Competition for forest resources between the biofuels and the forest industry in Sweden

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Abstract

The aim of this project was to determine the consequences of the large-scale introduction of wood-based biofuels in the road transport sector. Therefore a model has been developed to project the demand for wood in Sweden in the period from 2007 to 2050.

The wood-using sectors that were taken into account are: the sawmill industry; the paper and pulp industry, which was split in three: integrated chemical paper mills, integrated mechanical paper mills, and chemical market pulp mills; the district heating (DH) sector; the electricity sector; the producers of bioethanol; and Fischer-Tropsch (FT) diesel producers.

As the Swedish forest industry is export-oriented, working on the global market, the wood demand for the sawmill, paper and pulp industry was based on current and expected future developments in the production costs and product prices. For the DH sector, the demand was based on the estimated potential for DH, assuming unchanged policy. The same assumption was used for the electricity sector.

The transport demand developments are coupled to economic growth. As the present coupling (= the ratio of annual transport growth to annual economic growth percentages) is different for passenger and freight transport, the demand for transport was split in passenger and freight transport demand. It was assumed that government policy results in diminishing the coupling ratios. From this, the future total distance covered by vehicles was calculated, which was used to calculate the future wood demand from the transport sector. The model took three renewable transport fuels into account: bioethanol, electricity, and FT-diesel. The first two were used in passenger transport; FT-diesel was used in freight transport. The market introduction was assumed to start in 2011 for bioethanol and FT-diesel, and in 2020 for electric vehicles. The electricity for electric vehicles was assumed to be produced by CHP-plants in the DH sector.

The vehicle stock in the model was rejuvenated in a regular way. The choice between different fuel types for the cars to be replaced was done each year on basis of fuel costs, and can be influenced by taxes and subsidies.

Once the wood demands for all sectors are known, the model calculates the total demand for sawwood, pulpwood, wood chips, and bark. Based on differences in the sector's abilities to pay for the wood, the model calculates which sectors receive wood, and what quantities.

The model was used to study three scenarios: a CO_2 price scenario, a Subsidy scenario, and a Sustainability scenario. The CO_2 price scenario was based on pricing of fossil CO_2 production. The Subsidy Scenario combined exemptions of energy tax for renewable fuels with subsidies for purchasing renewable-energy fuelled vehicles. For the first 2 scenarios, subscenarios were made for low, average and high taxes and subsidies. The Sustainability scenario combined energy and CO_2 exemptions for biofuels with high subsidies for purchase of biofuel vehicles.

The results of these scenarios were used to test if the measures would be sufficient to fulfil targets set for the introduction of biofuels from domestic forests. The targets increased from 2.5% in 2020 to 75% of the energy used in transport in 2050. For the scenarios with average subsidies and/or taxes, all but one target for the biofuel introduction are reached. In the subscenarios in with higher taxes and more subsidies, all targets were reached too. The subscenarios in which the measures were less powerful (lower taxes or subsidies),

the results differed: in the CO_2 price scenario, they were fulfilled from 2030 onwards; in the Subsidy scenario all targets were met.
A competition for wood was observed in all scenarios. In the CO_2 price and Subsidy scenarios, the transport biofuel sectors' abilities to pay for wood were initially too low to purchase wood. However, once these sectors were able to compete with other sectors, it the paper and pulp industry was the sector which was the first to lose the competition. This resulted in lower production levels, in some scenarios even in closing down of the entire sector. In some scenarios, the DH sector and the sawmill industry were affected by the competition as well. In the Sustainability scenarios, all other sectors were forced to close down as a consequence of rapidly rising wood prices.
To test the robustness of the model outcomes, a sensitivity analysis was performed in which 5 important parameters of the ‘average’ subscenarios were varied: economic growth, forest industry product price, annual increment of the wood stock, biofuel production cost development, and oil price. These analyses demonstrated robustness with regard to changes in the first 4 inputs. However, the height of the oil price was shown to influence seriously the outcomes of most scenarios. A low oil price ($30/barrel in 2007, rising to $50 in 2050) slowed the introduction of biofuels, a high oil price ($50 in 2007, $110 in 2050) resulted in a faster introduction. For the average scenarios, the oil price was assumed at $40 in 2007, increasing to $80 in 2050. However, the sustainability scenario was not sensitive to the oil price levels.

Keywords

Competion for wood, biofuels, transport sector, scenarios, modelling

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TABLE OF CONTENTS

1. INTRODUCTION

The Swedish government has identified climate change as one of the challenges for the future. It has committed itself to a strategy to combine climate measures and economic growth, with the ambition to become a model for other modern societies aiming at sustainability (Swedish Ministry of Environment, 2008).
The transport sector is the largest source of CO_2 emissions in Sweden (Swedish Ministry of Environment, 2008). The country is large and has a low population density. Furthermore, the average Swedish car is heavier than the European average. In fact, it is the heaviest of all European countries (Kågeson, 2005). However, the government is working on decreasing the impact of the vehicle fleet, recognizing the transport sector as one of the sectors in which considerable emission reductions can be achieved.

Wood may serve as important source of bio-energy in Sweden. It is already widely used in District Heating (DH) systems, as a consequence of change in taxation in the early 1990s (Johansson *et al.*, 2002). Wood can also be used to produce transport fuels.
On the other hand, the forest industry, consisting of sawmills and the pulp and paper industry, is important for the Swedish economy. The sector makes up 25 to 30% of the total production value of the Swedish industry (Björheden, 2006), generating 11% of the export revenues in 2007 (Statistics Sweden, 2009).

This research project focuses on the potential consequences of greening of the transport sector in the period until 2050. It is assumed that by this time, a large portion of the vehicles will be fuelled by renewable energy, partly produced from Swedish wood. In this research, road transport (both passenger and freight) is addressed. Other sectors, like railways, air and sea transport are not taken into account.
The question that arises is what consequences a large-scale introduction of renewable fuels will have for the forest industry when a large share of the fuel comes from a domestic source. Will there be conflicts for resources between the forest industry and the transport sector? Or will biomass-based transport fuels compete with biomass use for DH and electricity production purposes?

In order to answer these questions, this project aims to forecast, using a model, how the biomass demand for transport, DH and electricity, and sawn wood, paper and pulp production purposes may develop in the period from now until 2050 for a number of scenarios, and compare these outcomes with the total amount of biomass available in Sweden.

From the aim stated in the previous paragraph, it follows that the main question of this research project is '*to what extent will conflicts for resources arise between the biofuels and the forest industry in case of a transition to a sustainable transport sector by 2050?*'

Based on this research question, a number of sub questions are defined for the different sectors that will be studied.

1. Transport in Sweden: biofuel production and biomass demand
   - 1.1 What are the characteristics of the Swedish transport system?
   - 1.2 To what extent are biofuels currently used in Sweden?
   - 1.3 What are the plans of the Swedish government for the transport sector in general, and the introduction of biofuels?
   - 1.4 What are reasonable scenarios for greening the Swedish transport sector by 2050?
   - 1.5 What techniques are currently available or under development for conversion of biomass to biofuels, and what is their current and expected efficiency?
   - 1.6 How does the requirement for biomass depend on the (mix of) transport biofuels chosen for implementation?

2. Forest industry production and biomass demand
   2.1 What are reasonable scenarios for the development of the demand for sawn wood, paper and pulp, and consequently for the demand of raw materials, until 2050?
   2.2 What are the efficiencies of current techniques in these sectors, and how are the prospects of increasing these efficiencies?
   2.3 How are the side products of these sectors currently used?
   2.4 What policy does the Swedish government have with regard to the forest industry?
   2.5 What are the consequences of a large-scale introduction of transport biofuels made from wood for the forest industry?

3. Biomass demand for DH and electricity
   3.1 To what extent is biomass currently used in Swedish district heating systems and electricity production?
   3.2 What are the plans of the Swedish government with regard to these applications?
   3.3 What are the consequences of a large-scale introduction of transport biofuels made from wood for the district heating and electricity production sector?

4. Wood resources in Sweden
   4.1 How much woody biomass is annually available in Sweden?
   4.2 How is this area of productive forest land expected to change in the future?

In the remainder of this report, first an overview of the literature available on the different sectors (sawmills, paper and pulp industry, DH and electricity, transport) is given. This literature section will answer a number of the research questions given above: 1.1, 1.2, 1.3, 1.5, 2.1, 2.2, 2.3, 2.4, 3.1, 3.2, 4.1, and 4.2. In order to answer the remaining sub questions (1.4, 1.6, 2.5, 3.3), and for answering the main research question, a model is made to determine the total wood demand and deliveries. The model is described in chapter 3. In this Method chapter, the different scenarios used in the modelling are described. The Results chapter will answer the subquestions 1.4, 1.6, 2.5, 3.3 and the main research question. Before drawing conclusions, the assumptions made in the model are discussed, as well as the implications of the results.

2. SYSTEM DESCRIPTION

In this chapter, an overview of the literature about the different sectors that incorporated in the model is given. This chapter focuses mostly on the current situation, but now and then also some historic data are given, whenever they are considered important for the current situation, or when they are expected to be of relevance for the future. The current and forecasted trends are required for answering the research questions 1.1, 1.2, 1.3, 1.5, 2.1, 2.2, 2.3, 2.4, 3.1, 3.2, 4.1, and 4.2.
This chapter is built up as follows: first, some general information about the supply of wood in Sweden. After that, the different sectors using wood are discussed, starting with the current users (sawmills, pulp and paper industry, district heating, and electricity), followed by wood users that are expected to enter the market in the future (transport biofuel producers). Finally, the transport sector will be described.

2.1 Wood supply in Sweden

For Sweden, 1903 is the year in which a first step towards sustainable forestry was set. With the introduction of the Forestry Act, forest owners were obliged to replant the forest areas they cut clear (Lämås&Fries, 1995), thus sustaining the resource base for biomass production. The forest area was increased from the 1930s on with the restructuring of the Swedish agriculture which freed land for forestry: as a consequence of increasing efficiency, less arable land was needed for food production (Johansson *et al*., 2002). Nowadays, the forestry sector is by far the largest consumer of primary biomass. Some wood is used a fuelwood, but the sawmills and pulpwood consumption from the forestry sector was almost 88% of the total raw wood used in Sweden in 2006, taking imports and exports of wood to and from Sweden into account (Swedish Forest Industries Federation, 2007). Table 2.1 gives an overview of the raw wood used in Sweden in 2006.

Table 2.1: Raw wood use in Sweden, 2006 (Swedish Forest Industries Federation, 2007)

Wood supply		Wood use	
	Volume (Mm^3sub)	Sector	Volume (Mm^3sub)
Taken from forest	75.5	Sawmilling	38.2
Import	6.8	Pulp and Paper	35.9
Export	3.0	Fuelwood	6.2
Total	79.3	Total	80.3

Compared to the wood consumption, the annual wood increment averaged 95 Mm^3sub in the period 2004-2008 (Swedish Forest Industries Association, 2007). In fact, the annual increment has been larger than the fellings in almost every year since 1940, partly because of the agricultural reforms from the 1930s onwards (Johansson *et al.*, 2002).
This does, however, not mean that much more wood can be taken from the forests: 21.5 Mha woodland is productive forest land, the forest industry has voluntarily set aside 2.0 Mha productive forest land, and 4.0 Mha unproductive land is excluded from cultivation (Swedish Forest Industries Federation, 2007). Therefore, not all the unfelled increments can be used in the forestry or energy sectors. From the percentage of land used for growing trees, taking 95 Mm^3sub as total annual wood increment, and given that 46% of a tree can be used as wood for sawmilling (sawwood), another 46% being suitable as wood for pulping, it follows that the annual increment of both saw- and pulpwood is 43.9 Mm^3sub.
The Swedish Forest Agency (2005) notes that current wood harvests are almost as high as the potential harvests. Increase of the capacity of the forest industry will have to be fuelled mainly by wood imports. Some more wood can be used for energy purposes, but in the longer term, supply of wood for energy will also be limited.

The Swedish forestry policy aims to balance production and environmental objectives. A number of quantitative goals for the forest policy were introduced by the Swedish Forest Agency (SFA, 2005).
For the production of wood, the general policy means that 'forest and forest land shall be utilized efficiently, with the goal of achieving a sustainable yield of high market value' (SFA, 2005). In order

to do so, a number of concrete targets have been set, for example with regard to reducing substandard regenerations, increasing pre-commercial thinning, and protecting forest from browsing by elk.
No targets have been set for increasing harvest levels, even though fertilization, genetic improvements to tree species, reforestation, and improved regenerations are seen as ways to increase the forest growth. On the other hand, substantial increases in harvesting levels are not considered realistic (SFA, 2005).

Based on the data given above, research questions 4.1 and 4.2 ("How much woody biomass is annually available in Sweden?" and "How is this area for biomass production expected to change in the future?") can be answered.
It was found that the total increment is 95 Mm^3sub, the total increment of both sawwood and pulpwood being 43.9 Mm^3sub. These values are unlikely to change.

2.2 The Swedish sawmill industry
Using 38.2 Mm^3sub wood, the Swedish sawmill industry produces approximately 6% of the sawn wood annually consumed worldwide, or 16% of the European demand (FAO, 2009). In the period 1980-2007, the annual production of sawn wood has increased annually with 2% on average, from 11.0 to 18.6 Mm^3 (Swedish Forest Industries Federation, 2009).
Although the export prices of sawn wood may vary strongly from year to year, the overall trend is that the prices are relatively stable: highly volatile on the short term, but stable on the long term (Kangas&Baudin, 2003). Looking at the prices for sawwood in Sweden in the period 1995-2008, the prices also seem more or less stable, except for a dip in 2005-2006, probably as a consequence of a large number of trees felled by hurricane Gudrun, which hit south-Sweden in January 2005.
For the future, the prices of sawn wood are expected to remain stable (Kangas&Baudin, 2003; Smeets&Faaij, 2007), and the demand is expected to continue to increase as it is related to GDP growth, industrial activity and population (Binkley, 2009). For Europe, the UN Food and Agricultural Organization (FAO) expects the demand to increase with 1.8% annually up to 2020 (FAO; 2005). Most of the demand is expected to come from Eastern Europe, which catches up with Western Europe in terms of wood use. After these former socialist states have reached the same wood consumption level as Western Europe, the demand is expected to level off.
The future trends that will be used for this project (subquestion 2.1) are stable product prices, the demand for sawn wood growing with 1.8% annually until 2025, and with 1.0% annually afterwards. In table 2.7 at the end of this chapter, an overview of the data used for the sawmill industry is given.

Looking at the efficiency of sawn wood production (subquestion 2.2), it was found that half of the wood entering a sawmill leaves it as sawn wood. When a tree is transported to a sawmill, it is first debarked, and then sawn twice. The first saw produces a thick block of wood and side boards, which can be processed further. The second saw turns the thick block into centre and side boards. Finally, the wood is dried (Johansson, 2007). In the process, 3 side products are formed: bark (10% of the wood mass), sawdust (10%) and wood chips (30%).
The side products are used either internally or externally (subquestion 2.3). Bark is used internally for generating the heat for drying. Sawdust is partly used for the same purpose, sold to be upgraded to wood pellets, or sold to the particle board industry. Wood chips are nowadays mostly sold to the paper and pulp industry (Johansson, 2007).

2.3 The Swedish pulp and paper industry
The paper and pulp industry is the other large industrial wood consumer in Sweden. Apart from 11.2 Mm^3sub woodchips from the sawmill industry, 35.9 Mm^3sub pulpwood was used for pulping in Sweden in 2006 (Swedish Forest Industries Federation, 2007).

Wood can be converted to pulp in 2, non-competitive ways: chemical and mechanical pulping. In the first process, chemicals are applied to separate cellulose and other wood components from lignin, the natural 'binding agent' of wood. The pulping efficiency is low, typically in the order of 40 to 50%, producing side products like bark, pitch oil, and black liquor (BL). BL is the main side product, a mixture of lignin and the chemicals used for pulping. It is burned on-site to recover the chemicals, producing heat and electricity. Modern chemical pulp mills not only cover their own electricity and heat demand, they sometimes even produce a surplus electricity and heat, to be sold on the market. In the future, a surplus bark may be sold on the market (Ådahl, Harvey & Berntsson, 2006).

Mechanical pulping, on the other hand, separates wood fibres mechanically, resulting in a yield of over 90%, as well as a large electricity consumption, which can not be covered by combustion of side products, in this case mostly bark. Efficiency increase in this sector is therefore mainly aimed at energy conservation (Holmberg&Gustavsson, 2007).

The techniques are non-competing: mechanical pulp contains lignin, which makes the paper produced from the pulp turn yellow, and is therefore used in low-quality applications such as newsprint. Paper from chemical pulp retains its white color longer, and is used mainly for writing and printing paper. For this reason, the paper produced from chemical pulp is referred to as printing and writing paper in this report, that from mechanical pulp will be called newsprint.

Thus, the answer to subquestion 2.2 ("What are the efficiencies of current techniques in these sectors, and how are the prospects of increasing this?") is that pulping efficiencies are around 45% for chemical pulping, and over 90% for mechanical pulping. Major increases in the efficiencies are unlikely. Research is mainly aimed at more efficient use of side products. Looking at the side products of pulp and paper mills (subquestion 2.3), it was found that these are mostly used internally.

Table 2.2 gives an overview of the development of the Swedish pulp and paper industry in the period 1980-2007. In this period, the production capacity and the actual production increased. The market pulping capacity decreased, however. Most of the market pulp is exported (Swedish Forest Industries Federation, 2009). The majority of the produced paper is exported, too, mostly to European markets. Sweden produces 8% of all printing and writing paper consumed in Europe, and 20% of the newsprint (FAO, 2009).

Table 2.2: Swedish pulp and paper industry, 1980-2007 (Swedish Forest Industries Federation, 2009)

Year	Total paper and pulp industry				Market pulp industry			
	Capacity Mton	Production Mton	Chemical pulp %	Mechanical pulp %	Capacity Mton	Production Mton	Chemical pulp %	Mechanical pulp %
1980	10.5	8.7	77	23	4.6	3.6	85	15
2007	13.3	12.4	70	30	4.3	4.1	90	10

In the period 1995-2007, the demand for pulp and paper increased, but prices generally decrease (based on FAOstat, 2009). Table 2.3 gives an overview of the demand and price trends. The price drops are attributed to overcapacity on the market, shift of production capacity to countries with lower production costs, and replacement of paper by information and communication technology. In OECD countries, the growth of paper consumption is no longer directly related to economic growth. This used to be the case for a long time, but the demand for newsprint has declined in the US since 1987, and other countries have followed. This may also happen for other paper grades (Seppälä, 2007).

Table 2.3: Trends in the pulp and paper sector, 1995-2007 (FAOstat, 2009)

	Demand (%/y)	Price (%/y)
Writing and printing paper	+4.5	-2.9
Newsprint	+2.4	-1.7
Market pulp	+1.2	+1.2

As was the case for sawn wood consumption, the demand for paper and pulp grows slower than the economic growth in most Western European countries. In the Eastern European countries, paper consumption is expected to grow much faster until the consumption there has reached the level of Western Europe. After that, the growth of paper consumption is expected to level off (Kaunas&Baudir, 2003).

Based on this, the future trends that will be used later on in this report were determined (subquestion 2.1). It was assumed that the current trends in demand will remain the same until 2020. After that, the

demand is assumed to start levelling off, so that the growth in demand is 0% after 2030. In contrast to the currently observed trend, the prices for paper are assumed to remain constant until 2050.
In table 2.7, at the end of this chapter, all data are presented.

2.4 Wood use in district heating systems

The first District Heating (DH) system in Sweden was opened in 1948, but it was not before the 1960s that the systems, then fuelled by heavy oil, were introduced on a large scale. After the oil crises in the 1970s, the Swedish government decided to phase out oil, leading to an increase in coal use in the 1980s until a tax reform in the early 1990s made biomass the most favourable fuel. This led to a rapid growth of the use of biomass (Johansson *et al.*, 2002).

A quota system for green electricity was introduced in 2003, the Green Certificate System. For every MWh of renewable electricity generated, the producer receives a certificate from the state. This certificate can then be sold for extra revenue (Swedish Ministry of Industry, Employment and Communications, 2004). This systems was expected to lead to the introduction of more Combined Heat and Power (CHP) in the DH sector (Wang, 2006).

Taking the sum of fuel cost, energy and CO_2 tax, the costs for fuelling a biomass-DH installation are lower than the costs for using oil, coal or gas (Knutsson, Werner & Ahlgren, 2006; assuming EUR 1=SEK 11). Table 2.4 compares the prices of the fuels.

Table 2.4: Comparing the fuel costs in DH systems (Knutsson, Werner & Ahlgren, 2006)

Fuel type	Biomass	Natural gas	Coal	Oil
Cost (SEK/MWh_{fuel})	175	410	480	540

As of 2007, wood fuels are the dominant fuels in DH systems. Wood fuels made up 54% of the total energy used in heat only plants, generating 8.4 TWh heat. In CHP plants, wood fuels made up 39% of the total fuel use, totalling 10.8 TWh heat. Looking at the entire DH sector, wood fuels produced 19.2 out of 43.6 TWh heat: 44% of the energy input (Statistics Sweden, 2009b). So, answering subquestion 3.1, it can be concluded that wood fuels are used to a large extent in the DH sector.

Some years ago Svensk Fjärrvärme, the Swedish DH producers association, reported an annual growth of 2 to 3% in the heat delivered, as well as expectations of a market share of 75% to be attainable: This comes down to 80 TWh heat (Svensk Fjärrvärme, 2004). On the other hand, if current trends continue, heat deliveries in 2025 will be 9% lower compared to the current demand, whilst 10% more primary energy is used (Johansson, Nylander & Johnsson, 2007). However, the government policy (subquestion 3.3) is aimed at replacing electric heating with district heating. This is not taken into account by Johansson *et al.*(2007).

For this project, it is assumed that in the future the share of wood fuels in DH systems will remain constant, unless the heat producers have to switch to other fuels because they can no longer purchase wood. Moreover, it is assumed that the prognosis of Svensk Fjärrvärme will turn out to be optimistic. Rather, heat deliveries will increase to 65 TWh annually, of which 28 TWh wood fuels. Using a 2% annual growth in heat deliveries, the 28 TWh heat deliveries will be reached in 2027. After that, demand will remain constant. The additionally installed DH is assumed to consist of CHP installations with a heat:electricity ratio of 0.4.

2.5 Wood use in the electricity sector

Wood and wood products are of minor importance in the Swedish electricity production system. As of 2007, hydropower and nuclear power are dominant in Swedish electricity production, each producing 45% of the electricity output (Statistics Sweden, 2009b).

Some electricity is produced in CHP plants in the DH sector, totalling 5.9 TWh_e, or 4% of the total Swedish electricity production. Combustion of side products in the pulp and paper industry such as black liquor and pitch oil yielded another 3.2 TWh.

As most of the electricity from wood is CHP-electricity from the DH sector, it was decided to set the demand for wood from the electricity sector to 0. The Green Energy Certificate system is not expected to lead to more conventional electricity produced from wood. Therefore, the demand is also assumed to remain 0 in the future.

2.6 Wood use in the road transport sector

Renewable fuels based on woody biomass for the transportation sector are not currently produced in Sweden, apart from a pilot plant in Örnsköldsvik, where sulphite pulp is used to produce ethanol in an old pulp mill (Grahn, 2004).

The Swedish interest in renewable energy sources for transport fuels can be split in 3 waves. The first, from 1973 to 1985, was triggered by the oil crisis, the main aim being oil substitution. Most interest was focused on methanol, and in the process biomass gasification was also developed. In the second wave, 1985-1996, local air pollution was seen as the main problem. This led to small-scale introduction of first-generation biofuels, such as bioethanol and rapeseed methyl ester (RME), used in for example bus fleets. The third wave, since 1998, is driven by concerns about climate change and oil supplies. The main driver of this wave is no longer the national government, but the EU (Hillman & Sandén, 2008).

Looking at the forest industry, a number of side products, such as pitch oil and black liquor, can be used to produce transport fuels. The quantities of pitch oil are too low for a large-scale production of transport fuels, but black liquor (BL) is produced in considerable quantities. It can be gasified to obtain syngas, which can be combusted in a CHP plant. BL can also be used to produce methanol or hydrogen. Otherwise, the lignin can be extracted to be combusted. A lot of experience with BL gasification has been gained over the last decades (Andersson & Harvey, 2006). So, BL can be used to produce a number of transport fuels: methanol, hydrogen, or electricity. However, the paper and pulp industry is still very reluctant to introduce BL gasification due to concerns over plant availability (pers.comm. Karin Ericsson, April 9, 2009).
Other side products, like wood chips and sawdust, can be used for the production of the same transport fuels as from raw wood. These fuels include the second generation biofuels methanol, ethanol, Fischer Tropsch (FT) diesel, as well as third generation fuels like hydrogen and electricity.

For this research project, 3 renewable transport fuels are selected which can be produced from wood, allowing large-scale introduction: bioethanol, FT-diesel, and electricity produced from wood combustion. In the remainder of this section, the choice for these fuels is explained.
Bioethanol was chosen as this fuel is already in use, although not produced from woody biomass. As a consequence, the infrastructure for this fuel is currently present. Thus, when the bioethanol produced from woody biomass is ready for the market, it can be introduced without any problems. A potential competitor to bioethanol is biomethanol, which was seen as a gasoline substitute in the 1970. This fuel has higher production efficiency, but disadvantages are that it is corrosive and toxic, and the technology for producing it from wood is not a proven technology (Grahn, 2004).
FT-diesel was used because it is fully compatible with fossil diesel, thus requiring no infrastructural adjustments.
Third, electricity for battery electric vehicles was chosen as the energy source for the future in the field of passenger transport. Another option here was hydrogen. At the moment, the future for both types of fuels is uncertain (Jorgensen, 2008). Electricity and hydrogen vehicles both have issues that need to be solved. For the electric vehicle the range and battery cost and weight are problems. Hydrogen, on the other hand, is difficult to store, and the low density of hydrogen results in large tanks and/or high storage pressures. Additionally, hydrogen has a bad reputation. Both fuels probably require the construction of new infrastructure. In contrast to electricity, hydrogen is expected to be an expensive fuel (Jorgensen, 2008).
The choice for using the electric vehicle in this study is based on the expectation that battery issues will be solved earlier than the hydrogen storage issues, and the general public's negative image of hydrogen. Furthermore, in the future plug-in hybrids may pave the way for a gradual introduction of the battery electric vehicles.

In the next sections, the production process and the efficiencies of these processes are given, thus answering the research question 1.5. Furthermore, the expected cost development of the fuels is given.

2.6.1 Bio-ethanol

Bio-ethanol can be produced from woody biomass in a number of pathways. All synthesis routes start with pre-treatment of the wood, in which the wood is cleaned and milled to smaller particles to increase the efficiency of the following steps.

The first path is the hydrolysis fermentation route. Hydrolysis is used to convert cellulose into glucose and hemicellulose into xylose. Lignin is unaffected, and can be removed. In the second step, the glucose and xylose are fermented to ethanol. Purification is done by distillation. Another pathway is gasification chemical synthesis. The first step is gasification of biomass to syngas, after which the conversion of syngas is done by chemical catalysis. Depending on the pathway, the efficiency of the ethanol production, in terms of wood energy ending up in the fuel, varies between 27 and 37%. (Wei, Pordesimo, Igathinathane & Batchelor, 2008). It is expected that the conversion efficiency rises to 45% in the future (Åhman & Nilsson, 2008).

The production cost of cellulosic bioethanol are currently around SEK 250/GJ, and are expected to decrease to SEK 140/GJ in the next 10 years. Around 2025, the costs will probably have decreased further to SEK 100/GJ (Hamelinck, Van Hooijdonck & Faaij, 2005; EUR 1 = SEK 11). Åhman, Modig and Nilsson (2005) give even lower prices, but note that lowering of the price depends on the successful developments in the field of enzymatic hydrolysis. Furthermore, these authors assume lowering of the production price of biomass, to be achieved by costs reductions, the introduction of modern technologies, dedicated plantations, and the emergence of a global biomass market.

Whether bioethanol can compete with gasoline, depends not only on the ethanol price, but also on the gasoline price. Production costs of gasoline vary between SEK 30 and 80/GJ for raw oil prices of SEK 130-375 per barrel, which is roughly $15-45/barrel (Hamelinck & Faaij, 2006).

So, without increasing oil prices, or tax measures, bioethanol will not be competitive with oil in the next 15 years.

Apart from a pilot plant, no production capacity is available for bioethanol from woody biomass. However, the Swedish government provides financial means to promote commercialization of this fuel in the period 2009-2011. In 2008, Inbicon A/S from Denmark presented a liquefaction-based process to produce bioethanol from lignocellulosic biomass, which is expected for commercialization in 2012 (Larsen, Østergaard Petersen, Thirup, Li & Krogh Iversen, 2008).

For this study, it is assumed that bioethanol from wood will be introduced on the market in 2011. The production efficiency increases linearly from 35% to 45% in the period 20007-2027, and remains stable after that year. The expected cost development for this fuel is drawn in figure 2.1. The costs presented in this figure exclude wood costs.

2.6.2 Fischer-Tropsch diesel

The first Fischer-Tropsch (FT) diesel production facilities were built by Ruhrchemie in Germany in 1935 and shut down in 1945. These plants, as well as the Sasol factories in South-Africa which were built in the late 1970s, used coal-to-liquid techniques. Currently, gas-to-liquid factories are under construction to use natural gas otherwise burnt at oil wells (Van Vliet, Faaij & Turkenburg, 2009).

The production process to produce FT-diesel from biomass starts with pre-treatment, where the biomass is grinded and dried, after which the biomass is gasified to produce syngas, a mixture of H_2 and CO. The gas is then cleaned, followed by the actual FT synthesis (Tijmensen, Faaij, Hamelinck & Van Hardeveld, 2002). The mixture of hydrocarbons thus produced requires refining (Åhman & Nilsson, 2008). The efficiency of the synthesis is in the order of 42-52% (Tijmensen, Faaij, Hamelinck & Van Hardeveld, 2002; Van Vliet, Faaij & Turkenburg, 2009). At the moment, Sweden has one pilot plant for the production of syngas from biomass, but it has been closed temporarily due to financing problems. The process seemed to function well (Swedish Energy Agency, 2008).

The production costs of FT-diesel are higher than that of gasoline, due to the final refining step (Åhman & Nilsson, 2008). However, the costs estimates are varying. Van Vliet, Faaij and Turkenburg (2009) listed a number of cost estimates, finding values between SEK 165 – 450 (EUR 15 - 41) per GJ, the average being SEK 250/GJ. The long-term production costs are forecasted to SEK 140, which would mean break-even with oil when the oil prices are well above $80 per barrel (Hamelinck & Faaij, 2006).

For this study, the date for market introduction of FT-diesel from woody biomass is set in 2011. The production efficiency is assumed to increase from 42% in 2007, to 52% in 2027. After that, the efficiency does not increase further. The cost development for the production of FT-diesel, excluding wood costs, used in this study is shown in figure 2.1.

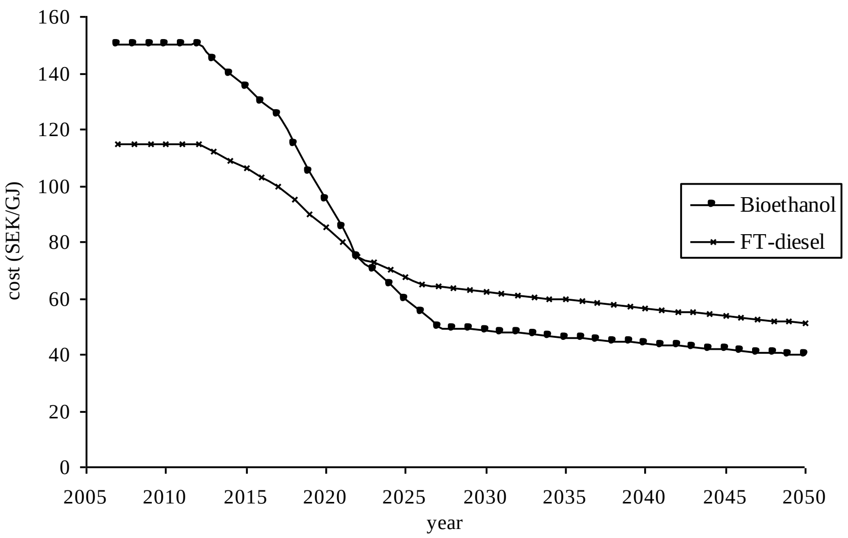

Figure 2.1: Cost development for production costs bioethanol and FT-diesel, excluding wood costs

2.6.3 Electric vehicles

For this project, electric vehicles are considered as the vehicles of the future for passenger transport. The electricity is produced by combustion of wood, mainly in CHP plants for DH purposes.

As of 2007, 126 battery electric vehicles (BEVs) were registered in Sweden, next to almost 10,000 vehicles with electricity as second fuel (Swedish Institute for Transport and Communications Analysis SIKA, 2008a). This does, however, not mean that BEVs are market-ready. A number of problems still has to be solved. Examples are a limited range, durability and costs of batteries, and the corresponding high purchasing costs for the vehicle (Jorgensen, 2008). Other battery issues are size and weight (Kromer&Heywood, 2007).

An electricity-fuelled vehicle differs from bioethanol- and FT-diesel-vehicles in that it uses no internal combustion engine (ICE), but electric motors to convert stored energy to motion. As the losses of the electric drive train are lower than the losses of an ICE-drive train, less energy is needed to drive the same distance.

The electricity required for charging the battery of a BEV can be taken from the grid, using the sockets currently present in buildings. However, this limits the recharging speed and location. In the future, special infrastructure for fast recharging may be required (Jorgensen, 2008).

The future of BEVs is uncertain, so it is impossible to estimate the year in which this type of vehicle is ready to enter the market on a large scale. Estimates vary from 'not likely to become more than a niche market in the next 30 years' (Kromer&Heywood, 2008) to 'breakthroughs for large market scale introduction (…) are estimated around 2015' (SIKA, 2008b). For this project, the BEV was assumed to be market-ready in 2020.

2.7 Transport sector: Trends and plans

In this section, the Swedish road transport sector is described. First, the trends in demand for transport are discussed, as well as the expected future demand. Second, the plans of the Swedish government with regard to transport in general, and for the introduction of biofuels, are described. In doing so, the research questions 1.1 ("What are the characteristics of the Swedish transport system?"), 1.2 ("To what extent are biofuels currently used in Sweden?"), and 1.3 ("What are the plans of the Swedish government for the transport sector in general, and the introduction of biofuels?") are answered.

The following discussion will only deal with road transport, as this sector is the only one addressed in this research project. Thus, the aviation, railway, and shipping sectors are not taken into account. In the road transport sector, a distinction is made between passenger and freight transport. Busses are included in the latter category, as the type of fuel used and the energy consumption per kilometer is more comparable to lorries than to passenger cars.

Total energy use in transport was 130 TWh in 2007 (Swedish Energy Agency, 2009), with the road transport consuming 94 TWh (Statistics Sweden, 2009).

2.7.1 Trends in transport demand

The demand for both passenger and freight transport has traditionally been coupled to the growth of GDP. Table 2.5 shows the elasticity of transport demand, which is defined as the ratio of growth of transport demand and growth of GDP growth, for Sweden in the period 1970-2000. In the table, the elasticity of freight transport is calculated on basis of the distances travelled by Swedish transport operators. Thus, foreign transport movements on Swedish roads are not included (Tapio, 2005).

Table 2.5: Elasticity of transport demand (after Tapio, 2005)

transport type		1970-1980	1980-1990	1990-2000
passenger	%pkm/%GDP[1]	1.12	1.06	0.60
freight	%tkm/%GDP[2]	0.33	0.48	0.50

1: pkm = passenger kilometer, the movement of one car passenger (in which the passenger may be the car driver) over 1 kilometer. 2: vkm = vehicle kilometer, the movement of 1 tonne of freight over 1 kilometer

From the table it can be seen that the increase of passenger transport, as compared to GDP growth, is levelling off over the course of the decades. The drop of the elasticity in the 1990s compared to the period 1970-1990 is large. Eurostat (2009) data show that the ratio passenger transport volume/GDP has been decreasing in the period 1996-2007. This is an indication that transport volume increased less than GDP, which is in agreement with the data from Tapio (2005). However, this does not mean that the absolute volume of transport also decreased. In fact, both passenger and freight transport volume, in term of vehicle kilometers, increased almost each year since 1975 (US Federal Highway Administration, 2003, 2006a, 2006b; SIKA, 1999, 2006, 2007, 2009).

The freight transport volume, relative to GDP growth, has been increasing over the last decades, as can be seen from table 2.3. Eurostat (2009) data show that the relation between transport volume and GDP is decreasing slightly in the period 1996-2007, which indicates that less tkms are produced per unit of GDP, thus hinting at slight decoupling.

For the transport intensity in Sweden, Stead (2001) shows that little has changed in the period 1970-1995. In the same period, passenger transport has become little more energy efficient, for freight transport the efficiency decreases slightly. The transport energy consumption per capita per year shows little change.

Concluding, looking at the Swedish transport sector, it is found that the total volume of both passenger and freight transport have been growing steadily in the last decades. Both forms of transport are still coupled to GDP growth. In passenger transport, the coupling is weakening, for freight transport this was not the case in the period 1970-2000, but in recent years this seems to be changing.

2.7.2 Use of biofuels in the road transport sector

The use of biofuels in the transport sector accounts for a small percentage of the total energy use: just over 3% in 2006. In a European context, only Germany and Austria reached a higher percentage. This percentage is increasing, as Sweden aims at having 5.75% renewables in transport by 2010, in

accordance to the indicative target set in the EU directive 2003/30/EC (Swedish Energy Agency, 2008).
The largest share of the renewable transport fuels is imported. Most bioethanol used for blending with gasoline is imported sugar cane bioethanol from Brazil, which is cheaper than domestically produced ethanol. Sweden has at the moment one plant producing bioethanol from wheat, as well as a plant that produces rapeseed methyl ester (RME), which is added to diesel. However, a major part of the RME is imported from other countries. Furthermore, there is an experimental plant that converts woody biomass to bioethanol (Swedish Energy Agency, 2008).
So, the current share of biofuels in transport is low, but increasing. No biofuels produced from forest biomass is used at the moment.

2.7.3 Government plans for the transport sector

For the future, the Swedish government is aiming not only to break the coupling between increased energy and materials use and economic growth, it is also planning to introduce biofuels on a large scale.

Focusing first on the coupling between transport demand and economic growth, the government is willing to take 'forceful' measures, including a shift of taxes towards energy and CO_2 taxation, with the focus on gasoline and diesel, as well as higher vehicle taxes. (Swedish Ministry of Environment, 2007). More specific, the following measures have been introduced: a CO_2 tax on fuels, height of vehicle tax based on CO_2 emissions of the vehicle, a tax incentive for diesel vehicles with low particle emissions, and an annual bonus for clean light-duty vehicle (Swedish Ministry of Environment, 2007).

Looking at the introduction of biofuels in the transport sector, the Swedish government is following the EU directive on the promotion of the use of energy from renewable sources (2009/28/EC). The aim set out in this directive is the introduction of 20% biofuels in transport in 2020 as a follow-up to directive 2003/30/EC (5.75% biofuels in transport in 2010). For the period following 2020, the government recently presented the ambitious goal of having the Swedish transport sector independent of fossil fuels in 2030. An action plan to reach this goal was presented as well. (Swedish Ministry of Enterprise, Energy and Communications and Swedish Ministry of the Environment, 2009).
Until now, a few measures have been taken. An energy tax and a CO_2 tax have been introduced for all energy carriers. The energy tax is mainly a fiscal tax, meant to generate income for the state (Biopact, 2008). The CO_2 tax was intended to diminish the CO_2 emissions from the combustion of fossil fuels, although there was a short-term fiscal motivation too (Bohlin, 1998).
Biofuels have been exempt of both taxes since 2004. This measure is planned to remain in place until 2013 (Hillman&Sanden, 2008). For the current situation, the taxes are listed in table 2.6.

Table 2.6: Taxation measures transport fuels 2004-2013

Fuel	Energy tax (SEK/L)	CO_2 tax (SEK/L)	Total (SEK/L)
Gasoline	2.9	2.1	5.0
Diesel	1.0	2.6	3.6
Biofuels	0	0	0

For E85, a mixture of 85% bioethanol and 15% gasoline, the ethanol part is free of energy tax (Grahn, 2004), making this fuel competitive with gasoline, both in terms of price/L and in price/energy content (Swedish Energy Agency, 2008).
Other measures include obliging all large fuel stations to offer at least 1 biofuel (Swedish Ministry of Environment, 2007). The definition of 'large' is being lowered from at least 3000 m^3 sales volume to 1000 m^3 sales volume, leading to the availability of biofuels at 60% of the gasoline stations (Swedish Energy Agency, 2008). Funds are available to increase the availability of biofuels.
The action plan to reach fossil fuel independence includes a variety of measures. First of all, increased blending (up to 10% ethanol and 7% RME, if allowed by the EU) will be allowed, quota requirements for biofuels will be introduced, the energy tax on diesel will be raised (but other diesel taxes will be lowered), and light commercial vehicles will be included in a vehicle tax system. This tax system will

be differentiated, based on the CO_2 emissions of vehicles. Subsidies will be given to the development of second-generation biofuels, aiming to enable commercialization in 2009-2011. A knowledge-base about the market for electric and plug-in hybrids will be developed. Finally, the Swedish automotive cluster will be strengthened (Swedish Ministry of Enterprise, Energy and Communications and Swedish Ministry of the Environment, 2009).

For the period until 2030, the EU is optimistic about decoupling transport from economic growth. This optimism is based on saturation effects in passenger transport demand, as well as stagnating population growth. Freight transport demand decoupling is forecasted to take place as a combination of saturation effects and structural change of the economy towards a more service-oriented economy (European Commission, 2007).

2.8 Summary

In this chapter, a number of research questions has been answered. In this section, a short overview of the answers is given.

"What are the characteristics of the Swedish transport system?"
The demand for road transport, both passenger and freight transport, is coupled to economic growth. In both areas, the coupling is slowly weakening.

"To what extent are biofuels currently used in Sweden?"
Biofuels made up 3% of the energy used in road transport in 2006, the target is 5.75% in 2010. At the moment, no biofuels produced from forest biomass are in use for transport.

"What are the plans of the Swedish government for the transport sector in general, and the introduction of biofuels?"
The aim of the Swedish policy is to break the coupling between economic growth and the demand for road transport. Furthermore, the government uses EU targets for the introduction of biofuels: 5.75% of the energy used in transport has to come from biofuels in 2010, 10% 2020. For 2030, the government proposed to become independent of fossil fuels.

"What techniques are currently available or under development for conversion of biomass to biofuels, and what is their current and expected efficiency?" and " What are reasonable scenarios for the development of the demand for sawwood, paper and pulp, and consequently for the demand of raw materials, until 2050?" are answered in table 2.7.

"What are the efficiencies of current techniques in these sectors, and how are the prospects of increasing this?"; "How are the side products of these sectors currently used?"
The production of sawn wood from sawwood results in half the wood ending up in side products. Woodchips are mainly used in the paper and pulp industry. Bark is mainly used internally, sawdust is used in the particle board industry, or used for energy purposes.
In chemical pulping, the efficiency is less than 50%, mechanical pulping gives yields of over 90%. Increases are unlikely, but more efficient use of side products may be an option. Side products of pulping are combusted to meet the internal needs of pulpmills. Surplus heat, electricity, or bark may be sold.

"What policy does the Swedish government have with regard to the forest industry?"
The aim of the Swedish government is to combine economy and ecology in forest management. With regard to the forest industry, the policy aims at sustainable, high wood yields. No active policy towards the sawmill, and pulp industry was found.

"To what extent is biomass currently used in Swedish DH systems and electricity production?"
In 2007, wood fuels accounted for 44% of the energy used in DH systems. Apart from electricity produced by CHP-plants in the DH sector, wood is hardly used in electricity production.

"What are the plans of the Swedish government with regard to these applications?"
As a consequence of taxation measures, wood fuels are the cheapest fuels in DH. The introduction of Green Energy Certificates has led to an increase in the production of electricity through CHP. No policy is in place to stimulate electricity production from wood in conventional power plants.

"How much woody biomass is annually available in Sweden?"; "How is this area for biomass production expected to change in the future?"
It was found that the total increment is 95 Mm^3sub, the total increment of both sawwood and pulpwood being 43.9 Mm^3sub. These values are unlikely to change.

Finally, table 2.7 gives an overview of the data given in this chapter that will be used later on as input for the model for the wood use in Sweden. In the middle column, the value for 2007 is given, the right column gives the forecasts used for the model, until 2050.

Table 2.7: Overview of data required for the model

	Sawmill industry	
Market demand	20.7 Mm^3 sawn wood	+1.8% annually until 2025, +1.0% afterwards
Price market	SEK 1352/m^3	Constant
	Pulp and paper industry	
Market demand CPaM	7.5 Mton paper	+4.5% annually until 2020, linearly decreasing to 0% growth from 2030 on
Price market CPaM	SEK 5895/tonne	Constant
Market demand MPaM	4.3 Mton paper	+2.4% annually until 2020, linearly decreasing to 0% growth from 2030 on
Price market MPam	SEK 4140/tonne	Constant
Market demand CPuM	3.5 Mton pulp	+1.2% annually until 2020, linearly decreasing to 0% growth from 2030 on
Price market CPuM	SEK 4623/tonne	Constant
	District Heating sector	
Demand heat from biofuels	19.2 TWh	+2% annually until 2027, 28 TWh afterwards
CHP heat:electricity ratio	0.4	
	Electricity sector	
Demand el from wood	0	Demand nonzero only if electricity is needed for electric vehicles, which can not be provided by CHP
	Bioethanol sector	
Fixed production cost	SEK 150/GJ	Constant to 2012; -SEK 5/GJ/y 2013-2017; -SEK 10/GJ/y 2018-2022; -SEK 5/GJ/y to 2027; -1% annually up to 2050
Production efficiency	35%	Linear increase to 45% in 2027, then constant
	FT diesel sector	
Fixed production cost	SEK 115/GJ	Constant to 2012; -SEK 3/GJ/y 2013-2017; -SEK 5/GJ/y 2018-2022; -SEK 3/GJ/y to 2027; -1% annually up to 2050
Production efficiency	42%	Linear increase to 52% in 2027, then constant
Stock sawwood	43.9 Mm^3	-
Stock pulpwood	43.9 Mm^3	-
Stock woodchips	12.2 Mm^3	-
Increment sawwood	43.9 Mm^3/y	Constant
Increment pulpwood	43.9 Mm^3/y	Constant

3. METHOD

In the previous chapter, a number of the research questions stated in the introduction were answered. To answer the remaining questions and the main research question, a model was made to study the consequences of the large-scale introduction of forest biofuels in road transport.
This chapter describes the model made to analyze the wood demand and possible competition for wood between the forest industry and the biofuels industry in Sweden. The model description starts with some general information about Stella, the program used to build the model. Then, a short overview of the model is given, followed by a more extensive discussion of the different components of the model.
Second, different scenarios were used in the modelling, simulating different measures taken to stimulate the introduction of biofuels. These scenarios are described in the second part of this chapter. Finally, an overview of all the data needed as model input is given.

3.1 Stella

The Stella program is developed to model dynamic systems. For this research project, Stella Research 6.0.1 for Windows by High Performance Systems (Hanover, NH, US) is used. The program makes use of stocks to model accumulations of for example wood in forests or production capacity. In the program, stocks can be used to model all things that accumulate, from population to knowledge (MM High Performance Systems, 2000). Secondly, flows into or out of the stock make the stock increase or decrease, respectively. In the case of the stock 'sawwood', the flows affecting the stock are 'increment' and 'fellings': the inflow and outflow, respectively. Thirdly, Stella makes use of converters in order to manipulate the flows. For example, the demand for sawwood is a converter that determines the total fellings of sawwood. Dependencies between stocks, flows and converters can be expressed using connectors.
The model works in iterative steps, i.e. in small time steps. The results of the calculations in time frame X are used as input for time frame X+1, and so on.

In practice, Stella has been used for different purposes, especially modelling of ecosystems (for example Neill *et al.*, 2005). Other applications are modelling the transformation of nitrogen compounds in discharge water (Mayo & Bigambo, 2005), the potential for CO_2 storage in an mature oil field using an enhanced oil recovery technique (Gaspar Ravagnani, Ligero & Suslick, 2009), and even modeling of Hamlet (Hopkins, 1992).

3.2 Brief overview of the wood use model

A model for wood use in Sweden was developed to gain insight in the total industrial demand for wood in Sweden, in the forest industry on the one hand, and the biofuel sector on the other hand. The period considered is the near and medium-term future, until 2050.
The system includes the sawmill industry, the pulp and paper industry, the district heating (DH) sector, electricity production using wood, and 2 biofuels from woody biomass: bioethanol and FT diesel.

The model works as follows: the demand for sawn wood and 3 different kinds of products (which together make up the major part of the production) from the paper and pulp industry are determined. This demand is used to calculate the demand for raw wood: sawwood and pulpwood, that is to be taken from the forests. As the forest industry is export-oriented, with most of the exports going to other European countries, the demand is assumed to increase with the demand on the European market.
In contrast, the biofuels sector is focused on the Swedish domestic market. Therefore, the demand for wood for DH, electricity, and the transport fuels is based on the expected development of the domestic demand.
The wood volume available for felling consists of the annual increment of sawwood and pulpwood and unused stocks of both, as well as side products such as wood chips that enter the market. So, side products that are used internally in the industry are excluded from the model.

Given the supply and demand for wood, the total deliveries of wood are calculated. When the total demand is smaller than the supply, all sectors are able to buy the wood they need. However, when the demand is higher than the supply, the prices that the different sectors can pay, are mutually compared, and compared to the price for wood. From the sectors that can afford wood, the sectors with the highest abilities to pay are supplied with wood, until at some point the available supplies are 0. At that point, the sectors with lowest ability to pay are left without wood supplies.
Then, based on the wood demand and supply, a new price for raw wood is calculated, which is used in the next iterative step of the model.
So, as a response to a changing demand, the system dynamics will try to restore an equilibrium, of supply and demand, through changing prices for raw materials.

3.3 Detailed description of the model

In this section, the functioning of the model is described in more detail than in the previous section. After the determination of the demand for wood in the different sectors, the calculation of the production capacity for the different sectors is discussed. Then, the determination of the total demand for sawwood, pulpwood, woodchips, and other raw materials is described.
Furthermore, modelling of the price development of the raw materials is discussed, as well as the delivery of raw materials to the different sectors.
In order to keep this section structured, the following discussion is divided into a number of subsections.

3.3.1 System boundaries

In total, 8 wood-demanding sectors were taken into account in the model:
- The sawmill industry (SMI)
- Integrated chemical pulp and paper mills (CPaM)
- Integrated mechanical pulp and paper mills (MPaM)
- Market chemical pulp mills (CPuM)
- District Heating (DH)
- Electricity production (El)
- Bioethanol production
- FT diesel production

The paper and pulp sector was split in 3, because of the different production processes and products. Forecasted trends for demand and products prices in these sectors are pointing in different directions. Therefore, it was decided to consider them individually. Market pulp mills, producing pulp for newsprint (i.e. mechanical pulp), make up less than 15% of the market pulp production, and were therefore left out of the model. Instead, the demand for chemical and mechanical market pulp was considered as demand for chemical pulp.
To avoid double counting of wood demand, the wood used to generate electricity in combined heat and power (CHP) plants were included in the district heating sector.

Side products from the forest industry such as wood chips, sawdust, bark, and black liquor were only included in the model if they were sold on the market. In other words: the side products that are used internally to generate process heat or electricity are not taken into account. The particle board industry, which consumes a portion of the sawdust from sawmills, is left out of the model, as this industry is relatively small compared to the other forest industry sectors, its total production volume amounting to less than 5% of the total sawn wood production volume (Swedish Forest Industries Federation, 2009) and inclusion of this sector would increase the complexity of the model. Furthermore, wood extractions for small-scale heating is also found outside the system boundaries.

3.3.2 Determining the wood demand of the forest and biofuels sectors

In this section, the calculation of the demands for wood in the 8 sectors given in the previous section will be described.

The wood demand for the sawmill industry and the paper and pulp sector is determined using the same method.
First, the total market demand for the product of the sector is determined. For the Swedish forest industry, this market is mainly the European market: In the case of the sawmill industry, over 70% of the wood is exported to other countries in Europe, the remainder going to North-African countries and Japan. For the pulp and paper industry, 84% of the pulp, and 86% of the paper production goes to other European countries (Swedish Forest Industries Federation, 2007).
The total demand is determined by taking the 2007 demand combined with a forecasted trend for the development of demand in the future. Products of the Swedish forest industry are only demanded, however, if the sector is competitive in terms of prices. That is, if the sector has product costs lower than or equal to the market costs. Whether this is the case, is determined by the production costs and by the price of raw wood.
The product price is set externally, as the Swedish forest industry operates in a global market, and its market shares are too low to significantly influence product prices. The prices are based on expert forecasts. Taking the market product price, and the fraction of the total production costs that a mill can spend on wood, determines the maximum price the sector can pay for wood. The shares of wood in total costs are set to 65, 22, 18, and 31% for SMI, CPaM, MPaM, and CPuM, respectively. It is assumed that these percentages vary among the different producers. Therefore, the model uses a minimum percentage and a maximum percentage, leading to minimum and maximum total product costs.
The next step is a comparison between the market price and the Swedish production cost (based on the wood price of the previous iterative step of the model). If the Swedish maximum product cost is lower than the market price, the total market demand can be met. If the Swedish minimum cost is higher than the market price, the demand for the Swedish products is 0. If the market cost is found to be lower than the maximum price, and higher than the minimum price, only a part of the Swedish industry is competitive. This fraction is calculated on basis of a triangular distribution, starting from 0% produced as the market price is Swedish minimum price, via 50% production if the market price equals the average Swedish production price, to 100% production if the market price is the maximum Swedish production price.
When the total market demand for forest industry products and the fraction of the Swedish industry that can produce competitively are known, as well as the ratio between product mass and wood volume, the demanded wood volume can be calculated.
Finally, it has to be noted that a part of the total demand for wood from the paper and pulp industry is met by recycled paper. This taken into account in the model.
Summarizing, the demand for wood from the different sectors in the forest industry depends on the competitiveness of the sector in the international market, and the sector's efficiency of production.

The demand for wood from the DH and El sectors are calculated in a similar way, based on the estimated demand for heat and electricity, the efficiency of conversion, and the sectors' ability to pay.
In contrast to the forest industry, the DH and El sectors are not oriented on an international market, but rather on a domestic market with less competition. Wood use is not so much related to market forces, but rather to political decisions and measures influencing fuel prices.

The demand for wood for the transport fuels bioethanol and FT-diesel is calculated from the biofuel demand, efficiency of conversion of wood to fuel, and the price of gasoline. The first 2 parameters, the biofuel demand and the efficiency of conversion determine how much raw wood is needed. The biofuel demand in turn depends on the fraction of biofuels in transport, distances driven, and the fuel efficiency of the average car.
However, whether the sector has the ability to purchase wood is assumed to depend on the oil price and taxation. For gasoline, bioethanol and FT-diesel, the total prices are calculated as the sum of production costs, energy tax, and CO_2 tax. The other costs such as value-added tax and transportation costs are assumed to be the same for all the fuels.
Given the taxation measures in place (depending on the scenario), and the production costs of gasoline, the production costs of the alternative fuels are calculated. The biofuel production costs are split into wood costs and all the ‘other’ costs. Using forecasts for the ‘other’ costs, the maximum wood

costs at which the biofuel is still competitive with gasoline is calculated. This value is assumed to be the price that the transport sector can afford to pay for wood.

3.3.3 Calculation of supplies and price of raw wood

In the previous section, the calculation of the demand of wood from the different sectors was described. In this section, a description of how these demands determine the prices for the different kinds of wood used in the model is presented, as well as the calculation of the amount of wood that is available.

The model takes 4 types of wood into account: sawwood, pulpwood, woodchips & sawdust, and bark. The first is the wood suitable for sawn wood production, the second is the wood of lower quality, not suitable for sawn wood production. Wood chips and sawdust are the rest product of sawmills, useful for all other sectors. Finally, bark is assumed to be useful for electricity and heat production only.
In the model, supplies of wood chips and bark are carried out first (see next section), after which the remaining demands for pulp- and sawwood are calculated.

The supplies of sawwood and pulpwood are modelled in the same way. In the following discussion, sawwood is used as an example.
The sawwood supplies are governed by 2 stocks: the material stock and the price stock. The first stock is the amount of sawwood available for felling. The inflow to this stock is the annual increment of sawwood. The outflow out of this stock is the total deliveries of wood to the different sectors.

The total demand for sawwood is determined by comparing the prices the different sectors can pay for the wood with to the actual sawwood price. Then, the sawwood demand from the sectors that can use and afford the wood is summed. If a sector can both use and afford saw- and pulpwood, it is assumed that this sector will purchase the wood type with the lowest price.
With the total demand and supplies of sawwood known, the new price for the material can be determined, using the price elasticity of demand of sawwood. This elasticity gives the relation between change in price of a product as a consequence of a change in the demand of that product.

For wood chips and bark, the same procedure is followed.

3.3.4 Determining the wood deliveries to the sectors

In the previous sections, the wood demands from the individual sectors were determined, as well as the effect of the total demand on the price of different types of wood. In this section, the deliveries of wood to the different sectors is dealt with.
For the calculation of the total demand for sawwood and pulpwood, the wood demands from the individual sectors are summed. However, the model aims to give insight in where the wood goes. Therefore, the total deliveries of sawwood and pulpwood have to be split over the different sectors.

Determining the deliveries of sawwood and pulpwood are calculated in an identical way. Sawwood is used as an example here. The demands for sawwood from the different sectors are known, and so are the prices the sectors can pay. The prices and demands are known, and the maximum price is sought. The corresponding sector is supplied with the demanded wood. After that, the second-highest price is sought, and the sector that can pay that price is supplied, etcetera, until either all sectors have received wood or until the stock is empty.

Because of the complexity of the modeling of the supply of sawwood and pulpwood, and because the relatively small volumes of wood chips, sawdust, and bark, a different approach was chosen for the calculation of the supply of these side-products.
If the woodchips price is lower than the pulpwood price, sectors will demand chips, in addition to a pulpwood demand. The demand for wood chips from the paper and pulp industry is limited to maximally 25%. Then, the ratio between woodchips supply and demand is calculated. If the demand is lower than the supply, all sectors are supplied with as much wood chips as demanded. Otherwise, all sectors receive a fraction of the wood chips in proportion to the share of the sector’s demand in the

total demand. So, it is assumed that there is no competition for woodchips in the sense that some sectors will not be able to purchase woodchips. The supplies to each sector may however be limited as a consequence of competition.
For the supplies of bark, the same procedure is followed as for wood chips.

Finally, the total deliveries of wood to a sector are calculated by summing the deliveries of sawwood, pulpwood, wood chips and possibly bark to that sector.

3.3.5 Side products

In the description of the production processes in the sawmill, paper and pulp industry, it was shown that considerable amounts of wood end up as side products. Some are used internally, some are sold on the market.
The wood volumes that end up in side products are calculated from the total deliveries of wood to the different sectors and the fraction of raw wood that end up in side products. In order to calculate how much wood enters the market rather than being used internally, the fraction of side products that enter the market is used in the model. In practice, this fraction is set to 0 for all sectors, except for wood chips and sawdust from the sawmill industry.

3.3.6 Transport demand

The final part of the model described here is the part that calculates the demand for road transport, and the corresponding demand for renewable transport fuels.
The model makes distinction between passenger and freight transport. The former includes passenger cars and a fraction of the light freight vehicles, the latter category is formed by all freight vehicles except for some light vehicles, and all busses. The inclusion of busses in freight transport is based on the energy use per km driven.

In the literature chapter, it was shown that the demand for transport is coupled to economic growth. In the model, economic growth, combined with this coupling, is used to determine the increase in transport demand. The increase of transport demand is then added to a stock called transport demand. This is done for both passenger and freight transport.
The stock of passenger cars consists of fossil fuel, bioethanol and electric vehicles, the freight transport stock is made up of fossil fuel and FT-diesel vehicles. Every year, percentage of the stock is replaced, the percentage depending on the average lifetime of Swedish vehicles. The fuel type of the new vehicles is based on the consumer fuel costs. These costs are calculated as the sum of production cost of the fuel, energy tax and CO_2 tax. All other taxes and costs are assumed to be the same for all fuels. The car having the cheapest fuel is most popular with consumers, so that most of the new cars are fuelled with this type of fuel. The percentage of consumers that is modelled to buy the vehicle type with the cheapest fuel can be varied, which leaves room for the inclusion of subsidies in the model.
When the total distances travelled and the composition of the vehicle stock are known, the wood use for transport is calculated.
The total demand for wood from the biofuels sector (including the wood needed to generate the electricity for electric vehicles) is calculated from the energy use per km driving, the efficiency of producing the biofuel from wood, and the energy contained in a given volume of wood determine the wood use.

In the transport demand part of the model, different tax measures and heights, different couplings between economic growth and transport demand, and subsidies for biofuel vehicles purchase can be used as input. In this way, different scenarios can be drawn.

3.4 Scenarios

In order to describe possible paths for the introduction of transport biofuels in Sweden, different scenarios have been designed.
The aim of the scenarios is to illustrate the introduction of biofuels so that an increasing percentage of the Swedish fuel demand is covered by renewable fuels. However, the pathways leading to fulfilling this aim are different.

The names of the scenarios mainly refer to the situation in which the export-oriented Swedish forestry sector has to operate. So, in the market scenario, it is assumed that the sawmills, paper and pulp industry have to deal with a situation in which market forces play a dominant role. In the subsidy scenario, the role of policy is larger, with governments setting targets, and providing financial means to reach these aims. In order to allow comparison between the scenarios, all model inputs not directly related to the pathways for introducing biofuels, such as forest product demand and prices, are kept the same.
In the next sections, the scenarios as well as the data used as inputs for the model, corresponding to the scenarios are given. Finally, all other data needed to run the model are given.

3.4.1 Targets for the introduction of second and third generation biofuels and choice of biofuels

In the literature chapter, the targets for the introduction of biofuels in the transport system were described: 5.75% (on energy basis) biofuels in 2010 and 10% in 2020, and the intention towards independence of fossil fuels in 2030.
There are no current aims for the percentage of biofuels that have to be produced domestically or from domestic forest resources. Therefore, assumptions were made.

In this research project, it is assumed that the proposed target for 2030 is adjusted so that independence of fossil fuels will become the target for 2050. In for the earlier years, less ambitious targets are set. Furthermore, assumptions were made for targets of the fraction of the biofuels that have to be produced from Swedish biomass, and the percentage of this produced from wood. The aims that follow from these assumptions are found in table 3.1.

Table 3.1: Assumed aims for the introduction of biofuels in the Swedish road transport sector, 2007-2050

Year	Total biofuels (%)	of which domestic biofuels (%)	of which wood-based biofuels (%)	Net fraction wood-based biofuels[1] (%)
2010	5.75	50	0	0
2020	10	50	50	2.5
2030	25	60	75	11.25
2040	60	100	75	45
2050	100	100	75	75

1: Biofuels include bioethanol, FT-diesel, and electricity

In table 3.1, the second column gives the total share of biofuels in the road transport energy use in the year given in the first column. The third column is the share of biofuels from domestic resources, and the fourth column gives the share of the domestic biofuels that are assumed to be produced from forest biomass. The last column is the total share of domestic, wood-based biofuels in the road transport sector in the given year.
These values are used as targets for both the passenger and freight transport sector. The targets refer to the entire Swedish road transport sector. Electricity produced by wood combustion for use in electric vehicles is considered a biofuel. No obliged blending in of forest biofuels with fossil fuels was assumed.
The feasibility of the targets given in table 3.1 will be tested using scenarios described below.

3.4.2 The CO_2 price scenario

In the world of this scenario, market forces focussing most on short-term issues and profits, are more important than in the subsidy scenario. Even though there is awareness that economic growth can not go on infinitely at the expense of natural resources, it is still given priority. Environmental problems are preferably solved with technical measures rather than prevention or behavioural change.
In this world, the Swedish government is willing to support the introduction of biofuels. If not for climate-change related issues, this policy is a continuation of the policy to grow independent of imported fossil fuels. However, the government does not take an active role to introduce biofuels as was the case in the subsidy scenarios. No subsidies are given to promote for example the introduction of a specific biofuel. The government rather sets a binding target, and then leaves it to market parties to find solutions to reach that target in some way or another. A general measure that is in place is to

introduce biofuels in general, and to abandon fossil fuel use, is a price on the production of CO_2 from non-renewable sources.

As of 2009, CO_2 and energy taxes are in place for transport fuels, from which biofuels are exempt until 2013. The current exemption of biofuels from energy tax will stop after 2013 in this scenario. From then on, the energy tax will be as high as for fossil fuels: SEK 90/GJ. However, the exemption of biofuels from CO_2 tax will remain in place after 2013. Instead, the CO_2 tax for fossil fuel is changed. 3 Levels of these taxes are considered in different sub-scenarios: half the current price of SEK 910/ton CO_2 or SEK 65/GJ, the current price, and twice the current price.
As a consequence of changing the CO_2 prices, the costs for the forestry industry will also change. Currently, industries have a CO_2 tax exemption of almost 80%. This exemption is assumed to remain in place.
Several authors note that the indirect effect of rising electricity prices, caused by the European Union Emission Trading Scheme, may have more consequences than only the direct effect of the CO_2 tax (Brännlund&Lundgren, 2007; Johansson, 2006). Taking the indirect effect into account, Johansson (2006) calculated an increase in production cost of 0.15% for every SEK 100 added to the CO_2 tax for the sawmill industry. For the paper and pulp industry, this percentage is 0.82. These data were used for the CO_2 price scenario.

In this scenario, no measures influencing consumers' choices when replacing their vehicles are assumed to be in place. Therefore, the replacement of the vehicle stock is done in such a way that 95% of the replaced vehicles is of the type which uses the cheapest fuels. Depending on the number of other fuels available on the market, the remaining 5% goes completely to the vehicle types fuelled by the second-cheapest fuel, or is split over the 2 other fuels as indicated in table 3.2 for the 'no subsidies'case.

3.4.3 The subsidy scenario

This scenario is based on the idea of a world in which most people are convinced that a transition to a sustainable economy is needed, whilst a minority of the people doubt the urgency or potential impacts of problems such as global warming, and stress that radical solutions will be too costly. Therefore, a compromise between the 2 fractions of the population has to be found. This results in political forces becoming the determining factors for the introduction of biofuels. Governments set goals for the introduction of transport biofuels, and help companies and consumers to fulfil these goals by taxes and subsidies, possibly without compromising the economic growth.
For the transport sector, this means that the government tries to steer people into buying cars that are fuelled by renewable energy sources. Furthermore, the government aims to change the transport mode of passengers and freight, thus breaking the coupling between transport demand growth and GDP growth.
In this context, the measures used for the model are subsidies and taxes. Subsidies are used to convince people to buy biofuel vehicles, even though these vehicles may not be the vehicles with the lowest fuel costs. Taxes are used to raise the price of fossil gasoline and diesel compared to biofuels, thus making the latter more competitive.
At the moment, biofuels are exempt from CO_2 and energy taxes. The government is planning to have these exemptions in place until 2013. After that, the CO_2 tax exemption of biofuels is assumed to remain in place. The energy tax exemption is (partly) lifted. 3 levels of this tax are used for the different scenarios: no exemption, half exemption, and full exemption.
The subsidies applied in this scenario are direct subsidies to consumers. When they purchase a new vehicle which is fuelled by a biofuel (including electricity), they receive a financial reward. This subsidy is assumed to be in place only when the operational costs of biofuels are higher than those of fossil fuels. 3 Levels of subsidies are modelled: no subsidy, low subsidy, and high subsidy.
In the situation without subsidies, it is assumed that 95% of the consumers purchases the vehicle with the lowest operational cost. The remaining 5% of the consumers buy vehicles fuelled by the other fuel(s). In the low subsidy scenario, if fossil fuels are the cheapest option, the percentage of consumers purchasing a biofuel-vehicle is increased to 15%. In the high scenario, the percentage increases further to 25%. When fossil fuels are the second-cheapest fuel, only the more expensive fuel is modelled to

receive subsidies. When fossil fuels are the most expensive option, the subsidy scheme is stopped. Table 3.2 gives a detailed overview of all the percentages used for replacement of the vehicle stock under the different scenarios and different relative prices of fossil fuels.

Table 3.2: Assumptions on fuel use in new vehicles as a function on relative price and subsidy regime

	Fossil cheapest			Fossil second			Fossil most expensive		
Scenario	fuel 1[1] (%)	fuel 2 (%)	fuel 3 (%)	fuel 1 (%)	fuel 2 (%)	fuel 3 (%)	fuel 1 (%)	fuel 2 (%)	fuel 3 (%)
No subs., 2 fuels[2]	95	5	-	95	5	-	-	-	-
No subs., 3 fuels	95	4	1	95	4	1	95	4	1
Low subs., 2 fuels	85	15	-	95	5	-	-	-	-
Low subs., 3 fuels	80	15	5	95	3	2	95	4	1
High subs., 2 fuels	75	25	-	95	5	-	-	-	-
High subs., 3 fuels	70	25	5	95	2	3	95	4	1

1: fuel 1 is the cheapest fuel, fuel 2 is more expensive, fuel 3 is the most expensive
2: number of fuels are the number of competing fuels on the market

With 3 different tax options, and 3 subsidy levels, no less than 9 different scenarios can be made. As also the model will also be run for different oil and forest industry prices, the number of possible scenarios increases even further. Therefore, not all possible scenarios were put into the model. This chapter will conclude with an overview of the scenarios that have been used (see section 3.4.7).

3.4.5 A special case: the sustainability scenario

A third scenario is the sustainability scenario. In fact, this is a combination of the subsidy and CO_2 price scenarios. In the sustainability scenario, the world is aiming at a quick transition to a renewable world. There is consensus that environmental and climate problems need to be solved. In order to do so, the government takes the lead and sets aims. These aims have to be reached through a combination of subsidies and taxes.

The introduction of biofuels is stimulated through subsidies for biofuel vehicles, and taxes on non-renewable CO_2 emissions and on fossil energy use to make biofuels competitive with fossil fuels.

For this specific scenario, the high subsidy regime from table 3.2 is used, as well as CO_2 and energy tax exemptions for biofuels. For fossil fuels, the current CO_2 prices will be doubled, and the energy taxes will stay in place.

Replacement of the vehicle stock is done on basis of the percentages given in the 'high subsidies' scenario in table 3.2.

3.4.6 Other data required for the model

So far, the scenarios have only taken measures in the transport sector into account. However, for the other sectors included in the model, data are needed to make the model run. In the end of the literature section, the data found from the literature study were presented (see table 2.7). In addition to these data, table 3.3 gives an overview of the remaining data required for the model. Most data used are from 2007, because this was the most recent year from which an almost complete data set could be made.

In the table, wood chips is the only side product mentioned. Sawdust is taken into account in the model as wood chips. Other side products are assumed to be used for internal use in the forestry sector, and not used in the model.

The prices of sawwood and pulpwood are the unweighted averages of 2007 prices for pine and spruce sawlogs and pulpwood, respectively (Swedish Forest Agency, 2008).

The price elasticity of the wood deliveries was set to 0.30, the value found for the Finnish forestry sector in the period 1960-1992 (Toppinen&Kuuvulainen, 1997). Own calculations showed the average elasticity for the Swedish pulpwood price in the period 1995-2007 was 0.32, but with large variations.

Finally, the share of recycled paper was set to 0.20. In 2007, the actual fraction of recycled fibres in the Swedish paper and pulp sector was 0.14 in 2006 (Swedish Forest Industries Federation, 2007), but 0.20 was used to calibrate the model. Keeping all factors unchanged, assuming 20% recycled fibres made the model show steady-state behaviour.

Table 3.3: List of data used as input for the model, per sector

Wood supply	
Price sawwood	444 SEK/m^3
Price pulpwood	262 SEK/m^3
Price woodchips	236 SEK/m^3
Price elasticity raw wood	0.3 (sawwood, pulpwood, wood chips)
Fraction recycled fibres	0.2 (all sectors)
Sawmill industry	
Production capacity SMI	21.7 Mm^3/y sawn wood
Ratio product:raw SMI	0.5 m^3/m^3
Pulp and paper industry	
Production capacity CPaM	7.9 Mton/y paper
Ratio product:raw CPaM	0.21 $t_{product}/m^3_{wood}$
Production capacity MPaM	4.4 Mton/y paper
Ratio product:raw MPaM	0.37 $t_{product}/m^3_{wood}$
Production capacity CPuM	3.8 Mton/y pulp
Ratio product:raw CPuM	0.19 $t_{product}/m^3_{wood}$
District Heating sector	
Production capacity DH	19.2 TWh biofuels-based heat
Max price for wood	SEK 265/m^3 wood in 2007, increasing with increase GDP
Electricity sector	
Production capacity El	0
Max price for wood	SEK 265/m^3 wood in 2007, fixed
Bioethanol sector	
Production capacity BioEtOH	0
FT diesel sector	
Production capacity FT	0
Road transport	
Coupling passenger transport demand & GDP growth	0.95 in 2007, decreasing 0.02 annually
Coupling freight transport demand & GDP growth	0.80 in 2007, decreasing 0.015 annually
Replacement rate passenger	5.88% (lifetime of vehicle assumed 17 years)
Replacement rate freight	7.70% (lifetime of vehicles assumed 13 year)
Distance travelled passenger	66028 Mvkm
Distance travelled freight	12570 Mvkm
Energy use, ICE passenger	2.2 MJ/vkm in 2007, linear decrease to 1.1 MJ/km in 2050
Energy use, ICE freight	19.2 MJ/vkm in 2007, linear decrease to 15 MJ/km in 2050
Energy use, electric vehicles	0.75 MJ/vkm in 2007, linear decrease to 0.40 MJ/km in 2050
Energy content wood	6840 MJ/m^3s (based on Swedish Forest Agency, 2009; 1 MWh = 3600 MJ)
Other Parameters	
GDP growth	2% per year

The production capacities in these forestry sectors were based on the 2007 production capacities (Swedish Forest Industries Federation, 2009). The ratios between product output and wood input were calculated from process efficiencies (Johansson, 2007 for sawmills; Joelsson&Gustavsson, 2008 for paper and pulp industry), and filler content of paper (Holmberg&Gustavsson, 2007).

For the DH sector, the production capacity is based on the 2007 wood-based heat deliveries (SCB, 2008). The maximum wood price was based on the unweighted average wood chip price in North and South Sweden in the period 2003-2005 (Swedish Forest Agency, 2008), and was assumed to grow as fast as GDP. Production capacity for electricity from wood was set to 0, as explained in the literature section.

For the transport sector, the coupling between transport demand and economic growth was calculated from the GDP growth and transport demand growth in the period 2005-2008 (SIKA, 2006; 2007; 2009). The replacement rate is based on the number of newly registered cars and the total Swedish car stock in the period 2000-2009 (SCB, 2009). The distances covered in 2007 were taken from SIKA (2009).

3.4.7 Overview of the scenario's

With the measures discussed in the previous sections, a large number of scenarios can be drawn, especially when different oil prices and price developments for the products of the forest industry are used. Not all of these scenarios are as likely to become reality. A number of reasonable scenarios have been tested using the model. These are listed in the table 3.4. This table is a summarized answer to research question 1.4 ("What are reasonable scenarios for greening of the Swedish transport sector by 2050").

Table 3.4: Overview of the scenarios

	CO_2 Price Scenario		
Name	CO_2 tax		
C1	low		
C2	average		
C3	high		
	Subsidy Scenario		
Name	Energy tax	Subsidy	
S1	high	no	
S2	average	low	
S3	low	high	
	Sustainability Scenario		
Name	Energy tax	Subsidy	CO_2 tax
Su1	low	high	high

For the subsidy scenario, the height of the subsidies is varied between no, low, and high subsidies as set out in table 3.2. In this scenario, the energy tax for transport biofuels can be high, average, and low: as high as for gasoline, half the gasoline energy tax, and a full exemption.

For the CO_2 price scenario, the CO_2 prices for fossil biofuels can be low, average, and high, which means half, once, and twice the current CO_2 taxes.

4. RESULTS

In this chapter, the results for the model runs are given. Rather than presenting all data for all the models, one scenario (C2) is described extensively to explain the functioning of the model. Then, the results for the other scenarios are compared to this scenario, to indicate the differences and similarities. The results are summarized in 2 tables in section 4.5, showing the percentages of forest biofuels in transport and giving an overview of the outcomes of the competition for wood.
The results presented here answer the research questions 1.6, 2.5, and 3.3:

- How does the requirement for biomass depend on the (mix of) transport biofuels chosen for implementation?
- What are the consequences of a large-scale introduction of transport biofuels made from wood for the forestry sector?
- What are the consequences of a large-scale introduction of transport biofuels made from wood for the district heating and electricity production sector?

Graphs with the complete results for the model runs can be found in the appendix.

4.1 Scenario C2

In scenario C2, biofuels were exempt from CO_2 taxes. An energy tax exemption for biofuels is in place until 2013. The CO_2 price for the production of fossil CO_2 is as high as the current tax: SEK 910/tonne CO_2 for general customers, and SEK 190/tonne CO_2 for the industry.
First, graph 4.1 shows the changes in the composition in the car fleet in the period 2007-2050. For the passenger transport sector, the graph shows that the market share of vehicles that drive on bioethanol is limited. This means that the fuel can not compete with fossil gasoline in the first part of the modelled period, and later not with the electric vehicle. After its market introduction in 2020, the electric vehicle is the cheapest option, and quickly gains market share. Looking at the freight transport sector, it can be seen that FT-diesel vehicles quickly gain some market share in the period 2011-2013. The introduction then stagnates for almost a decade. FT-diesel is no longer exempt from biofuels, which makes it no longer competitive with fossil diesel. However, after 10 years biodiesel is once again competitive, and FT-diesel vehicles start to take over the market for freight vehicles.

Figure 4.2 (next page) gives the development of transport demand in Sweden in the period 2007-2050. With the coupling between GDP growth and transport demand loosening, the transport demand slowly levels off.

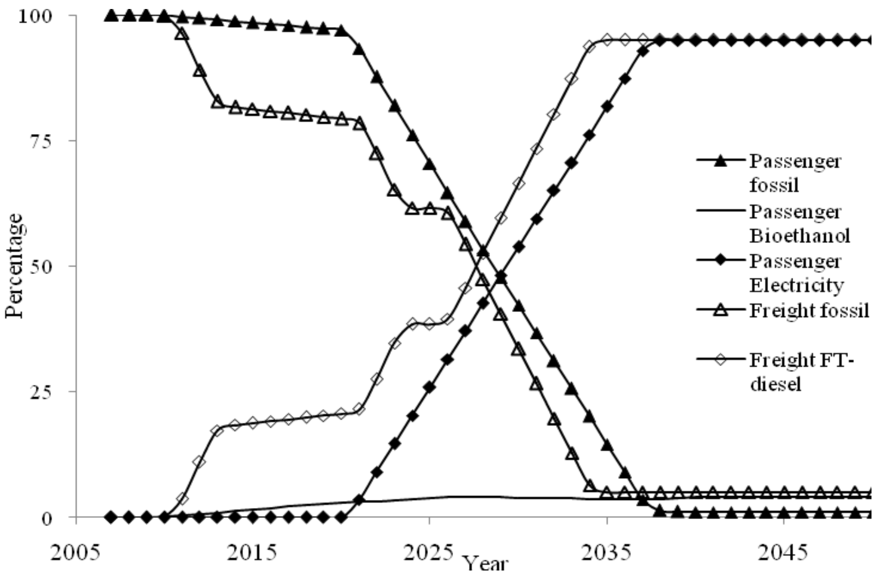

Figure 4.1: Composition of the passenger and freight vehicles fleets

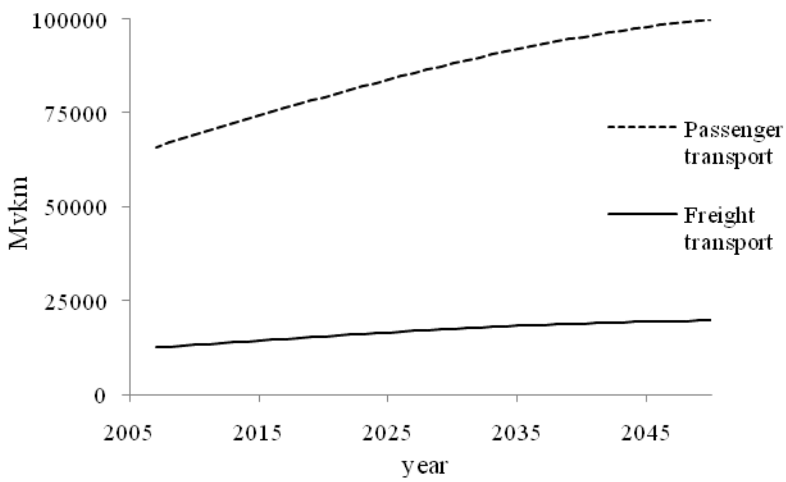

Figure 4.2: Demand for passenger and freight transport in Sweden, 2007-2050

From the total demand for transport and the share of biofuel-vehicles, the total demand for wood from the transport sector can be calculated.

The ability to pay (ATP) of the bioethanol and FT-diesel producers are compared with the ATPs of the other sectors in figure 4.3. The ATPs of the biofuels producers are relatively high when the sectors enter the market in 2011. When the energy tax exemption for biofuels is lifted in 2013, the ATP drops considerably. From then on, however, it increases again: the oil price rises and the production costs of biofuels production decrease. These effects increase the competitiveness of the biofuels producers.
From the forecasts of forestry product prices as given in table 2.7 (no change in price), it follows that the ATP of the sawmill, pulp and paper sectors does not increase. The ATP of the district heating (DH) sector increases as fast as the GDP growth, which was set to 2% annually (see table 3.3). The ATP of the electricity producers was constant (see table 2.7).

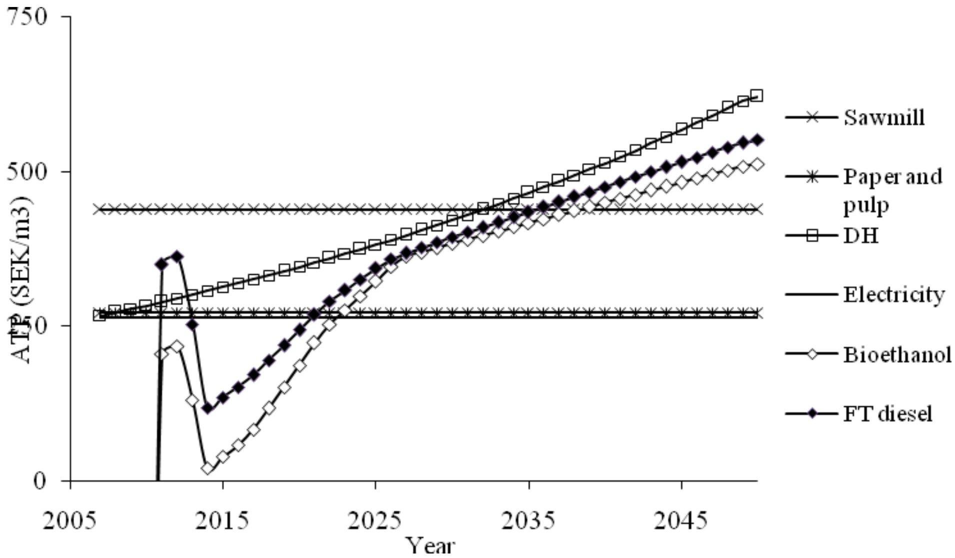

Figure 4.3: Development of abilities to pay for wood of the different sectors, 2007-2050

The figures 4.4 and 4.5 give the total demand for wood of the different sectors and the wood deliveries to the sectors. The electricity demand and deliveries are left out, as they were both 0 in the modelled period, indicating that enough additional CHP is installed in the DH sector to cover the electricity demand of the electric vehicles. For the sawmill industry, the wood demand is limited by the availability of saw wood. For the DH sector, the demand follows the forecast given in table 2.7. The wood demand for bioethanol and FT-diesel is calculated on basis of the data given in the graphs 4.1 and 4.2, using the efficiencies given in table 2.7.

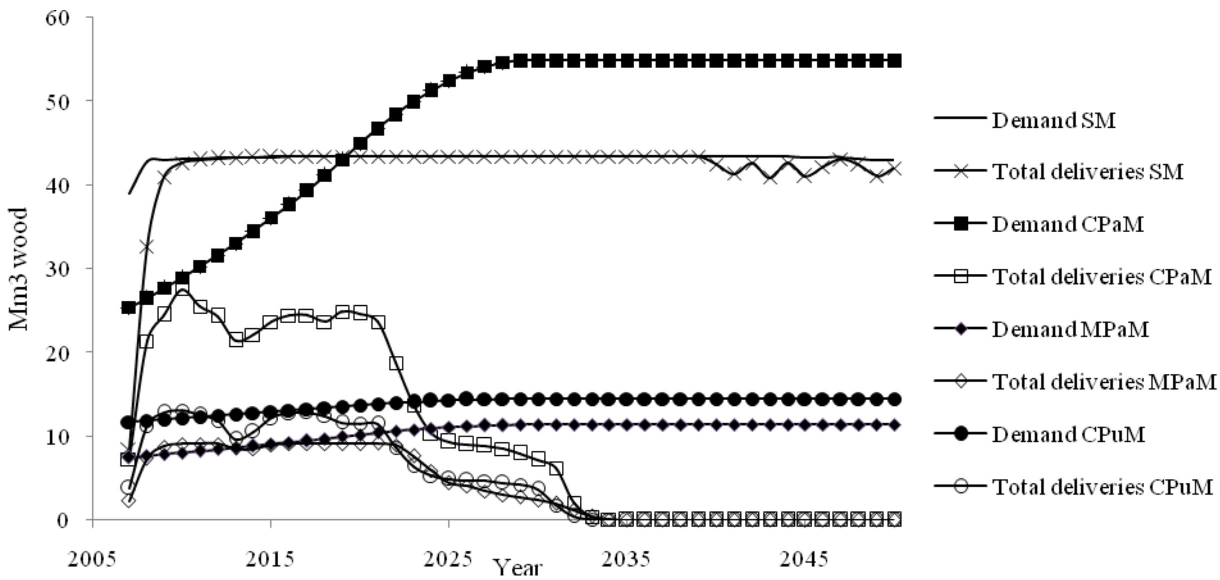

Figure 4.4: Demand and delivery of wood to the sawmill, pulp, and paper industry in Sweden, 2007-2050

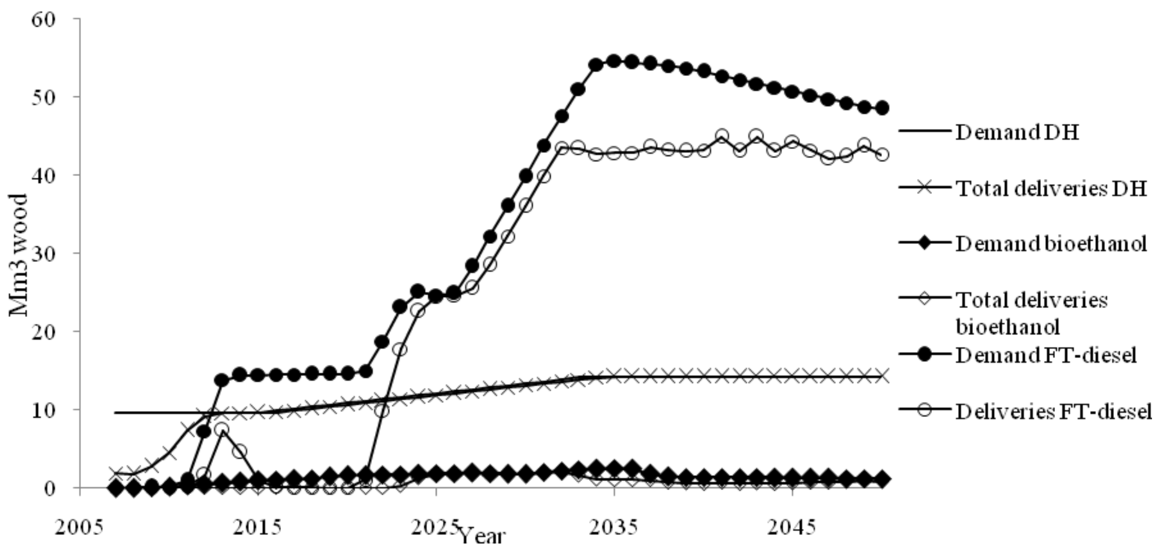

Figure 4.5: Demand and delivery of wood to the DH and transport fuels sectors in Sweden, 2007-2050

The figure shows that the ATPs of both the bioethanol and FT-diesel producers are initially too low, so that the sectors can not compete for wood with other sectors. However, from figure 4.3 it can be seen that between 2020 and 2025 the ATP of the biofuel producers becomes higher than the ATPs of the different sectors in the pulp and paper industry. From then on, the biofuel producers start to buy all the pulpwood. In the next 10 years, before 2035, the complete pulp and paper sector has to close down.

As a consequence of the high demand for wood from the transport biofuel producers, the sawwood prices also go up. Towards 2050, the sawmill industry now and then faces small difficulties in purchasing wood.

Graph 4.5 shows that considerable amounts of wood are allocated to the producers of biofuels, mainly the FT-diesel sector. Graph 4.6 (next page) gives the total share of biofuels in the road transport sector, on an energy basis for scenario C2, along with the percentages for the scenarios C1 and C3 which will be discussed in the next section. The graph shows that the target is not met in 2020. However, for later years, the targets are met. Looking at the ATPs of the forest biofuels producers, it is not surprising that the target for 2020 is not met.

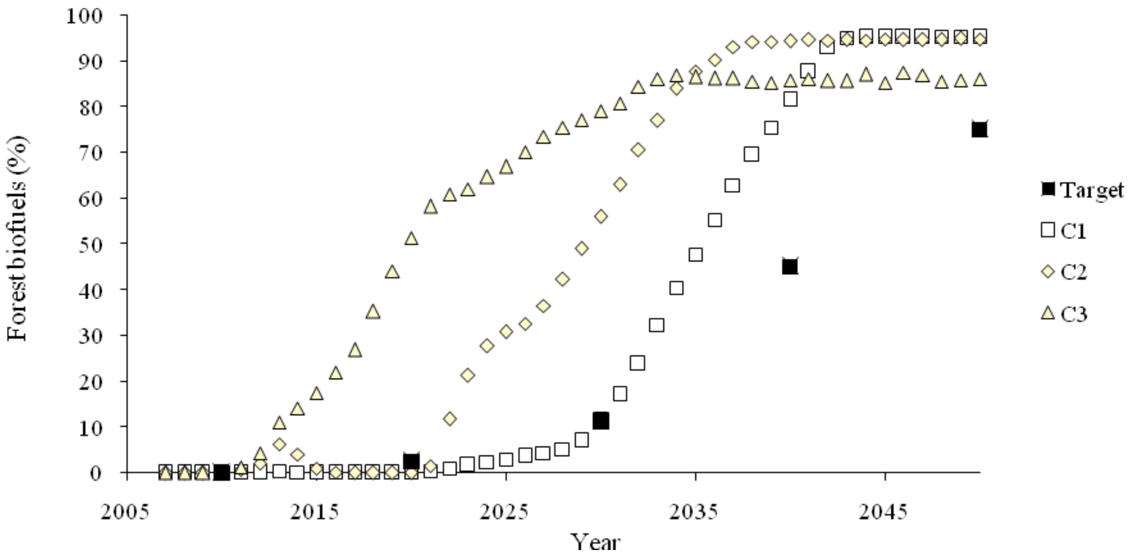

Figure 4.6: Percentage of biofuels in transport on energy basis for the CO_2 price scenarios, 2007-2050

Summarizing, graphs 4.4 and 4.5 show that the growth of the biofuel-producing sectors will come at the expense of the pulp and paper industry. As shown in graph 4.6, the targets set for the introduction of biofuels are met from 2030 onwards. The target for 2020 is not met, as the biofuel producers can not compete with the other sectors for wood from 2020-2025 onwards.

4.2 Results scenarios C1 and C3

In this section, the results obtained for the scenarios C1 and C3 are compared with the results of scenario C2, which were described in the previous section. In scenario C1, the CO_2 price was half the value used in C2; in C3 the price had doubled to SEK 1820/tonne CO_2.

In scenario C1, the lower CO_2 tax results in a slower introduction of biofuels in the transport sector. It takes to around 2030 before the producers of bioethanol and FT-diesel can purchase wood. As a consequence, the target set for the biofuels introduction is just met in 2030, the targets for 2040 and 2050 are easily met. The consequences of the biofuel producers entering the market are the same as in scenario C2: the pulp and paper industry loses the competition, even though it does not completely disappear in this scenario. The DH sector and the sawmill industry have no problems purchasing the wood they need.

In scenario C3, the introduction of higher CO_2 taxes leads to a quicker introduction of biofuels in the road transport sector. FT-diesel and bioethanol producers can compete with the pulp and paper industry as soon as the production techniques are market-ready in 2011. Because the energy demand per km driven, and consequently the wood demand, decreases with time, earlier introduction of biofuels leads to a higher wood demand. As a consequence, the wood demand of the transport sector is higher. This leads to the prices of sawwood and pulpwood to increase. Not only the pulp and paper industry are affected, but the sawmill industry and the DH sector are affected as well. The former closes down completely, the latter has to switch partly to another fuel. As a consequence, only some electricity is produced for electric vehicles. However, the targets for the introduction are met.

In figure 4.6 the rates of biofuels introduction are compared for the 3 CO_2 price scenarios.

4.3 Scenarios S1, S2, and S3

In this section, the results of the Subsidy scenarios are given, by comparing them to the results of scenario C2. In all the Subsidy scenarios, biofuels were exempt from CO_2 tax. Furthermore, subsidies were introduced to improve the rate of introduction of biofuel vehicles.

Scenario S1 was based on no biofuel vehicle purchase subsidies, and an energy tax that is as high for biofuels as it is for fossil fuels. The changes in the composition of the car fleet are comparable to those

shown for scenario C2 in figure 4.1. The biofuels producers start to compete for wood in the period 2020-2025, leading to closing down of the pulp and paper industry by 2035. The sawmill industry and the DH sector not affected by the competition. So, the results are very similar to those described for scenario C2 in section 4.1.
In scenario S2 low subsidies for purchasing biofuel-powered vehicles were introduced, and a 50% exemption of the energy tax for biofuels. As a consequence of the subsidies, the share of bioethanol vehicles in the passenger car fleet reaches 18% in 2020, compared to 5% when no subsidies are in place. However, in the first couple of years the ATP of the bioethanol producers is low, so their wood demand can not be met. After 2020, the electric vehicles take over the market. In contrast to bioethanol, FT-diesel is competitive with fossil fuels immediately after its market introduction in 2011, leading to a rapid introduction of this fuel. Because of the higher demand of wood from the bioethanol and FT-diesel producers, combined with the high ATP of these sectors, first the pulp and paper sector is driven off the market. Compared to scenario C2, this closure happens 10 years earlier, before 2025. In addition to that, the sawmill industry and DH sector can no longer purchase wood around 2035.
In scenario S3, higher subsidies were introduced, as well as a full exemption from energy tax. This leads to a high fraction (approximately 40%) of bioethanol vehicles in the passenger vehicles stock. Again, FT-diesel is competitive with fossil diesel from its market introduction onwards. As the demand for wood in this scenario is even higher than in scenario S2, the consequences for the other sectors are the same as in that scenario: the prices rise too high for all the other sectors to be able to compete.

Scenario S1 was very similar to scenario C2, and the targets for the introduction of biofuels were met from 2030 on for this scenario. For S2 and S3, the target set for 2020 was also met. Figure 4.7 shows the percentage of biofuels in the road transport sector produced from Swedish wood for the scenarios S1, S2, and S3.

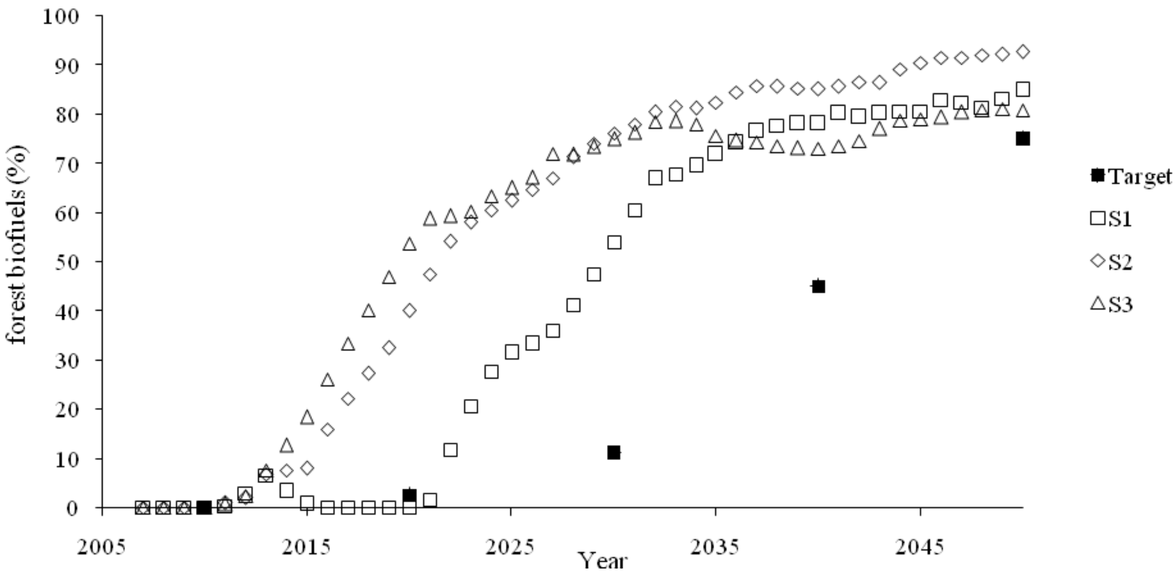

Figure 4.7: Percentage of biofuels in transport on energy basis for the Subsidy scenarios, 2007-2050

4.4 Results sustainability scenario

In the sustainability scenario, the high subsidies for purchasing biofuel-driven vehicles and a full exemption of biofuels of energy tax from the subsidy scenarios are combined with a doubling of the CO_2 price from the CO_2 price scenario.
In this scenario, the combination of taxes leads to bioethanol and FT-diesel being competitive with fossil fuels immediately after their market introduction. As a consequence, they rapidly gain market share. The highest share of bioethanol is around 60% in 2025, then declining after the introduction of

the electric vehicle. The high market shares for bioethanol and FT-diesel, combined with a high ATP for wood for the producers of these fuels, lead to a quick rise in wood prices. The consequences for the other sectors are the same as in the scenarios S2 and S3: the sawmill industry and the DH sector can no longer pay for the wood they need, so that the former sector has to close down and the latter has to look for another fuel. As was the case in S2 and S3, the targets for the introduction of biofuels were met. Figure 4.8 shows the percentages of biofuels in the transport sector.

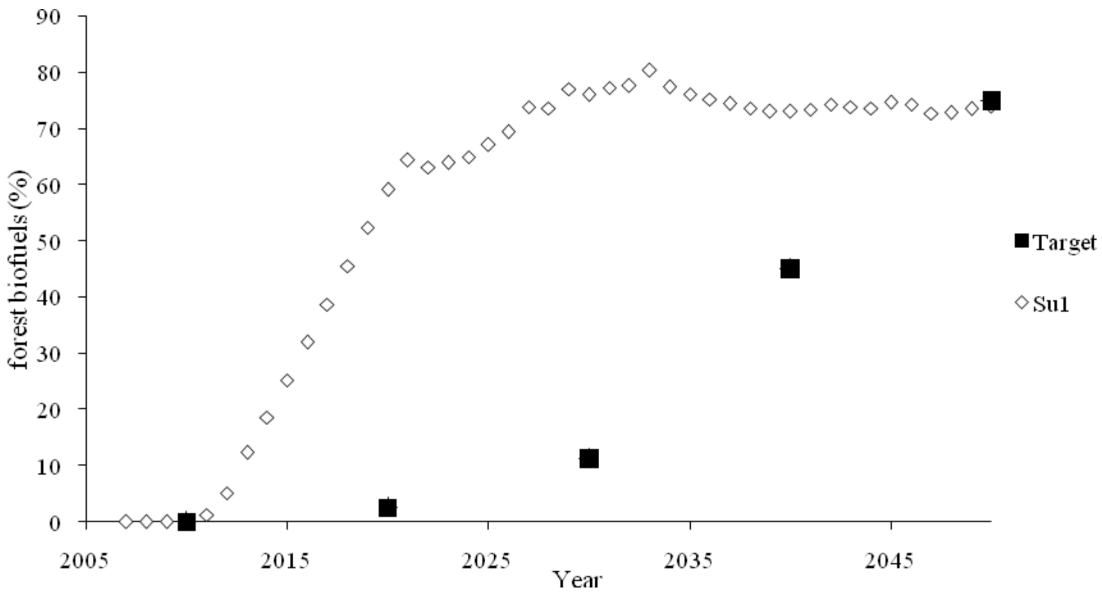

Figure 4.6: Percentage of biofuels in transport on energy basis for the Sustainability scenario, 2007-2050

4.5 Summary of the results

In table 4.1 a short summary of the results obtained will be given. For each of the scenarios, the fraction of biofuels in the transport sector is given, as well as the aim set for that year. This table answers research question 1.6, about the share of biofuels in transport.

In table 4.2, the results of the competition for wood are summarized, answering the research questions 2.5 and 3.3, dealing with effects of competition for wood on the different sectors. If a sector lost the competition for wood, resulting in closing down of the entire sector, it is given a (--) in the table. If a sector lost the competition, but survives at a lower production level, it is market with a (-). If the sector is unaffected, it is indicated with (0). When a sector has grown, but not its complete demand met, it has a (+). If a sector has won the competition for wood, and is able to purchase the complete amount of wood needed, it is given a (++). Table 4.2 refers to the situation in 2050, compared to 2007.

Table 4.1: Percentages biofuels in total road transport energy use for the different scenarios

Scenario	Aim 2010	Actual 2010	Aim 2020	Actual 2020	Aim 2030	Actual 2030	Aim 2040	Actual 2020	Aim 2050	Actual 2050
C1		0		0		12		82		95
C2		0		0		56		94		95
C3		0		51		79		86		86
S1	0	0	2.5	0	11.3	54	45	78	75	85
S2		0		40		76		85		93
S3		0		54		75		73		81
Su1		0		56		76		73		75

Table 4.2: Outcome of the competition for wood: winners and losers

Scenario	SMI	CPaM	MPaM	CPuM	DH	El	BioEtOH	FT-diesel
C1	0	-	-	-	0	0	+	+
C2	-	--	--	--	0	0	+	+
C3	--	--	--	--	--	-	+	+
S1	0	--	--	--	0	0	+	+
S2	--	--	--	--	--	-	+	+
S3	--	--	--	--	-	-	+	+
Su1	--	--	--	--	--	-	+	+

Table 4.2 shows that the different sectors of the pulp and paper industry are affected most by the introduction of wood-based biofuels in the transport sector. The sawmill industry and DH sector are affected in some scenarios. In the scenarios where the wood deliveries to the DH sector drop, a demand for wood-based electricity production will arise. This demand can not be met. By the end of the modelled period, the producers of bioethanol and FT-diesel are the winners of the competition.

5. DISCUSSION

In the following chapter, the results in the previous chapter are discussed. First, the assumptions made in the modelling process are discussed, as well as their consequences. The extent to which these assumptions have an effect on the results, can not be assessed using the model, but are discussed in section 5.1. Then, a sensitivity test is used to determine how the model reacts to changes in the input values. In this way, the results can be validated. After that, some general findings are discussed. Finally, the results obtained for the different scenarios are discussed.

5.1 About the model

When the model was made, assumptions were made, too. In the following, the most important assumptions and their consequences are discussed.

First, an important assumption made in the model is that, even when a sector can both afford sawwood and pulpwood, the sector demands only the raw wood source that is cheapest. This assumption was made to prevent the model to become too complex.

As a consequence, sawwood is demanded only by the sawmill industry for the largest part of the modelled time in the majority of the scenarios. For most of the scenarios tested, this assumption does not appear to have significantly affected the results. In most cases, the district heating (DH) and transport fuel sectors' ability to pay (ATP) for wood increases with time, reaching a point at which they could theoretically purchase sawwood. However, the wood demands for these sectors were met for the largest part by wood chips and pulpwood, at the expense of the wood deliveries to the paper and pulp industry. This only leaves some residual demands to be met with sawwood (see for example figure 4.5). As the ATP of the sawmill industry is lower than that of the FT-diesel producers and the DH sector in the end of the modelled period, this means that the sawmill industry may have been affected in more scenarios. In that case, the wood deliveries to the transport biofuels producers would increase, leading to slightly higher shares of biofuels in transport as compared to the values given in table 4.1.

On the other hand, another simplification in the model is that the revenues from side product sales were not included in the model, leading to underestimation of the ATP for wood for the sectors that produce most side products. The sector selling the most side-products was the sawmill industry.

The third assumption was that changes in wood prices on the Swedish market do not affect global word prices. With the Swedish forest industry having a market share of around 10% (Swedish Forest Industries Federation, 2007) in the global production, this assumption is probably justified.

Fourth, the supply of woodchips to the different sectors is not based on competition, but split between the sectors on basis of the demands of the different sectors. This was done because of the relative small size of the market for wood chips, which is around 15% of the combined sawwood and pulpwood market. This, combined with the fact that modelling the wood chip market on basis of competition would have resulted in a greatly increased complexity in the model, is the reason for making this assumption. As the relative share of the woodchip market is small, this has probably not affected the outcomes of the model.

Other simplifications are the assumption that all passenger vehicles are currently fuelled by gasoline, and that all freight vehicles drive on diesel. In reality, a fraction of the passenger vehicles uses diesel (10%), light freight vehicles and some heavy vehicles use gasoline (28 and 2%, respectively; data from Sika, 2008). The introduction of new technology, such as electric vehicles, follows an S-shaped curve, which was not taken into account. Furthermore, the use of wood as firewood, amounting approximately 10% of the annual fellings (Ericsson & Nilsson, 2004), was excluded, even though this exclusion was partly compensated for by the exclusion of wood imports, the net imports amounting to 5% of the total Swedish wood use (Swedish Forest Industries Federation, 2007).

The influence of these assumptions on the model outcomes were not tested, so it is hard to say whether they to what extent they have altered the findings.

With regard to the introduction of biofuel-driven vehicles in the vehicle stock, a number of assumptions and limitations were made in the modelling process.

First of all, the total number of fuels was limited to 3. Furthermore, bioethanol and electricity were assumed to be introduced on the passenger vehicle market only, and FT diesel only on the freight transport market.
However, bioethanol can also be used at fuel for light freight transport vehicles, and FT-diesel may be used for a fraction of the passenger vehicles. This has not been taken into account. The energy use per vkm in the transport sector was considerably higher than in the passenger transport sector: energy uses of 19.3 vs. 2.2 MJ/km in 2007, and 15 vs. 1.1 MJ/km in 2050 were used in the model. Therefore, the demand for FT-diesel may have been estimated too high. On the other hand, this also means that the bioethanol demand was calculated as too low, so the 2 probably more or less balance each other.
A consequence of the energy uses per kilometer is that, even though the total vehicle kilometers in the freight transport sector are approximately 20% of those in the passenger transport sector, most energy is used in the freight transport sector. When the electric vehicle is introduced in passenger transport, this effect becomes even more pronounced.
Another option would have been to include electric vehicles in freight transport, for example in light distribution vehicles. The consequence of this would have been that the demand for wood from the transport biofuel sector would have been lower, as the tank-to-wheel efficiency of electric vehicles is much higher than that of vehicles with combustion engines, resulting in an energy use of 0.75 and 0.40 MJ/km in 2007 and 2050, respectively, even though the efficiency of electricity production from wood is around lower than the bioethanol and FT-diesel production efficiencies. Furthermore, most of the electricity could be generated via CHP in the DH sector.
An alternative, or rather a competitor, for the battery electric vehicles (BEV) is the hydrogen-fuelled fuel cell vehicle (FCV). Had the FCV been used in the model rather than the BEV, the electricity demand would have been higher, because the well-to-wheel efficiency of fuel cell vehicles (FCV) is approximately 3 times lower than that of the battery electric vehicles (BEV) used for this study (SIKA, 2008b). Thus, the wood demand for electricity production would have been larger.

Looking at replacement of vehicles, little literature is available on the choices people make when it comes to choosing between a conventional, gasoline vehicle or a more expensive vehicle which can be fuelled by a renewable fuel.
For sales of hybrid-electric vehicles (HEV), which are more expensive than conventional vehicles, in the USA, it was shown that the elasticity of the market share of HEVs with respect to tax incentives is smaller than the elasticity with respect to gasoline prices (Leonard, 2008). Thus, the effect of tax incentives is smaller than the effect of changing fuel prices. For South Korea, it was shown that lower operational costs were the main driver behind the purchase of more expensive diesel fuels, instead of gasoline cars (Lee&Cho, 2009). For the USA, it was shown that even when methanol and CNG were cheaper than gasoline, consumers preferred gasoline. This was because the 2 alternative fuels were only available at a limited number of fuel stations (Brownstone, Bunch, Golob&Ren, 1996). More in general, it had been shown that environmental impact is not an important factor when it comes to purchasing a new car, and that consumers think producers should come up with more efficient vehicles (Coad, De Haan&Woersdorfer, 2009).
As the Swedish government is working on the availability of alternative fuels, as described in the literature chapter, it was decided that the operational costs were the model's main determinant for the choice of vehicle, and that without subsidies maximally 5% of the consumers is willing to buy a vehicle that uses a more expensive fuel. In Sweden, before the introduction of a grant for environmental-friendly vehicles (miljöbilar), the fraction of vehicles fuelled by alternative fuels was around 10% in 2006, and almost 0 in earlier years (SIKA, 2008a). From this, it can be concluded that that the 5% used for the scenarios is at least in the right order.
A final point here is that the model considers bioethanol and gasoline, and FT-diesel and fossil diesel as 2 non-compatible fuels: a gasoline car can not drive on bioethanol, and vice versa. In reality, both pairs of fuel are compatible to a high extent (Åhman&Nilsson, 2008). For the model, this assumption means that the percentage of biofuels that are introduced may be underestimated. Once the biofuels become competitive with fossil fuels, more consumers will switch to biofuels. On the other hand, in the scenarios where the tax exemptions for biofuels are removed in 2013, fossil fuels become once again most competitive. This will lead to a lower share of biofuels in the transport sector.

5.2 Sensitivity analysis

A sensitivity analysis was conducted to check the validity of the results. In the scenarios C2 and S2, 5 input parameters were varied to see whether this had an effect on the outcomes of the model. These inputs are (1) the oil price, influencing the ATP of the biofuels sector; (2) the forest industry product price, determining the ATP of the forest industry; (3) the annual increment of wood, which may vary as a consequence of protection of woodland, increase of woodland and wood imports; (4) GDP growth, determining the demand for road transport; and (5) development of biofuels production costs.
Table 5.1 gives the differences between the numbers and trends used for the sensitivity analysis, compared to the data used to obtain the results as presented in chapter 4.

Table 5.1: Data used for sensitivity analysis

Parameter	Normal value	Sensitivity Analysis	
		lower value	higher value
Oil price	\$40+ \$1/y per barrel	\$30+ \$0.5/y per barrel	\$50+ \$1.5/y per barrel
Forest product price	constant	- 0.5%/y	+ 0.5%/y
Wood increment	constant at 87.8 Mm^3	- 5%, constant at 83.4 Mm^3	+ 5%: constant at 92.2Mm^3
GDP growth	+2%/y	+1.5%/y	+2.5%/y
Biofuel production cost	see table 2.7	25% slower decrease	25% faster decrease

Graph 5.1 shows a plot of the percentage of biofuels in the Swedish road transport sector in the period from 2007 to 2050 for the sensitivity analysis of scenario C2, figure 5.2 shows the sensitivity analysis for the S2 scenario.

Especially figure 5.1, but also figure 5.2 shows that the results are sensitive to the oil price: variations in the oil price have a considerable effect on the introduction of biofuels. With low oil prices, it takes longer before biofuels are competitive with fossil fuels, and it then also takes longer before the biofuels producers can start to compete with the other wood-using sectors to purchase wood.
However, the model is relatively unsensitive to changes in the other tested parameters. The impact of changes in these parameters is that the large-scale introduction of biofuels in the transport sector is delayed or quickened with a few years. In the Subsidy scenario, the effect of variations in the oil price on the results is smaller than in the CO_2 price scenario. However, the results are still most sensitive to this parameter.

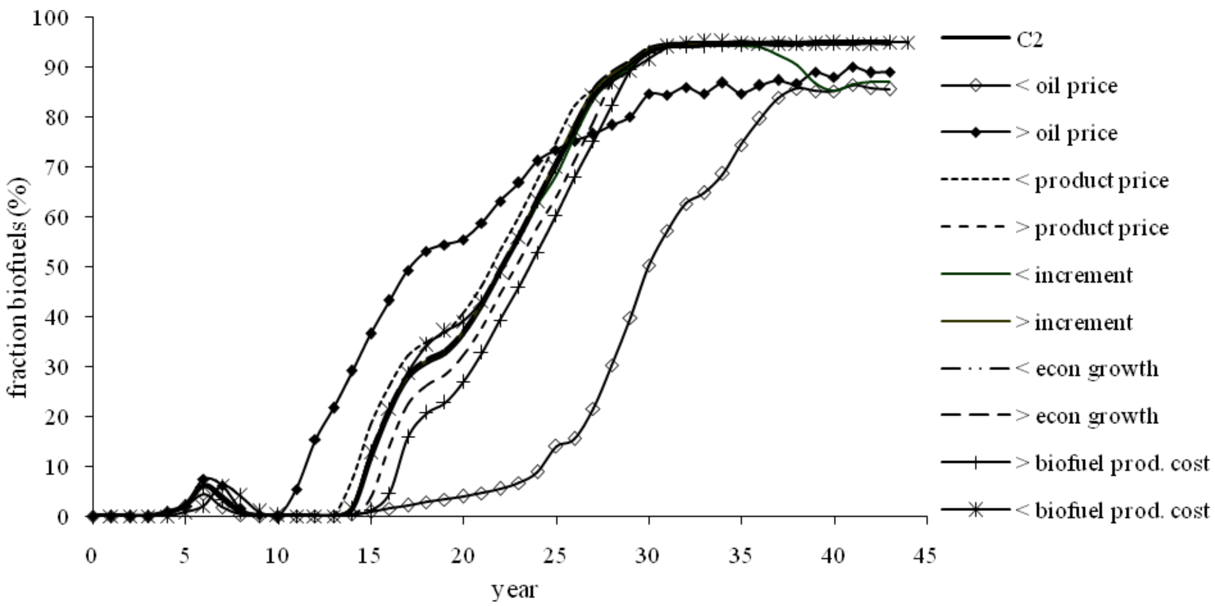

Figure 5.1: Sensitivity analysis of scenario C2

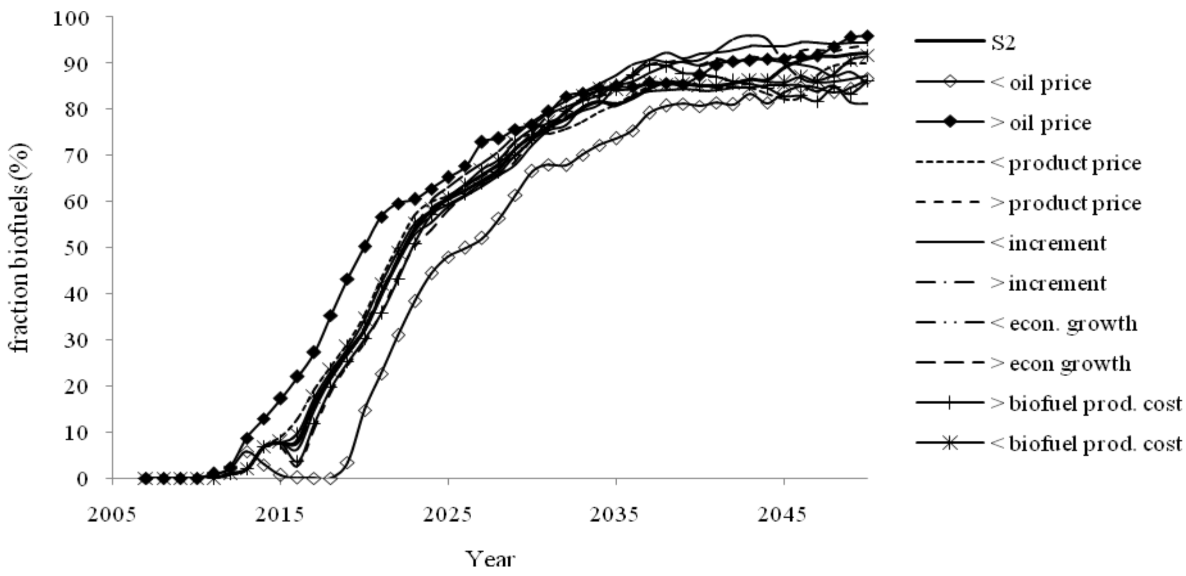

Figure 5.2: Sensitivity analysis of scenario S2

A smaller sensitivity analysis was done carried out for the Sustainability scenario. Based on the results of the sensitivity analyses of the CO_2 price and Subsidy scenarios, only the oil price was varied. The results are given in figure 5.3. The figure shows that variations in the oil price have little effect on the results of the Sustainability scenario.

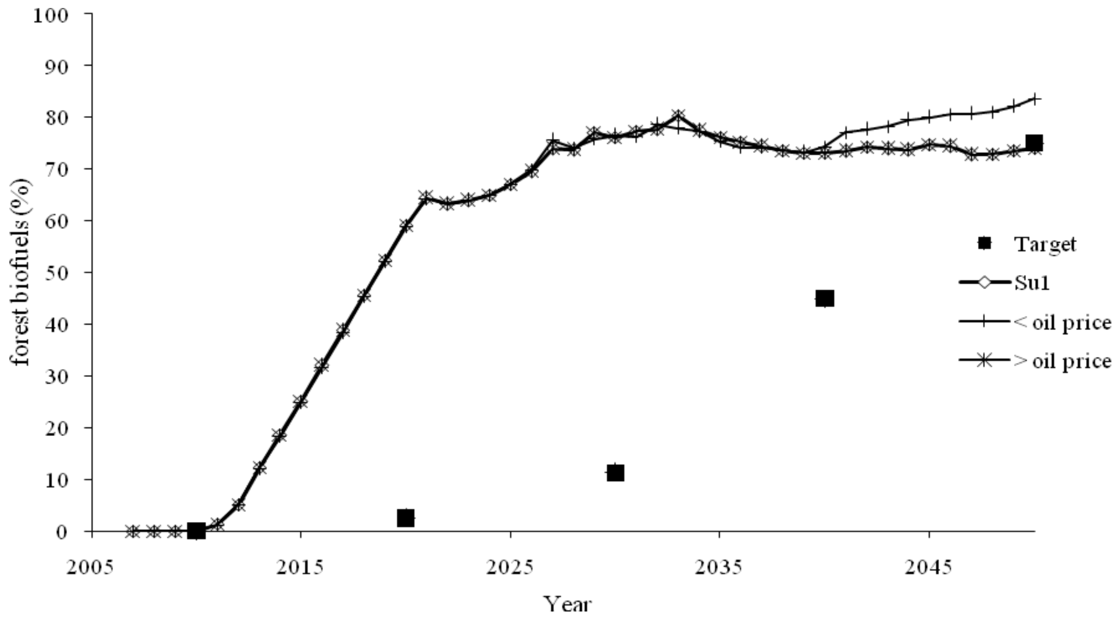

Figure 5.3: Sensitivity analysis of scenario Su1

Little literature is available on the large-scale introduction of biofuels from woody biomass. Engelbrecht (2006) gives the effects of the use of biofuels on the forest industry in the medium-term future. The pulp and paper industry is the sector that will be affected most, as pulpwood is the cheapest type of roundwood. Mechanical pulp and paper mills also face increasing energy prices. The chemical pulp and paper mills, on the other hand, may benefit as well by selling excess biomass-based heat and electricity. In the longer term, this sector may transform into a biorefinery sector. According to Engelbrecht (2006), the sawmill industry is not affected in the medium term, as the prices of

sawwood are too high for the bioenergy sector, and the sector may benefit from selling side products on the bioenergy market.
From the sensitivity analysis, it can be concluded that the results obtained using the model are valid. The external literature confirms this conclusion.

5.3 Results discussion

In this section, the results are discussed. First, some general remarks that refer to all scenarios are made. After that, the scenarios are discussed individually.

5.3.1 General remarks about the results

In all scenarios, the share of biofuels in the energy consumption of the road transport was high (at least 75%) by 2050. Furthermore, most of the wood demand of the bioethanol and FT-diesel was met, and enough electricity could be produced from wood in Combined Heat and Power plants to provide electricity for all electric vehicles. A simple calculation in box 5.1 shows that the increment of wood in the Swedish forests is in the same order as the wood demand from the transport sector, in the situation in which all energy in this sector is produced from Swedish wood.
Second, comparing the scenarios, it can be concluded that there are small differences in the rate of introduction of biofuels for the subsidy and CO_2 price scenario. On the other hand, especially for the CO_2 prices scenario, the differences between the subscenarios are large. In the subsidy and the sustainability scenarios, the rate of introduction of biofuels is comparable. In other words, the height of taxes and subsidies is more important than the names the measures carry.
Furthermore, in most of the scenarios in which the tax benefits for biofuels which are currently in place, were left unchanged or made even more favourable for the introduction of biofuels, the aims set in table 3.1 in the method chapter were fulfilled. However, for this situation the sensitivity analysis showed that the oil price is an important variable. A low oil price can have the result that the targets for the biofuels introduction are not met. The oil price not only determines whether biofuels are competitive in the first place, but it also influences the biofuel sector's ATP for wood.
The oil price is very hard to predict. It not only depends on supply and demand, political decisions also play a role (Huang, Yang & Hwang, 2008), as well as speculation and lowering reserves (Hamilton, 2008). Given the assumptions used here, and assuming unchanged wood prices, the long-term break-even price of bioethanol is around \$60/barrel, and \$80/barrel for FT diesel. Depending on the scenario, it will take 10 to 20 years for bioethanol and 20 to 40 years for FT-diesel to reach the break-even point. However, in most of the scenarios the wood price did increase, placing the break-even point even further in time. So, it is clear that tax benefits are needed to introduce biofuels, no matter what scenario is chosen for the oil price.

Box 5.1: Calculation of wood demand for transport fuels in 2050
In this box, the wood demand for transport fuels in Sweden in 2050 is calculated, assuming that by then all vehicles are biofuel vehicles and that all wood comes from Swedish forests. As a simplification, all vehicles in the passenger transport sector are assumed to be electric vehicles, all freight vehicles are FT-diesel vehicles. The first step is the calculation of the energy demand of the passenger transport sector in 2050. Passenger transport: 66028 Mvkm (million vehicle kilometers) in 2007, growth coupled to GDP growth (2%/y) with the following relation: 0.95-0.02*T, where T is time. T_0=2007, so in 2050 the coupling between transport demand and GDP growth is 0.06. From this, it can be calculated that the transport demand in 2050 is 99.971 Mvkm. For the electric vehicle, the energy use in 2050 was assumed to be 0.40 MJ/km. So, $40.0 \cdot 10^9$ MJ is required. Assuming a conversion efficiency of 35% in a CHP plant, the total energy demand is $1.1 \cdot 10^{11}$ MJ for passenger transport. The second step is the calculation of the energy in freight transport in 2050. Freight transport: demand is 12570 Mvkm in 2007. The coupling here is 0.80-0.015*T. From this, it follows that the transport demand in 2050 equals 19.771 Mvkm. In 2050, a freight vehicle was assumed to consume 15 MJ/km. So, $297 \cdot 10^9$ MJ is needed for the freight transport sector. The conversion efficiency of wood to FT-diesel in 2050 was forecasted to be 52%. Thus, $5.7 \cdot 10^{11}$ MJ is required. In total, $1.1 \cdot 10^{11} + 5.7 \cdot 10^{11} = 6.8 \cdot 10^{11}$ MJ is needed. Wood contains $6.84 \cdot 10^3$ MJ/m^3 standing volume. From this, it follows that $99.4 \cdot 10^6$ Mm^3 wood is required in 2050 for the transport sector. The annual increment currently is 95 Mm^3, and this value was assumed to remain unchanged until 2050.

When looking at the increased demand of products for both the sawmill industry and the pulp and paper industry, the modelling results show that this demand can only be met in the first few years of the modelled period. Afterwards, the annual increment of wood was not enough to cover the wood demand. This conclusion is in line with the findings of the Swedish Forest Agency (2005) that the current wood harvest is almost at the maximum harvest level.
For calculation of the wood demand for the DH sector, it was assumed that the mixture of fuels in this sector will remain unchanged. However, with the current policy in place, the share of wood fuels in this sector is likely to increase. In that case, the demand of wood needed in the DH sector used in this model is an underestimation.

The results show that the battery electric vehicle (BEV) quickly becomes the major vehicle in passenger transport after its market introduction, which was assumed to be in 2020. Thus, for converting the passenger transport sector into a renewable energy-fuelled sector, the electric vehicle seems important. The question therefore is what would happen if the BEV would enter the market later. In order to find the answer, the scenarios C2, S2, and Su1were ran with the introduction year of the BEV set as 2030.
In the subsidy scenario, the differences are small. The market share of bioethanol fuels is higher than in the original scenario S2: almost 70% vs. 40%. So, more wood is needed for the production of bioethanol, but this increased demand is small compared to the demand for wood for FT-diesel. As a consequence, the effects of the competition for wood observed when the BEV is introduced in 2030 are not different than when the BEV enters the market in 2020. In the CO_2 price scenario, delay in the market introduction of the BEV has important consequences. Due to the increased wood demand from the bioethanol producers, the sawwood sector can no longer purchase wood, and disappears. In the 'normal' C2 scenario, this was not the case. For scenario Su1, the differences are small. The other sectors are no longer able to purchase the wood they need to fulfil the demand, but this was also the case when the BEV was introduced in 2020. For all scenarios, the targets for the introduction of biofuels are still met.

Finally, the fact that forest industries own 25% of the productive forests was not taken into account (Swedish Forest Agency, 2007). Thus, the industry is likely to receive at least a part of the wood it requires from its own lands. This may dampen the reduction in the wood deliveries to the paper and pulp sector that were observed in most of the scenarios.

5.3.2 Discussion CO_2 price scenario

For the market scenario, CO_2 prices were set to half, once, and twice the current CO_2 price of SEK 910/tonne CO_2 for general customers. The industry currently is partly exempt from this tax due to concerns about international competitivity (Palm&Larsson, 2007), and pays SEK 190/tonne CO_2 (Hammar&Jagers, 2007). This situation was assumed to remain in place. The Swedish CO_2 prices are high compared to the expected damage costs of CO_2. These costs are estimated between SEK 5 and 750/tonne CO_2, and are unlikely to exceed SEK 105/tonne CO_2 (Hammar&Jager, 2007). For this reason, a scenario with halved carbon prices was tested.
As the CO_2 tax was intended to diminish the CO_2 emissions from the combustion of fossil fuels, the CO_2 price scenarios were designed in such a way that biofuels were not subject to the CO_2 tax.
With regard to the replacement of vehicles, the same values were used here as in the subsidy scenarios in which no subsidies were in place. Thus, the underlying assumption is that 95% of the consumers purchase the vehicle with the lowest fuel (operational) cost. As stated in section 5.1, little literature is available on consumers' choices when purchasing a new vehicle, and the choice is between a cheaper, fossil-fuelled vehicle, and a more expensive biofuel-vehicle. If the value of people buying bioethanol- or FT-diesel-fuelled vehicles had been higher, this would have led to a quicker introduction of biofuels, and consequently to fulfilling the aims set for 2020 in the scenarios M1 and M2. So, for the first years of the modelled period, the assumptions made in consumer's vehicle purchasing behaviour may have had an effect on the results.

The effect of changing the CO_2 prices on the ATP for wood on the sawmill industry and the pulp and paper industry were small. Transport costs will increase, but transport makes up only 3% of the costs in the paper and pulp industry, and 13% in other wood industries (Hammar, Lundgren&Sjöström, 2006). The indirect effect of rising electricity prices may have farther reaching consequences than only the direct effect of the CO_2 tax (Brännlund&Lundgren, 2007; Johansson, 2006). Looking at the data calculated by Johansson (2006), the small effect of changing the CO_2 price on the forestry sector should not come as a surprise.
Finally, the results show that pricing CO_2 is a good option to stimulate the introduction of forest biofuels for transport purposes. With the current tax in place, fulfilling the aims for the introduction of biofuels in 2020 depend on the development of the oil price and consumers vehicle purchasing behaviour, but in the period after 2020, current taxes should be enough. In the CO_2 price scenario, producing biofuels from woody biomass goes at the expense of the paper and pulp industry, and, if biomass demand and price get even higher, also at the expense of the sawmill industry and the DH sector. Lowering CO_2 taxes, however, will not result in fulfilling the aims set.

5.3.3 Discussion Subsidy scenario

In designing the Subsidy scenario, a number of assumptions were made, especially with regard to the effects of subsidy on vehicle purchasing behaviour, and the height of the energy tax.
The literature available on the effects of subsidies on consumers' choices for purchasing new vehicles, is limited. In Sweden, a SEK 10,000 (€950) 'environmental friendly vehicle' (miljöbil) grant is in place. In 2007, 12% of the newly registered cars were 'alternative fuel' vehicles (SIKA, 2008). This roughly corresponds to the situation used for scenario S2, where, in the absence of electric vehicles on the market, 15% of the new vehicles was assumed to be bioethanol vehicles.
With regard to the energy tax, it was assumed in the scenarios S2 and S3 that biofuels would get half or full exemption of this tax, independent of their market share. Given that this tax is mainly a fiscal tax (Biopact, 2008), it is not very likely that this exemption will remain in place after biofuels have reached a considerable market share. This was not taken into account in the model. For reasons of comparison, a test run has been done with scenario S3, in which biofuels were exempt from the tax if the market share of the biofuels was smaller than 25%. When the market share was between 25 and 50%, the taxes were raised to 50% of the gasoline taxes. Above 50% market share, full taxes had to be paid.
In this case, the FT-diesel production sector was affected. The fuel was no longer competitive with fossil fuels, and the ATP of the FT-diesel producers was lowered. For bioethanol, the market share did not exceed 25%. On the other hand, when policies are made, the actual prices and the effects of raising taxes can be taken into account in order to avoid stagnation of biofuels introduction.

Looking at the effect of the subsidies, the results show that these only work in a few years in the beginning of the modelled period. After that, the taxation measures make biofuels cheaper than fossil fuels, so that consumers prefer to buy biofuel-driven vehicles anyway.
A further conclusion that can be drawn from the Subsidy scenarios is that although consumers start to buy vehicles that are driven on renewable fuels as a response to subsidies, this does not mean that all these fuels can be provided from domestic wood-based biofuels: in most of the scenarios, the transport fuels sector's ATP for wood is too low to be able to win the competition with other sectors in the initial part of the modelled period, leaving the sector with too little wood to fulfil the fuel demand.
On the other hand, as scenario S3 demonstrates, when the ATP is sufficient to purchase all the wood required, the other sectors are pushed off the market due to the high demand for wood, especially from the FT-diesel producing sector. So, the targets set for the introduction of forest fuels may be attainable, as shown by scenario S3, it may not necessarily be desirable.
From the above discussion, it follows that in the Subsidy scenario, taxes are needed to introduce biofuels. The effect of subsidies for vehicle purchases is small.

5.3.4 Discussion sustainability scenario

The sustainability scenario is a combination of the CO_2 price and Subsidy scenario. The combination of energy tax exemptions, doubling of the CO_2 prices and high subsidies is enough to let biofuels enter the market.

The large demand for wood in this scenario made the wood prices rise to a level at which they become too high for first the paper and pulp industry, and then for the sawmill industry. As can be seen from figure 4.8 in the previous chapter, the total percentage of biofuels introduced by 2050 does only just meet the aim set. The reason for this is not in the ATP of the sectors, but is a consequence of the modelling. As a sector can only demand pulpwood or sawwood, the amounts of wood that can be purchased by the bioethanol or FT-diesel producers is limited to the supplies of this wood sort. Furthermore, in the sustainability scenario, the sawmill industry closes down, so that woodchips are no longer produced. Both effects limit the total amount of wood delivered to the biofuel producers. In reality however, when the ATP is high enough, the transport biofuels sectors can buy both pulpwood and sawwood in order to fulfil the demand. So, the model underestimates the total wood deliveries to these sectors, which means that the total fraction of forest biofuels used in transport is higher than indicated by the model.

5.4 Lessons for the Swedish politics

The calculation in box 5.1 shows that the volume of wood required in 2050, when a transition towards a sustainable Swedish road transport sector has been made, is comparable to the annual increment of wood. In other words, a transition to a green transport sector means that little or no wood is left for the district heating (DH) sector, and the sawmill, pulp and paper industry.

The Swedish forestry sector (sawmills, pulp and paper industry) is important for the countries' economy, making up 25 to 30% of the Swedish industry, taking related industries into account (Björheden, 2006), and generating 11% of Sweden's export revenues (Statistics Sweden, 2009). In addition to that, using wood fibre for energy production rather than for pulp or paper production generates 13 times less employment, and 8 times less added value (Roberts, 2008). So, a large-scale introduction of biofuels will result in loss of jobs in the forest industry. Furthermore, Sweden will lose a considerable part of its export revenues, even though this may be compensated for as less oil has to be imported.

An alternative for using Swedish wood in the transport sector is import of biofuels. However, this may come down to changing the dependence on oil-exporting countries for a dependence on countries that export biofuels. Even though biofuels can be produced sustainably, dependence on other countries leaves Sweden in a vulnerable position when an increased demand for transport fuels results in competition for biofuels. Another option is turning chemical paper mills into biorefineries, producing not only paper products, but also electricity, heat, and fuels such as FT-diesel, methanol or dimethylether (Engelbrecht, 2006).

Raw wood can be used only once, and in the end biofuels can not be introduced on a large scale while maintaining the position of the sawmill industry and the pulp and paper industry. Therefore, it is important for politicians to think twice about the consequences of embarking on a policy to introduce biofuels on a large scale in the transport sector.

6. CONCLUSION

In this chapter, the main results of this research project as well as recommendations for further research are given.

6.1 Conclusion

This research project investigated the competition for wood between the forest industry (paper and pulp sector, sawmill industry) on the one hand, and the biofuels sector (district heating, electricity, and transport fuels) on the other hand, using different scenarios. This was done for the period 2007-2050. Aims were set for the introduction of the share of transport biofuels produced from domestic woody biomass.
The attainability of these aims was tested using a Subsidy, CO_2 price, and a Sustainability scenario. In the CO_2 price scenario, a price was put on the production of fossil CO_2. In the Subsidy scenario, subsidies to stimulate the purchase of vehicles fuelled by these biofuels were used in combination with different energy tax exemptions for biofuels. The sustainability scenario combined the other 2 scenarios.

For all the scenarios, it was found that a competition for wood will occur. Once the ability to pay for wood of the biofuels sector was high enough to compete with the other sectors, the successful introduction of transport fuels came at the expense of the paper and pulp industry. Moreover, in some sub-scenarios the DH sector and sawmill industry were affected as well. As it was assumed that the electricity for electric vehicles would be produced by wood-fuelled Combined Heat and Power (CHP) plants in the DH sector, this had an effect on the total fraction of energy in transport coming for forest.

It was found that in the scenarios using the current subsidies and taxation measures (C2 and S2), the targets set for 2050 are reached. However, for the early years in the modelled period, the measures proved not always sufficient.
In the subscenarios in with higher taxes and more subsidies (C3 and S3), all targets were reached. The subscenarios in which the measures were less powerful (C1 and S1), with lower taxes or subsidies, the results differed: in the CO_2 price scenario, the aims were reached from 2030 onwards, in the Subsidy scenario, all aims were met.
A sensitivity analysis was done, which showed that the outcomes of the model are robust with regard to changes in the price of forest industry products, annual increment of wood, economic growth, and production costs of biofuels. However, the outcomes of the model were sensitive to the oil price.
For the especially the CO_2 price scenario, but also for the Subsidy scenarios, successful introduction of transport biofuels proved to be dependent on the oil price. With low oil prices, biofuels were initially not competitive with fossil fuels. When the biofuels were just competitive, the ability to pay for wood of the producers was often too low to win the competition for wood. Unfortunately, the oil price is hard to predict.
A third scenario, the Sustainability scenario combined high subsidies with a full energy tax exemption for biofuels and a high fossil CO_2 price. This resulted in a quick introduction of transport biofuels. The robustness of the outcomes of this scenario was tested by varying the oil price. It was shown that the introduction of biofuels was not dependent on the oil price.

In general, it was observed that higher subsidies, and higher taxation measures beneficial for the biofuels sector lead to an earlier introduction of biofuels on a larger scale.

6.2 Recommendations

For further research, the model made for this research project could be refined further. The system boundaries of the model could be expanded to include possible wood imports, a market for firewood, inclusion of the particle board industry, to give a few examples.
It was assumed that the production costs of the forest industry are fixed, but the sector is always aiming at cost reductions. This can be put in the model, and the effects of the cost reductions may influence the results in one way or another.

A final recommendation for refining the model would be to include a way to split the wood demand of a sector over pulp- and sawwood. As was shown in the case of the sustainability scenarios, the current situation in which a sector can only demand either pulpwood or sawwood may lead so small errors in the modelling results.

Furthermore, other variables can be put into the model, to see how this influences the results. First, the model used here assumed that the policy with regard to the electricity market will remain the same in the future. However, a policy change to make electricity production from wood the financially favourable option can also be modelled. In this project, only 1 scenario for the growth of the demand for wood for district heating was used, but more scenarios can be added.

Another option here would be to include more or other transport biofuels that can be made from wood. With regard to the transport sector, it may be considered to use electric vehicles in the freight transport sector as well. The coupling between transport demand and economic growth can be varied to determine what effects this has on the competition for wood.

So, there is a number of options to expand or refine the model further, and to test other variables with the model.

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APPENDIX: MODELLING RESULTS

In this appendix, the results of the model runs for the different scenarios are presented in graphs.
For the sawmill industry and the pulp and paper industry, the wood demand and deliveries are shown. The demand meant here is not the demand that would be needed to fulfill the growing demand from the international market, but the final demand from the sector, which is the demand after determining which fraction of the sectors can produce competitively on the international market.
For the DH and electricity sectors, as well for the bioethanol and FT-diesel producers, the wood demands and deliveries are shown. Furthermore, a graph of the prices of sawwood, pulpwood, and woodchips is given for each scenario.

Scenario S1

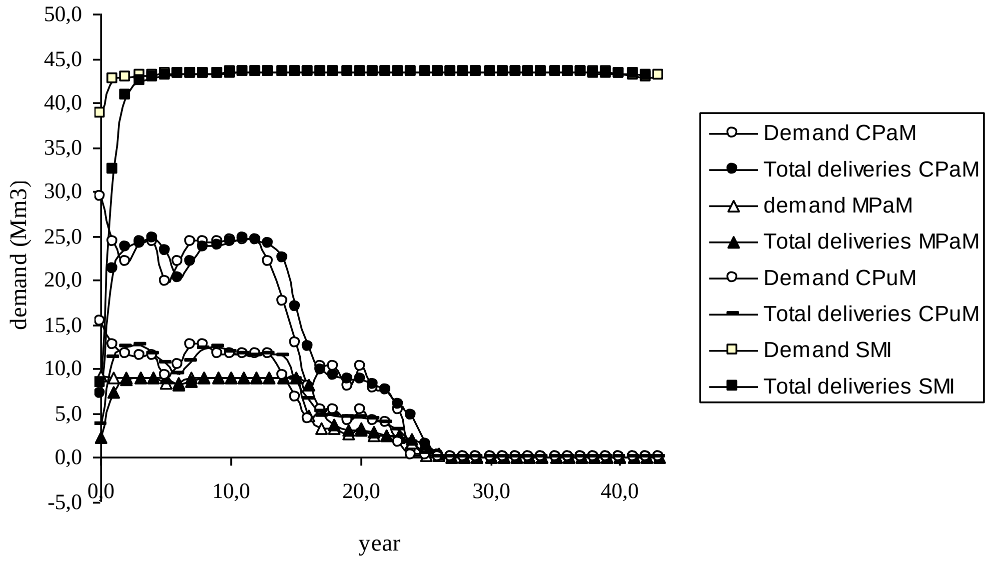

Figure A.1: Demand paper, pulp and sawmill industry, scenario S1

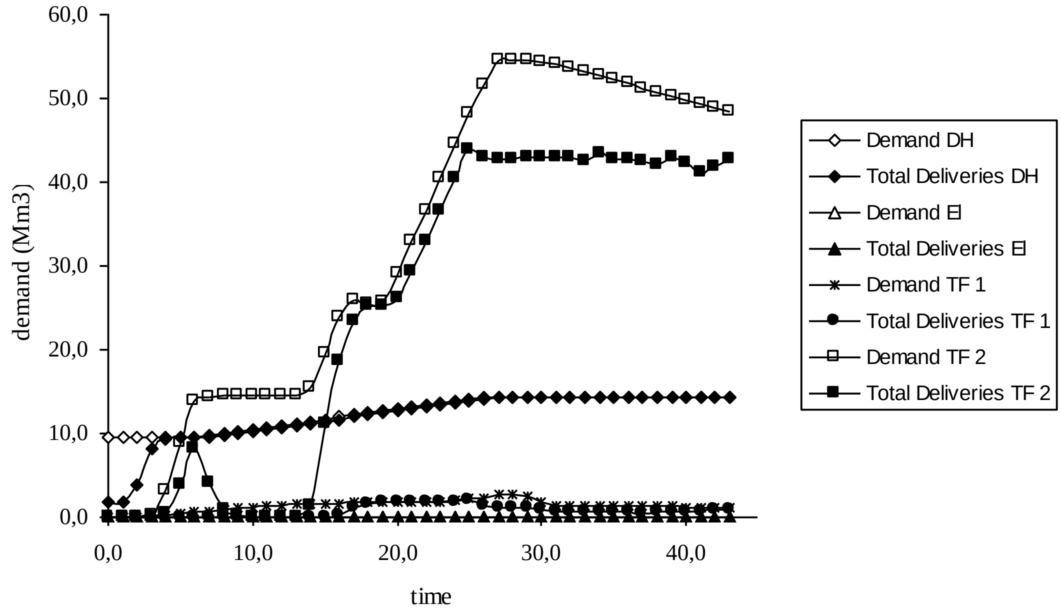

Figure A.2: Demand DH, el, bioethanol (TF1), and FT diesel (TF2) sectors, scenario S1

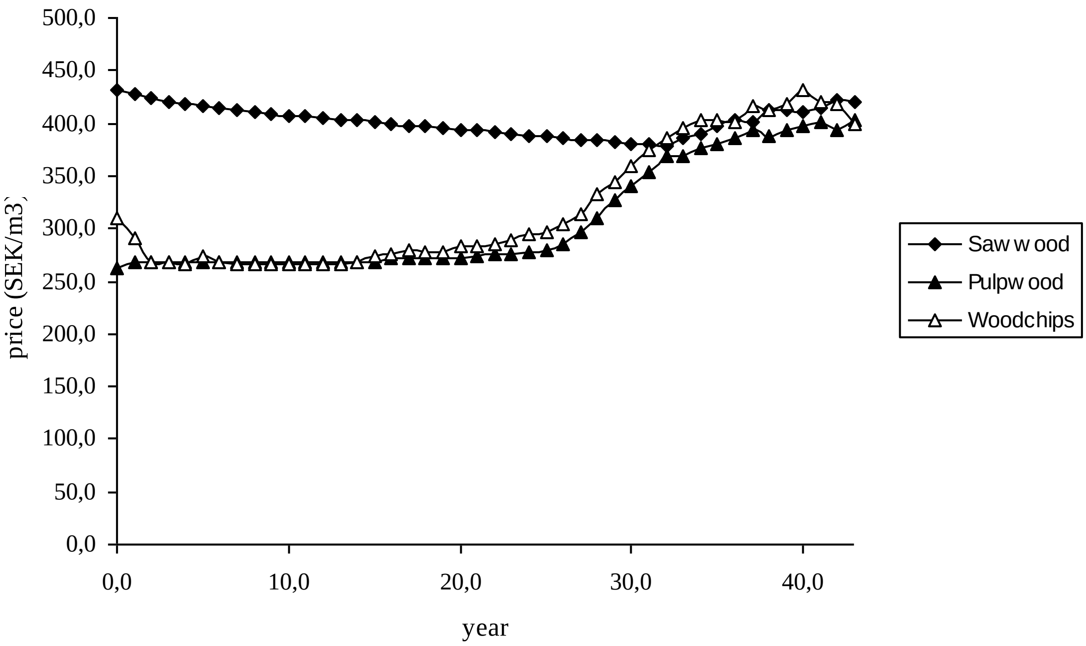

Figure A.3: Prices for sawwood, pulpwood, and woodchips, scenario S1

Scenario S2

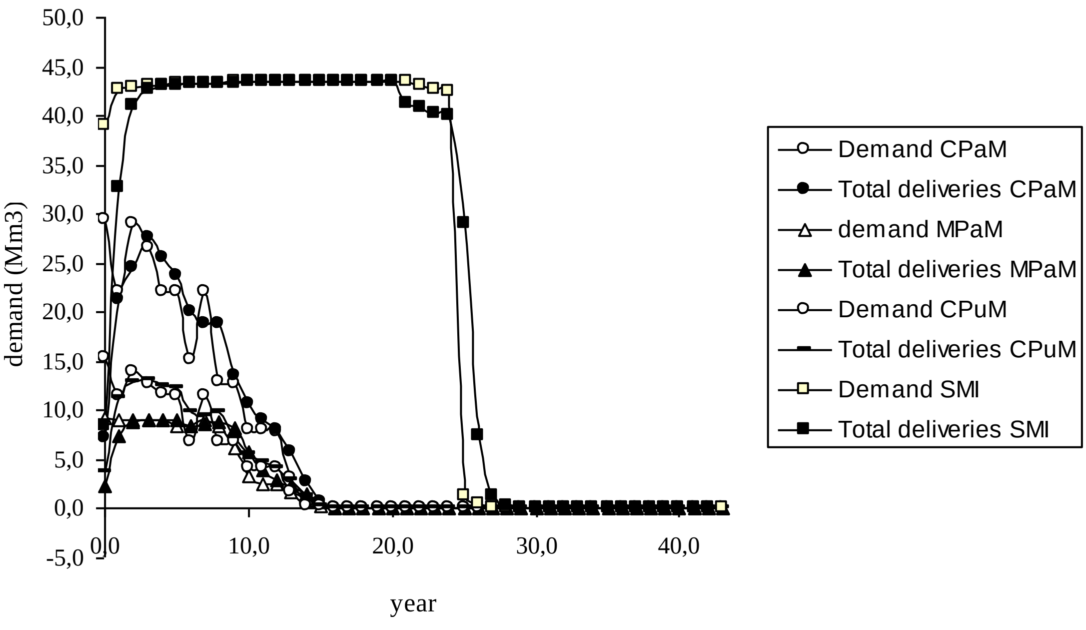

Figure A.4: Demand paper, pulp and sawmill industry, scenario S2

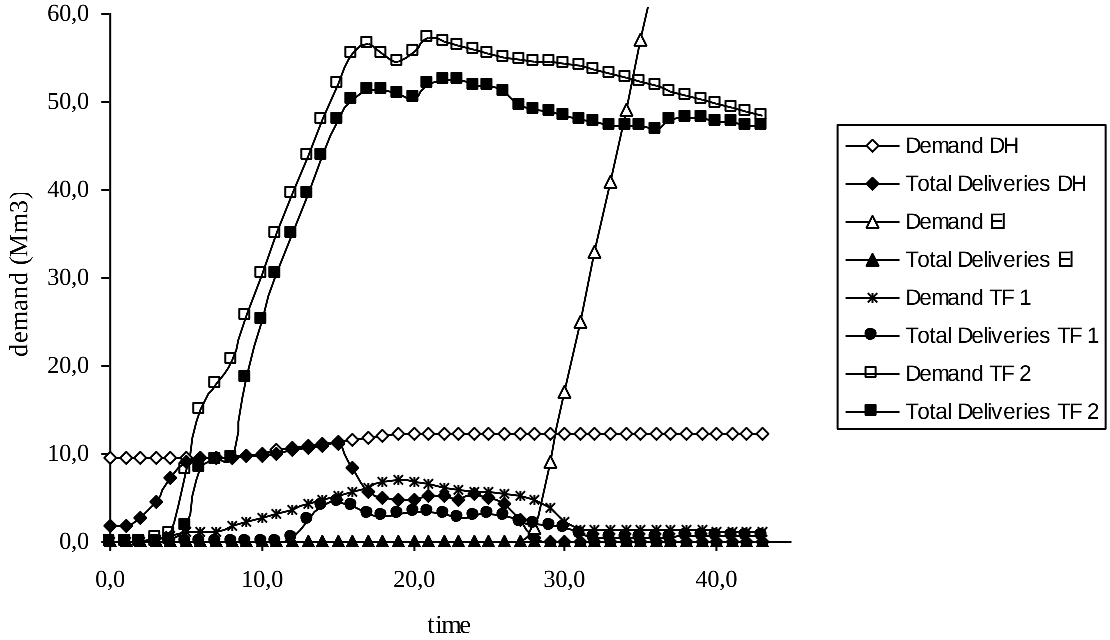

Figure A.5: Demand DH, el, bioethanol (TF1), and FT diesel (TF2) sectors, scenario S2

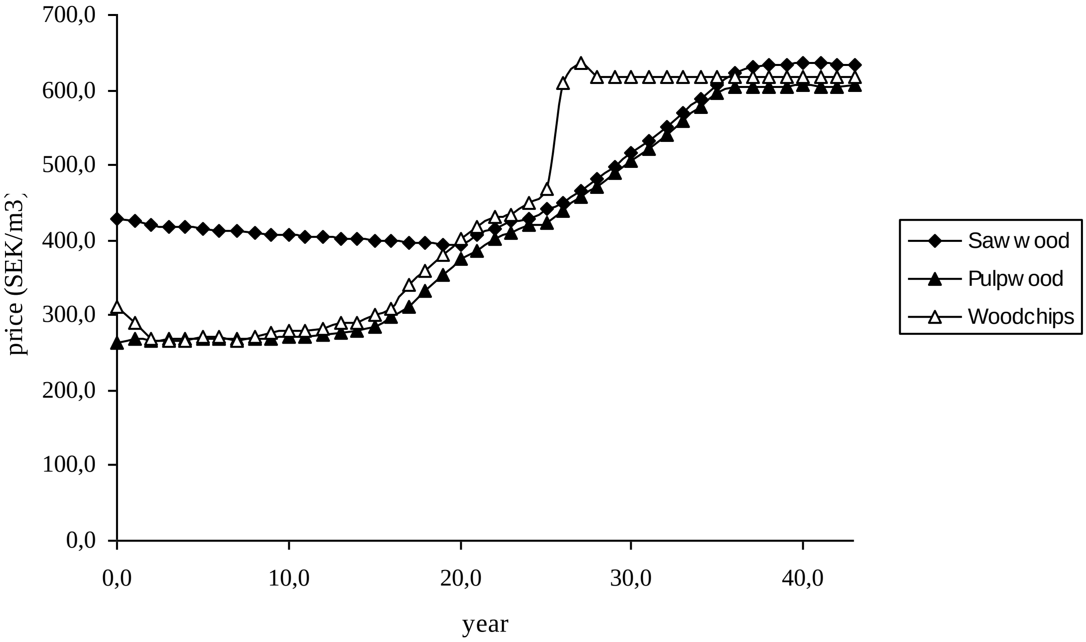

Figure A.6: Prices for sawwood, pulpwood, and woodchips, scenario S2

Scenario S3

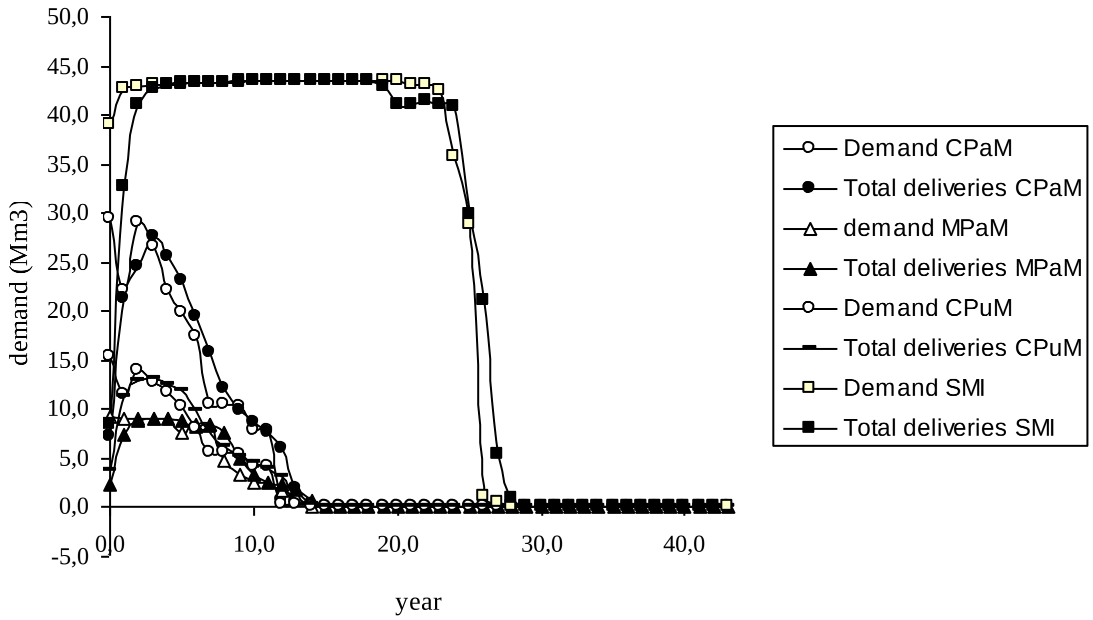

Figure A.19: Demand paper, pulp and sawmill industry, scenario S3

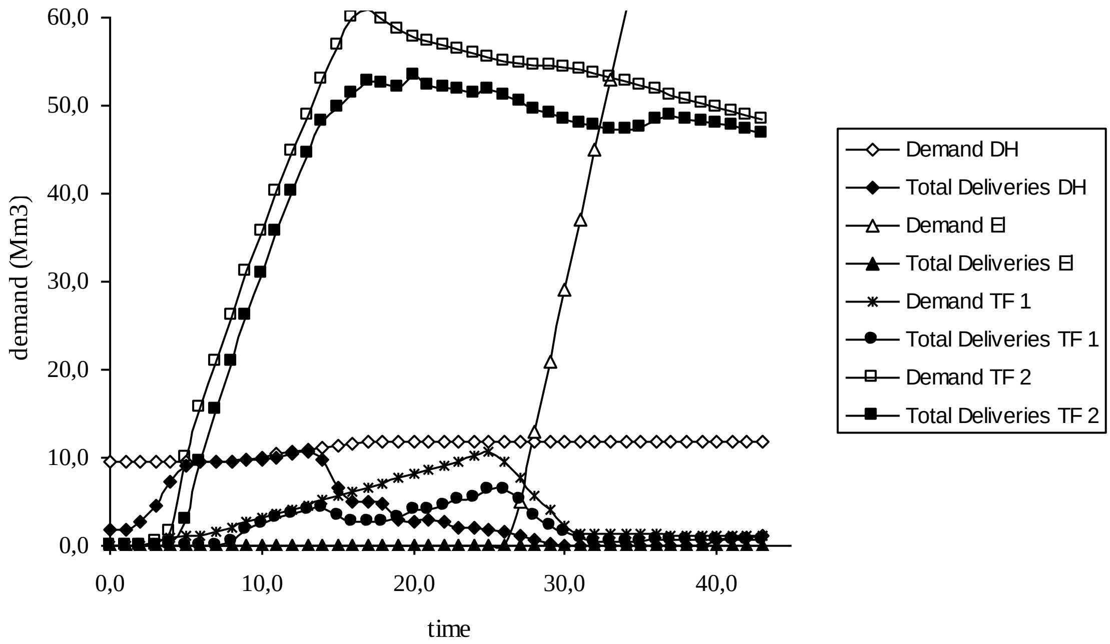

Figure A.20: Demand DH, el, bioethanol (TF1), and FT diesel (TF2) sectors, scenario S3

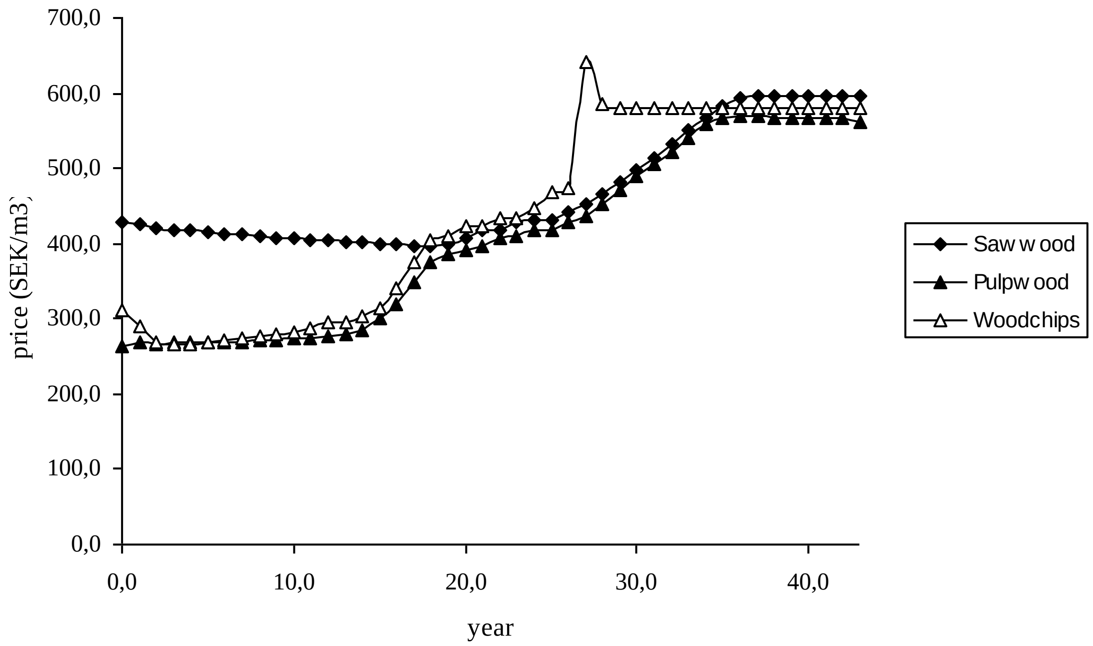

Figure A.21: Prices for sawwood, pulpwood, and woodchips, scenario S3

Scenario C1

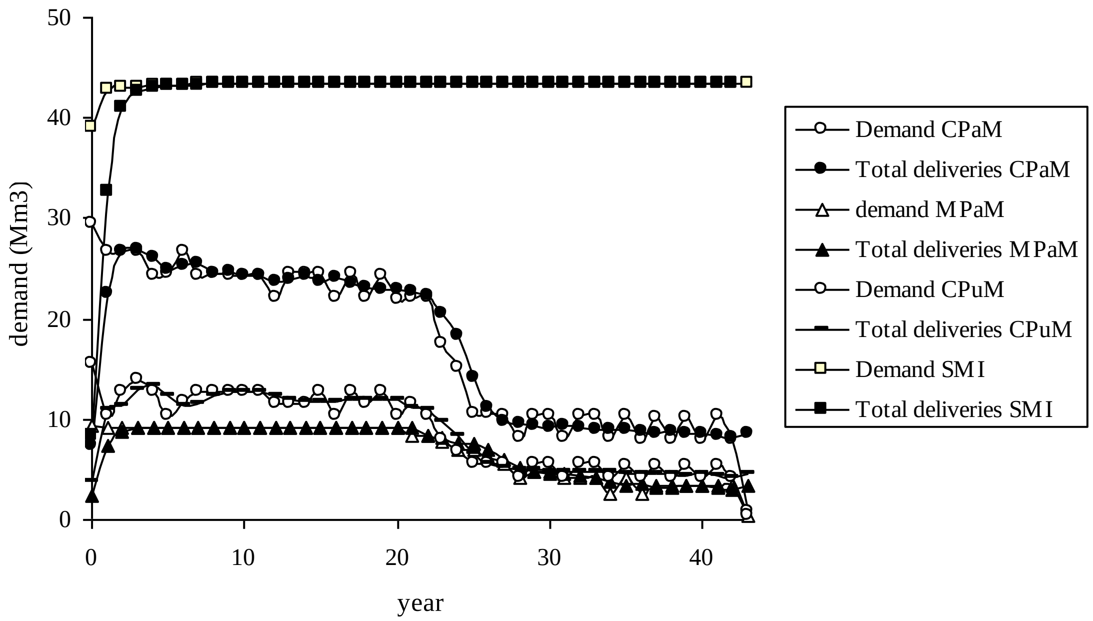

Figure A.22: Demand paper, pulp and sawmill industry, scenario C1

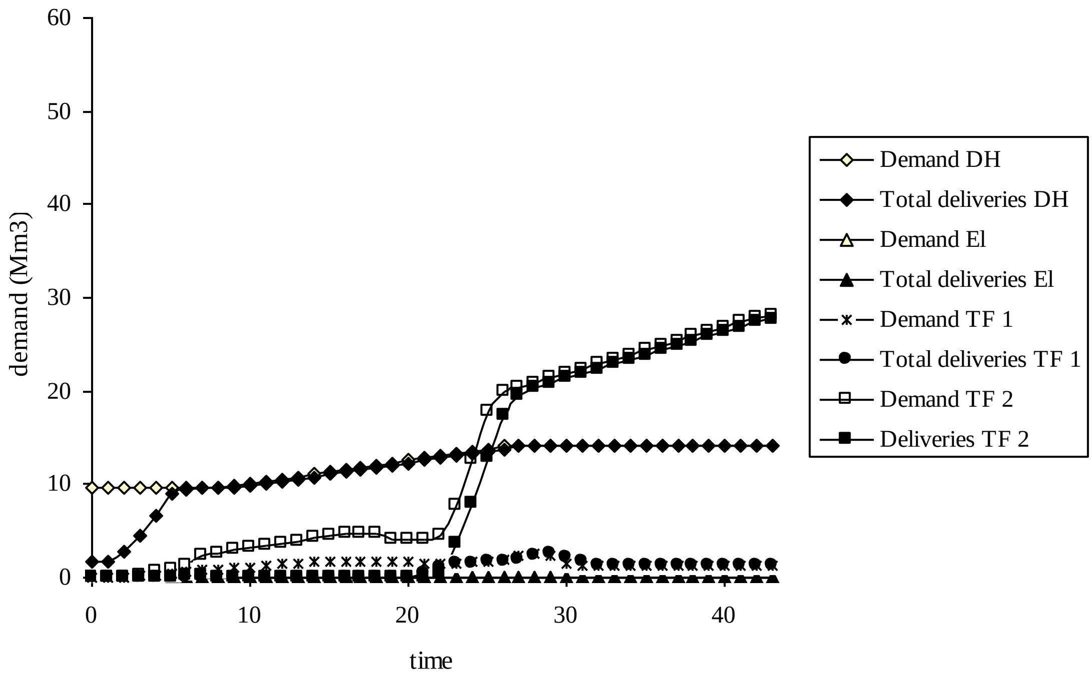

Figure A.23: Demand DH, el, bioethanol (TF1), and FT diesel (TF2) sectors, scenario C1

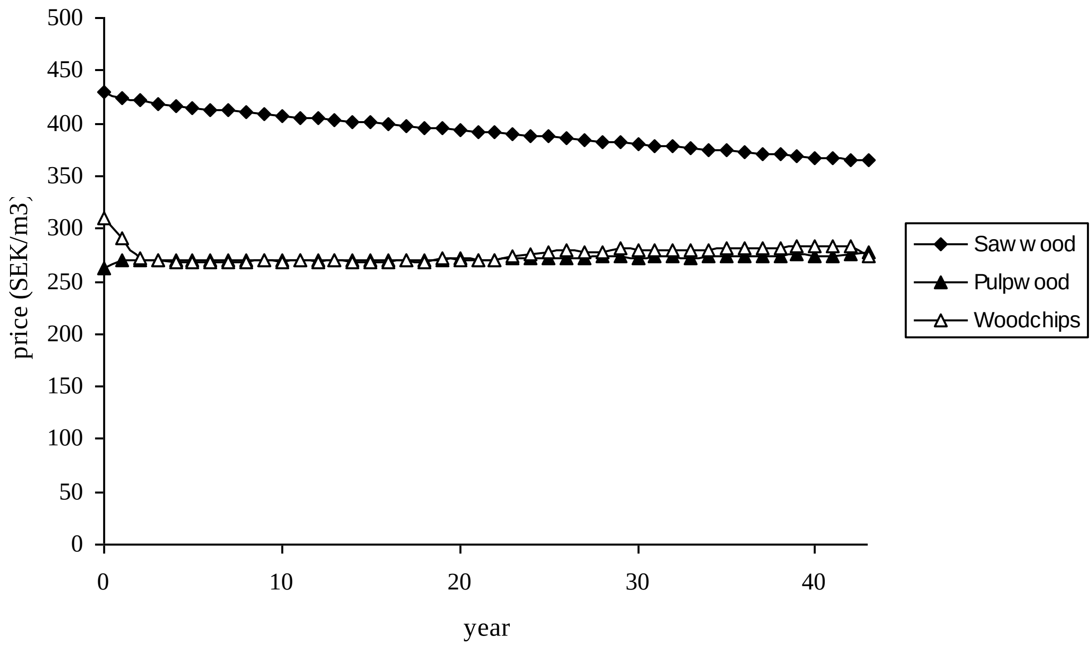

Figure A.24: Prices for sawwood, pulpwood, and woodchips, scenario C1

Scenario C2

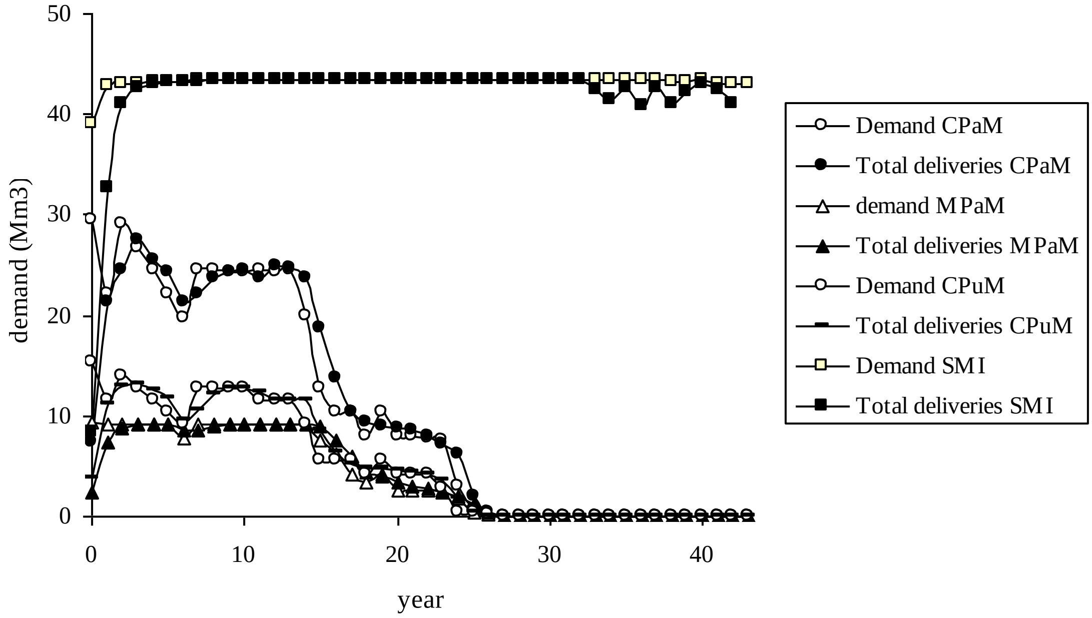

Figure A.25: Demand paper, pulp and sawmill industry, scenario C2

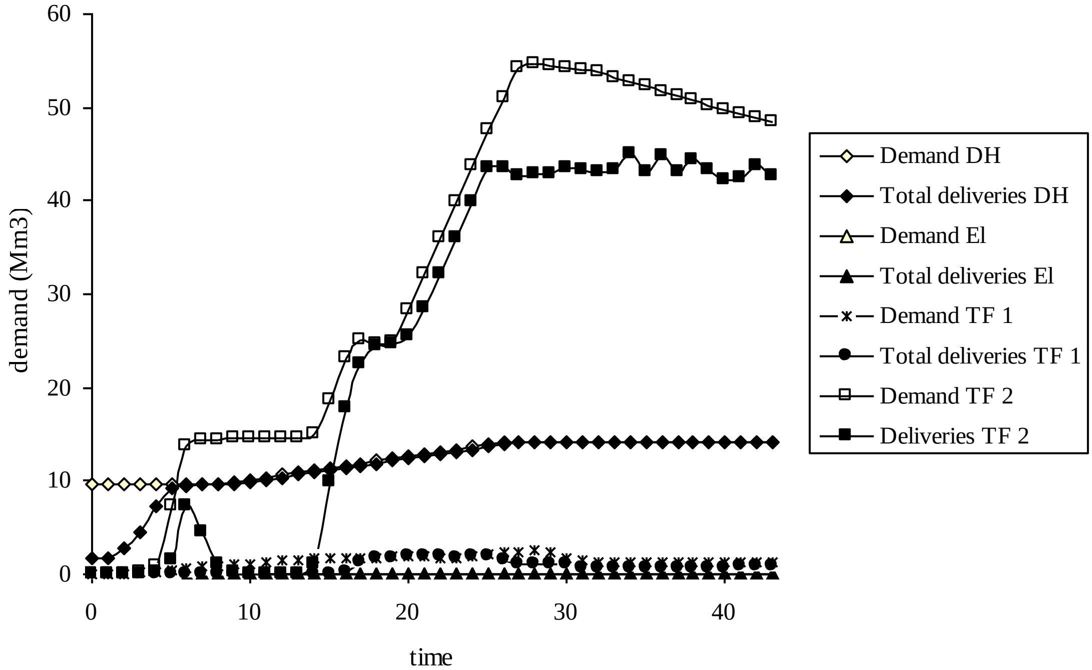

Figure A.26: Demand DH, el, bioethanol (TF1), and FT diesel (TF2) sectors, scenario C2

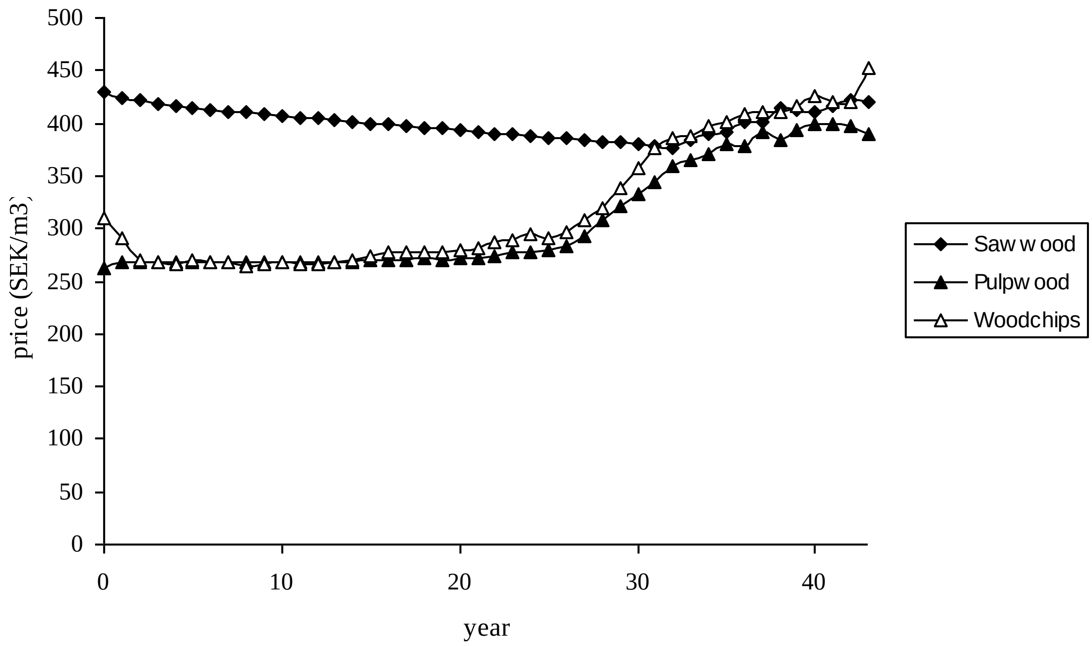

Figure A.27: Prices for sawwood, pulpwood, and woodchips, scenario C2

Scenario C3

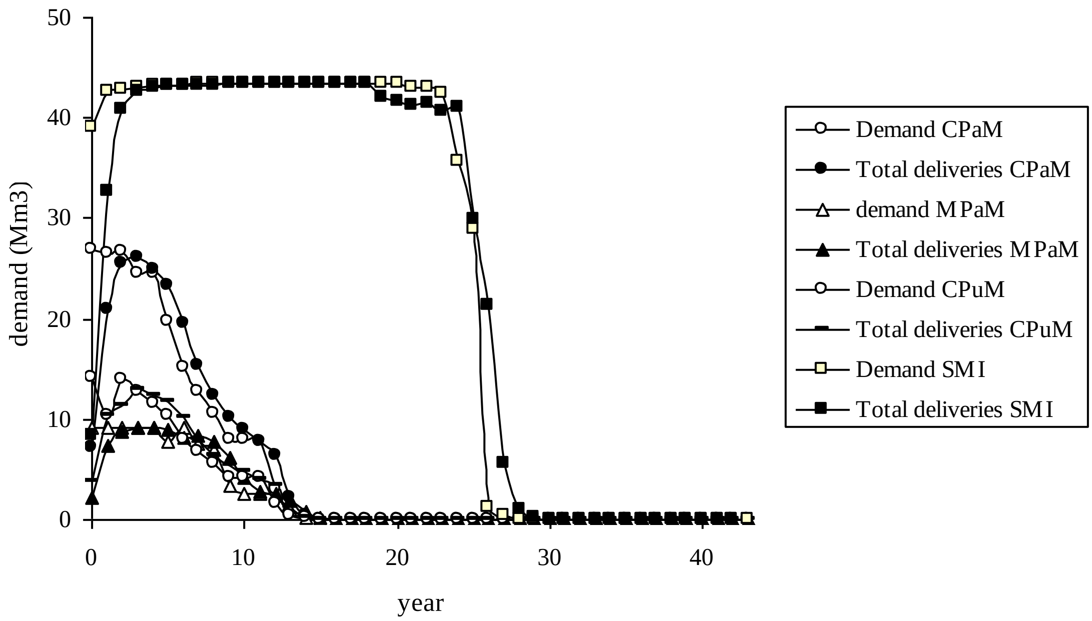

Figure A.40: Demand paper, pulp and sawmill industry, scenario C3

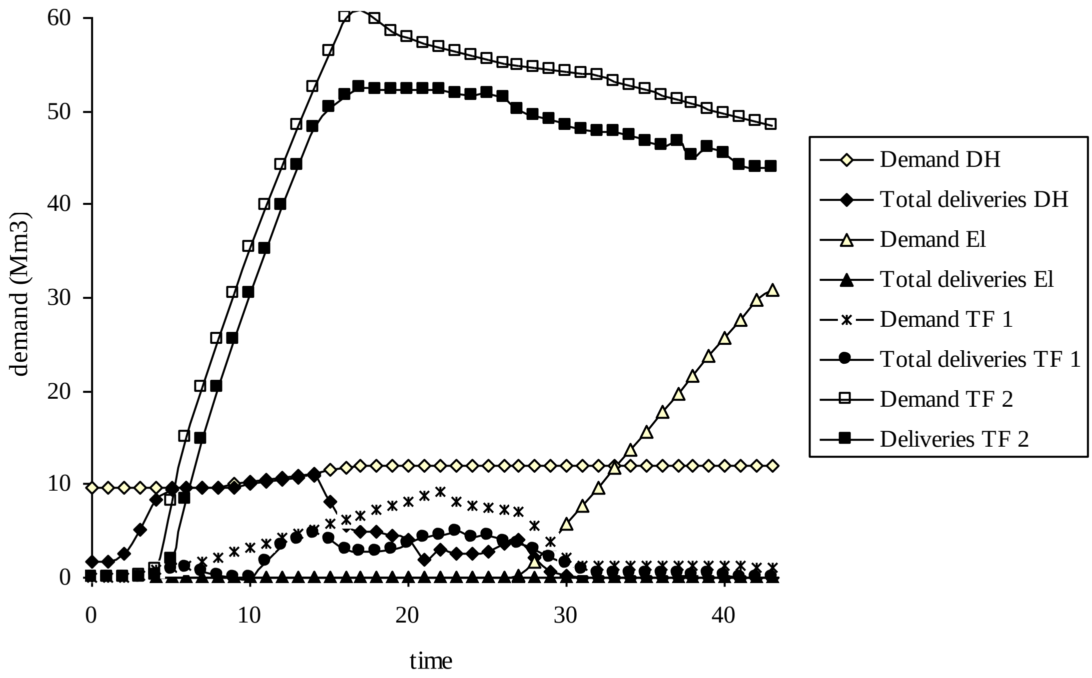

Figure A.41: Demand DH, el, bioethanol (TF1), and FT diesel (TF2) sectors, scenario C3

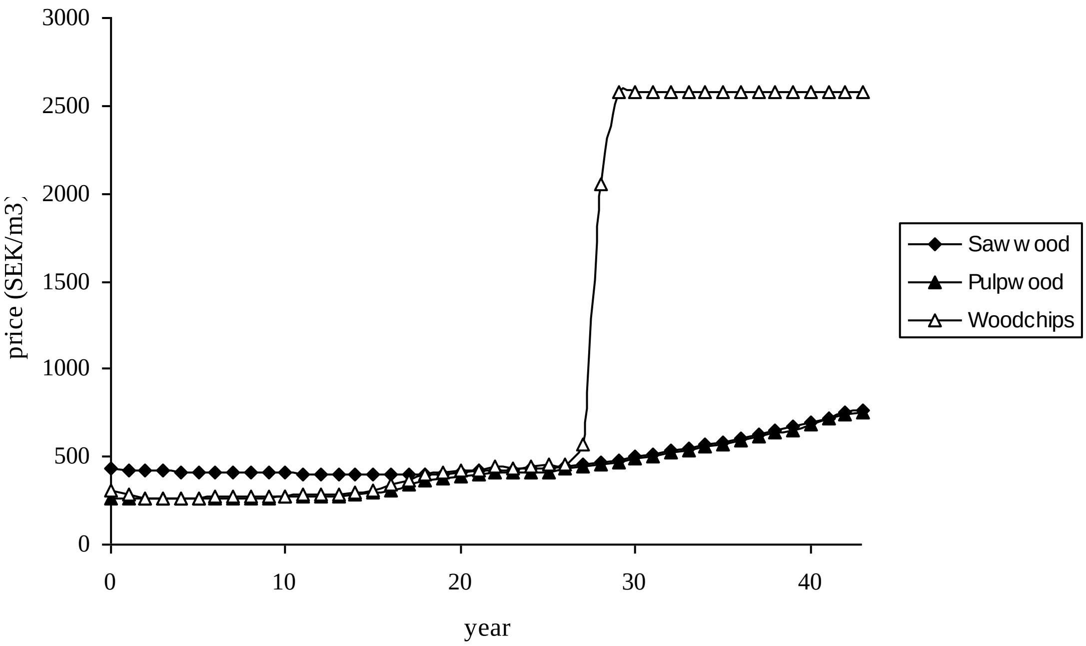

Figure A.42: Prices for sawwood, pulpwood, and woodchips, scenario C3

Scenario Su1

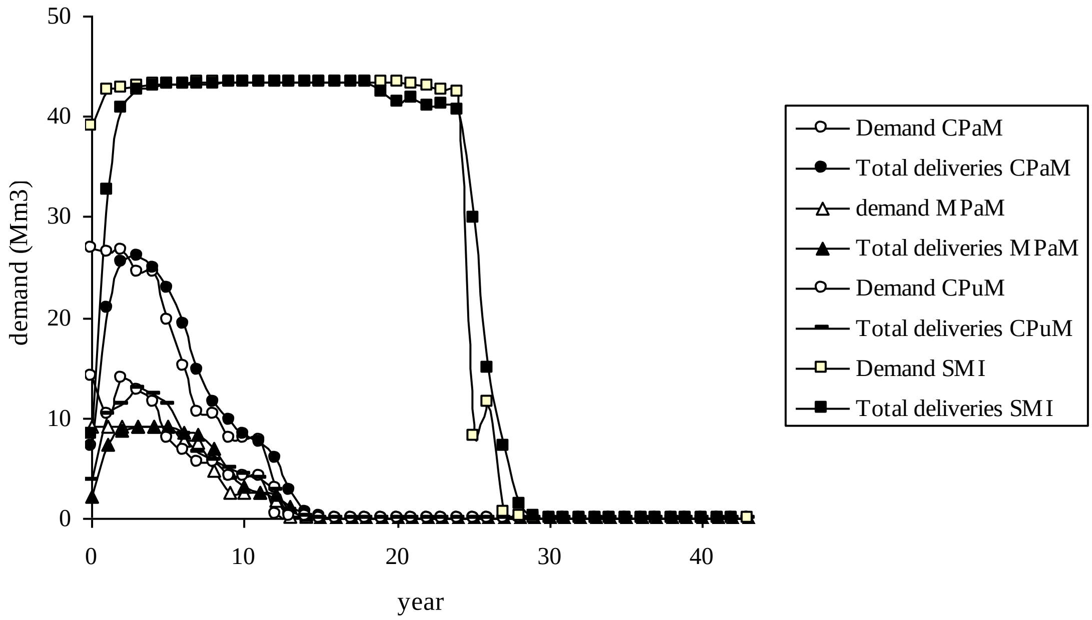

Figure A.46: Demand paper, pulp and sawmill industry, scenario Su2

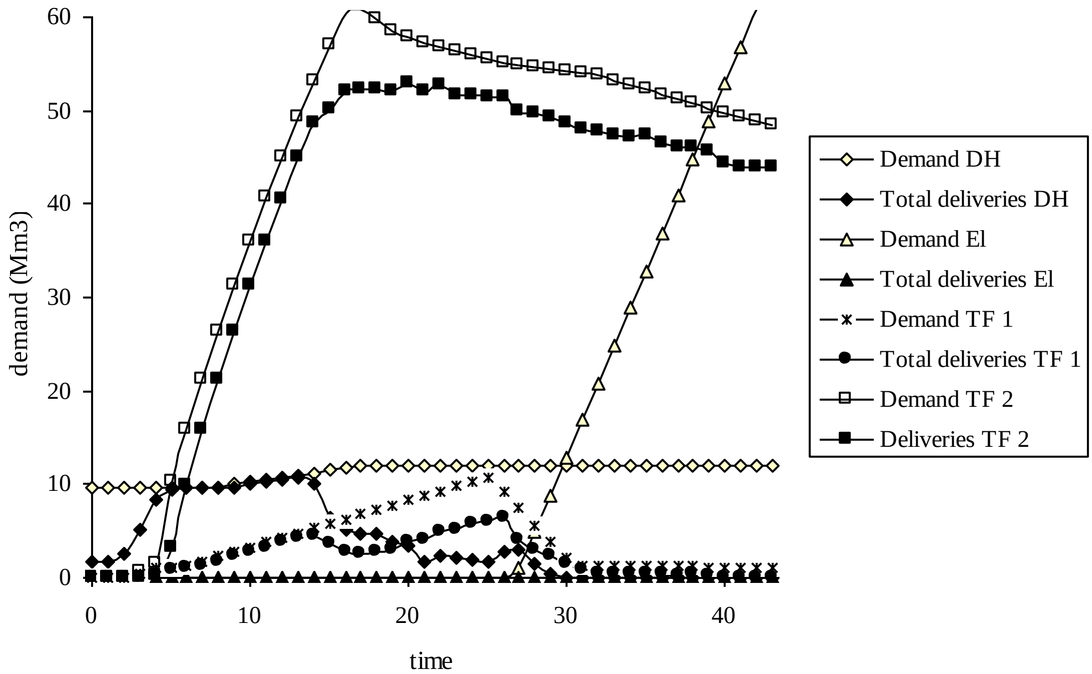

Figure A.47: Demand DH, el, bioethanol (TF1), and FT diesel (TF2) sectors, scenario Su2

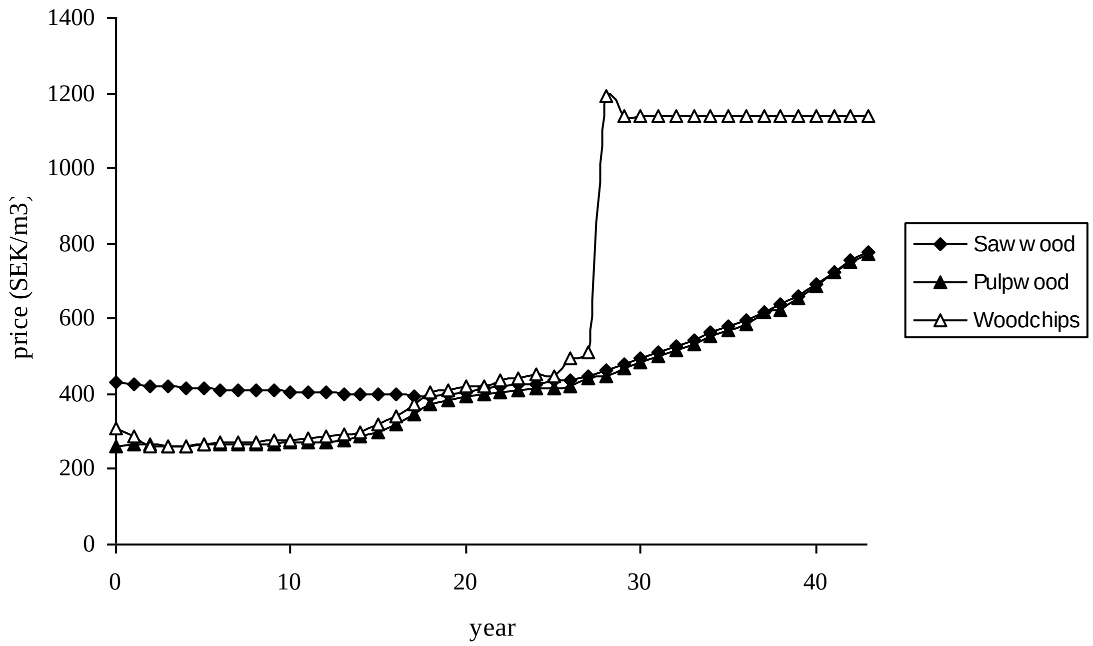

Figure A.48: Prices for sawwood, pulpwood, and woodchips, scenario Su2