buongiorno et al 2003). Over the last few years a number of partial equilibrium models with the bioenergy sector as an integrated part of the forest sector have been developed. The Norwegian NTMII-model (Bolkesjø 2004; Bolkesjø et al 2006; Trømborg & Solberg 2010) was the first of these. Among the more recent ones are Schwarzbauer & Stern (2010); Buongiorno et al (2011); Moiseyev et al (2011); and Lestander (2011).

As pointed out by Delacote and Lecoqc (2011) there is a critical interrelation between the production of forest based wood fuels and other wood products (pulp and paper, sawn goods and wood boards). Wood based fuels are primarily made up of forest industry by-products and harvest residues, but could also come from industrial roundwood. Up to a certain point, the utilization of these resources for energy purposes is largely beneficial for the wood processing industries – in particular for the sawn goods producers – since it constitutes an additional income stream from by-products. Rising utilization levels will, however, eventually lead to increasing competition for raw materials between the energy sector and the wood processing industries. Wood board producers are often affected most severely since industrial by-products are their primary raw material inputs. If the demand for wood based bioenergy cannot be met by harvest residues and industry by-products, it is expected that pulpwood will be used for these purposes at the expense of pulp and paper producers. These conclusions are supported by a number of recent forest sector modeling studies (e.g. Buongiorno et al 2011; Moiseyev et al 2011; Schwarzbauer & Stern 2010; Trømborg & Solberg 2010), as well as by economic-engineering studies, such as Lundmark (2004).

In Sweden, the use of bioenergy has risen sharply over the last 20-30 years. The industrial by-products have to a large degree been utilized for energy purposes, at the expense of a declining wood boards sector. There is still some scope for increasing the use of harvest residues. However, further increases in demand for wood energy – either as an effect of direct subsidies, renewable energy supply targets, rising fossil fuel prices, or increasing costs for carbon emissions – could lead to implications for the raw materials availability and costs for the wood processing industries.

The main purpose of this study is to analyze the impacts of increased wood based bioenergy demand on the Swedish forest sector in different regions. A static partial equilibrium model of the Swedish sector – based on the EFI-GTM (Kallio et al 2004) model structure – will be presented and then run subject to binding targets of increased use of wood based bioenergy. The contributions are mainly of empirical nature. The emphasis is on generating supply curves for wood based bioenergy in Sweden; and on analyzing how the increased demand for industrial roundwood and forest industry by-products from the bioenergy sector affects the traditional forest industries.

2 The Swedish Forest Sector

This section gives an overview of the Swedish forest sector and trends in quantities and prices, over the last two or three decades.

More than half (22.5 million hectares) of Sweden's land area is classified as productive forest land (SFA 2010). The forest inventory on productive forest land (excluding protected land) is estimated at 2.89 billion m^3 standing volume. The coniferous tree species Scots pine and Norway spruce together make up 81% of the standing volume of timber, while the non-coniferous birch (12%) make up most of the rest. The annual increment is around 110 million m^3, while the gross fellings amount to 80-90 million m^3. These levels of annual increment and fellings are projected to remain stable over the next three decades (SFA 2008).

Table 1 and *Table 2* summarize some basic information about the structure of the Swedish forest sector. In 2008 the forest sector contributed to 2.5% of Sweden's gross national product (GNP), 2.2% of national employment, and a tenth of national export value. Forestry refers to the raw material side of the sector, primarily extraction of roundwood. The wood product manufacturing group includes sawmills that use saw logs to produce sawn and planed products, and wood board manufacturers that use saw logs or sawmill by-products to produce fiberboards, particle board, veneer and plywood. Pulp mills use pulpwood, wood chips or recovered paper to produce pulp which is used as input in the manufacturing of paper products, such as newsprint and other printing paper, soft tissues, paperboard, and other packaging materials.

Table 1. *The Forest Sector in the Swedish Economy 2008 (Statistics Sweden 2012a; SFA 2012)*

	Forestry[a]	Wood product manufacturing[b]	Pulp & paper manufacturing[c]	Total
Value added (billion SEK)[d]	32.7	19.5	29.1	80.3
share of GNP	*0.99%*	*0.61%*	*0.91%*	*2.51%*
Employment ('000s)[e]	28	40	34	102
share of total employment	*0.60%*	*0.87%*	*0.74%*	*2.21%*

a. Industry classification codes 02 in SNI2002 and A02 in SNI2007; b. Industry classification codes 20 in SNI2002 and C16 in SNI2007; c. Includes wood pulp, recovered paper pulp, paper and paperboard production. Industry classification codes 21 in SNI2002 and C17 in SNI2007; d. SCB(2012); e. SFA (2012)

Table 2. *Exports and Imports of Forest Sector Products 2008, billion SEK (SFA 2010)*

	Exports	Imports
Roundwood	1.6	4.2
Pulp and paper products	95.6	16.0
Sawn goods	22.4	1.3
Wood boards	1.9	3.5
Other forest sector products	5.8	5.0
Total	127.3	30.1
share of national export value	*10.7%*	

Harvested quantities of saw logs and pulpwood have increased from 47 million m^3sub in 1980 to 72 million m^3sub in 2010 (*Figure 1*). Saw logs and pulpwood were harvested in almost equal quantities until the early 1990s, when saw log harvest increased while pulpwood harvest remained stable. After a major storm in 2005 the proportion of saw logs to pulpwood is back at a one-to-one level.

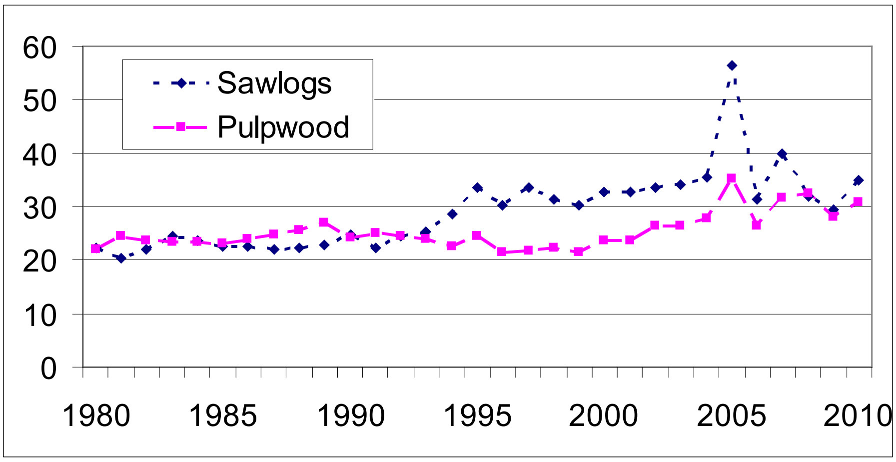

Figure 1. Roundwood harvest 1980-2009, million m^3sub (SFA 2012). Data for saw logs exclude the almost negligible harvest of non-coniferous saw logs. The abnormal harvest levels in 2005 can be attributed to a major storm in January of that year, which also led to slightly lower than normal harvest levels in the following years

Throughout the period Sweden has been a net importer of pulpwood (*Figure 2*). The imported quantities have been equivalent to 10-25% of annual domestic pulpwood harvest, which indicates that the Swedish pulp and paper sector is larger than what is supported by its domestic raw material base. Sweden has also been a net importer of other wood materials over the entire period, with a substantial increase from 1995 to 2005. These materials are either used as biofuels, or as inputs to pulp or wood board production.

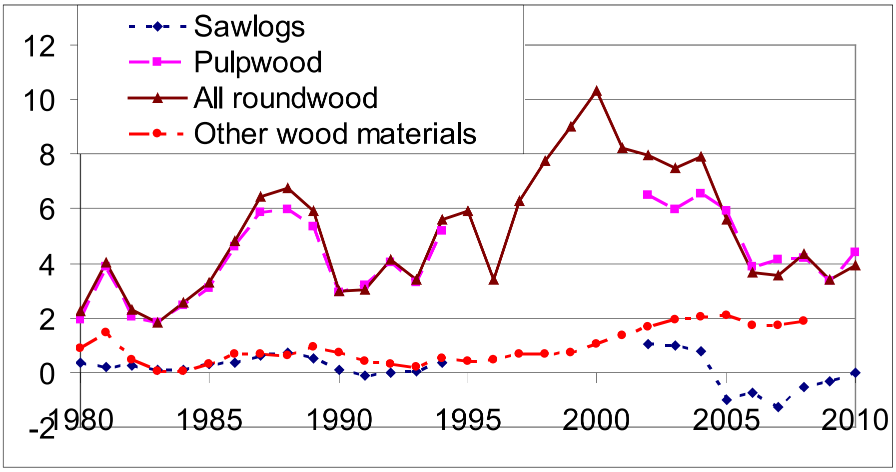

Figure 2. Net imports of roundwood 1980-2009, million m^3sub (SFA 2012). There is a gap in the trade data for saw logs and pulpwood for the years 1995-2001. All roundwood include saw logs, pulpwood, and other roundwood (e.g. poles, pilings). It seems reasonable to assume that the net import of all roundwood 1995-2001 is primarily made up of pulpwood. Other wood materials include wood chips, sawdust, wood pellets, and wood refuse.

Pulp and paper production have increased since 1980, but seem to have reached a plateau since around 2005 (*Figure 3* & *Figure 4*). Newsprint production has increased by a third since 1980, but it has decreased recently. Production of other printing and writing paper has tripled since 1980, while the production of other paper and paperboard has increased by around 60%.

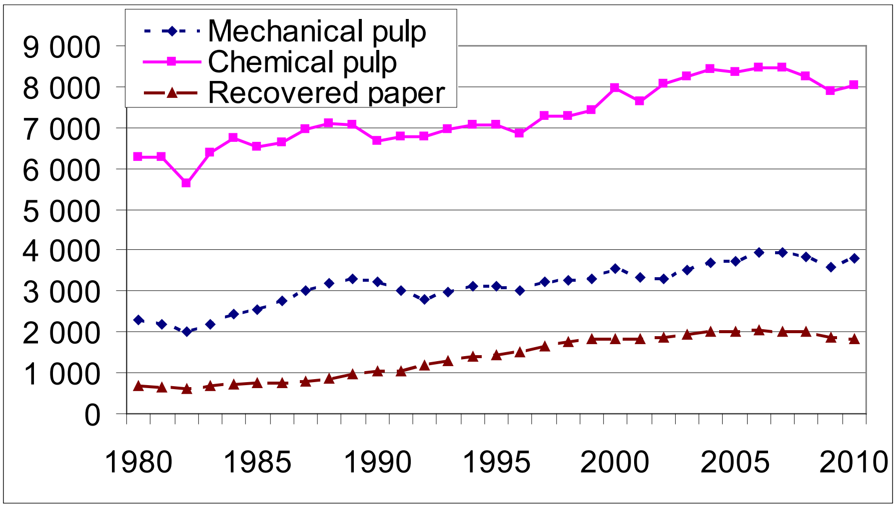

Figure 3. Pulp production and use of recovered paper 1980-2012, 1000 tons (SFA 2012). Mechanical pulp includes semi-chemical pulp. Chemical pulp is comprised of sulphate and sulphite. Recovered paper refers to the quantities used as input into recovered paper pulp production

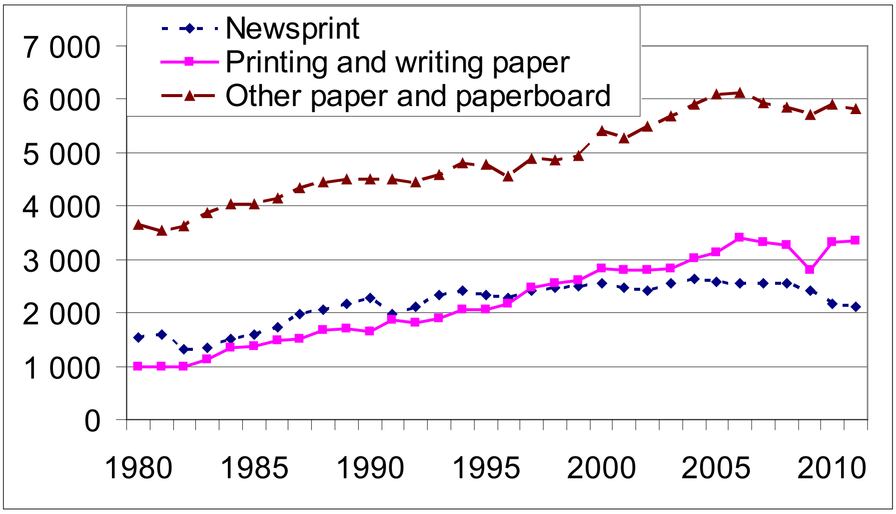

Figure 4. Produciton of paper and paperboard 1980-2011, 1000 tons (SFA 2012). Printing and writing paper does not include newsprint

Production of sawn goods (*Figure 5*) has also increased substantially, almost 50% since the early 1980s. Sawn goods production is almost completely dominated by spruce and pine, while the quantity of sawn goods from non-coniferous trees is almost negligible. Wood boards production (*Figure 6*) declined drastically in the 1980s, when particle board and fiberboard production was halved. Since then particle board production has been relatively stable, while the production of fiberboards and plywood (including veneer) has declined.

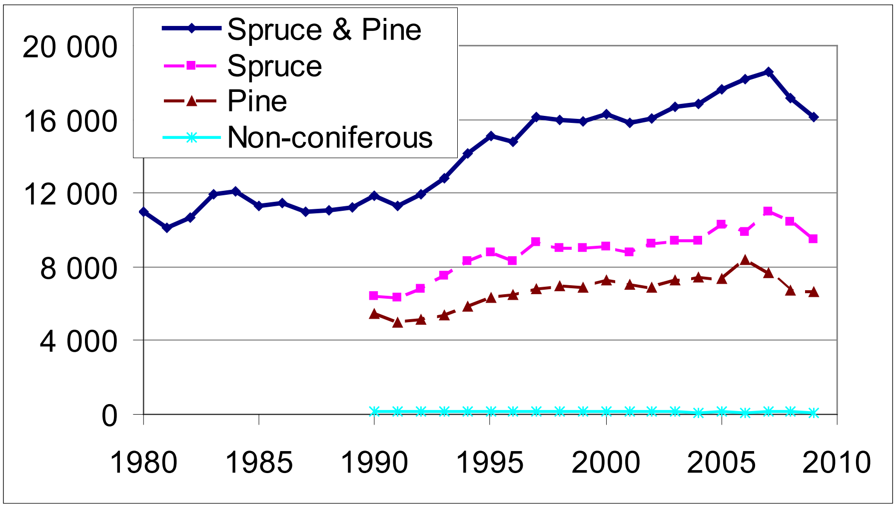

Figure 5. Sawn goods production 1980-2008, 1000 m^3 (SFA 2012). Note that the peak in sawn goods production after 2005 can be attributed to the major storm in that year (see also *Figure 1*)

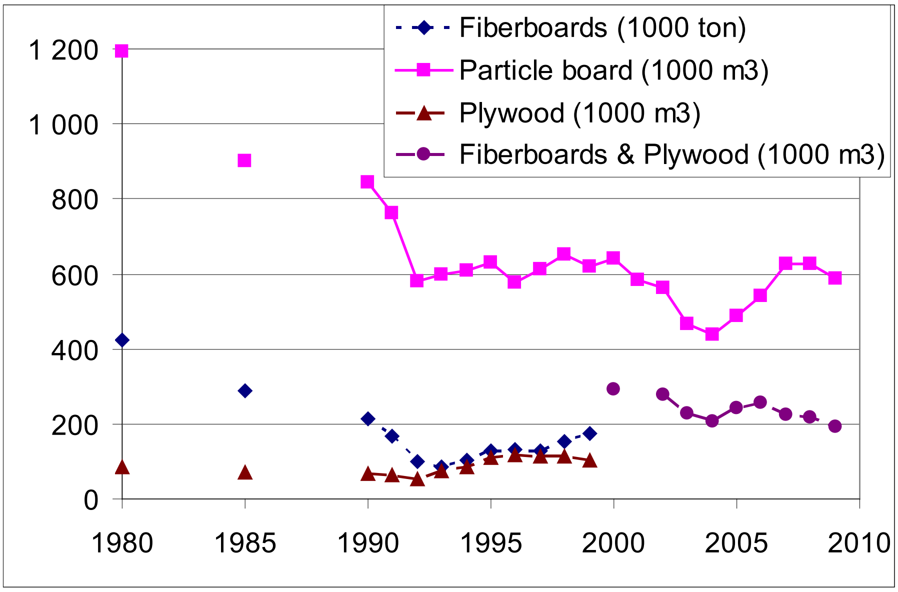

Figure 6. Wood board production 1980-2009 (SFA 2012). Note that fiberboards until 1999 are measured in 1000 tons, while the other product categories are in 1000 m^3. Also note that from 2000 and onwards fiberboards and plywood are reported jointly

The manufacturing of sawn goods and paper products is mainly geared towards the international markets (SFA 2010). Two thirds of the sawn goods and nearly nine tenths of the paper products are exported. Pulp production is, on the other hand, mainly for internal use as around two thirds of the quantities produced never reaches the marketplace since it is used internally in the producing firm's own production of paper products.

In 2008 the total use of bioenergy (excluding peat and refuse) in Sweden was around 108 TWh (*Figure 7*). This corresponds to 18% of primary energy use in Sweden, or 28% of end use. The bioenergy used to produce industry process heat is from black liquors and solid industry by-products (wood chips, sawdust, bark). District heating biofuels consist of solid industry by-products, refined wood fuels (pellets, briquettes, and wood powder), and forestry harvest residues (slash). Electricity is cogenerated together with industrial process heat or district heating.

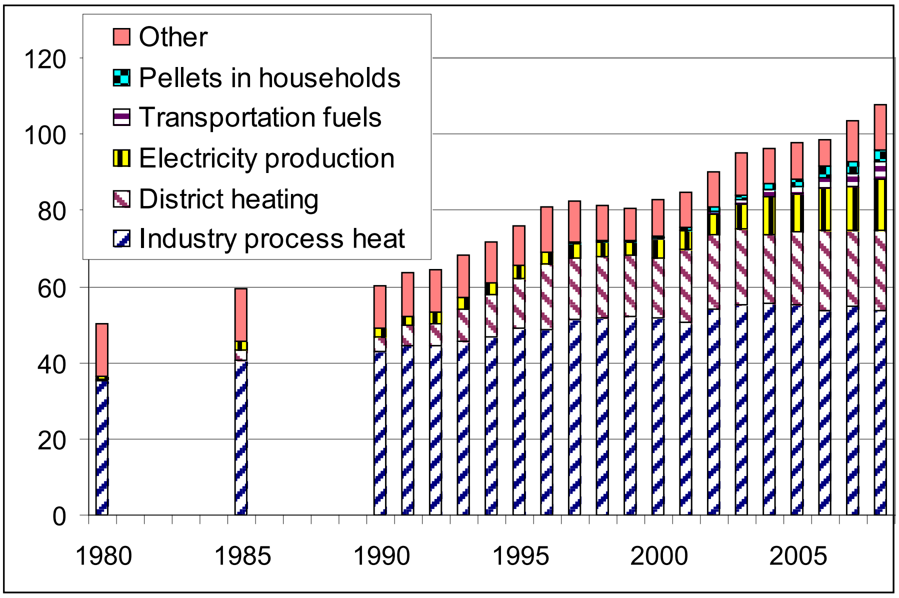

Figure 7. Bioenergy use by sector in Sweden 1980-2008, TWh (SEA 2010; Statistics Sweden 2012b. 'Other' primarily covers the use of fire wood in households, and it is calculated as a residual between SBC (2012) data on total bioenergy use and SEA (2010) data on use in the reported sectors (excluding refuse and peat).

Nearly all – around 95 TWh in 2008 – of the bioenergy use in Sweden originates from the domestic forest sector. The exceptions are the transportation sector fuels (4.4 TWh in 2008 (Statistics Sweden 2012b)), which are produced from raw materials supplied by the agricultural sector; solid fuels from the agricultural sector – mainly straw and wood chips from willow – amounting to less than 1 TWh/year (SGO 2007); and wood refuse (3.3 TWh in 2008 (SDHA 2012)). The net import of other wood materials (chips, sawdust, pellets, and wood refuse) amounts to around 2 million m^3sub (*Figure 2*), which is equivalent with 4.4 TWh of fuel.

Roundwood prices (*Figure 8*) have been on a downward trend – in real terms – since 1980, but seem to have increased towards the end of the period. Note that the price for saw logs lies consistently above that of pulpwood, which is explained by the wider range of uses for saw logs. The prices for the two varieties of roundwood follow a similar pattern, where prices shifted down by about 100 SEK(2008)/m^3sub around 1990 and have remained lower than in the 1980s since then.

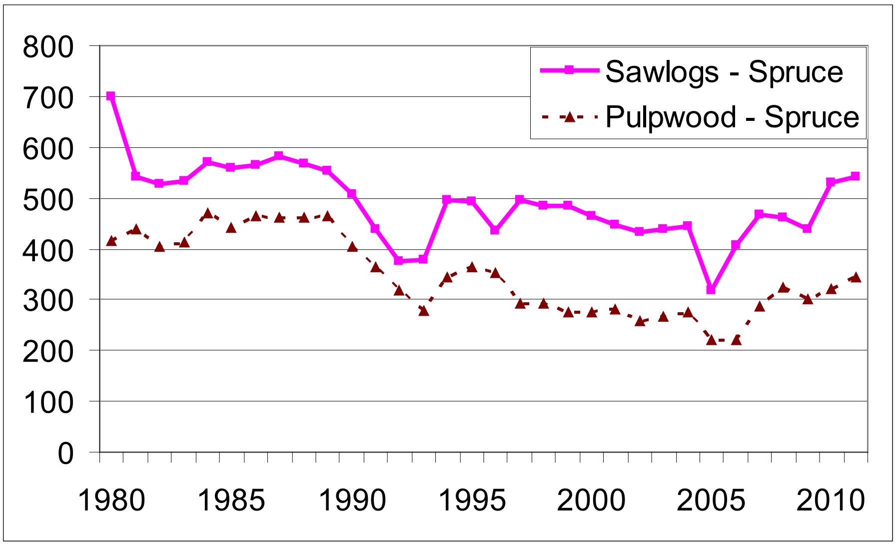

Figure 8. Real roundwood prices at roadside 1980-2011, SEK(2008)/m^{3}sub (SFA 2012) Roundwood prices, in SEK(2008) per cubic meters solid under bark, at the site of harvest. The data is based on two different time series, with a shift between 1995 and 1996. The low prices in 2005-2006 can be attributed to the major storm in January 2005.

For the forest industry products (*Figure 9* & *Figure 10*), the general picture is that prices have been on a downward trend over the last two decades. Pulp prices have been very volatile: after a decline in the early 1990s chemical pulp prices have been 20-40% lower than in 1990 for the entire period, with few exceptions. Mechanical pulp prices have oscillated in a range of plus/minus 25% relative to the price level in 1990. Paper prices have also been volatile, but the general trend is that they have declined over the period. The prices of printing paper (including newsprint) have declined by around 25% in real terms since 1990. Other paper products have also declined in price, but to a lesser degree. Sawn goods prices declined by about a quarter in the early 1990s but have remained relatively stable since.

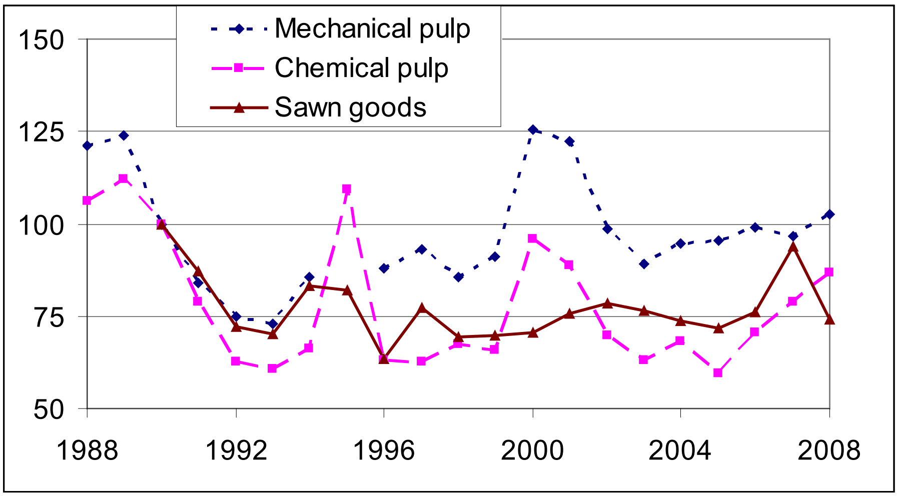

Figure 9. Real pulp and sawn goods prices (Index 1990 = 100) 1988-2008 (SFA 2012). Chemical pulp price is for unbleached sulphate, while sawn goods price is for sawn and planed spruce and pine

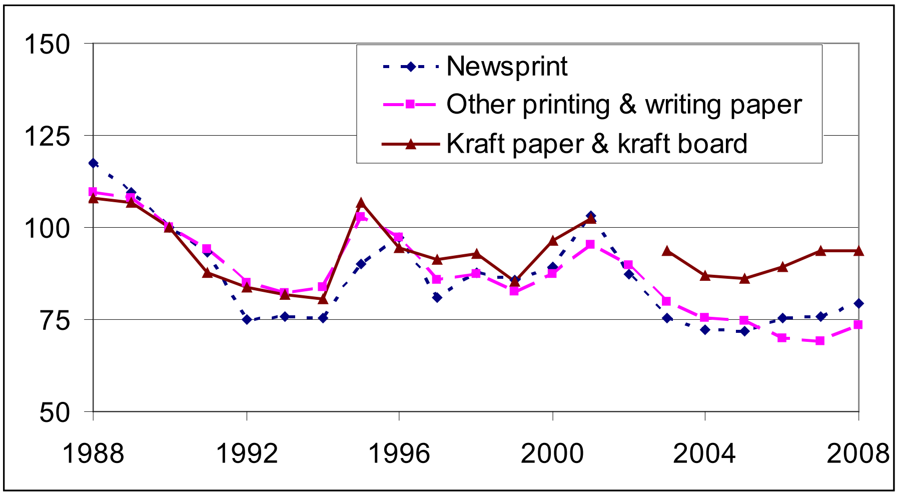

Figure 10. Real paper prices (Index 1990 = 100) 1988-2008 (SFA 2012).

Wood chips prices (*Figure 11*) have remained stable for most of the period, 1993-2009, despite substantial increases in fossil fuel prices. After 2000 we can see a distinct increase in wood chips prices, but fossil fuels still costs more than twice as much.

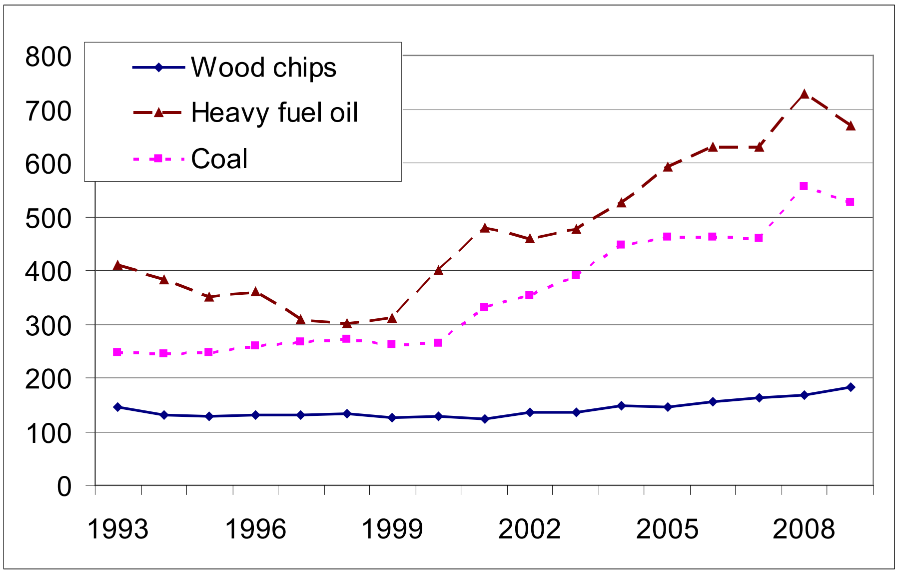

Figure 11. Real fuel prices in Sweden 1993-2009, SEK(2008)/MWh (SEA 2010). Prices include energy and emissions taxes, but not VAT. Wood chips prices are those paid at thermal power stations.

The trends in real prices indicate that the energy sector's willingness to pay for forest based biomass has risen relative to that of the forest industries. When we derive the energy sector´s approximate willingness to pay for roundwood – based on the wood chips prices above, adjusting for the energy content of wood and for transportation and chipping costs –and compare them to pulpwood prices, we can see that the energy sector´s and the pulp industry´s willingness to pay for roundwood have converged towards the end of the period. (*Figure 12*). If these trends continue, the redirecting of biomass inputs from wood boards producers to the energy sector may very well be followed by a persistent shift of roundwood from the pulp and paper sector towards the energy sector.

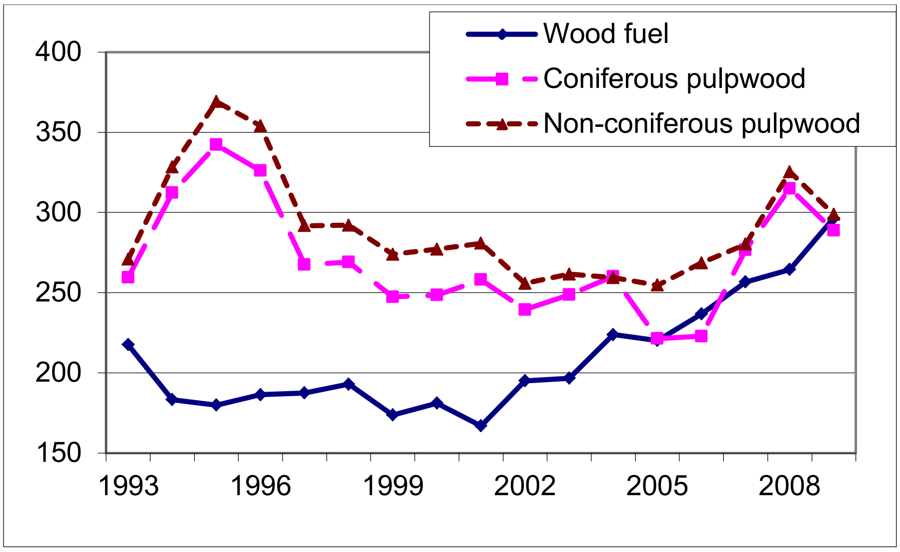

Figure 12. Real pulpwood and (approximated) wood fuel prices at roadside 1993-2009, SEK(2008)/m^3sub (SEA 2010; SFA 2012). Willingness to pay for wood fuel is derived from the wood chips prices in Figure 11, an energy content of wood of 2.2 MWh/m^3sub (SFA 2009), chipping costs of 33 SEK/m^3sub (Athanassaidis et al 2011) and transportation costs of 70 SEK/m^3sub (FRIS 2009)

Some general conclusions can be drawn from this overview of the Swedish forest and bioenergy sectors. Roundwood harvest and forest industry production have risen considerably over the last three decades in Sweden, even though the data over the most recent years indicate a stabilization of harvested and produced quantities. The wood boards sector is an exception, where the decline in produced quantities coincides with an increase in biomass use in district heating and electricity production. We can also see that trends in real prices indicate that the energy sector's willingness to pay for forest based biomass has risen relative to that of the forest industries.

3 Swedish Forest Sector Trade Model

The Takayama-Judge (1964) type spatial partial equilibrium model of the Swedish forest sector presented in this paper largely resemble the global GTM (Kallio et al 1987) and EFI-GTM (Kallio et al 2004) as well as the national NTMII (Bolkesjø 2004) models in structure and general assumptions about supply and demand curves. This model is however a static one-period model, with the possibility of extending it to include dynamics in later developments. Lestander (2011) developed some of the fundamentals for this model in the Swedish Forest Sector Trade Model (SFSTM), hence the modeled described in this section will be referred to as the SFSTMII model. The model is programmed and simulated using the software GAMS (General Algebraic Modeling System), and the solver CONOPT.

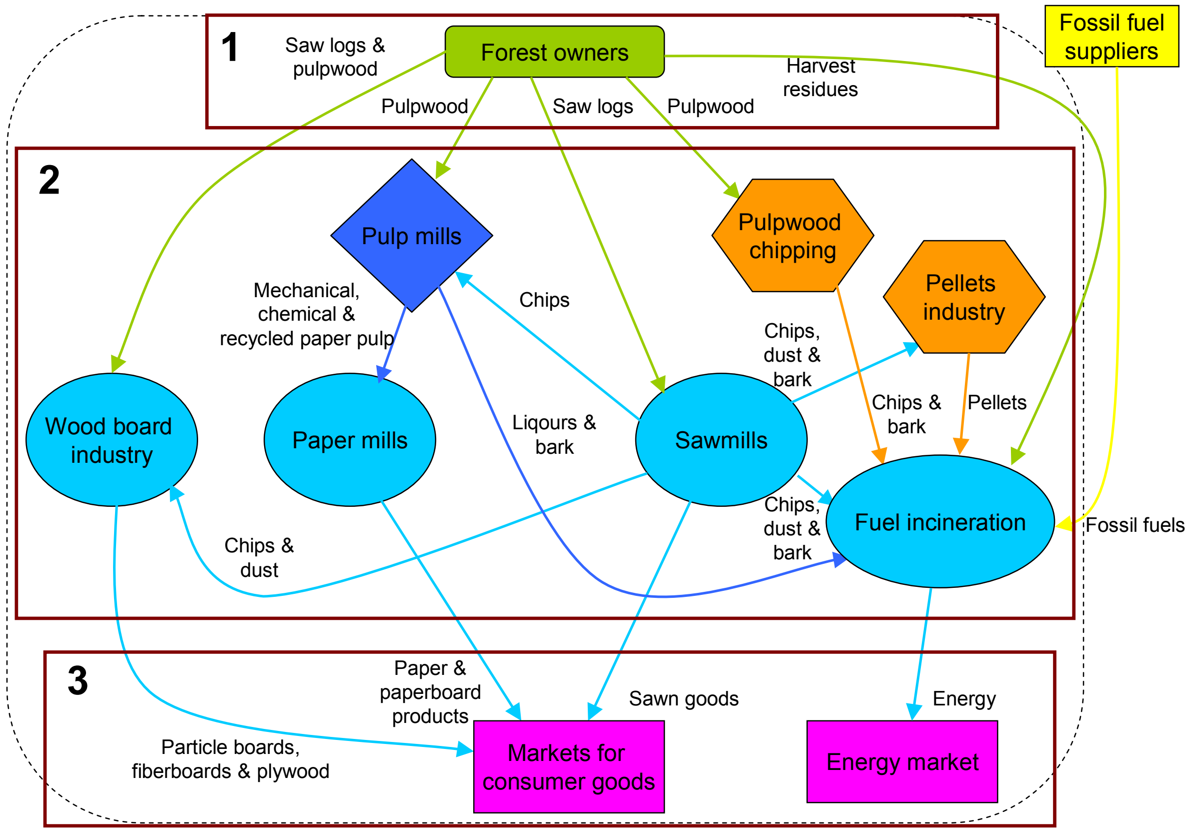

Figure 13. Schematic overview of material flows in the forest sector

Figure 13 provides a schematic overview of the material flows in the sector, as they are described in the model. The modeled process from raw materials supply to demand for forest sector products can be described by a three stage process. (1) Supply curves are defined for roundwood (saw logs and pulpwood) and roundwood harvest residues. (2) These raw materials are used by industry that produces intermediate and final goods, as well as energy services, using Leontief production functions that are specified through input-output coefficients. Industrial output is thus dependent on inputs in fixed proportions. The forest sector is characterized by intricate interdependencies between its sub-sectors, where sawmills have a central role as their by-products can be used as inputs in all the other sub-sectors. (3) Consumers then obtain forest based consumer goods (sawn goods, paper, wood boards) and energy services, according to pre-defined demand curves.

As in Bolkesjø et al (2006) and other more recent studies (e.g. Ince et al 2011; Moiseyev et al 2011; Schwarzbauer & Stern 2010; Trømborg & Solberg 2010) the market for forest based bioenergy is included. The bioenergy supply consists of roundwood harvesting residues (slash), forest industry by-products (chips, dust, bark, and liquors), chipped pulpwood, and refined by-products (wood pellets). These wood based fuels compete with fossil fuels supplied in unlimited quantities at an exogenously given price. The demand for energy comes from small- (mainly individual households) and large-scale users (industry and district heating plants).

3.1 Production, Consumption, and Trade

There are three types of products in the model: endogenous products, *k*; exogenous fossil fuels, *o*; and all other exogenous inputs (e.g. labor, materials, and recycled paper), *n*. The set of endogenous products, *k*, is comprised of roundwood, *w*; harvest residues, *d*; intermediate products, *u*; industrial by-products, *b*; consumer products, *f*; and energy; *e*; i.e. $w,d,u,b,f,e \in k$. All products, their corresponding classifications, and respective measurement units are defined in Table A.3 in Appendix A.

The price for fossil fuel, p_o, is given as data, while the price of other exogenous products, p_n, is set to unity. The prices for endogenous products, $p_{i,k}$, differ across regions, *i*, and are determined within the model. The reference level prices for endogenous products are specified through data observations and a calibration procedure, in compliance with spatial equilibrium theory.

Supply of forest sector raw materials – box 1 in *Figure 13* – is described by inverse supply functions where the marginal costs are assumed to be increasing functions of harvested volumes. The supply of roundwood type *w* in region *i* is defined as:

$$p_{i,w}(H_{i,w}) = \mathrm{A} + \alpha_{i,w} H_{i,w}^{\beta_{i,w}} \quad (1),$$

where $p_{i,w}$ is the price of roundwood delivered to an industrial site, and $H_{i,w}$ is the volume of roundwood delivered. *A* is the harvesting cost, which can be interpreted as a reservation price under which no roundwood would be sold, and thus it provides the intercept of the supply curve. $\alpha_{i,w}$ (>0) is a supply shift parameter and $\beta_{i,w}$ (>0) is the inverse supply elasticity of roundwood, both calibrated to observed reference level quantities and prices.

The supply function for harvesting residues has a similar form. There is however a difference in that the supply of residues takes into account the quantity of roundwood harvested, such that increased roundwood harvest leads to a lower slope on the residue supply curve. Supply of residue *d* in region *i* is defined as:

$$p_{i,d}(R_{i,d}) = B + \frac{\sum_{w} \hat{H}_{i,w}}{\sum_{w} H_{i,w}} \varsigma_{i,d} R_{i,d}^{\eta_{i,d}} \quad (2),$$

where $p_{i,d}$ is the price of residues at the point of use, $R_{i,d}$ is the quantity of harvest residue utilized, while $\hat{H}_{i,w}$ and $H_{i,w}$ are the reference quantity and the chosen quantity of roundwood harvest, respectively. B is the reservation price for residues, $\zeta_{i,d}$ (>0) is a supply shift parameter and $\eta_{i,d}$ (>0) is the inverse supply elasticity of harvest residues.

The industrial processing activities – within box 2 in *Figure 13* – converts the raw materials – with or without intermediary steps – into consumer products or energy. These product conversion processes are modeled through region specific input-output matrices. The matrices describe the quantities of inputs required, and the quantities of by-products generated, to produce one unit of main output from a particular industrial processing activity, l. An endogenous product, k, can be generated – either as a main output or as a by-product – through several different activities. The main output of an activity is denoted by m, which is an element of k, and has a coefficient, $\Gamma_{i,m,l}$, equal to plus 1. The other coefficients for endogenous products – $\Gamma_{,i,k,l}$ (where $k \neq m$) – are non-positive for inputs and non-negative for by-products. The exogenous products, o and n, are only used as inputs, and thus they always have non-positive coefficients, $\Gamma_{i,o,l}$ and $\Gamma_{i,n,l}$. The input coefficients for other exogenous inputs, $\Gamma_{i,n,l}$, are derived in a model calibration procedure, described in Section 5.2. An overview of the activities defined in the model, and their respective main output produced, endogenous inputs required, and by-products generated are presented in Table A.4 in Appendix A.

Industrial processing is limited by manufacturing or – in the case of the energy activities – fuel incineration capacity. Additional capacity of activity l in region i, $G_{i,l}$, can be constructed to allow for higher output levels. The capacity constraint is defined as:

$$O_{i,l} \leq \Phi_{i,l} + G_{i,l} \qquad (3),$$

where $O_{i,l}$ is the magnitude of the activity – and, consequently, the level of output of main product m from that activity – and $\Phi_{i,l}$ is the existing production capacity. The default in this model is to assume that the existing capacity equals the observed production level. The cost for constructing additional processing capacity is given by:

$$C_{i,l}\left(G_{i,l}\right) = \sigma \delta_l G_{i,l} \qquad (4),$$

where σ is an annuity factor and δ_l is the unit investment cost for new capacity of activity l. Based on the above, each activity l in region i have a linear production cost function, differing depending on the need for additional capacity:

$$\begin{aligned} C_{i,l}\left(O_{i,l}\right) &= -\sum_{k \neq m} p_{i,k} \Gamma_{i,k,l} O_{i,l} - p_o \Gamma_{i,o,l} O_{i,l} - p_n \Gamma_{i,n,l} O_{i,l} && \text{if } O_{i,l} \leq \Phi_{i,l} \\ C_{i,l}\left(O_{i,l}\right) &= -\sum_{k \neq m} p_{i,k} \Gamma_{i,k,l} O_{i,l} - p_o \Gamma_{i,o,l} O_{i,l} - p_n \Gamma_{i,n,l} O_{i,l} + \sigma \delta_l \left(O_{i,l} - \phi_{i,l}\right) && \text{if } O_{i,l} > \Phi_{i,l} \end{aligned} \qquad (5).$$

Note that the input coefficients are non-positive – indicating that costs increase with input use – while by-product coefficients are non-negative, such that production costs are negatively correlated with the generation of by-products. Also note that fossil fuels are only used as an input in energy production, and not in the production of intermediates or consumer goods.

In box 3 in *Figure 13*, the forest based consumer products and energy supplied through the industrial processing activities above meet the consumers' demand functions. The demand function for final consumer good f in region i is defined as:

$$Q_{i,f} = \hat{Q}_{i,f}\left(p_{i,f} / \hat{p}_{i,f}\right)^{\gamma_{i,f}} \quad (6),$$

where $Q_{i,f}$ is the quantity demanded, $p_{i,f}$ is the price, and $\gamma_{i,f}$ (<0) is the own-price elasticity. $\hat{Q}_{i,f}$ and $\hat{p}_{i,f}$ are reference consumption and price levels. The reference point, where $Q_{i,f} = \hat{Q}_{i,f}$ and $p_{i,f} = \hat{p}_{i,f}$, is given by data on observed consumption and price levels, and at this point the slope of the curve equals $\gamma_{i,f}$.

The demand function for energy is defined in a similar manner:

$$X_{i,e} = \hat{X}_{i,e}\left(p_{i,e} / \hat{p}_{i,e}\right)^{\mu_{i,e}} \quad (7),$$

where i is the region, e is the energy market, $X_{i,e}$ is the quantity demanded, $\hat{X}_{i,e}$ is the reference consumption level, $\hat{p}_{i,e}$ is the reference energy price level, and $\mu_{i,e}$ is the own-price elasticity. Consumer benefit from goods and energy use is given by integrating the inverses of (6) and (7), respectively.

Endogenous products, k, can be traded (except those products exempted through restrictions below) between region i and any other region, j. The cost of trading is defined by:

$$C(T_{i,j,k}) = T_{i,j,k} \min_v (\mathrm{M}_{k,v} + \mathrm{N}_{k,v}\Lambda_{i,j}) \quad (8),$$

where $T_{i,,j,k}$ is the quantity traded, v indicates the mode of transportation (road, rail, or sea), $M_{k,v}$ is a loading cost, $N_{k,v}$ is the cost per distance unit, and $\Lambda_{i,j}$ is the distance between the trading regions. The cheapest mode of transportation is chosen for each region-region-product combination.

3.2 Constraints

Five types of constraints are applied in this model: trade constraints; balance constraints; capacity constraints; raw material supply constraints; and the bioenergy constraint. The use of energy, residues, and the by-product liquor; is assumed to be limited to the region where the products are produced. Hence, trade in these products is prohibited:

$$T_{i,j,e} = 0 \qquad \forall i,j,e \quad (9),$$

$$T_{i,j,d} = 0 \qquad \forall i,j,d \quad (10),$$

$$T_{i,j,\text{"liqour"}} = 0 \qquad \forall i,j \quad (11).$$

There are balance constraints for all endogenous product types; final consumer goods, f; intermediate goods, u; by-products, b; roundwood, w; residues, d; and energy, e. These constraints make sure that use does not exceed supply of any good; and are all formulated as: Consumption – Production + Net exports ≤ 0.

$$Q_{i,f} - \sum_l \Gamma_{i,f,l} O_{i,l} + \sum_j \left(T_{i,j,f} - T_{j,i,f}\right) \le 0 \qquad \forall i,f \quad (12),$$

$$-\sum_{l}\Gamma_{i,u,l}O_{i,l} + \sum_{j}\left(T_{i,j,u} - T_{j,i,u}\right) \le 0 \qquad \forall i,u \qquad (13),$$

$$-\sum_{l}\Gamma_{i,b,l}O_{i,l} + \sum_{j}\left(T_{i,j,b} - T_{j,i,b}\right) - \Psi_{i,b} \le 0 \qquad \forall i,b \qquad (14),$$

$$-\sum_{l}\Gamma_{i,w,l}O_{i,l} - W_{i,w} + \sum_{j}\left(T_{i,j,w} - T_{j,i,w}\right) \le 0 \qquad \forall i,w \qquad (15),$$

$$-\sum_{l}\Gamma_{i,d,l}O_{i,l} - R_{i,d} \le 0 \qquad \forall i,d \qquad (16),$$

$$X_{i,e} - \sum_{l}\Gamma_{i,e,l}O_{i,l} \le 0 \qquad \forall i,e \qquad (17).$$

Note that the input-output coefficients ($\Gamma_{i,k,l}$) are non-positive for inputs, non-negative for by-products, and equal to one for the main output of activity *l*. $\Psi_{i,b}$ is an exogenous supply of by-products presented in more detail, as a model calibration procedure, in Section 5.3.

In addition to the trade and balance constraints we also have restrictions on industrial capacity and raw material supply:

$$O_{i,l} \le \Phi_{i,l} + G_{i,l} \qquad \forall i,l \qquad (18),$$

$$H_{i,w} \le \Theta_{i,w}\hat{H}_{i,w} \qquad \forall i,w \qquad (19),$$

$$R_{i,d} \le \mathrm{I}_{i,d}\sum\nolimits_{w} H_{i,w} \qquad \forall i,d \qquad (20).$$

As described above, $\Phi_{i,l}$ is the existing production capacity and $G_{i,l}$ is additional capacity. $\hat{H}_{i,w}$ is reference roundwood harvest, while $\Theta_{i,w}$ and $I_{i,d}$ are restriction parameters.

A bioenergy constraint is introduced to allow for analysis of scenarios with an exogenously decided policy target for increased domestic bioenergy use. The bioenergy constraint is defined as:

$$\sum\nolimits_{swe,bio} O_{i,l} \ge Z + \sum\nolimits_{swe,bio} \hat{O}_{i,l} \qquad (21),$$

where $\hat{O}_{i,l}$ is the observed reference output level, while $O_{i,l}$ is the chosen output level, *Z* is the target for increased use wood based bioenergy, *swe* is a subset of *i* indicating the domestic Swedish regions, and *bio* is a subset of *l* indicating the wood based fuel incineration activities. The implications of this restriction will be covered in more detail in Section 3.4.

Finally, all the decision variables may only be non-negative:

$$O_{i,l}, Q_{i,f}, R_{i,d}, G_{i,l}, H_{i,w}, X_{i,e}, T_{i,j,k} \ge 0 \qquad (22).$$

3.3 Objective Function

The decision problem is specified as choosing the social welfare maximizing levels of the decision variables, subject to the restrictions in equations (9)–(22). The social welfare function (23) is defined as the net between the benefits of goods and energy consumptions, on the one hand; and, on the other hand, the costs of raw materials, fossil fuels and other exogenous inputs, additional industrial processing capacity, and trade.

$$
\begin{aligned}
& Max_{O,Q,R,G,H,X,T} \\
& \sum_{i,f} \int_0^{Q_{i,f}} p_{i,f}\left(Q_{i,f}\right) dQ_{i,f} \\
& + \sum_{i,e} \int_0^{X_{i,e}} p_{i,e}\left(X_{i,e}\right) dX_{i,e} \\
& - \sum_{i,w} \int_0^{H_{i,w}} p_{i,w}\left(H_{i,w}\right) dH_{i,w} \\
& - \sum_{i,d} \int_0^{R_{i,d}} p_{i,d}\left(R_{i,d}\right) dR_{i,d} \\
& - \left(- \sum_{i,l,n} p_n O_{i,l} \Gamma_{i,l,n}\right) \\
& - \left(- \sum_{i,l,o} p_o O_{i,l} \Gamma_{i,l,o}\right) \\
& - \left(\sum_{i,l} \sigma \delta_l G_{i,l}\right) \\
& - \sum_{i,j,k} T_{i,j,k} \min_v (M_{k,v} + N_{k,v} \Lambda_{i,j})
\end{aligned}
\qquad (23).
$$

Equations (9)–(23) define a convex optimization problem, where any solution satisfying the Kuhn-Tucker conditions of the problem is optimal. The equilibrium prices for all products and regions are given by the shadow values of the material balance constraints. The optimal solution to this model is in line with the conditions for a competitive market (Samuelson 1952, Takayama & Judge 1964).

3.4 The Market for Wood Based Bioenergy

Figure 14 pictures a schematic description of how the energy markets are represented in the model. The supply of fossil fuels is horizontal, indicating that unlimited quantities can be supplied at the exogenously given price, p_o. Wood based fuels (harvest residues, industry by-products, wood pellets, and chipped pulpwood) are supplied until their joint supply curve intersects – at X_{bio} in *Figure 14* – either the energy demand curve or the fossil fuels supply curve. The use of fossil fuels is given by the difference between X_{total} and X_{bio}.

The model assumes two different energy markets, *e*, for each region, *i*. Households and other small-scale users are restricted to a choice between wood pellets (made from chips, dust, or bark) and fossil fuels. Large-scale users – consisting of district heating plants, forest industries and other industries – may choose between harvest residues, industry by-products, wood pellets, and fossil fuels. The energy services provided through these energy markets are not explicitly modeled, but they mainly include electricity, industrial process heat, space heating and cooling, and hot water.

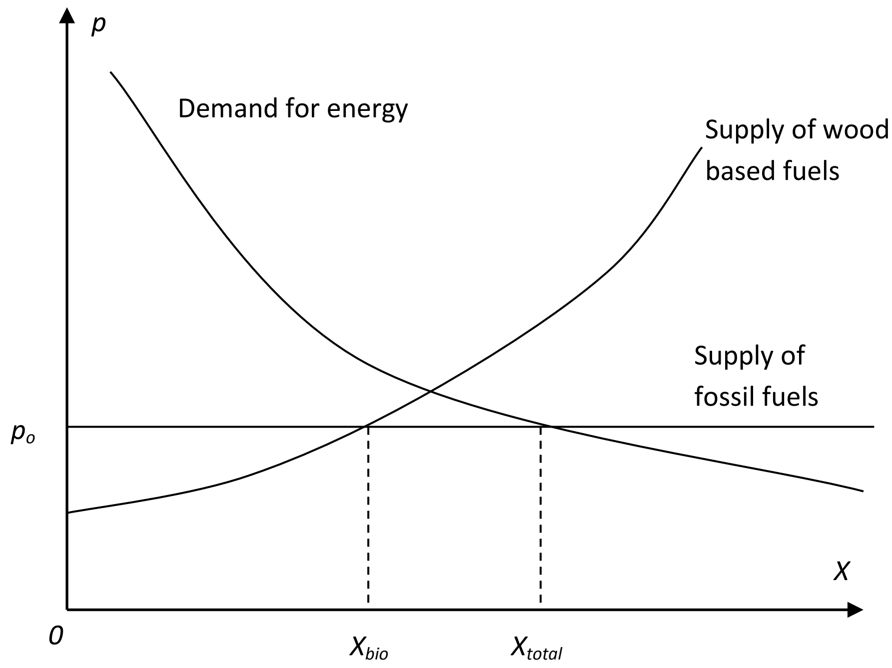

Figure 14. Schematic representation of the energy market

The bioenergy constraint defined in equation (21) allows us to analyze the implications of an exogenously decided policy target for wood based bioenergy use, where *Z* indicate the targeted increase above the reference level. The marginal cost of increases in Z is given by the shadow value of the constraint in equation (21). Another way to phrase the restriction in equation (21) is that *Z* is required to be larger than, or equal to, a sum of output changes ($z_{swe,bio}$) of each Swedish regions´ wood fuel incineration activities (see *Table 3*):

$$Z \geq \sum_{swe,bio} z_{swe,bio} = \sum_{swe,bio} \left(O_{swe,bio} - \hat{O}_{swe,bio} \right) \quad (24).$$

Table 3. *Wood fuel incinerating activities*

Wood fuel incinerating activity (*bio*)	Main output (*m*)	Endogenous input (*k*)
SlashFuel	EnergyLarge	Slash
ChipsFuel	EnergyLarge	Chips
DustFuel	EnergyLarge	Dust
BarkFuel	EnergyLarge	Bark
LiqourFuel	EnergyLarge	Liquors
PelletsFuelLarge	EnergyLarge	Pellets
PelletsFuelSmall	EnergySmall	Pellets

The wood fuel incinerating activities here are collectively indexed by *bio*, and is a subset of all processing activities, I, see Table A.4

The cost of producing $O_{i,l}$ units of main output *m* using activity *l* in region *i* is given by equation (5). Assuming that the existing capacity is fully utilized in the reference situation, *i.e.* that *Φ* =*Ô*, and differentiating $C_{i,l}(O_{i,l})$ with respect to $O_{i,l}$, yields the marginal costs:

$$MC\left(O_{i,l}\right)^{O_{i,l} \geq \Phi_{i,l}} = -\sum_{k \neq m} p_{i,k} \Gamma_{i,k,l} - p_o \Gamma_{i,o,l} - p_{i,n} \Gamma_{i,n,l} + \sigma S_l \quad (25),$$

where k is the set of endogenous inputs, o refers to exogenous fossil fuels, n is an aggregate of all other exogenous inputs, $p_{i,k}$, p_o, and p_n are prices, $\Gamma_{i,k,l}$, $\Gamma_{i,o,l}$, and $\Gamma_{i,n,l}$ are input-output coefficients, σ is a capital investments annuity factor, and S_l indicates unit investment costs for production capacity.

Note that fossil fuels are only used as inputs in the fossil fuel incinerating activities, that fossil fuel incinerating activities have no costs for other exogenous inputs[1], and that the price for other exogenous inputs, p_n, is set equal to one. Using the notation from equation (24) above, we can formulate the marginal cost for increasing output from any of the wood fuel incinerating activities in any domestic region as:

$$MC(z_{swe,bio}) = -\sum_{k \neq m} p_{swe,k}\Gamma_{swe,k,bio} - \Gamma_{swe,n,bio} + \sigma S_{bio} \qquad (26).$$

The marginal cost curve is illustrated in *Figure 15*. At the reference point, where $O_{swe,bio}=\hat{O}_{swe,bio}$, the energy markets are assumed to be in cost minimizing equilibrium, such that wood fuel incineration activities are used as long as their marginal costs are below the marginal costs for fossil fuel incineration, p_o. Any increase in output above $\hat{O}_{swe,bio}$ would require a capacity increase at a marginal cost of σS_{bio}, which leads to a discontinuous jump in the curve. As long as the increase in wood energy use substitutes fossil fuel use, the area bordered by $MC(O_{swe,bio})$, p_o, $\hat{O}_{swe,bio}$, and $\hat{O}_{swe,bio}+z_{swe,bio}$, illustrates the net social cost ($C(z_{swe,bio})$) from increasing output by $z_{swe,bio}$.

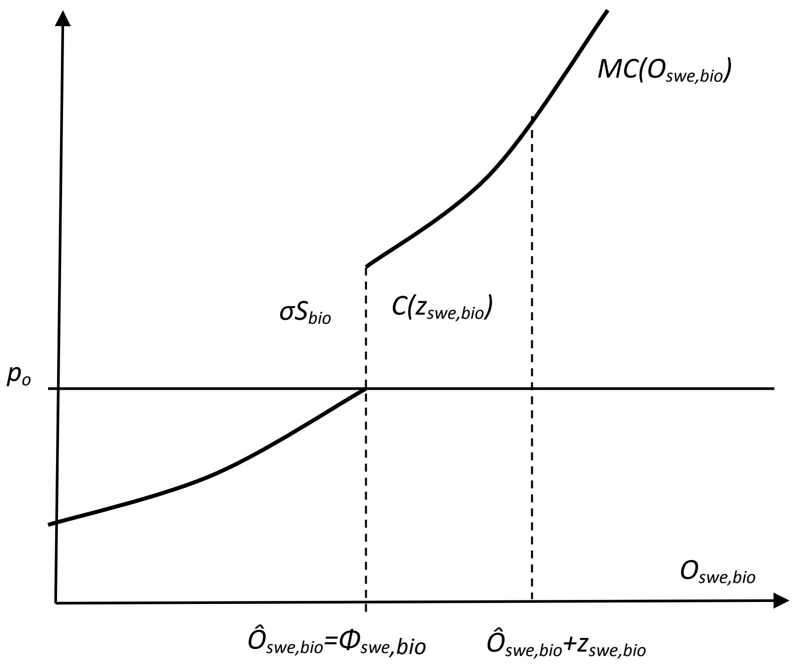

Figure 15.The marginal cost curve for a wood fuel incinerating activity

The optimization model in equations (9)-(23) is used to find the minimum net social cost of reaching a given bioenergy increase target Z, or in other words, the least cost solution satisfying equation (27): $C(Z) = \min \sum_{swe,bio} C(z_{swe,bio})$ s.t. $\sum_{swe,bio} z_{swe,bio} \geq Z$ (27).

[1] This is a simplifying assumption of little importance. A positive cost would lead to an equal shift upwards in the wood fuel incinerating activities costs for other exogenous inputs, through the calibration process in Section 5.2

4 Empirical Specifications and Data

This section describes the empirical specifications of the SFSTMII, and presents the data applied in the model. All data is from the year 2008, which is used as a reference period. All prices and costs are in terms of Swedish Krona (SEK)[2] at 2008 price levels. Lists of variables, parameters and indices are provided in Appendix A, while data tables can be found in Appendix B.

4.1 Regions

The domestic Swedish regions used in this study are based on Sweden's four timber measurement associations. Some of the data is given based on these regions, while other parts of the data is national or based on Sweden's 20 local government regions (counties). The borders between measurement regions do not entirely coincide with those of the local government regions.

Region 1 = 'North': Norrbotten, Västerbotten, Jämtland, Västernorrland

Region 2 = 'East': Dalarna, Gävleborg, Västmanland, Uppsala, Stockholm

Region 3 = 'West': Värmland, Örebro, Västra Götaland

Region 4 = 'South': Södermanland, Östergötland, Jönköping, Kronoberg, Kalmar, Gotland, Halland, Blekinge, Skåne

Figure 16. Swedish regions in the SFSTMII model and their corresponding counties (SDC 2009)

Figure 16 shows the assignment of local government regions to the timber measurement regions that is applied in this study. This approximation is used throughout these data when aggregating data on local government regions to the timber measurement regions.

In addition to the four domestic Swedish regions, an external region is also defined. This region, labeled ROW (for "rest of world"), serves as a trade partner and competitor to the domestic regions. Reference levels of production and demand in the ROW region are based on data for the European Union – except Sweden – and Norway. Unless explicitly stated, prices and elasticities are assumed to be the same in the ROW region as in the domestic regions.

[2] 2008 average currency exchange rates: 1 EUR = 9.62 SEK; 1 US$ = 6.54 SEK

4.2 Raw Material Supply

4.2.1 Roundwood Supply

Roundwood markets are assumed to be perfectly competitive and the marginal costs are assumed to be increasing with the quantity of roundwood harvested, as stated in equation (1). Observed prices, $\hat{p}_{i,w}$, and quantities, $\hat{H}_{i,w}$, determine the level of the supply curve. The slope parameter $\alpha_{i,w}$ is defined by replacing $p_{i,w}$ and $H_{i,w}$ in equation (1) with the observed reference price and quantity, and then solving for $\alpha_{i,w}$:

$$\alpha_{i,w} = \frac{\hat{p}_{i,w} - A}{\hat{H}_{i,w}^{\beta_{i,w}}} \qquad (28).$$

$\beta_{i,w}$ is determined by the inverse of the supply elasticity, $\varphi_{i,w}$), adjusted by observed price, $\hat{p}_{i,w}$, and harvesting cost, *A*:

$$\beta_{i,w} = \frac{1}{\varphi_{i,w}}\left(\frac{\hat{p}_{i,w}}{\hat{p}_{i,w} - A}\right) \qquad (29).$$

The harvesting cost parameter, *A*, covers the costs of harvesting roundwood and bringing it to a roadside location for further transport. According to FRIS (2009) these costs amount to around 200 SEK/m^3sub. The variations across regions and roundwood types are considered negligible here.

Roadside roundwood prices are gathered from the Swedish Forest Agency (SFA 2009). These roadside prices are added with the approximated transportation costs (FRIS 2009) to acquire approximate industrial site prices. Price data for non-coniferous logs are approximated as the average import cost, also extracted from SFA (2009).

When running the model, a calibration of the price differences between the regions is performed (see Section 5.1). Region West is used as the reference region when calibrating the model. Prices in other regions – including ROW – adjust to this price level, trade flows and trade costs. Therefore, only the price data for West are of any relevance. Reference case roundwood prices after calibration are presented in *Table B.1*.

Harvested quantities in the domestic regions are derived from SDC (2009) data on roundwood use in the wood processing industry and interregional trade. The roundwood use in industry is the sum product of the input-output coefficients in Section 9.2.3 and the produced quantities in Section 0. The net exports of roundwood are provided in *Table B.2*. Harvested quantities, *Table B.3*, are by definition the sum of industry use and net exports.

There are two relatively recent econometrical studies of the Swedish forest sector which estimate price elasticities of roundwood supply ($\varphi_{i,w}$). Ankarhem (2005) calculates the supply elasticities using time-series data stretching from 1968 to 2003. The model assumes that the capital stock adjustments are sluggish. The model also controls for labour and energy input costs, forest inventory size and the price of final outputs from the sector (sawn goods, pulp and district heating). The estimated supply elasticity is 0.18 for saw logs and 0.51 for pulpwood. Geijer et al (2011) is largely similar to Ankarhem (2005), with the addition of allowing for technological development and lags in the adjustments to price changes. The time-series is extended to 1966-2006, and also includes dummy variables for major exogenous shocks for six of these years. The elasticities are evaluated at the average of all variables between 2000 and 2004. The estimated supply elasticity is 0.28 for saw logs and 0.14 for pulpwood. The estimate for pulpwood is, however, not significant at the 5% level. These studies do not distinguish long run short run elasticities for roundwood supply. Since the annual increment in the standing forest volume and the sustainable level of harvest is assumed to remain relatively stable over, at least, the coming three decades (SFA 2008), the supply elasticities can be assumed to be similar for the short run and for the long run. The average estimates in these two studies are used for saw logs and pulpwood respectively. The supply elasticity for saw logs is set at 0.23 while the elasticity for pulpwood is 0.33.

Roundwood harvest is assumed to be limited in volume by the annual growth of the standing timber volume. Equation (19) sets a restriction for increases in harvest levels. The increase restriction parameter values, $\vartheta_{i,w}$, are set as in *Table B.4*, based on data from SFA (2008) and Eurostat (2009).

4.2.2 Harvest Residues Supply

The marginal cost of harvesting residues supply is assumed to be increasing with the quantity of residues used, $R_{i,d}$, and decreasing with the quantity of roundwood harvested, $H_{i,w}$, as stated in equation (2).

In this version of the model, only one type of harvest residues – slash from final fellings – is included. This can however be extended to include other types of residues, such as stumps, small trees and slash from intermediate cutting, in later model versions.

The parameter estimates in the harvest residue supply function are derived from a study by Athanassaidis et al (2011), who use a bottom-up approach to calculate economic-engineering costs of collecting harvest residues and delivering them to the market. Sweden's productive forest land is divided into 2210 sites (based on the Swedish National Forest Inventory). Quantity of annual harvest residues and costs per unit are calculated for each site, under four different technological supply systems for slash from final fellings.

The quantities are subjected to environmental and technical restrictions, and extraction is prohibited in a range of forest types: areas of nature protection; areas where soils have low bearing capacity, areas with uneven ground structure, and areas less than 25 meters from lakes or other waterlines are excluded. From the forest areas where extraction is allowed, 40% of the logging residues are assumed to be left at the felling site.

By choosing the cheapest system for each site and ordering the sites by cost per oven dry ton (ODT) of residue, an aggregated national supply curve (as well as regional curves) can be formed (*Figure B.1*).

Estimates for the inverse supply elasticity of residues, $\eta_{i,d}$, are obtained from a log-linear regression model based on the economic- engineering bottom-up supply cost estimates. The intercept is slightly manipulated – all costs below 600 SEK/ODT is assumed to equal 600 SEK/ODT – in order to get estimates of $\eta_{i,d}>1$, so that the functional form yields reasonable estimations of the economic-engineering bottom-up supply curve, and, in addition, also mimic the functional form used for roundwood supply. The regression model is defined as:

$$\ln(p_{i,d} - 600) = \omega_{i,d} + \eta_{i,d} R_{i,d} + \varepsilon_{i,d} \quad (30),$$

where $p_{i,d}$ is the approximated supply cost from the economic-engineering study, $R_{i,d}$ is the aggregated quantity of residues at the given cost in the economic-engineering study, $\omega_{i,d}$ is a regression intercept, $\eta_{i,d}$ is the coefficient to be estimated, and $\varepsilon_{i,d}$ is the regression error term. The regression results are presented in *Table B.5*.

Forest Agency data (SFA 2010) indicate that 8.4 TWh of residues were used for fuel in 2008. There is no official price data on harvest residues, instead the price for wood chips at thermal power stations (167 SEK/MWh) is used as the reference price. A conversion factor of 4.9 MWh/ODT (SFA 2010) yields that the market equilibrium point is 818 SEK/ODT and 1.716 million ODT. This point is above the economic-engineering supply curve (see *Figure B.1*), where the same quantity indicates a price of 680 SEK/ODT. The differences can be due to deficiencies in the price and quantity data or due to ignored costs in the bottom-up study. The difference is compensated for by shifting the entire economic-engineering supply curve upwards, by 138 SEK/ODT, so that the approximated market equilibrium point is on the curve. The intercept, *B*, is thus at 738 SEK/ODT, and the reference price, $\hat{p}_{i,w}$, is at 818 SEK/ODT.

$\zeta_{i,d}$ is derived in a fashion similar to how $\alpha_{i,w}$ was derived above:

$$\varsigma_{i,d} = \frac{\hat{p}_{i,d} - B}{\hat{R}_{i,d}^{\eta_{i,d}}} \quad (31),$$

where $\hat{p}_{i,d}$ is the observed reference price, and $\hat{R}_{i,d}$ is the observed quantity of residues used.

Regional supply curves from these estimated parameter values and the economic-engineering supply curves from Athanassaidis et al (2011) are displayed in *Figure B.2*. Ocular inspection of the estimated supply curves indicate that the method used here gives a reasonable approximation of economic-engineering supply curves, even though the method utilized to obtain them included some manipulation of the intercept. Since we, in Section 6, only will look at scenarios where the use of harvest residues increase, the interesting part of the supply curves are to the right of the reference quantities.

Residue supply is restricted by an upper limit ($R_{i,d}^{max}$), as in equation (20). The limit for each region is set where the economic-engineering supply curves bends steeply upwards and is more than 49 SEK/ODT, equivalent with 10 SEK/MWh, above the curves based on the estimated parameters. The restriction parameter, $l_{i,d}$, is given by the ratio of $R_{i,d}^{max}$ over the sum of observed roundwood harvest for each region. The parameter values for reference quantity, maximum quantity and $l_{i,d}$ are given in *Table B.6*.

4.3 Industrial Processing

There are 30 industrial processing activities in the model. They can be divided into four groups depending on their main outputs; intermediate goods producing activities, consumer goods producing activities, fuel incineration activities, and roundwood conversion activities. An overview of these activities, and their respective inputs and outputs, are given in *Table A.4*.

4.3.1 Input-Output Coefficients

This section contains the input-output coefficients, Γ, used to model the forest industry. Coefficients are defined per industrial processing activity (*l*), region (*i*) and product (*k*, *n* or *o*). The coefficients are non-positive for inputs, non-negative for by-products and equal to one for the main output of the activity. The units used for the various products are listed in *Table A.3*. The ROW region is assumed to have similar technological conditions as the other regions, and its coefficients are averages of the other regions' coefficients.

The input coefficients for other exogenous products, $\Gamma_{i,l,n}$, are derived in a calibration process described in Section 5.2.

Sawn goods input coefficients (*Table B.10-12*) are derived from SDC (2009) data – for each Swedish region and tree type – on saw logs input and production of sawn goods. SDC (2009) data is also used to derive coefficients for by-products per unit of sawn goods for each region.

Input coefficients for production of wood boards (*Table B.13-15*) are derived from SDC (2009) data on raw material inputs and quantity of output, for each board type and region.

Input coefficients for paper products (*Table B.9*) – equal across regions – have been obtained from the GFPM world model, 2009 version (Buongiorno et al 2009).

Mechanical pulp (*Table B.7*) and chemical pulp (*Table B.8*) coefficients have been derived in a slightly more complicated way. Average coefficients – use of a specific input (e.g. spruce pulpwood) for chemical pulp and mechanical pulp in aggregate – were obtained from SDC (2009) data. In order to disaggregate these inputs to chemical pulp and mechanical pulp production respectively, SFA (2009) proxies for total wood input needed to produce one unit of each pulp type (4.69 for chemical pulp (weighted average of sulphate and sulphite) and 2.40 for mechanical pulp) were used. For each region a SFA-proxy average (weighted with proportions of mechanical pulp and chemical pulp production within the region) was derived. The input coefficients per region, input and industrial activity (MechPulp and ChemPulp) were then calculated as the SDC (2009) aggregate input coefficient multiplied with the pulp type specific SFA proxy and then divided by the region specific SFA proxy.

In addition to these inputs, bark and liquor are produced as by-products. Liquor is a by-product from chemical pulp production, and the coefficient is estimated from the use of liquor in the pulp sectors fuel supply, and tall oil pitch in district heating supply, given by the Swedish Energy Agency (SEA 2010). Bark is a by-product from both mechanical and chemical pulp production. Total bark is derived from SEA (2010) data on pulp sector by-products (except for liquor) used as fuel. This has then been divided by total roundwood input in the Swedish pulp sector, and then distributed across regions and technologies in proportion to their input of roundwood.

Recovered paper is not classified as an endogenous input in this model. Instead it is included in the other exogenous inputs, *n*, category. Thus recovered paper pulp has no endogenous inputs. This specification does not take any recovered paper supply limitations into account.

Pellets can be produced through either of three different activities. Each of them has a single input – chips, dust or bark. The input coefficients (*Table B.16*) are derived from energy content estimates (*Table B.18*).

The model allows for production of chips from pulpwood (*Table B.17*). It is assumed that one unit of pulpwood gives one unit of chips, with bark as a by-product. The bark estimate equals the coefficient used for bark from pulp production.

Increased demand for bioenergy will in this model eventually lead to production of chips from pulpwood. Saw logs could also be used for this purpose, or as an input to pulp production, but are used to produce sawn goods, which cannot be produced through the use of other inputs. Large increases in pulpwood demand will push pulpwood prices up towards the price levels of saw logs. To avoid a situation where pulpwood prices rise above saw logs prices, a processing activity that converts saw logs into pulpwood at a one to one ratio, and no exogenous costs, is introduced.

Table B.18 gives the quantities of fuel needed by each technology to produce 1 MWh for the energy markets. The estimate for slash is from Athanassaidis et al (2011). The coefficients for chips, dust and bark are from SFA (2009), while the coefficient for pellets is from SEA (2010).

4.3.2 Output Quantities

The observed output levels, $\hat{O}_{i,l}$, from the intermediate goods and consumer goods producing activities are presented in *Table B.19-23*. These data on industrial output in Sweden was gathered from SDC (2009), the Swedish Forest Agency (SFA 2009), the Swedish Forest Industries Federation (SFIF 2009 & 2010) and the Swedish Association of Pellet Producers (SAPP 2011). Output in ROW is calculated as the residual between total consumption (Sweden+ROW) and production in Sweden. The fuel incineration activity levels are covered in the energy market section below (4.4.2).

Quantities produced are constrained by production capacity. For each industrial activity and region there is an initial capacity and any additional production above this existing capacity has to be accompanied with new production capacity. The default in this model is to assume that the existing capacity equals the observed production level, i.e. $\Phi_{i,l} = \hat{O}_{i,l}$.

Table B.24 gives the assumed investment costs per unit of new capacity, δ_l, for each technology. These costs are then annualized with a factor of $\sigma = 0.08$, equivalent with 5% interest and 20 year production plant life.

The investment cost data for sawn goods, wood boards, pulp and paper are from Bolkesjøs (2004) data on industrial capacity costs in Norway, using a conversion factor of 1.27 SEK(2008)/NOK(2004). Investment costs for plywood board have been assumed to equal those for particle board while costs for recovered paper pulp have been assumed to equal mechanical pulp costs. The investment costs for pellet production have been obtained from Zakrisson (2002), using a conversion factor of 10.09 SEK(2008)/EUR(2002). The investment costs for pulpwood chipping are estimated from

Athanassaidis et al (2011). For the large scale fuel technologies, cost estimates from Elforsk (2011) have been used, while estimates from Bolkesjø (2006) were used for the small scale fuel technologies.

4.4 Consumer Sector

4.4.1 Forest Industry Consumer Goods Market

Approximations of reference demand for consumer products, $\hat{Q}_{i,f}$, in Sweden are based on the production data above and trade data from the Swedish Forest Agency (SFA 2009) and Eurostat (2010). The data on production and net export in *Table B.25* are used to derive estimates of consumed quantities for Sweden in total. These quantities have then been assigned to the Swedish regions in proportion to population (*Table B.26*). Approximations of consumption in ROW have been calculated from Eurostat (2010) production and trade data. ROW is defined as the European Union (EU27), except Sweden, and Norway. The reference consumption levels can be found in *Table B.27-29*.

The reference prices for intermediate products, $\hat{p}_{i,u}$, consumer goods, $\hat{p}_{i,f}$, and industry by-products, $\hat{p}_{i,b}$, are either export (free on board) prices in Swedish ports or an average import/export price based on data on traded quantities and the total value of these. Import (export) prices have been chosen for goods where Sweden is a net importer (net exporter). In the model these prices (see *Table B.30-32*) are set for Region West, while the prices in the other regions are decided in a price calibration process, see Section 5.1.

Buongiorno et al (2003) have made a review of ten previous studies on own-price elasticities, γ, for forest products. The median of these and the elasticity estimates for high income countries used in Buongiorno et al (2003) are used in this model (*Table B.33*).

4.4.2 Energy Market

Since energy is assumed to be a non-tradable product, all energy used in a region also has to be supplied by fuel incineration activities in that region. The fuel incineration activities producing energy for the large- and small-scale markets, respectively, are listed in *Table A.4*. The fuel markets reference level demand quantities and their corresponding activity output levels are presented in *Table B.34-36*. The fossil fuel use quantities in these tables are approximated quantities of substitutable fossil fuels.

The fossil fuel price, p_o, has been obtained from the Swedish Energy Agency (SEA 2010). Prices include all energy and emissions taxes, but VAT is excluded. The price of heavy fuel oil (729 SEK/MWh[3]) is used for both energy markets. This price is used as the energy price for the energy markets. This implies that the cost for other exogenous inputs, *n*, is assumed to be zero for fossil fuel

[3] In the reference year, the price for crude oil was approximately 400 SEK/MWh (~100 US$/barrel). The difference between the crude oil price and the consumer level prices for oil is made up of refining and distribution costs, and taxes.

incineration activities. The exogenous inputs required for the wood based incineration activities are decided through the model calibration process in Section 5.2.

A review of the literature on energy elasticities (Atkinson & Manning 1995; Brännlund et al 2007; Ghalwash 2007; Hellmer 2011; Nässén et al 2008) indicate that own-price elasticity (μ) estimates for aggregate energy demand in the sectors studied in this model generally range from -0.1 to -0.5. In the model presented in this report, an estimate of -0.3 will be used.

The reference fuel demand and output from the various incineration activities in the ROW region are assumed to be fixed. The output from wood based fuel technologies in ROW are residuals in the model and the fossil fuel use is set to meet an arbitrarily decided demand level.

4.5 Trade

The cost of trading one unit of product *k* from region *i* to region *j* has two elements: a loading cost independent of transportation length, and a cost per distance unit. There are three different modes of transportation, *v*: road, rail, and sea; and the cheapest mode is used.

Cost per kilometer and loading cost per unit for road and rail transports are taken from Bolkesjø (2004), see *Table B.37*. An exchange rate of 1.27 is used to convert from NOK(2004) to SEK(2008).

Sea transportation costs are gathered from Suurs (2002). Data on transportation cost per ton of dry matter is given for two distances and three product groups – logs, chips and pellets (*Table B.38*). Linear regressions based on the cost estimates for the two distances are used to get intercept and slope for each product type. The cost estimate for logs is used for all roundwood and sawn goods, particle boards and plywood boards after converting to cubic meter using a factor of 0.42 (SFA 2009). The same method is used to convert the cost estimate for chips, which is also assumed to hold for dust and bark. For pellets the cost estimate is corrected for moisture content to get a cost per ton, and then a conversion factor of 0,65 ton per m^3 (SFA 2009) to get a cost per m^3. To get transportation cost estimates for pulp, paper and fiber boards; the cost per ton of logs is used, after adjusting for moisture content. An exchange rate of 10.09 is used to convert from EUR(2002) to SEK(2008).

All in all this yields the loading costs, $M_{k,v}$, and variable costs, $N_{k,v}$, in SEK(2008) listed in *Table B.39*. Transportation distances between regions, Λ_{ij}, vary slightly between modes of transportation (Lestander 2011). Trades to and from the international ROW region are assumed to go by sea only. The distances used are provided in *Table B.40-42*. Trade costs per unit, depending on trading regions and product, are presented in *Table B.43-46*.

Energy, liquor and harvesting residues are not traded in this model; i.e. these products are assumed to be used in their regions of origin only.

5 Model Calibration

The model calibration consists of three parts. First, the price relationships between regions are calibrated to conform to spatial equilibrium theory. In short, all production and consumption levels are fixed at the reference levels and then the objective is to minimize trade costs under material balance constraints. Second, input coefficients for an exogenous good – assumed to cover all inputs (except for fossil fuels) needed for the industrial activities that are not endogenous in the model – is derived under an assumption that all activities yields zero profit in the reference setting. In the third calibration procedure, an exogenous supply of by-products is introduced to cover for material imbalances in the model.

The first two calibration procedures are based on an assumption of competitive market equilibrium. This assumption is not unproblematic. Parts of the Swedish forest sector are dominated by a limited number of large actors; including state-owned forest land, industrial processing firms owned cooperatively by small scale forest land holders, and horizontally integrated investment-owned companies. On the basis of this observation Bergman & Brännlund (1995) attempts to measure oligopsony power in the Swedish pulp sector. They conclude that oligopsony power in the market for pulpwood is moderate for most of the studied period, but that during times of low capacity utilization in the pulp sector (coinciding with substantial business cycle downturns) the market inefficiencies increase. Brännlund et al (2006) studies the market for wood fuels and finds that the purchaser´s marginal value is consistently higher than the market price for the fuel. They do, however, also conclude that this market inefficiency has decreased over time. For now we will assume that we are dealing with a competitive market, but this is an area where the model could be developed in later versions, and we will discuss this further in Section 7.3.

5.1 Price Calibration

The theoretical basis for the model presented in this paper is that of spatial price equilibrium in competitive markets as described by, among others, Samuelson (1952) and Takayama & Judge (1964). To conform to this trade theory, the price relationships between regions are calibrated. In short, all production and consumption levels are fixed at the reference levels and then the objective is to minimize trade costs under material balance constraints. The objective function in this procedure is total trade cost, which is minimized subject to the material balance constraints in equations (12)-(17) and the non-negativity constraints in equation (22). Total trade cost (*TTC*) is obtained by summation of equation (9) over regions (*i* and *j*) and products (*k*):

$$TTC = \sum_{i,j,k} T_{i,j,k} \min_{v}(\mathrm{M}_{k,v} + \mathrm{N}_{k,v}\Lambda_{i,j}) \quad (32).$$

The resulting solution is the cheapest way of trading products between regions under reference production levels and still satisfying all the reference consumption levels. The shadow values of the balance equations indicate optimal price differences between the regions. The product prices for each region are then set using one region as a reference region. The price observed in data is assigned to the reference region, and the prices in the other regions are set as the net between the shadow values in the region and the reference region in aggregate with the observed price. Region West (see *Figure 16*) has been used as the reference region.

After the price calibration procedure, the price dependent parameters $\alpha_{i,w}$ and $\beta_{i,w}$ (Section 4.2.1) are recalculated with the new regional-specific reference prices.

5.2 Quantities of Other Exogenous Inputs

In this model, the markets are assumed to be in equilibrium, and all actors are assumed to make zero profit on the margin. The costs for other exogenous inputs, $p_{i,n}\Gamma_{i,n,l}$, are set so that all industrial processing activities yield zero profit. The price of these inputs, $p_{i,n}$, is normalized to one, and the quantities of it required to achieve zero net profits for each activity and each region is defined by:

$$\Gamma_{i,n,l} = -\sum_{k} \hat{p}_{i,k} \Gamma_{i,k,l} O_{i,l} - \sum_{o} p_o \Gamma_{i,o,l} O_{i,l} \quad (33),$$

where k is the set containing all endogenous products (inputs and outputs), and $\hat{p}_{i,k}$ are the reference prices derived in the price calibration above. o is the index for fossil fuels, which is only used in the fossil fuel incineration activities. p_o is the exogenously given fossil fuel price.

For technologies (chipping of pulpwood and conversion of saw logs to pulpwood) that are not utilized in the reference case, exogenous costs are estimated and introduced into the model separately. For the activities converting saw logs to pulpwood, the assumption is that there are no exogenous costs. The exogenous costs of chipping pulpwood have been derived from Athanassaidis et al (2011), who estimate the cost of crushing slash to 84 SEK per ton dry matter, equivalent to 17 SEK/MWh or 33 SEK/m^3s of chips. Approximately 27 SEK/m^3s are costs for labor, fuel and other costs included in exogenous cost parameter in this model. The remainder is due to capital costs, and is introduced when capacity increases are required. Since the price calibration process yield spruce and pine pulpwood prices that are considerably lower than the observed prices in Region South, the exogenous cost parameter for chipping these pulpwood types in this region is set at a higher level, 141 SEK/m^3s, as a compensation.

5.3 Exogenous Supply of By-Products

The material balance constraint for by-products, equation (14), contains a parameter of exogenous supplies, $\Psi_{i,b}$, of chips and dust, This is introduced to cover for material imbalances in the model. These supplies are of two types: to match supply and demand of chips and dust in the ROW region; and to match the supply and demand of wood based fuels in the Swedish regions.

In the ROW region the amounts of chips and dust produced as by-products – using the same input-output coefficients as in the Swedish regions – from reference sawn goods production does not match the quantities required as inputs for reference quantities of wood boards, pulp and pellets production. Exogenous supplies of chips and dust in the ROW region is introduced to cover for this shortage. The quantities are derived in *Table B.47*. Another alternative to cover for the shortage would be to adjust the by-product coefficients from sawn goods production in the ROW region, but this would cause substantial differences in the relative competitiveness between Swedish and ROW sawn goods production when the prices of these by-products change.

In the Swedish markets for wood based bioenergy there is a gap between reported use in industry and district heating systems at an aggregate level and the supplied quantities of each fuel type that has been gathered directly from data or via the by-product coefficients used in this model. This gap is 10.9 TWh in energy terms, which in the model is covered by an exogenous supply of 5.7 million m^3s of wood chips (*Table B.48-49*). One possible explanation for this gap is that some bioenergy supplies are not fully included in the model. For example, there is a potential of nearly 10 TWh from small trees from early thinnings (Athanassaidis et al 2011), but the available data on the use of this resource is uncertain. Additionally, the agricultural sector produces around 1.5 TWh of bioenergy (solid fuels, bioethanol and biogas) per year (SGO 2007). Other possible explanations for the gap are: deficiencies in the supply, demand and trade data used in the model, as indicated by Joshi (2010); or deficiencies in the approximated input-output coefficients.

This exogenous supply will form a constant supply, irrespective of by-product prices. Therefore it will not affect any decisions on the margin, and, consequently, not affect the optimizing solutions.

6 Model Simulations

In these model simulations we will test the outcome of changing the bioenergy increase target scalar (*Z*).[4] The use of wood based bioenergy is forced to increase by between 0 and 30 TWh/year (in steps of 5 TWh/year each), from the reference level given by *Table 4*. From the Lagrange multiplier of the bioenergy constraint in equation (21) we will generate supply curve estimates for wood based bioenergy in Sweden. We will also be able to draw some conclusions on how the different forest industry sub-sectors would be affected, as well as on how the losses in net social welfare would be distributed across regions.

Table 4. Reference level energy use, by fuel type and Swedish region (TWh/yr)

TWh/yr	Forest based bioenergy							Fossil[a]	All
Region	Slash	Chips	Dust	Bark	Liquors	Pellets	Total[b]		
North	1.958	1.528	0.296	2.565	12.545	0.726	19.618	6.498	26.116
East	2.127	5.677	1.589	6.040	8.312	3.094	26.839	14.482	41.320
West	0.892	1.519	0.486	1.179	6.965	1.669	12.710	5.838	18.548
South	3.433	5.077	1.444	5.236	10.603	3.392	29.185	11.446	40.632
Sweden[c]	8.410	13.801[d]	3.815	15.020	38.425	8.880	88.351	38.265	126.616

For references, see Section 9.2.7.[a]Fossil refers to an approximation of substitutable fossil fuels in each region. [b]The difference between the total use presented here and the use of forest based fuels discussed in Section 2, can be attributed to the use of firewood ('Other' in Figure 7). [c]Sum of regions. [d]Includes the exogenous supply introduced in Section 5.3.

6.1 Simulation Results

The estimated total cost – in terms of losses in net social welfare – of increasing the use of wood based bioenergy by 30 TWh/year in Sweden is 5.4 billion (10^9) SEK/year. The cost within Sweden is 6.3 billion SEK, while the ROW region gains 0.9 billion SEK (upper left in *Figure 17*). The gain in ROW can be explained by increased prices in roundwood and by-products. The cost for reaching the 5 TWh/year target is estimated to 0.83 billion SEK/year.

In absolute terms, the largest share of the cost is carried by region East; while region North, which is sparsely populated but relatively intense in forest industry, suffer the highest losses in per capita terms (upper right in *Figure 17*).

A large proportion of the total cost can be attributed to the construction of additional wood fuel incineration capacity (as illustrated in *Figure 15*). Excluding these capacity costs, the total cost is reduced from 0.83 to 0.03 billion SEK/year for reaching a target of 5 TWh/year, or from 5.4 to 0.6 billion SEK/year for reaching a target of 30 TWh/year (lower left in *Figure 17*).

[4] Outputs from fuel incineration activities, and the pulpwood chipping activities, are kept fixed at the reference level for the rest-of-world-region (ROW).

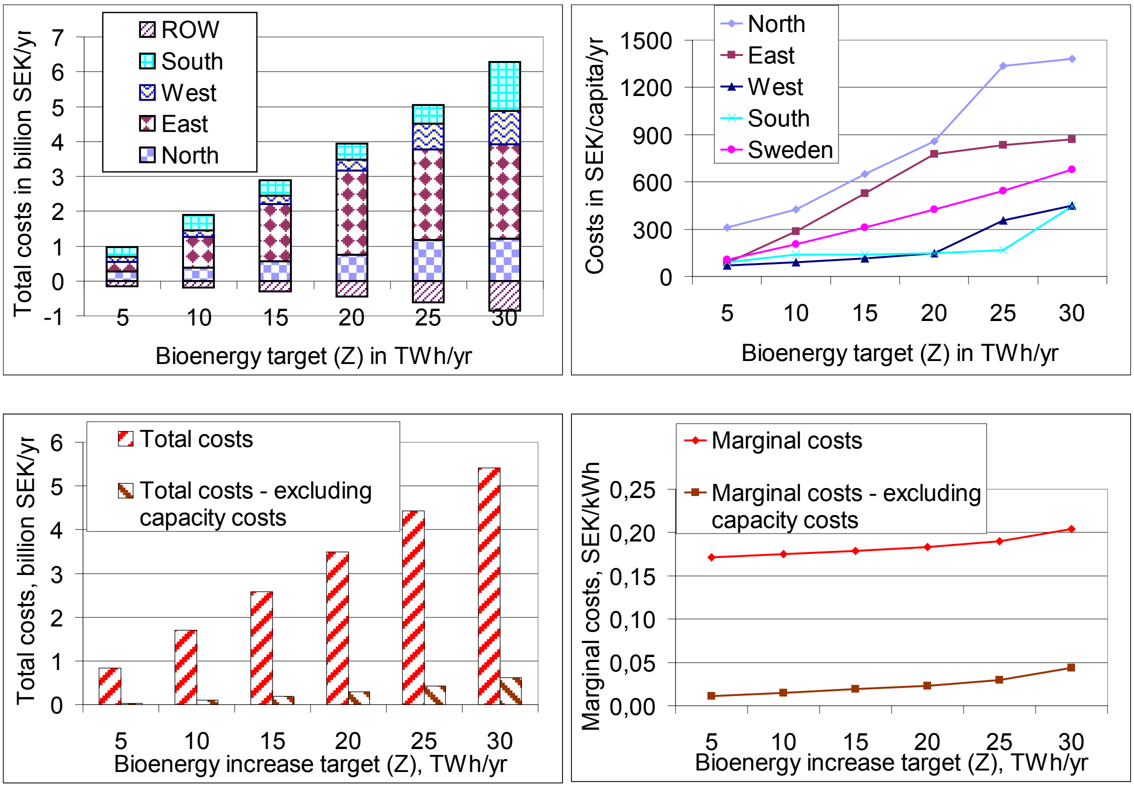

Figure 17. Welfare losses of reaching a binding target for increased use of wood based bioenergy

The marginal cost of an additional increase of the bioenergy target, *Z*, rises from 0.17 SEK/kWh (equivalent to 0.17 billion SEK/TWh) at a target of 5 TWh/year to 0.20 SEK/kWh when the target is 30 TWh/year (lower right in *Figure 17*). If the wood fuel incineration capacity costs are excluded, then the marginal costs are 0.01 SEK/kWh at 5 TWh/year, and 0.04 SEK/kWh at 30 TWh/year.

The required increases in wood based bioenergy use are primarily met by increased utilization of harvest residues and by using pulpwood for energy purposes (*Figure 18*). The use of liquors – which is a by-product from chemical pulp production – does not change at all, while the use of solid industrial by-products – chips, dust, and bark from sawmills; and bark from pulp mills – for fuel increase slightly. The use of pellets – made from chips, dust, or bark, from sawmills or from chipped pulpwood – also increase to a relatively small degree.

The results indicate that a few TWh of harvest residues (slash) are available at relatively low marginal costs. Most of the required increase in wood based bioenergy use is, however, met by diverting pulpwood from industrial uses to the energy sector. In the 30 TWh case, nearly 10 million m^3sub of pulpwood are used for fuel. This corresponds to 30% of the reference level pulpwood harvest in Sweden. The scope for increasing pulpwood harvest domestically is limited and most of the shortfall is met by increased pulpwood imports (*Table 5*). This substantial rise in imports requires limited competition for pulpwood on the international market. In Section 6.2, scenarios where there is fiercer competition for roundwood are analyzed.

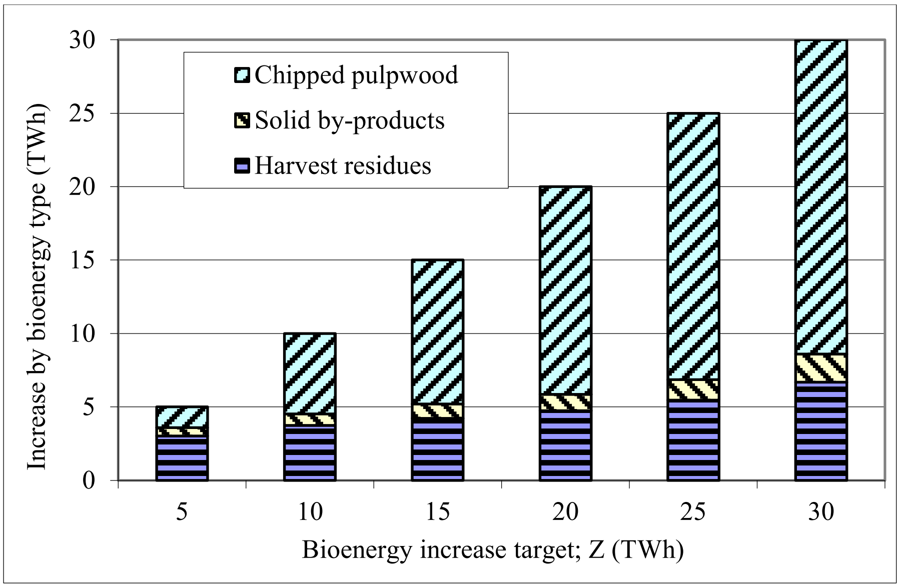

Figure 18. Changes in the use of bioenergy types at different target levels in the base case

Table 5. *Reference levels and changes in pulpwood supply and use (million m^3sub) at different bioenergy increase targets in the base case scenario*

Bioenergy target; Z	Reference	5 TWh	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
Harvest	31.81	+0.11	+0.35	+0.60	+0.85	+1.10	+1.31
Net import	4.09	+0.52	+2.11	+3.83	+5.55	+7.13	+8.40
Use in industry	35.89	-0.01	-0.05	-0.05	-0.05	-0.05	-0.05
Chipped for fuel		+0.64	+2.50	+4.47	+6.45	+8.28	+9.76

Empty boxes indicate 0

The analyzed bioenergy targets lead to decreased output from Swedish wood board producers (fiber board, particle board, plywood and veneer) by up to 30% (*Table 6*). This is a direct consequence of rising demand for some of their inputs – chips, dust, and pulpwood – from the energy sector. Pulp, paper, and sawn goods output is unaffected by the increased use of bioenergy. The effect on total sector output – measured as production revenue at reference prices – is less than 1%. The forest industry in the South region is unaffected, while the effects are spread relatively homogeneously across the other three Swedish regions.

Table 6. *Reference production revenue (billion SEK) in Swedish forest industries and changes (at reference prices) at different bioenergy increase targets in the base case scenario*

Bioenergy target; Z	Reference	5 TWh	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
Pulp	53.58						
Paper	66.26						
Sawn goods	30.89						
Wood boards	2.32	-19.6%	-27.0%	-30.1%	-31.1%	-16.2%	-16.2%
Total[a]	86.79	-0.5%	-0.7%	-0.8%	-0.8%	-0.4%	-0.4%
North[a]	23.78	-0.8%	-0.6%	-0.9%	-1.0%	-1.0%	-1.0%
East[a]	21.08		-1.2%	-1.6%	-1.6%		
West[a]	13.67		-1.1%	-1.1%	-1.1%	-1.1%	-1.1%
South[a]	28.26						

Empty boxes indicate 0. [a]In the aggregated measures, paper is excluded to avoid double counting of pulp and paper production

6.2 Sensitivity Analysis

6.2.1 Roundwood Import Restriction

The simulation results above implied a substantial rise in pulpwood imports, equivalent with a quarter of domestic pulpwood harvest. In this scenario we modify the base case scenario by including a restriction on roundwood imports. This is implemented by subjecting the objective function (24) to an additional constraint:

$$T_{"ROW",swe,w} \leq \hat{T}_{"ROW",swe,w} \qquad \forall swe, w \qquad (34),$$

which sets an upper limit on roundwood, *w*, trade from ROW to any of the Swedish regions at the reference trade quantities, $\hat{T}$. There are at least two reasons to analyze a scenario of increased wood energy use where roundwood imports are restricted. One reason is that there are policies supporting demand for renewable energy sources in several of Sweden's neighboring countries, and in the EU overall, which could lead to fierce competition over the available resources from Sweden's major suppliers of roundwood. Another reason is that a model simulation where roundwood imports may not increase will generate an estimation of a forest based bioenergy supply curve, based on domestic resources only.

The major difference in this scenario is that all of the required bioenergy increase has to be met by domestic supplies. Apart from the limited potential increases in harvest residue utilization and roundwood harvest, the energy target can only be reached by diverting sawmill by-products, and pulpwood, from industrial uses.

The assumed roundwood import restriction makes it substantially more costly to supply additional wood based fuels to the energy sector. The estimated total cost of increasing the use of wood based bioenergy by 30 TWh/year in Sweden is 8.0 billion SEK/year, compared to 5.4 billion SEK/year in the base case scenario. The cost within Sweden is 9.0 billion SEK, while the ROW region gains 1.1 billion SEK (upper left in *Figure 19*).

As in the base case scenario, the largest share of the cost is carried by the East region. In per capita terms the region North suffers the highest costs for bioenergy increase targets of 5-25 TWh/year (upper right in *Figure 19*). The costs in region East rises steeply with higher bioenergy targets; and with a target of 30 TWh/year the per capita costs in East is higher than in North. The steep rise in costs in East can, at least partly, be explained by the relatively high reference level of substitutable fossil fuel use in that region (*Table 4*). A relatively large share of the bioenergy use increase occurs in East, which have substantial impacts on the region's traditional forest industries (*Table 7*).

Excluding the capacity costs, the total cost range from 0.04 billion SEK/year for reaching a target of 5 TWh/year, to 3.2 billion SEK/year for the 30 TWh/year target (lower left in *Figure 19*). These costs are up to five times higher than in the base case scenario.

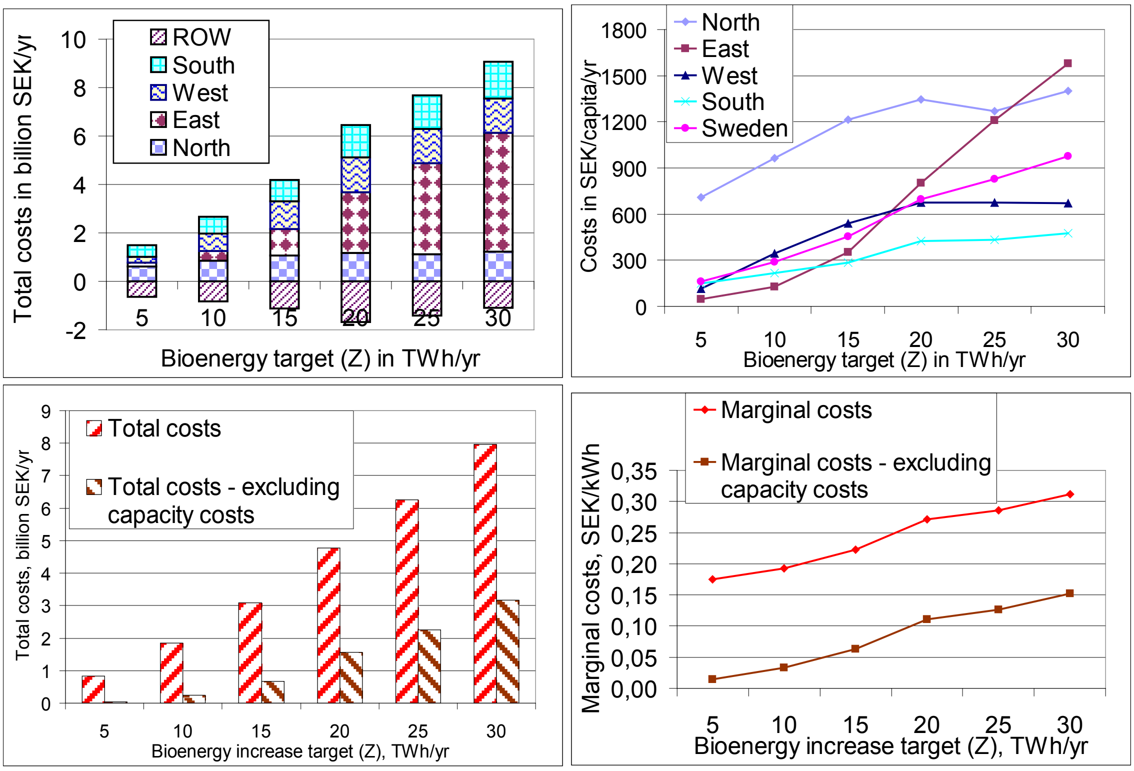

Figure 19. Changes in the use of bioenergy types at different target levels, when roundwood imports are restricted

Table 7. *Reference production revenue (billion SEK) in Swedish forest industries and changes (at reference prices) at different bioenergy increase targets when roundwood imports are restricted*

Bioenergy target; Z	Reference	5 TWh	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
Pulp	53.58					-4.6%	-7.7%
Paper	66.26					-1.6%	-5.3%
Sawn goods	30.89					-0.4%	-1.0%
Wood boards	2.32	-24.9%	-32.2%	33.2%	-46.4%	-46.6%	-61.4%
Total[a]	86.79	-0.7%	-0.9%	-0.9%	-1.3%	-4.2%	-6.7%
North[a]	23.78	-1.0%	-1.0%	-1.0%	-1.0%	-1.0%	-1.6%
East[a]	21.08	-1.6%	-1.6%	-1.7%	-2.6%	-14.9%	-23.0%
West[a]	13.67		-1.1%	-1.1%	-2.0%	-2.0%	-3.2%
South[a]	28.26		-0.1%	-0.1%	-0.1%	-0.1%	-0.6%

Empty boxes indicate no change. [a]In the aggregated measures, paper is excluded to avoid double counting of pulp and paper production

The roundwood import restriction implies a steeper marginal cost curve (lower right in *Figure 19*). While the base case had marginal costs (excluding capacity cost) of 0.04 SEK/kWh at the 30 TWh/year target; merely 10-15 TWh/year would be supplied at these marginal costs if only domestic wood resources were available.

The required increases in wood based bioenergy use are at the lowest target levels primarily met by increased use of harvest residues (*Figure 20*). This supply is however capped at around 7-8 TWh. At the higher levels solid by-products – which were previously used in the production of wood boards and pulp – constitute around 5 TWh.

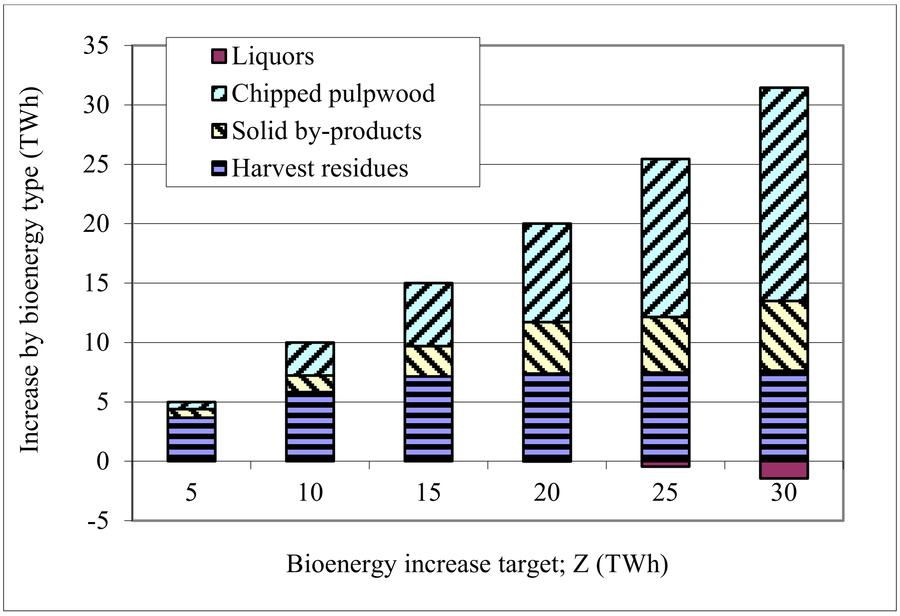

Figure 20. Changes in the use of bioenergy types at different target levels, when roundwood imports are restricted

The remainder is made up of chipped pulpwood, and at the 30 TWh target level 18 TWh comes from chipped pulpwood. Since imports of roundwood are restricted, a large share of this pulpwood is diverted from industrial uses (*Table 8*). The energy sector's demand leads to an increase in the pulpwood price, causing it to converge with the price of saw logs. When this occurs, we can also note that saw logs are converted to pulpwood to satisfy the energy sector's demand.

At the highest target levels the use of liquors decline. This is a consequence of reductions in chemical pulp production (*Table 7*). Pulp and paper production is reduced at bioenergy increase targets above 20 TWh/year. Even sawn goods production is reduced at these target levels, but to a smaller degree. As in the base case scenario, wood board production is heavily affected. Total output from the Swedish forest industries (measured as change in revenue at reference level prices) is around 1% at bioenergy increase targets up to 20 TWh/year. At the higher target levels, industry output is more seriously affected. Most of the decrease in industrial output takes place in region East, which is in line with the reasoning in connection with *Figure 19* above.

Table 8. *Reference levels and changes in pulpwood supply and use (million m^3sub) at different bioenergy increase targets, when roundwood imports are restricted*

Bioenergy target; Z	Reference	5 TWh	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
Harvest	31.81	+0.26	+1.20	+2.06	+2.54	+2.63	+2.78
Net import	4.09						
Converted[a]				+0.28	+1.15	+1.90	+2.71
Use in industry	35.89	-0.01	-0.06	-0.06	-0.07	-1.53	-2.67
Chipped for fuel		+0.28	+1.26	+2.42	+3.78	+6.07	+8.18

Empty boxes indicate 0. [a] Converted from saw logs to pulpwood

6.2.2 High Roundwood Price Scenario

The previous scenario assumed a binding restriction on roundwood imports. Although it can be seen as an interesting illustrative scenario, it is unlikely to occur. One of the reasons for testing that scenario was that there are policies supporting demand for renewable energy sources also in many other countries, which will affect the market for roundwood.

Buongiorno et al (2011) analyzes forest sector impacts of a scenario with high global bioenergy demand (in line with IPCC scenario A1B), relative to a low demand reference scenario. They conclude that the high demand scenario will yield roundwood prices that are 17 US$/m^3 (~ 110 SEK/m^3) higher than in the low demand scenario.

This approximated roundwood price change due to rising global demand for bioenergy is used as the basis for this scenario, where the base case scenario above is modified through increased roundwood price levels. Pulpwood prices in the reference region (West) are thus increased from 371-386 SEK/m^{3}sub to 481-496 SEK/m^{3}sub, while saw log prices are increased from 502-945 SEK/m^{3}sub to 612-1055 SEK/m^{3}sub.

In this scenario an increase in bioenergy use of 30 TWh/year costs 6.5 billion SEK/year (upper left in *Figure 21*), compared to 5.4 billion SEK/year in the base case. The domestic Swedish costs are 8.4 billion SEK/year. As in the previous scenarios, region East carries most of the cost in absolute terms, while region North once again faces the highest per capita costs (upper right in *Figure 21*).

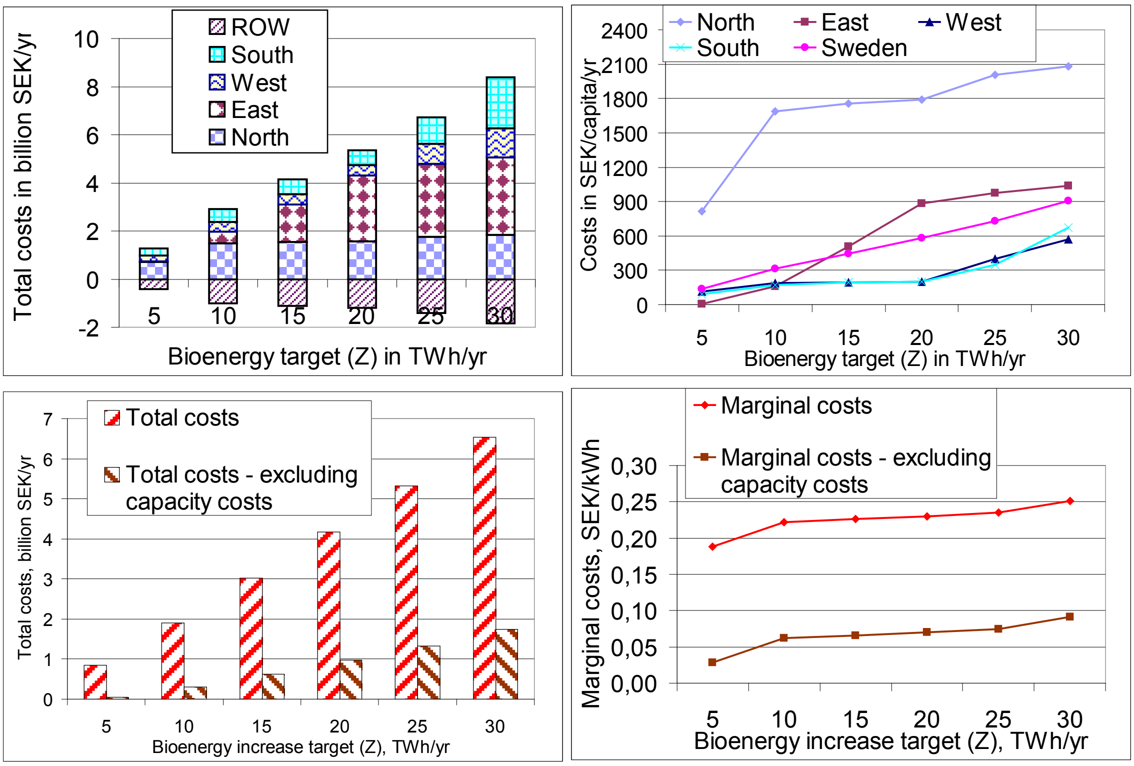

Figure 21. Changes in the use of bioenergy types at different target levels, in the scenario with high roundwood prices

Excluding the fuel incineration capacity costs, the costs of reaching the 5 TWh/year target is 0.05 billion SEK/year (lower left in *Figure 21*). The 30 TWh/year target costs 1.7 billion SEK/year, which is nearly three times the cost of the base case scenario. In this scenario, the marginal cost initially rises more steeply than in the two previous scenarios (lower right in *Figure 21*). Already at 10 TWh/year, the marginal cost is higher than the marginal cost at 30 TWh/year in the base case scenario. This is a consequence of the higher pulpwood prices. After the first 10 TWh/year, the marginal cost curve here is similar to that in the base case, apart from a shift of around 0.05 SEK/kWh.

The dominance of harvest residues at low target levels is even more pronounced in this scenario, than in the two previous ones (*Figure 22*). The increase in use of solid by-products – up to 2.5 TWh/year – is more than in the base case scenario, but less than in the import restriction scenario. The use of chipped pulpwood dominates the increase at high target levels also in this scenario, making up two thirds at the 30 TWh/year level.

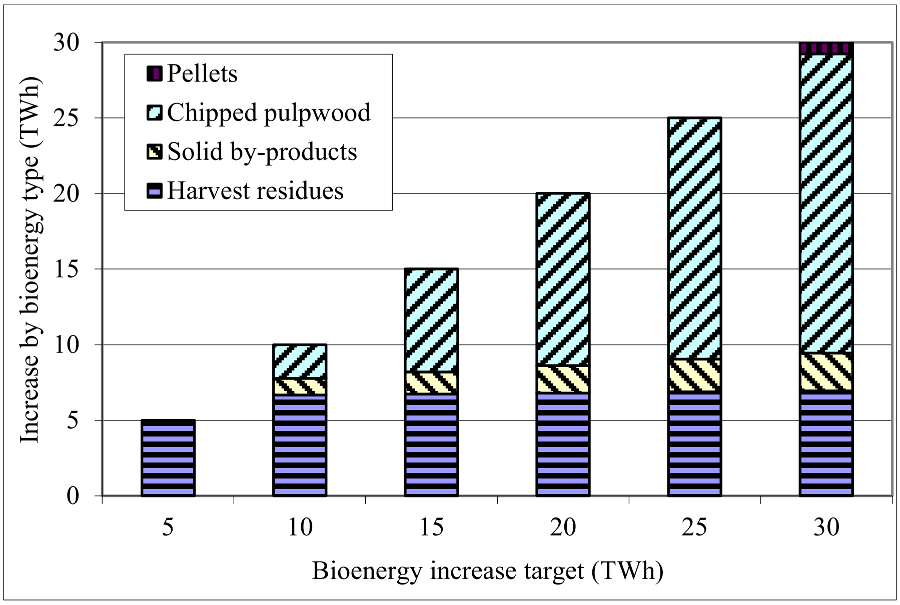

Figure 22. Changes in the use of bioenergy types at different target levels, in the scenario with high roundwood prices

The changes in pulpwood supply and use are similar to the base case scenario. Industry use is unaffected, while substantial increases in imports along with a smaller increase in domestic harvest is used to supply pulpwood for the energy sector (*Table 9*).

Table 9. *Reference levels and changes in pulpwood supply and use (million m^3sub) at different bioenergy increase targets in the scenario with high roundwood prices*

Bioenergy target; Z	Reference	5 TWh	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
Harvest	31.79	+0.10	+0.39	+0.65	+0.91	+1.17	+1.42
Net import	4.09	-0.10	+0.63	+2.45	+4.29	+6.11	+7.61
Converted[a]							
Use in industry	35.89						
Chipped for fuel			+1.02	+3.10	+5.20	+7.28	+9.03

Empty boxes indicate 0. [a] Converted from saw logs to pulpwood

The higher roundwood price in this scenario yields lower forest industry output levels compared to the reference situation. Sawn goods production declines by nearly five percent (*Table 10*). This decline diminishes with higher bioenergy targets, which can be explained by rising prices for the sawn goods producers' by-products. The reason that this support for the sawn goods producers from rising bioenergy demand shows up here, but not in the previous scenarios, is that increased production of sawn goods in those scenarios were held back by the need for production capacity investments. In this scenario, the decline in production emanating from the higher roundwood prices made some production capacity available, which could then be utilized when prices of by-products increased. Along with the two previous scenarios, the wood board producers are heavily affected. The pulp and paper producers' output levels are, however, unchanged.

Table 10. *Reference production revenue (billion SEK) in Swedish forest industries and changes (at reference prices) at different bioenergy increase targets when roundwood prices are high*

Bioenergy target; Z	Reference[b]	0 TWh[b]	5 TWh	10 TWh	15 TWh	20 TWh	25 TWh	30 TWh
Pulp	53.58							
Paper	66.26							
Sawn goods	30.89	-4.6%	-4.5%	-3.4%	-3.0%	-2.7%	-2.3%	-1.1%
Wood boards	2.32	-36.7%	-36.7%	-36.7%	-36.7%	-36.7%	-36.8%	-21.9%
Total[a]	86.79	-2.6%	-2.6%	-2.2%	-2.1%	-1.9%	-1.8%	-1.0%
North[a]	23.78	-2.5%	-2.5%	-1.0%	-1.0%	-1.0%	-1.0%	-1.0%
East[a]	21.08	-1.6%	-1.6%	-1.6%	-1.6%	-1.6%	-1.6%	-1.7%
West[a]	13.67	-2.8%	-2.7%	-9.5%	-8.8%	-8.0%	-7.1%	-2.0%
South[a]	28.26	-2.6%	-2.6%	-2.2%	-2.1%	-1.9%	-1.8%	-1.0%

Empty boxes indicate no change. [a]In the aggregated measures, paper is excluded to avoid double counting of pulp and paper production. [b]'Reference' refers the initial situation , with unchanged prices, while '0 TWh' gives the implications of increased roundwood prices.

6.3 Concluding remarks on the simulation results

Total costs and marginal costs in the three scenarios, at different bioenergy target levels, are presented in *Table 11*. The costs vary substantially depending on the assumptions on roundwood imports. These are the cost estimates for when the costs for expanded fuel incineration capacity have been excluded. The estimates can then be regarded as the costs of supplying the energy market with the quantities of forest based bioenergy stipulated by the exogenous policy target.

Table 11. *Summary of costs, and impacts on the forest industry, in the three simulation scenarios*

	Scenario	*5 TWh*	*10 TWh*	*15 TWh*	*20 TWh*	*25 TWh*	*30 TWh*
Total costs[a]; billion SEK	Base case	0.03	0.12	0.19	0.29	0.43	0.62
	Import restriction	0.04	0.24	0.68	1.57	2.26	3.17
	High wood price	0.05	0.31	0.63	0.97	1.33	1.74
Marginal costs[a]; SEK/kWh	Base case	0.011	0.015	0.019	0.023	0.030	0.044
	Import restriction	0.015	0.033	0.063	0.111	0.126	0.152
	High wood price	0.028	0.062	0.066	0.070	0.075	0.091
Impact on total industry output[b]	Base case	-0.5%	-0.7%	-0.8%	-0.8%	-0.4%	-0.4%
	Import restriction	-0.7%	-0.9%	-0.9%	-1.3%	-4.2%	-6.7%
	High wood price	-2.6%	-2.2%	-2.1%	-1.9%	-1.8%	-1.0%

[a]Excluding the costs for increased fuel incineration capacity. [b]Changes in total industry output (revenue at reference prices). Paper production has been excluded to avoid double counting of pulp and paper production

The regional distribution of the costs is fairly consistent between the three scenarios: region East suffers the highest welfare losses in absolute terms; while region North – which is sparsely populated but relatively intense in forest industry – generally face the highest per capita costs.

At the lower bioenergy target levels (up to increases of 5 or 10 TWh) the required increase is dominated by harvest residues, which are available to a limited degree at relatively low marginal costs. At higher target levels the required increase is mostly covered by chipped pulpwood. This pulpwood is obtained through increased domestic harvests, imports or diversions from wood boards or pulp production to the energy sector. All scenarios imply that solid by-products from saw mills and pulp mills to some degree are also diverted from the wood board producers.

In this study, the implications for the forest industries, of forest based bioenergy increases of less than 20 TWh, will largely be limited to the wood boards sector, even if strict pulpwood import restrictions are applied. The results imply that produced output from the wood processing industries overall would be low (<1%) (*Table 11*). If there is excess sawmill capacity, then sawn goods production will increase with higher wood energy target, at least initially, due to the fact that sawmill by-products increase in price. This is illustrated in the high roundwood price scenario (*Table 10*), where production capacity in the sawn goods sector is made available due to a decrease in output, arising from the higher input costs. This effect would show up in the other two scenarios as well, if the sawmills were not assumed to be fully utilized.

7 Discussion & Conclusions

The main purpose of this study was to analyze the impacts of increased forest based bioenergy demand on the Swedish forest sector. This has been accomplished through model simulations in the SFSTMII, a static partial equilibrium model of the sector. The emphasis has been on generating supply curves for forest based bioenergy in Sweden; and on analyzing how the increased demand for industrial roundwood and forest industry by-products from the bioenergy sector affects the wood processing industries.

7.1 Supply Costs for Forests Based Bioenergy in Sweden

The SFSTMII model was applied to estimate the costs – in terms of losses in producer and consumer surplus – of complying with binding targets for increased use of forest based bioenergy in Sweden. An increase by 5 TWh/year is estimated to cost 30 million SEK/year, while a 30 TWh/year increase would cost 620 million SEK/year. The marginal cost is estimated to be 0.011 SEK/kWh at 5 TWh/year, rising to 0.044 SEK/kWh at 30 TWh/year. These cost estimates exclude the costs of constructing additional fuel incineration capacity, and can be regarded as the costs of supplying the energy market with the quantities of forest based bioenergy stipulated by the policy target.

As a comparison, the marginal cost at 30 TWh/year, 0.044 SEK/kWh, is equivalent with an oil price increase of around 11 US$/barrel[5]. In terms of CO_2 emissions from heavy fuel oil incineration, 0.044 SEK/kWh is equivalent with an emissions permit price change of around 16 Euro/ton (or 24 US$/ton)[6].

The cost of reaching a targeted quantity for forest based bioenergy in Sweden is highly dependent on the availability of pulpwood imports. An import restriction – requiring the target to be reached through domestic resources only – would increase the total costs by up to five times above the unrestricted case. In this case the marginal costs reach 0.152 SEK/kWh, at a 30 TWh/year increase. This dependency on reliable roundwood imports could be alleviated by increased domestic supply of raw materials. A long-term scenario analysis from the Swedish Forest Agency (SFA 2008) does however indicate that the quantity of roundwood available for harvest will remain stable, around the supply limit assumed in this study, over the next two or three decades. Another option is increased utilization of harvest residues, beyond the restrictions assumed in Section 4.2.2. The potential from tree stumps is, for example, around 20 TWh/year (Athanassaidis et al 2011). Utilization of these resources comes with some possible drawbacks in terms of effects on biodiversity (Bouget et al 2012) and greenhouse gas emissions (Strömgren et al 2012), which could require priorities between different policy objectives.

[5] 1698 kWh/barrel*0.044 SEK/kWh = 75 SEK/barrel = 11 USD/barrel (at 6.54 SEK/US$)
[6] 44 SEK/MWh /0.282 ton CO2/MWh = 156 SEK/ton CO2 = 24 US$/ton CO2 = 16 Euro/ton CO2 (at 9.62 SEK/Euro)

7.2 Implications for the Wood Processing Industries

This study indicates that produced quantities of wood boards would decline substantially – simulation results vary between 16% and 61% – from rising demand for forest based bioenergy. This is, however, a relatively small part of the total output from the wood processing industries. Overall the effect on produced quantities (weighted by reference prices) in the Swedish wood processing industries would be low. If roundwood is readily available from the international markets, the effects on sawmill, and pulp- and paper mill production, are negligible. Even if increases in roundwood imports are prohibited, the wood processing industries would be largely unaffected (with the exception of the wood board producers), as long as the increase in use of forest based bioenergy is less than 15 TWh/year.

The implications of rising demand for bioenergy on wood processing industries and roundwood markets, in this study, are largely in line with previous partial equilibrium model analysis of the forest sector (e.g. Buongiorno et al 2011; Moiseyev et al 2011; Schwarzbauer & Stern 2010; Trømborg & Solberg 2010).

7.3 Recommendations for Future Research

One weakness in the model presented in this study is that increases in any industrial, or fuel incineration, activity causes a discrete "jump" upwards in the marginal cost of that activity (*Figure 15*). This is an assumption based in a static setting, where production increases require investments in new capacity, while existing producers can regard their previous capacity investments as sunk costs. An obvious improvement of the model would be to extend it to a dynamic setting. This is a common way of analyzing the forest sector (e.g. Kallio et al 2004; Buongiorno et al 2003). A dynamic setting would allow for retiring some capacity each period, making industrial regeneration with new capacity a natural feature of the model. The market equilibrium situation would then take into account the marginal revenue required for new capacity.

A dynamic approach would also allow for analysis of the implications for the stock of standing forest volume, and consequently, the stock of carbon stored in the forests. In such a model, the intricate relations and trade-offs between political ambitions in the fields of energy and climate change, and the industrial and consumer interests on the markets for forest industry products, could be analyzed. A recent report by Furtenback (2011) analyzes these issues – with the exemption of the implications for the industries – in a dynamic general equilibrium model.

On a related note, it would also be interesting to analyze the effects of looser restrictions on harvest residues utilization, as indicated in Section 7.1. Two possible alleviations are an allowance for leaving less slash on the ground (40% assumed in Athanassaidis et al 2011), or an allowance for utilization of tree stumps.

In Section 5 we noted that the model formulation and the calibration procedures are based on an assumption of competitive market equilibrium. This assumption is not unproblematic. Bergman & Brännlund (1995) and Brännlund et al (2006) imply that the sector analyzed in this study has elements of market inefficiencies. Cox & Chavas (2001) provide a methodology that can be useful in this regard. By introducing "price wedges" into the Takayama-Judge spatial equilibrium approach, we can allow for market inefficiencies in the sense that prices can diverge from marginal value and/or marginal cost pricing.

The simulation results indicate that the assumptions about the international market for roundwood have substantial impacts on the cost of reaching a bioenergy target. A more thorough description of this market would probably improve the model. Existing forest sector models (e.g. Buongiorno et al 2011; Moiseyev et al 2011), at the European or global level, could be a source of alternative scenarios to analyze in this regard.

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Appendix A. Symbol Explanations

Table A.1. List of decision variables

Equation symbol	Description
Q	Quantity of consumer goods demanded
O	Output of main commodity m from a
W	Quantity harvested roundwood
R	Quantity harvested residues
T	Quantity traded
G	New industrial production capacity
E	Quantity of energy demanded

Table A.2. List of parameters

Equation symbol	Description
p	Prices of endogenous and exogenous products
A	Reservation price for roundwood harvest
α	Roundwood supply slope coefficient
β	Roundwood supply exponential coefficient
ϕ	Price elasticity of roundwood supply
θ	Roundwood harvest upper limit multiplier
B	Reservation price for residues harvest
ζ	Residue supply slope coefficient
η	Residue supply exponential coefficient
I	Residue quantity restriction parameter
Γ	Input-Output coefficients
Φ	Observed existing production capacity
Δ	Investment cost per unit of new capacity
σ	Annuity factor for additional capacity investments
Λ	Distance between trading regions
M	Transportation vehicle loading costs
N	Transportation cost per distance unit
γ	Own-price elasticity for consumer goods
μ	Own-price elasticity for energy

Table A.3. Overview of products

Set	Subset	Product	Unit	Description
Roundwood (*w*)	Sawlogs	SpruceLog	m^3sub	Saw logs of spruce
		PineLog	m^3sub	Saw logs of pine
		NonConLog	m^3sub	Saw logs of broad-leaved trees
	Pulpwood	SprucePulp	m^3sub	Pulpwood of spruce
		PinePulp	m^3sub	Pulpwood of pine
		NonConPulp	m^3sub	Pulpwood of broad-leaved trees
Residues (*d*)		Slash	ODT	Branches and tops
Intermediate products (*u*)	Pulp	MechPulp	ton	Mechanical and semi-chemical pulp
		ChemPulp	ton	Chemical pulp – sulphate and sulphite
		RecoveredPulp	ton	Pulp from recovered paper
	RefinedBiomass	Pellets	m^3	Fuel pellets
Consumer products (*f*)	SawnGoods	SpruceSawn	m^3	Sawn spruce
		PineSawn	m^3	Sawn pine
		NonConSawn	m^3	Sawn broad-leaved trees
	PaperProducts	NewsPaper	ton	Newsprint
		PrintPaper	ton	Other printing and writing paper
		OtherPaper	ton	Wrapping, case materials, etc
	WoodBoards	FiberBoard	ton	Fiber boards
		ParticleBoard	m^3	Particle boards
		PlywoodBoard	m^3	Plywood and veneers
By products (*b*)		Chips	m^3s	Wood chips
		Dust	m^3s	Saw dust and shavings
		Bark	m^3s	Bark
		Liquor	MWh	Black liquor and tall oil pitch
Energy (*e*)		EnergySmall	MWh	Household and other small-scale fuel use
		EnergyLarge	MWh	Fuel use in industries and district heating plants
Fossil fuels (*o*)		FossilFuelSmall	MWh	Fossil fuel for small-scale users
		FossilFuelLarge	MWh	Fossil fuel for large scale users
Other exogenous products (*n*)		Other		All production inputs not covered by the classifications above, including labor, recycled paper and other materials, and energy inputs to industrial production

Note that the first six categories (*w, d, u, f, b* & *e*) are jointly categorized as all endogenous products (*k*)

Table A.4. Overview of industrial processing acitivities

Activity (l)	Main output ($m \in k$)	Endogenous inputs *($k \neq m$)*	By-products ($b \in k$)
Intermediate goods producing activities			
MechPulp	MechPulp	SprucePulp, PinePulp, NonConPulp, Chips	Bark
ChemPulp	ChemPulp	SprucePulp, PinePulp, NonConPulp, Chips	Bark, Liquor
RecoveredP[a]	RecoveredP		
RefinedChips	Pellets	Chips	
RefinedDust	Pellets	Dust	
RefinedBark	Pellets	Bark	
SpruceChips	Chips	SprucePulp	Bark
PineChips	Chips	PinePulp	Bark
NonConChips	Chips	NonConPulp	Bark
Consumer goods producing activities			
SpruceSawn	SpruceSawn	SpruceLog	Chips, Dust, Bark
PineSawn	PineSawn	PineLog	Chips, Dust, Bark
NonConSawn	NonConSawn	NonConLog	Chips, Dust, Bark
NewsPaper	NewsPaper	MechPulp, ChemPulp, RecoveredP	
PrintPaper	PrintPaper	MechPulp, ChemPulp, RecoveredP	
OtherPaper	OtherPaper	MechPulp, ChemPulp, RecoveredP	
FiberBoard	FiberBoard	Chips, Dust	
ParticleBoard	ParticleBoard	SprucePulp, PinePulp, NonConPulp, Chips, Dust	
PlywoodBoard	PlywoodBoard	SpruceLog, PineLog	
Fuel incineration activities			
SlashFuel	EnergyLarge	Slash	
ChipsFuel	EnergyLarge	Chips	
DustFuel	EnergyLarge	Dust	
BarkFuel	EnergyLarge	Bark	
LiqourFuel	EnergyLarge	Liqour	
PelletsFuelLarge	EnergyLarge	Pellets	
FossilFuelLarge	EnergyLarge	FossilFuelLarge[b]	
PelletsFuelSmall	EnergySmall	Pellets	
FossilFuelSmall	EnergySmall	FossilFuelSmall[b]	
Roundwood conversion activities			
SpruceConvert	SprucePulp	SpruceLog	
PineConvert	PinePulp	PineLog	
NonConConvert	NonConPulp	NonConLog	

[a]No endogenous inputs needed for recovered paper pulp in the SFSTMII. [b]These inputs are classified as exogenous fossil fuel, o, rather than inputs classified as endogenous inputs, k.

Appendix B. Data Tables

Roundwood Supply Data Tables

All roundwood volumes are given in cubic meters solid volume excluding bark, abbreviated by m^3fub, and all prices and costs are in SEK/m^3fub. In the cases where raw data from the original sources were given in terms of cubic meters standing volume, m^3sk, a conversion factor of 1.2 m^3sk(net)/m^3fub has been used (SFA 2009).

Table B.1. Roundwood prices, SEK/m^3sub, after price calibration

	SpruceLog	PineLog	NonConLog	SprucePulp	PinePulp	NonConPulp
North	492	675	942	389	381	396
East	494	673	944	387	379	394
West	502	567	945	379	371	386
South	499	573	1044	287	279	389
ROW	605	562	1048	276	268	283

Table B.2. Net exports of roundwood, 1000 m^3sub

	SpruceLog	PineLog	NonConLog	SprucePulp	PinePulp	NonConPulp
North	68	-52	1	-478	-563	-971
East	133	-208	1	-758	-571	-1027
West	163	109	4	-129	-407	-653
South	302	138	-2	1086	938	-572
Total Swedish net export						
SDC	667	-12	4	-279	-603	-3224
SFA	654	-81	-31	107	-1703	-2611

Net exports of roundwood per region derived from SDC (2009). Total net exports from Sweden in these data differ somewhat from the trade data provided by the Swedish Forest Agency (SFA 2009). The data from SDC are used here as they provide region specific estimates

Table B.3. Harvested roundwood, 1000 m^3sub

	SpruceLog	PineLog	NonConLog	SprucePulp	PinePulp	NonConPulp
North	4079	4945	5	3886	3850	1096
East	3413	4782	29	3439	2583	1120
West	3203	1368	27	2325	2282	641
South	11581	2937	193	6504	2790	1270
ROW	163578	39784	27538	87489	66196	43339

Table B.4. Roundwood harvest limit parameter (θ)

North	1.15
East	1.10
West	1.05
South	1.05
ROW	1.75

Harvest Residues Supply Data Tables and Figures

Table B.5. Results from regressions in equation (27)

		Coefficient	Std error	t-stat
North	ω	-12.0	0.21	-56.6
n=706; R^2=0.896	η	1.26	0.016	77.9
East	ω	-18.4	0.47	-39.0
n=513; R^2=0.809	η	1.75	0.037	46.5
West	ω	-13.0	0.29	-44.2
n=324; R^2=0.914	η	1.42	0.024	58.5
South	ω	-18.2	0.44	-41.7
n=667; R^2=0.784	η	1.67	0.034	49.2

Table B.6. Reference residue quantity, maximum residue quantity, and residue supply restriction parameter

	R (million **ODT**)	R^{max} (million ODT)	*l*
North	0.400	1.120	0.063
East	0.434	0.621	0.040
West	0.182	0.444	0.045
South	0.701	0.881	0.035

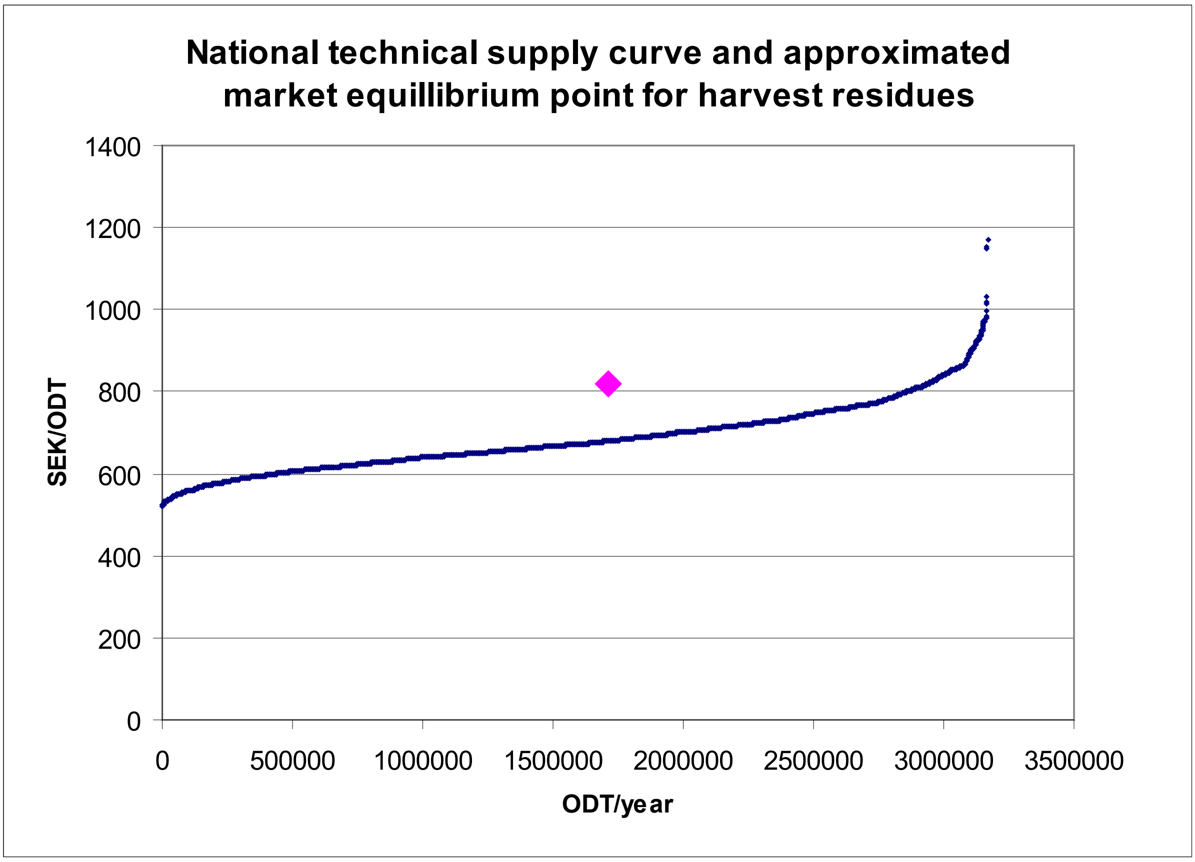

Figure B.1. Economic-engineering bottom-up supply curve from Athanassaidis et al (2011) and equilibrium point from SFA (2011)

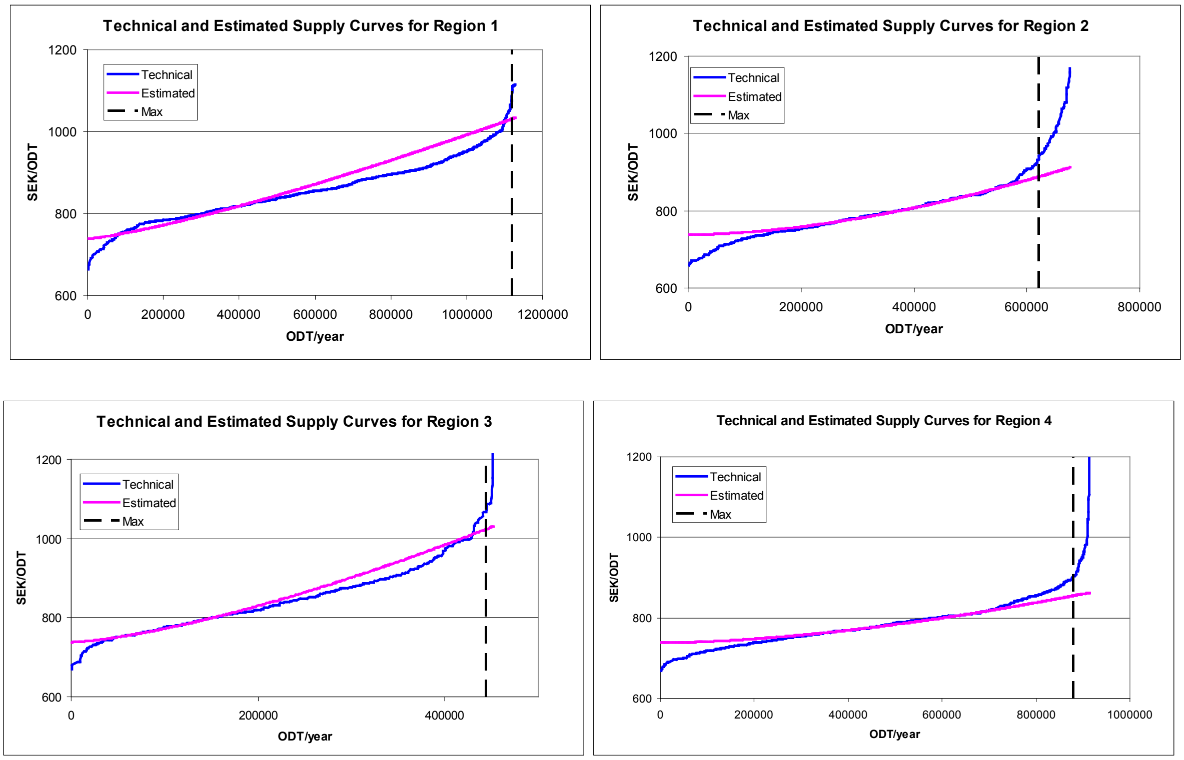

Figure B.2. Residue supply curves based, with reported parameter estimates and roundwood harvest at the reference level, compared with the supply curves from the economic-engineering bottom-up study by Athanassaidis et al (2011). Max indicates the residue supply restriction at reference roundwood harvest levels.

Input-Output Coefficient Tables

Table B.7. Input-Output coefficients for producing one unit of MechPulp

	SprucePulp	PinePulp	NonConPulp	Chips	Bark
North	-0.755	-0.763	-0.358	-0.584	0.317
East	-0.887	-0.667	-0.454	-0.494	0.340
West	-0.715	-0.784	-0.379	-0.447	0.318
South	-1.026	-0.343	-0.343	-0.674	0.290
ROW	-0.855	-0.628	-0.381	-0.562	0.315

Table B.8. Input-Output coefficients for producing one unit of ChemPulp

	SprucePulp	PinePulp	NonConPulp	Chips	Bark	Liquor
North	-1.475	-1.492	-0.699	-1.141	0.620	4.916
East	-1.733	-1.303	-0.886	-0.965	0.664	4.916
West	-1.397	-1.532	-0.740	-0.874	0.621	4.916
South	-2.006	-0.670	-0.670	-1.317	0.566	4.916
ROW	-1.670	-1.228	-0.745	-1.098	0.616	4.916

Table B.9. Input-Output coefficients for producing one unit of PaperProduct, all regions

	MechPulp	ChemPulp	RecoveredP
NewsPaper	-0.139	-0.446	-0.416
PrintPaper	-0.214	-0.500	-0.137
OtherPaper	-0.391	-0.492	-0.067

Table B.10. Input-Output coefficients for producing one unit of SpruceSawn

	SpruceLog	Chips	Dust	Bark
North	-2.135	0.695	0.292	0.219
East	-2.139	0.704	0.336	0.234
West	-1.990	0.603	0.283	0.204
South	-2.025	0.668	0.252	0.196
ROW	-2.056	0.675	0.284	0.211

Table B.11. Input-Output coefficients for producing one unit of PineSawn

	PineLog	Chips	Dust	Bark
North	-2.159	0.695	0.292	0.219
East	-2.134	0.704	0.336	0.234
West	-2.026	0.603	0.283	0.204
South	-1.933	0.668	0.252	0.196
ROW	-2.092	0.675	0.284	0.211

Table B.12. Input-Output coefficients for producing one unit of NonConSawn

	SpruceLog	Chips	Dust	Bark
North	-2.002	0.695	0.292	0.219
East	-1.957	0.704	0.336	0.234
West	-1.743	0.603	0.283	0.204
South	-2.102	0.668	0.252	0.196
ROW	-2.045	0.675	0.284	0.211

Table B.13. Input-Output coefficients for producing one unit of FiberBoard

	Chips	Dust
North	-2.309	-0.486
East	-1.126	-1.808
West	-1.453	-1.443
South	-1.453	-1.443
ROW	-1.453	-1.443

Table B.14. Input-Output coefficients for producing one unit of ParticleBoard

	SprucePulp	PinePulp	NonConPulp	Chips	Dust
North	-0.047	-0.047	-0.011	-0.303	-1.060
East	-0.143	-0.143	-0.095	-0.150	-0.891
West	-0.238	-0.238	-0.053	-0.262	-0.986
South	-0.181	-0.181	-0.155	-0.035	-0.769
ROW	-0.143	-0.143	-0.095	-0.150	-0.891

Table B.15. Input-Output coefficients for producing one unit of PlywoodBoard

	SpruceLog	PineLog
North	-1.535	-0.146
East	-1.205	
West	-1.678	-0.209
South	-1.535	-0.146
ROW	-1.535	-0.146

Table B.16. Input-Output coefficients for producing one unit of Pellets, all regions

	Chips	Dust	Bark
RefinedChips	-1.625		
RefinedDust		-1.625	
RefinedBark			-1.940

Table B.17. Input-Output coefficients for producing one unit of Chips

	SprucePulp	PinePulp	NonConPulp	Bark
SpruceChips	-1.000			0.169
PineChips		-1.000		0.169
NonConChips			-1.000	0.169

Table B.18. Input coefficients for production of 1 MWh of energy

Input	Input coefficient	Unit
Slash	-0.204	ODT
Chips	-0.521	m^3f
Dust	-0.521	m^3f
Bark	-0.622	m^3f
Liquor	-1.000	MWh
Pellets	-0.321	m^3
Fossil fuel	-1.000	MWh

Output Quantity Data Tables

Table B.19. Base year production of sawn goods, in 1000 m^3

	SpruceSawn	PineSawn	NonConSawn
North	1879	2314	2
East	1512	2329	14
West	1451	612	13
South	5571	1448	93
ROW	69197	18013	13468

Production in Swedish regions obtained from SDC (2009), while ROW production is a residual of total consumption in Section 9.2.5 and the production in Sweden

Table B.20. Base year production of wood boards, in 1000 m^3 or 1000 ton

	FiberBoard (1000 ton)	ParticleBoard (1000 m^3)	PlywoodBoard (1000 m^3)
North	28	211	0
East	74	0	39
West	0	72	90
South	0	349	0
ROW	10866	25181	7224

Swedish production data have been obtained from SDC (2009). ROW production is a residual of total consumption in Section 9.2.5 and the production in Sweden.

Table B.21. Base year production of paper, in 1000 ton

	NewsPaper	PrintPaper	OtherPaper
North	736	939	1679
East	730	930	1664
West	511	651	1165
South	583	744	1331
ROW	7621	27475	44345

Approximative calculations based on Swedish paper production by category from SFA (2009) and SFIF (2009) combined with SFIF (2010) data on paper production (all categories) by region. ROW production is a residual of total consumption in Section 9.2.5 and the production in Sweden

Table B.22. Base year production of pulp, in 1000 ton

	MechPulp	ChemPulp	RecoveredPulp
North	781	2552	328
East	1427	1691	60
West	639	1417	78
South	1002	2157	933
ROW	23756	36766	10402

Swedish pulp production from SFIF (2010). Production in ROW is a residual between total pulp consumption – paper production in Table B.21 multiplied by input coefficients in Table B.9 – and Swedish production

Table B.23. Base year production of pellets, in 1000 m^3

1000 ton	RefinedChips	RefinedDust	RefinedBark
North	37	646	51
East	22	389	31
West	11	202	16
South	51	901	72
ROW	493	8683	691

Data on total production of refined biomass in Sweden have been obtained from SAPP (2010), while ROW data is from EC-IEE (2009). Proportions of raw materials used (chips, dust and bark) in Swedish pellet industry from Porsö (2010) is used as a proxy to divide production between technologies

Table B.24. Investment cost per unit of new capacity

Activity	SEK/unit	Activity	SEK/unit
SpruceSawn	3815	SpruceChips	75
PineSawn	3815	PineChips	75
NonConSawn	3815	NonConChips	75
FiberBoard	12715	SpruceConvert	0
ParticleBoard	12715	PineConvert	0
PlywoodBoard	12715	NonConConvert	0
NewsPaper	14623	GrotFuel	2000
PrintPaper	14623	ChipsFuel	2000
OtherPaper	13987	DustFuel	2000
MechPulp	5341	BarkFuel	2000
ChemPulp	12715	LiquorFuel	2000
RecoveredP	5341	PelletsFuelLarge	2000
RefinedChips	84	FossilFuelLarge	1000
RefinedDust	84	PelletsFuelSmall	3328
RefinedBark	84	FossilFuelSmall	3328

Consumer Goods Demand data Tables

Table B.25. Production and consumption of final output products in Sweden 2008

	Production	Net export	Consumption
Sawn goods, 1000 m^3			
SpruceSawn	10413	6516	3897
PineSawn	6703	5197	1506
NonConSawn	122	-97	213
Wood boards, 1000s			
FiberBoard (ton)	102	-199	301
ParticleBoard (m^3)	632	-358	990
PlywoodBoard (m^3)	129	-148	277
Paper, 1000 tons			
NewsPaper	2560	2102	458
PrintPaper	3264	2519	745
OtherPaper	5839	4511	1328

All trade data from SFA (2009), except for coniferous sawn goods, where SFA (2009) only gives an aggregate number. Eurostat has data for sawn spruce and pine separately, as well as for total sawn coniferous goods. The proportions of spruce and pine respectively are multiplied with the data for coniferous sawn goods to get the results reported in the table. Trade data for paper has been adjusted after personal communications with Joshi (2010). For ParticleBoard a conversion factor of 0.65 ton/m^3, and for PlywoodBoard a factor of 0.5 ton/m^3, have been used

Table B.26. Population in the four Swedish regions 2008

	Population	Population share
North	877 758	9.48%
East	3 110 200	33.60%
West	2 109 236	22.79%
South	3 159 153	34.13%
Sweden, total	9 256 347	

Population data from Statistics Sweden (2010)

Table B.27. Reference demand for sawn goods, in 1000 m^3

1000 m^3	SpruceSawn	PineSawn	NonConSawn
North	370	143	20
East	1309	506	72
West	888	343	49
South	1330	514	73
ROW	75714	23210	13377

Reference demand for sawn goods in 2008 is approximated from Swedish consumption (Table B.25), divided by region proportional to population share (Table B.26). Approximations of reference demand in ROW are calculated from Eurostat (2010) production and trade data.

Table B.28. Reference demand for wood boards, in 1000 ton or 1000 m^3

1000s	FiberBoard (ton)	ParticleBoard (m^3)	PlywoodBoard (m^3)
North	29	94	26
East	101	333	93
West	69	226	63
South	103	338	95
ROW	10669	24824	7078

Reference demand for sawn goods in 2008 is approximated from Swedish consumption (Table B.25), divided by region proportional to population share (Table B.26). Approximations of reference demand in ROW are calculated from Eurostat (2010) production and trade data.

Table B.29. Reference demand for paper products, in 1000 ton

1000 ton	NewsPaper	PrintPaper	OtherPaper
North	43	71	126
East	154	250	446
West	104	170	303
South	156	254	453
ROW	9723	29994	48856

Reference demand for sawn goods in 2008 is approximated from Swedish consumption (Table B.25), divided by region proportional to population share (Table B.26). Approximations of reference demand in ROW are calculated from Eurostat (2010) production and trade data.

Prices and Elasticities

Table B.30. Prices of final output products

	SEK/unit
SpruceSawn (m^3)	1719
PineSawn (m^3)	1893
NonConSawn (m^3)	3340
NewsPaper (ton)	4469
PrintPaper (ton)	6500
OtherPaper (ton)	5771
FiberBoard (ton)	4703
ParticleBoard (m^3)	2038
PlywoodBoard (m^3)	4645

SpruceSawn and PineSawn prices from UNECE (2011). NonConSawn, FiberBoard, ParticleBoard and PlywoodBoard prices approximated as the average import price in SFA (2009) trade data. Paper product prices from SFA (2009) export price data, free on board in port.

Table B.31. Prices of intermediate products

	SEK/unit
MechPulp (ton)	3824
ChemPulp (ton)	4863
RecoveredP (ton)	994
Pellets (m^3)	846

MechPulp and ChemPulp prices from the Swedish Forest Agency (SFA 2009) export price data, free on board in exporting port. ChemPulp price is a weighted average of sulphate and sulphite prices. Price of recovered pulp has been approximated as the average import price in SFA (2009) trade data. Pellet price has been derived from SFA (2009) price of processed wood fuels at thermal power stations, using a conversion factor of 3.12 MWh/m^3.

Table B.32. Prices of industry by-products

	SEK/unit
Chips (m^3f)	321
Dust (m^3f)	301
Bark (m^3f)	252
Liquor (MWh)	271

Prices of chips, dust and bark from SFA (2009) data on prices of wood fuels at thermal power stations, using conversion factors of 1.608 MWh/m^3f of bark and 1.920 MWh/m^3f of chips and dust. Liquor price is assumed to equal the price for process wood fuels.

Table B.33. Own-price and income elasticities for final output products

	Own price elasticity	Income elasticity
SpruceSawn	-0.24	0.78
PineSawn	-0.24	0.78
NonConSawn	-0.53	0.65
NewsPaper	-0.60	1.04
PrintPaper	-0.60	1.27
OtherPaper	-0.38	1.02
FiberBoard	-0.37	0.95
ParticleBoard	-0.17	1.06
PlywoodBoard	-0.18	0.84

Buongiorno et al 2003

Energy Market Data Tables

Table B.34. Small-scale fuel use quantities and distribution between fuel technologies

(TWh)	Pellets	Fossil	Total
North	0.501	0.385	0.886
East	0.876	1.958	2.833
West	0.902	1.604	2.506
South	1.342	2.613	3.955
ROW	29.486	70.514	100.000

Pellets use data from the Swedish Energy Agency (SEA 2010). The quantity of substitutable fossil fuel is derived from estimates in Börjesson (2008). ROW quantities based on EC-IEE (2009)

Table B.35. Large-scale fuel use, by user and type

(TWh)	District heating systems		Forest industries		Other industries	Total
Region	Bio	Fossil	Bio	Fossil	Fossil	Bio & Fossil
North	2.697	0.620	16.420	0.710	4.783	25.230
East	9.887	7.147	16.075	0.695	4.683	38.487
West	3.634	1.500	8.174	0.353	2.381	16.042
South	10.413	3.002	17.431	0.753	5.078	36.677
Sweden	26.631	12.269	58.100	2.511	16.924	116.436

Data on bioenergy use in the district heating system have been derived from the Swedish District Heating Association (SDHA 2012) and the Swedish Energy Agency (SEA 2010). The quantities of substitutable fossil fuels in the district heating systems are based on scenario B1 in Börjesson (2008). Forest industry bioenergy use derived from SEA (2010). Substitutable fossil fuels in the industries are assumed to be half of the reported fossil fuel use quantities in Statistics Sweden (2010)

Table B.36. Large-scale fuel use quantities and distribution between fuel technologies

(TWh)	Residues		Industry by-products		Pellets		Fossil		Total
Region	Slash	Total	*Chips*	*Dust*	*Bark*	*Liqour*			
North	1.958	16.934	*1.528*	*0.296*	*2.565*	*12.545*	0.225	6.113	25.230
East	2.127	21.617	*5.677*	*1.589*	*6.040*	*8.312*	2.218	12.524	38.487
West	0.892	10.150	*1.519*	*0.486*	*1.179*	*6.965*	0.767	4.234	16.042
South	3.433	22.361	*5.077*	*1.444*	*5.236*	*10.603*	2.050	8.833	36.677
ROW	0	261.232	*0*	*0*	*80.505*	*180.727*	0	638.768	900.000

All residues and liquor are assumed to be used within the region they are produced. Total quantities of chips and dust used in Sweden are derived in Table B.48. Total Swedish quantities of pellets used in the large scale sectors are for district heating use from SDHA (2012), and the industries are assumed to use no pellets. Chips, dust, bark and pellets have been distributed across the Swedish regions in proportion to the net between total bioenergy use and use of slash and liquor. Fossil fuel quantities in Sweden are derived from Table B.35. In the ROW region all excess by-products are assumed to be used as bioenergy. The total energy use in the ROW region is decided arbitrarily, and the fossil fuel use is the residual between this total and the bioenergy use. When running the model total energy use and all incineration activities are fixed.

Trade Data Tables

Table B.37. Transportation costs in NOK(2004)

	Loading cost (*M*)	Variable cost (*N*)
Road transport		
Roundwood & chips (m3)	18,50	0,55
Sawn goods (m3)	10,00	0,70
Pulp, paper & wood boards (ton)	10,00	0,60
Rail transport		
Roundwood & chips (m3)	50,00	0,25
Sawn goods (m3)	50,00	0,25
Pulp, paper & wood boards (ton)	50,00	0,30

Bolkesjø (2004)

Table B.38. Sea transportation costs for three product types in EUR(2002) per ton of dry matter

Distance (km)	Logs	Chips	Pellets
1500	25	22	12
10000	42	55	21

(Suurs 2002)

Table B.39. Transportation loading and variable cost parameters per product type

	Road		Rail		Sea	
	Loading cost (*M*)	Variable cost (*N*)	Loading cost (*M*)	Variable cost (*N*)	Loading cost (*M*)	Variable cost (*N*)
Roundwood (SEK/m^3fub)	23,52	0,70	63,58	0,32	93,27	0,0085
Sawn goods, Particle board & Plywood (SEK/m^3)	12,72	0,89	63,58	0,32	93,27	0,0085
Pulp, Paper & Fiber board (SEK/ton)	12,72	0,76	63,58	0,38	124,36	0,0113
Pellets (SEK/m^3)	23,52	0,70	63,58	0,32	62,85	0,0064
Chips, Dust & Bark (SEK/m^3)	23,52	0,70	63,58	0,32	68,58	0,0165

Table B.40. Road transport distances in km

	North	East	West	South
North	0	473	820	1082
East	473	0	347	609
West	820	347	0	364
South	1082	609	364	0

Table B.41. Rail transport distances in km

	North	East	West	South
North	0	662	1009	1186
East	662	0	347	524
West	1009	347	0	398
South	1186	524	398	0

Table B.42. Sea transport distances in km

	North	East	West	South	ROW
North	0	402	1730	1063	2378
East	402	0	1452	796	2098
West	1730	1452	0	743	1152
South	1063	796	743	0	1452
ROW	2378	2098	1152	1452	0

Table B.43. Unit trade costs for roundwood, SEK/m^3fub

Exporter	Importer	SpruceLog	PineLog	NonConLog	SprucePulp	PinePulp	NonConPulp
North	East	97	97	97	97	97	97
North	West	108	108	108	108	108	108
North	South	102	102	102	102	102	102
North	ROW	113	113	113	113	113	113
East	North	97	97	97	97	97	97
East	West	106	106	106	106	106	106
East	South	100	100	100	100	100	100
East	ROW	111	111	111	111	111	111
West	North	108	108	108	108	108	108
West	East	106	106	106	106	106	106
West	South	100	100	100	100	100	100
West	ROW	103	103	103	103	103	103
South	North	102	102	102	102	102	102
South	East	100	100	100	100	100	100
South	West	100	100	100	100	100	100
South	ROW	106	106	106	106	106	106
ROW	North	113	113	113	113	113	113
ROW	East	111	111	111	111	111	111
ROW	West	103	103	103	103	103	103
ROW	South	106	106	106	106	106	106

Table B.44. Unit trade costs for pulp and paper, SEK/ton

Exporter	Importer	MechPulp	ChemPulp	RecoveredP	NewsPaper	PrintPaper	OtherPaper
North	East	129	129	129	129	129	129
North	West	144	144	144	144	144	144
North	South	136	136	136	136	136	136
North	ROW	151	151	151	151	151	151
East	North	129	129	129	129	129	129
East	West	141	141	141	141	141	141
East	South	133	133	133	133	133	133
East	ROW	148	148	148	148	148	148
West	North	144	144	144	144	144	144
West	East	141	141	141	141	141	141
West	South	133	133	133	133	133	133
West	ROW	137	137	137	137	137	137
South	North	136	136	136	136	136	136
South	East	133	133	133	133	133	133
South	West	133	133	133	133	133	133
South	ROW	141	141	141	141	141	141
ROW	North	151	151	151	151	151	151
ROW	East	148	148	148	148	148	148
ROW	West	137	137	137	137	137	137
ROW	South	141	141	141	141	141	141

Table B.45. Unit trade costs for sawn goods and wood boards, SEK/m^3(/ton for FiberBoard)

Exporter	Importer	Spruce Sawn	Pine Sawn	NonCon Sawn	Fiber Board	Particle Board	Plywood Board
North	East	97	97	97	129	97	97
North	West	108	108	108	144	108	108
North	South	102	102	102	136	102	102
North	ROW	113	113	113	151	113	113
East	North	97	97	97	129	97	97
East	West	106	106	106	141	106	106
East	South	100	100	100	133	100	100
East	ROW	111	111	111	148	111	111
West	North	108	108	108	144	108	108
West	East	106	106	106	141	106	106
West	South	100	100	100	133	100	100
West	ROW	103	103	103	137	103	103
South	North	102	102	102	136	102	102
South	East	100	100	100	133	100	100
South	West	100	100	100	133	100	100
South	ROW	106	106	106	141	106	106
ROW	North	113	113	113	151	113	113
ROW	East	111	111	111	148	111	111
ROW	West	103	103	103	137	103	103
ROW	South	106	106	106	141	106	106

Table B.46. Unit trade costs for pellets and by-products

Exporter	Importer	Pellets	Chips	Dust	Bark
North	East	65	75	75	75
North	West	74	97	97	97
North	South	70	86	86	86
North	ROW	78	108	108	108
East	North	65	75	75	75
East	West	72	93	93	93
East	South	68	82	82	82
East	ROW	76	103	103	103
West	North	74	97	97	97
West	East	72	93	93	93
West	South	68	81	81	81
West	ROW	70	88	88	88
South	North	70	86	86	86
South	East	68	82	82	82
South	West	68	81	81	81
South	ROW	72	93	93	93
ROW	North	78	108	108	108
ROW	East	76	103	103	103
ROW	West	70	88	88	88
ROW	South	72	93	93	93

Model Calibration Data Tables

Table B.47. Calculating exogenous supply of chips and dust in ROW region

(million m^3s)	Chips	Dust
Demand from industry in ROW[1]	76.102	64.145
Supply from saw mills in ROW[2]	67.927	28.630
Net Exports from ROW[3]	1.060	1.269
Exogenous supply in ROW[4]	9.235	36.783

[1]Inputs to pulp, pellets, and wood board activities. Derived from produced quantities in Tables B.20, B.22 & B.23, and input coefficients in Tables B.7, B.8, B.13, B.14 & B.16. [2]Supply of by-products from sawn goods production. Derived from produced quantities in Table B.19, and by-product coefficients in Tables B.10-12. [3]For chips: Swedish net imports of coniferous and non-coniferous wood chips (SFA 2008); for dust: Swedish net imports required to balance supply and demand in Sweden without any exogenous supply, see Table B.49. [4]Exougenous supply is derived as a residual from the data in the upper rows; defined as Demand – Supply + NetExports

Table B.48. Calculating Swedish energy sector demand for chips and dust

	Chips	Dust
Reference use in district heating sector[1] (TWh)	7.837	2.971
Reference use in industries (TWh)	5.965[2]	0.844[3]
Total reference use[4] (TWh)	13.801	3.815
Total reference use[5] (million m^3f)	7.188	1.987

[1]Data from Swedish District Heating Association (SDHA 2010). [2]Residual term defined as the net between the total bioenergy use in industry (Table B.35) and the use of other bioenergy sources (dust, bark, liquor, slash & pellets) as described in Table B.36. [3]Data from SDC (2009) on dust used for fuel in saw mills. Assumed that all sold dust go to the district heating sector or to non-energy uses. [4]Sum of district heating and industry use. [5]Total use converted to volume terms, using a conversion factor 1.920 MWh/m^3f

Table B.49. Calculating exogenous supply of chips in Swedish regions

(million m^3f)	Chips	Dust
Demand from industry in Sweden[1]	11.186	4.184
Demand from energy market in Sweden[2]	7.188	1.987
Supply from saw mills in Sweden[3]	11.630	4.902
Net Exports from Sweden[4]	-1.060	-1.269
Exogenous supply in Sweden[5]	5.684	0
of which North	1.485	
of which East	1.278	
of which West	0.819	
of which South	2.102	

[1]Inputs to pulp, pellets, and wood board activities. Derived from produced quantities in Tables B.20, B.22 & B.23, and input coefficients in Tables B.7, B.8, B.13, B.14 & B.16. [2]The demand for wood chips and dust from the energy sector as derived in Table B.48. [3]Supply of by-products from sawn goods production. Derived from produced quantities in Table B.19, and by-product coefficients in Tables B.10-12. [4]For chips: Swedish net exports of coniferous and non-coniferous wood chips (SFA 2008); for dust: Swedish net exports required to balance supply and demand in Sweden without any exogenous supply. [5]Exougenous supply is derived as a residual from the data in the upper rows; defined as Demand – Supply + NetExports. This total Swedish exogenous supply is then divided by region in proportion to total roundwood harvest

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