REPORT

Swedish long-term low carbon scenario

Exploratory study on opportunities and barriers

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Preface

Lars Zetterberg commissioned the study in his role as the Work Package Leader in the MISTRA-funded climate policy research programme CLIPORE. He has also been responsible for the industrial parts of the report. Jenny Gode has been the project leader and responsible for overall work as well as for the residential/service, electricity and heating sectors. Erik Särnholm has focused on the transport and biofuel sectors. Erik has also been responsible for the cross-sectoral linkages and has consequently been involved in work on all sectors. Jenny Arnell and Therese Zetterberg were responsible for the forest fuel utilisation chapter.

Summary

In 2009, the Swedish government proposed a vision of reaching zero net emissions of greenhouse gases in the year 2050. However, there are few details on concrete actions after 2020. In the light of the long investment cycles associated with energy, housing, transport infrastructure and heavy industry, we believe that the society now needs to start identifying possible pathways for reaching this vision. The pathways also need to be investigated in terms of their feasibility and consequences. The aim of our study has been to develop and elaborate on one potential future energy scenario where Sweden minimises the use of fossil fuels in 2050 and to identify opportunities and barriers.

The scenario we present is one of several possible scenarios and is obviously not a forecast. Our purpose is not to show a likely development, but rather to illustrate, by example, a society that is largely independent of fossil fuels and what would be required to get there. In a next step, more detailed scenarios as well as accurate impact assessments are needed. For example, the impact of high bioenergy utilisation needs to be carefully examined. The results also show several cross-sectoral measures and/or effects that need further study. There is also a need for thorough cost analyses as well as analyses of what is required to implement these measures in practice.

We have analysed potential fossil fuel reductions in the sectors industry, residential/service, transports and energy conversion. For these sectors, systematic investigations have been made on measures for replacing fossil fuels, improving energy efficiency and applying new technologies and industrial processes. Our scenario is to a great extent based on existing technologies. In addition to sector specific measures, we have applied cross-sectoral measures such as using industrial surplus heat in the residential sector or forest residues for producing heat and power. Furthermore, we have assumed a system change in transportation and limited use of carbon capture and storage (CCS). The applied measures influence the demand for electricity, heat/steam and fuels. The results indicate a very high demand for biofuels in the future.

The proposed measures used in the scenario substantially reduce Sweden's dependency on fossil fuels by 2050. In our scenario, energy-related carbon dioxide emissions including process emissions in industry are reduced from 59 million tonnes of carbon dioxide in 2005 to 12 million tonnes of carbon dioxide in 2050, a reduction of 79%. However, this requires a limited use of carbon capture and storage (CCS). A prerequisite for applying CCS is that the technique is mature and accepted in 2050 including e.g. secure storage, public acceptance, appropriate infrastructure and political framework. Without CCS, emissions total 17 million tonnes of carbon dioxide in 2050, a reduction of 72%. We have also anticipated that other techniques now under development will be available in 2050. This applies to plug-in hybrid technology for vehicles and second-generation transport biofuels[1].

In our energy scenario we have assumed increased GDP growth of 2.25% per year with increased industrial production, increased transport and an increased population. We assume improved energy efficiency so that the end-use of energy is kept at the same level in 2050 as in 2005. We regard the level of energy efficiency improvement as plausible. However, rebound effects (where lower energy costs lead to increased energy use), may counteract the assumed energy efficiency improvement. Strong incentives are probably needed and could potentially improve the energy efficiency even further.

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[1] Production of DME and synthetic natural gas (SNG) from residues from forestry or equivalent.

It is a great challenge to achieve a fossil-free transport sector. In our scenario, despite extensive improvements in efficiency and a switch to electric drive, the transport sector will need a large quantity of transport biofuels. This also applies if the whole passenger car fleet is assumed to switch to plug-in hybrids. Our results suggest that transport biofuels will be principally used for goods transport and as "back-up fuels" for plug-in hybrid cars.

In our scenario, residual emissions are mainly found in the industry sector where process related emissions are difficult or very expensive to mitigate. This applies in particular to the use of metallurgical coal in the steel industry, the release of chemically bound carbon from cement production and fugitive emissions in particular from the petrochemical industry. Some of these process emissions could potentially be reduced by CCS, but there will nevertheless be a certain quantity of remaining process emissions. These emissions may potentially be offset by reductions elsewhere in Sweden, for example through CCS of biogenic carbon dioxide from chemical pulp mills. The emissions can alternatively, in theory at least, be offset by reductions abroad, but our assessment is that such reductions/credits may be very expensive in 2050 when the whole world needs to reduce the emissions.

The need for electricity increases in the scenario by 7% by 2050 in comparison with 2005, which includes electricity needs for carbon capture and storage from industrial processes. The reason why the increase is not greater despite a sharp increase in the transport sector's need for electricity is mainly due to extensive energy efficiency improvement in the residential sector which reduces the use of electricity for heating. Present-day (2007) electricity production of approximately 150 TWh would thus almost be sufficient to meet the national need for electricity in 2050, also assuming growth in GDP of 2.25% per year. The future role of nuclear power is unclear at present. If nuclear power would be phased out partially or completely by 2050, up to 75 TWh of electricity will need to be produced in other ways. This may, for example, be accomplished through a mix of wind power, expanded hydro power production[2], solar power, wave power and bioenergy. We have not specified in the scenario exactly what the electricity production mix may look like and merely point to the need and what would be required for emissions to be as low as possible.

In our scenario, we estimate that virtually all use of fossil fuels in the district heating sector can be replaced by renewable alternatives and residual heat. A large proportion of the residual consists of excess heat from the production of transport biofuels which is assumed to take place in poly-generation plants. The basis for combined heat and power is reduced as a result of a substantial energy efficiency improvements and increase in the use of residual heat in the district heating production system.

The bioenergy demand increases substantially from the present use of around 114 TWh to 165-248 TWh depending on scenario. The most prominent increase in demand regards forest residues (logging residues and/or stumps) which increase from today's 7 TWh up to 50-128 TWh[3]. Swedish forests may contribute to a large extent, but meeting this demand may be in conflict with environmental concerns and targets. Different studies have investigated the future potential of bioenergy from logging residues and stumps in Sweden. These studies vary substantially in their estimates, ranging from 25 TWh (WWF, 2009) to 57-180 TWh (extrapolated data from Swedish

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[2] In particular as a result of increased precipitation from a changed climate.

[3] Note that these numbers do not include round wood, which today accounts for 17 TWh of the bioenergy supply. We have not estimate the future round wood potential, and therefore our assumption for the 2050 scenarios is that 17 TWh will be used in the future as well.

Forest Agency, 2008b)[4]. However, in addition to logging residues and stumps significant contributions to the bioenergy supply may be met by energy crops, waste fuels, by-products, round wood or even import. Other options are further improvement in energy efficiency or a switch of technology in the end-using sectors. We wish to emphasise the need for accurate environmental and impact assessments to investigate the true potential for sustainable bioenergy supply in 2050.
We have drafted on an alternative scenario, which is less dependent on bioenergy. In this scenario we still assume a major electrification of transports, but with the difference that fossil fuels are used as back-up fuels to electricity. The resulting fossil emissions are then offset by using CCS on an equivalent volume of biogenic carbon dioxide from paper and pulp mills. This alternative scenario, in comparison with the Biofuels scenario, gives an increase in oil use of 73 TWh and a decrease in bioenergy use of 83 TWh. The need for electricity increases by 4 TWh, of which 1.4 TWh is produced by combined heat and power.

Exports of electricity and biofuels to continental Europe may possibly provide greater global climate benefit than if Sweden uses them itself. This applies on condition that the exported electricity and the biofuels replace fossil fuels without CCS. The potential benefit of exporting Swedish biomass and/or electricity has not been examined in this study.

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[4] Note that the estimations made by WWF Sweden (2009) do not include stumps, due to uncertainties about environmental effects.

Svensk sammanfattning

År 2009 föreslog den svenska regeringen en vision om att Sverige år 2050 inte ska ha några nettoemissioner av växthusgaser. Trots det finns mycket få konkreta mål uppsatta efter år 2020. För att uppnå visionen krävs att vi redan nu lyfter blicken och ser bortom år 2020. Det är idag 40 år till år 2050. Det är inte lång tid för en kraftfull omställning av samhället. För våra långsiktiga investeringar i infrastruktur, industriella anläggningar och bebyggd miljö är det därför hög tid att påbörja planeringsdiskussionerna. Syftet med den här studien har varit att utveckla och resonera kring ett energiscenario där Sverige minimerat användningen av fossila bränslen år 2050 samt att identifiera möjligheter och svårigheter.

Scenariot är ett av många tänkbara scenarier och är givetvis ingen prognos. Vårt mål är inte heller att visa på en trolig utveckling utan att illustrera att en fundamental förändring mot ett samhälle som till stor del är oberoende av fossila bränslen är möjligt och att visa på vad som krävs för att komma dit. I ett nästa steg krävs mer detaljerade scenarier samt noggranna konsekvensanalyser. Bland annat behöver effekterna av ett kraftfullt uttag av biomassa från skogen analyseras noga. Resultaten visar på flera sektorsövergripande åtgärder och/eller effekter som också behöver studeras mer noggrant. Vidare finns ett behov att analysera vad som skulle krävas i praktiken för att implementera åtgärderna.

I studien har möjliga åtgärder analyserats för de tre energianvändande sektorerna industri, hushåll samt transporter. Systematisk genomgång och utredning har gjorts av åtgärder för ersättning av fossila bränslen, energieffektivisering samt utveckling av teknik och industriella processer. Scenariot baseras till stor del på existerande teknik, men vi har också antagit en systemförändring i transportsektorn och viss avskiljning och lagring av koldioxid (CCS). De antagna åtgärderna påverkar efterfrågan på el, värme/processånga samt bränslen. Generellt så innebär ersättning av fossila bränslen att efterfrågan på biobränslen ökar kraftigt. Det gäller trots att vi antagit kraftig energieffektivisering. Av det skälet omfattar rapporten även ett separat avsnitt om potentialen för bioenergi från den svenska skogen. Resultaten från studien visar tydligt att efterfrågan på biobränslen kan bli mycket hög och därför vill vi betona behovet av noggranna miljökonsekvensanalyser för att undersöka den verkliga potentialen för hållbart uttag av bioenergi år 2050.

De åtgärdsförslag som används i scenariot minskar Sveriges fossilbränsleberoende påtagligt fram till år 2050. De energirelaterade koldioxidemissionerna inklusive processemissioner i industrin kan minskas från 59 miljoner ton koldioxid år 2005 till 12 miljoner ton koldioxid år 2050, en reduktion om 79%. Detta kräver dock avskiljning och lagring av koldioxid (CCS). Utan CCS blir utsläppen 17 miljoner ton koldioxid år 2050, en reduktion om 72%. Vi har även räknat med att andra tekniker som nu är under utveckling kommer att finnas tillgängliga år 2050. Detta gäller plugin-hybridteknik för fordon samt andra generationens biodrivmedel[5]. Till stor del åstadkoms dock reduktionerna i vårt scenario med idag kända tekniker. En förutsättning för att använda CCS är förstås att tekniken är mogen och accepterad år 2050 inkluderande bland annat tillgång till säker lagring, infrastruktur, politiskt regelverk och allmänhetens acceptans.

I energiscenariot har vi antagit en ökad BNP-tillväxt med 2,25% per år med ökad industriproduktion, ökade transporter samt ökad befolkning. Energieffektivisering gör att slutanvändningen av energi bibehålls på samma nivå år 2050 som 2005. Energieffektiviseringsnivån anser vi vara rimlig, men med starka incitament kan troligen energieffektiviseringsgraden öka. Rebound-

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[5] Produktion av DME och syntetisk naturgas (SNG) från restprodukter från skogsbruket eller motsvarande.

effekter, dvs. att lägre energikostnader leder till ökad energianvändning, innebär dock att ytterligare energieffektivisering kan bli svårt att genomföra.

Det är en stor utmaning att göra transportsektorn fossilfri. Trots en omfattande effektivisering och övergång till eldrift kommer transportsektorn ändå att behöva en stor mängd biodrivmedel. Detta gäller även om hela personbilsflottan antas övergå till elhybrider. Biodrivmedel bedöms huvudsakligen användas till godstransporter och som "hjälpdrivmedel" till elhybridbilar. Observera att efterfrågan på biodrivmedel blir hög trots att vi räknat på en relativt kraftig övergång av godstransporter från väg till järnväg och att personbilar endast använder biodrivmedel som "hjälpdrivmedel. ".

I industrisektorn bedömer vi att en stor mängd fossila bränslen kan ersättas med förnybara bränslen. Industrins processemissioner bedöms dock vara svåra eller mycket dyra att helt ersätta med förnybara alternativ. Det gäller huvudsakligen användningen av metallurgiskt kol i stålindustrin, avgången av koldioxid vid cementproduktion, samt diffusa utsläpp från framför allt den petrokemiska industrin. En del av dessa processutsläpp kan minskas med CCS, men trots detta kommer det att finnas en viss mängd kvarvarande processemissioner. Dessa utsläpp kan eventuellt kompenseras av reduktioner på andra ställen i Sverige, exempelvis genom CCS av biogen koldioxid från kemiska massabruk. Utsläppen kan i teorin kompenseras av reduktioner utomlands, men vi bedömer att sådana reduktioner/krediter kan bli mycket dyra år 2050 då hela världen behöver minska sina utsläpp.

Elbehovet ökar i scenariot med 7% till år 2050 jämfört med 2005. Ökningen inkluderar elbehov för avskiljning och lagring av koldioxid från industriprocesser. Att ökningen inte blir högre än så trots att transportsektorn kraftigt ökar sitt elbehov, beror på omfattande energieffektivisering i bostadssektorn som minskar elanvändningen för uppvärmning. Dagens elproduktion om drygt 150 TWh skulle alltså nästan räcka för att möta det nationella elbehovet år 2050, även antaget en BNP-tillväxt på 2,25 % per år. Om kärnkraften skulle fasas ut till 2050 behöver dock elproduktion motsvarande ca 75 TWh produceras på andra sätt. Det kan exempelvis vara genom en mix av vindkraft, utökad vattenkraftsproduktion[6], solkraft, vågkraft och bioenergi. Vi har i scenariot inte specificerat exakt hur elproduktionsmixen kan se ut utan visar endast på behovet och vad som skulle krävas för att emissionerna ska vara så låga som möjligt.

Vi bedömer att i princip all fossilbränsleanvändning inom fjärrvärmesektorn ersätts av förnybara alternativ och restvärme. En stor del av restvärmen utgörs av överskottsvärme från biodrivmedelsproduktion som antas ske i energikombinat. På grund av en kraftigt ökad användning av restvärme, dels från biodrivmedelsproduktionen, dels från industrin, så minskar underlaget för kraftvärme.

Efterfrågan på bioenergi ökar kraftigt från dagens ca 114 TWh till 165-248 TWh beroende på vilket framtidsscenario som avses. Särskilt ökar efterfrågan på skogsbränslen (avverkningsrester och/eller stubbar) från dagens nivå om 7 TWh upp till 50-128 TWh[7]. Den svenska skogen kan troligen bidra, men att möta det framtida bioenergibehovet kan innebära en konflikt med andra miljömål. En rad studier har uppskattat framtida potentialer för avverkningsrester och stubbar. Resultaten varierar kraftigt, från ca 25 TWh (WWF, 2009) till 57-180 TWh (extrapolerade värden från Skogsstyrelsen,

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[6] Framförallt till följd av ökad nederbörd från ett förändrat klimat.

[7] Notera att dessa siffror inte inkluderar rundved, vilket idag står för 17 TWh av bioenergitillförseln. Vi har inte uppskattat framtidspotentialen för rundved, utan vi har antagit att 17 TWh används även i scenarierna för 2050.

2008b)[8]. Användningen av energigrödor från jordbruket, avfall, biprodukter och import kan dock utöver skogsbränslena bidra till den totala bioenergitillförseln. Andra möjligheter är ytterligare energieffektivisering i användarsektorerna eller andra teknikskiften. Vi ser ett stort behov noggranna miljökonsekvensbedömningar för att undersöka den verkliga potentialen för hållbar använding av bioenergi 2050.

Ett alternativ till ett intensivt användande av biodrivmedel i transportsektorn är att fortsätta att använda fossila bränslen i transportsektorn, samt att kompensera detta genom att använda CCS på motsvarande volym biogen koldioxid från exempelvis pappers- och massabruken. Detta alternativa scenario ger jämfört med scenariot med biodrivmedel en ökning av oljeanvändningen på drygt 73 TWh och en minskning av bioenergianvändningen på 83 TWh. Elbehovet ökar med 4 TWh varav 1.4 TWh produceras med kraftvärme när fjärrvärmeunderlaget ökar till följd av att restvärmeproduktionen från biodrivmedel minskar.

Export av el och biobränslen till kontinenten kan eventuellt ge en större global klimatnytta än att Sverige använder dem själva så som antagits i detta scenario. Detta gäller under förutsättning att den exporterade elen och biobränslena ersätter fossila bränslen utan CCS.

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[8] Observera att uppskattningarna som WWF Sverige gjort (2009) inte inkluderar stubbar, då WWF anser att stubbrytning är för osäkert ur miljösynpunkt.

Table of contents

1 Aim of the study

Sweden has a vision of zero net emissions of greenhouse gases in 2050 (Regeringskansliet, 2009). The aim of this study is to develop and elaborate on one potential energy scenario with minimised Swedish use of fossil fuels and greenhouse gas emissions in 2050 and with sustained economic growth. The focus is on reduction of fossil fuel utilisation and direct emissions of carbon dioxide.

2 Methodology

2.1 System boundaries

The whole energy system has been analysed with respect to energy supply, energy conversion and energy end-use in the three sectors residential and service, industry and transport, see Figure 1. It is worth noting that we have not analysed import and/or export of electricity and renewables, with the motive that this would require development of energy scenarios of other countries as well.

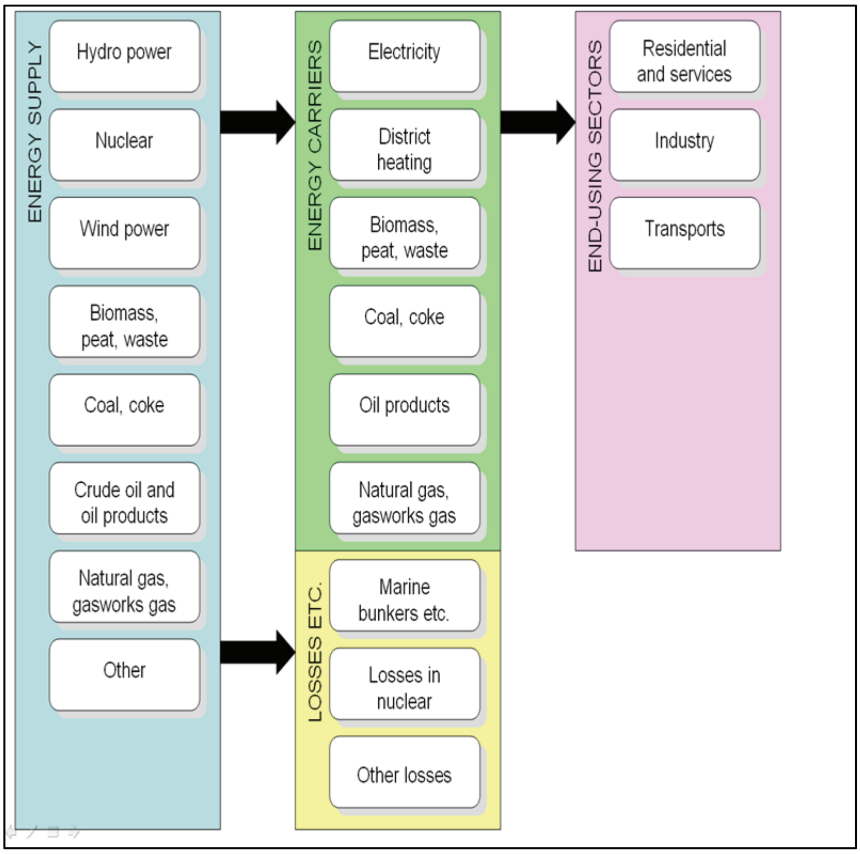

Figure 1. Illustration of the energy system studied, from energy supply to energy end-use without import and/or export of energy carriers (other than fossil fuels).

Energy supply, demand and emission reduction measures are thus analysed for the following sectors:

1. Energy end-using sectors
   a) Industry
   b) Transport (excluding international aviation and shipping)
   c) Residential and service
2. Energy converting/supplying sectors:
   a) Power production
   b) Heat production
   c) Fuel production

2.2 Methodology step by step

The methodology used can be divided into 5 stages:

1. **Energy demand (fuels/energy carriers) 2005 and 2030 in end-using sectors:**
   a. Industry sector – statistics based on Swedish Energy Agency (2009a)
   b. Transport sector – statistics based on Swedish Energy Agency (2009a)
   c. Residential and service sector – statistics for 2005 based on Swedish Energy Agency (2009a), no statistics for 2030 used, see below.

   The energy projections made by the Swedish Energy Agency (2009a) are based on projections of economic development for different subsectors made by the National Institute of Economic Research (Konjunkturinstitutet). These projections show GDP growth of 2.25% per year for the period 2005 to 2030. Energy demand grows much more slowly than GDP because of energy efficiency improvements and restructuring of the economy.

2. **Energy demand in 2050, assumptions:**
   a. Industry sector – Extrapolation of the statistics for 2005 and 2030 to 2050
   b. Transport sector – Extrapolation of the statistics for 2005 and 2030 to 2050
   c. Residential and service – Assumptions from Gode and Jarnehammar (2007)

3. **Measures for reduction of fossil fuel utilisation and carbon dioxide emissions in the end using sectors. Examples of important measures:**
   a. Shift from fossil fuels to biofuels
   b. Shift from fossil fuels to solar heat, district heating and heat pumps
   c. Shift from fossil fuels to electricity (in transport sector, e.g. introduction of plug-in hybrid cars)
   d. Shift from electricity heating (not for operating heat pumps) to solar heating, district heating, and heat pumps[9]
   e. District cooling
   f. Carbon capture and storage (CCS)

4. **The measures assumed for the end-using sectors as presented above result in demand for electricity, heating and fuels in 2050**

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[9] There may also be a shift from solar heating to small-scale bioenergy and vice versa. However, in this scenario we have assumed an overall effect towards more solar heat than small-scale bioenergy.

5. **Introduction of measures to reduce the use of fossil fuels and fossil carbon dioxide emissions in the energy converting/supplying sectors, for example:**
    a. Shift from fossil fuels to bioenergy/waste (stationary plants)
    b. Efficient use of by-products (excess heat from industry, excess heat and gases from biofuel production)
    c. Electricity produced without use of fossil fuels (except CHP production in industry and district heating systems from blast furnace gas (excess gas from steel production)).

Figure 2 illustrates energy interactions between the different sectors. The figure shows the end-using sectors on the left and the energy supplying sectors on the right. The figure also shows the interactions between the two groups of sectors.

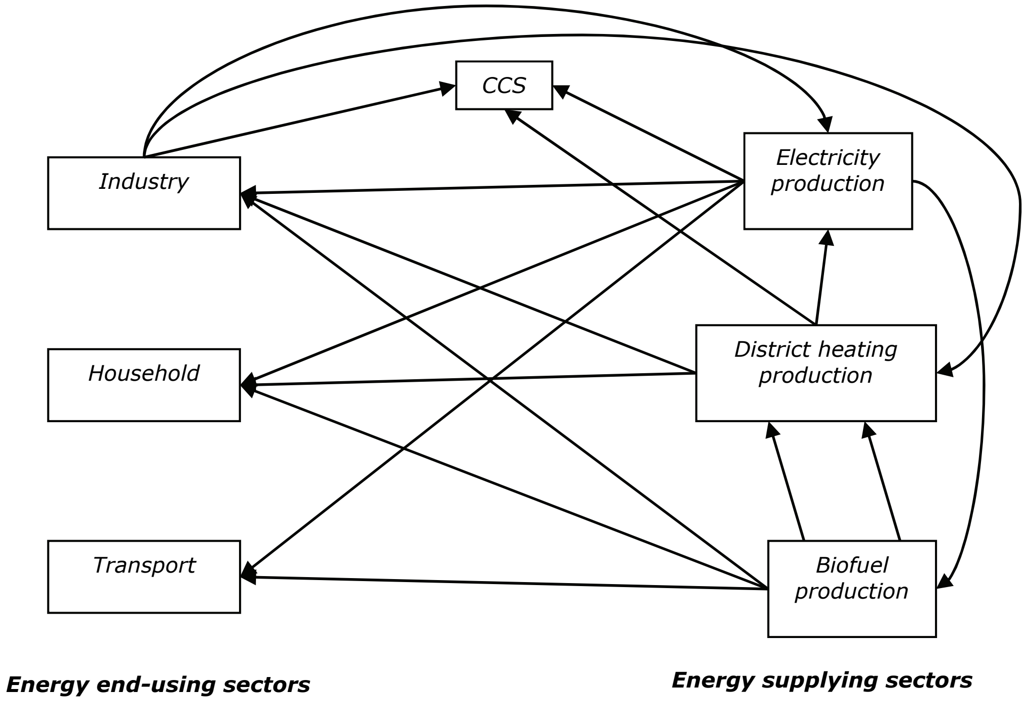

Figure 2. The energy flows between the different sectors. This figure only includes energy that flows from one sector to another. It does not include use of energy carriers other than electricity, district heating and the biofuels DME, SNG and biogas. The residuals from the forest industry (sawdust, etc) used in other sectors, for example, are therefore not included.

2.3 General assumptions and uncertainties

The scenario presented in this report is an illustration of an energy system with minimised use of fossil fuels and high utilisation of bioenergy. The scenario is not a projection of what the energy system will probably look like.

There are many uncertainties involved in developing scenarios for long-term future energy systems. There are many possible developments, and several assumptions are therefore needed to develop the scenario. Two of the most significant assumptions in the development of a scenario are firstly the future electricity production mix and secondly the future sustainable bioenergy potential.

The exact future electricity production mix is not specified in the scenario. Instead, the electricity is assumed to be produced by the present hydro power capacity, CHP production10 in industry and in district heating systems, and by fossil-free energy sources such as nuclear power, wind power, solar power, wave power and hydro power from increased rainfall. Consequently, the electricity mix is very close to being fossil-free. Total electricity production is assumed to be equal to the demand for electricity (no importing is assumed)11.

The future bioenergy potential is handled by applying an alternative scenario ("Fossil fuels + BECCS 2050") where it is assumed that fossil fuels are used instead of biofuels in the transport sector. The increase in fossil carbon dioxide emissions is assumed to be offset by BECCS (capture and storage of biogenic CO2 from stationary plants mainly in the pulp and paper industry).

2.3.1 Limitations

All use of energy in Sweden for energy purposes is included in the study. Neither use of energy products for purposes other than energy conversion nor energy for international aviation and shipping is included.

All fossil carbon dioxide (CO_2) emissions from energy conversion within Sweden are included, as well as CO_2 emissions from cement production. However, greenhouse gases other than carbon dioxide are not included.

Sweden is assumed to produce all the electricity and bioenergy (including waste) that is needed in the scenario for 2050. Other energy products such as oil and coal are still imported. However, the amount of imported fossil fuels in the main scenario for 2050 is substantially lower than in 2005.

No emissions are offset by purchasing international carbon credits. These are assumed to be very expensive in 2050, when the whole world will need to reduce carbon dioxide emissions.

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[10] CHP production is mainly fossil-free even if it includes some use of blast furnace gas

[11] We do not say that it is likely that Sweden will not import or export electricity (or other energy carriers). However, assuming imports would require scenarios for other countries' energy systems as well.

3 The industry sector

3.1 Description of the sector

The following industry sub-sectors are included in the study:

- **Steel sector.** Main emissions originate from two sites with blast furnaces (Luleå and Oxelösund).
- **Mineral sector**, including cement production. Main emissions originate from three sites where limestone is processed to clinker (Slite, Skövde and Degerhamn).
- **Petroleum refineries**
- **Chemical industry**
- **Pulp and paper**, **wood industry** and **graphic industry**.
- **Industry for the extraction of minerals**
- **Manufacturing industry**, **food industry**, **textile industry**, and other industries.

The following sectors/sources are not included in our definition of industry:

- Power, heat and fuel production
- Transport
- Residentialand service
- Agriculture
- Fisheries
- Industrial CHP units, mainly in the pulp and paper and steel industries. These are presented in the energy sector instead.
- Biogenic carbon fluxes from forests and forest soils: changes in biogenic carbon pools due, for instance, to land-use changes.

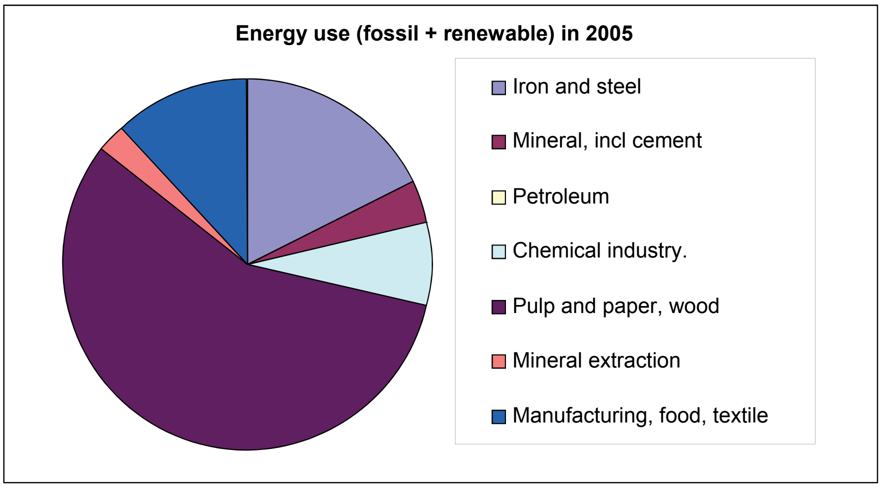

Figure 3. Total energy use (fossil + renewable) in 2005, classified by industrial sector. Total energy use is 155 TWh.

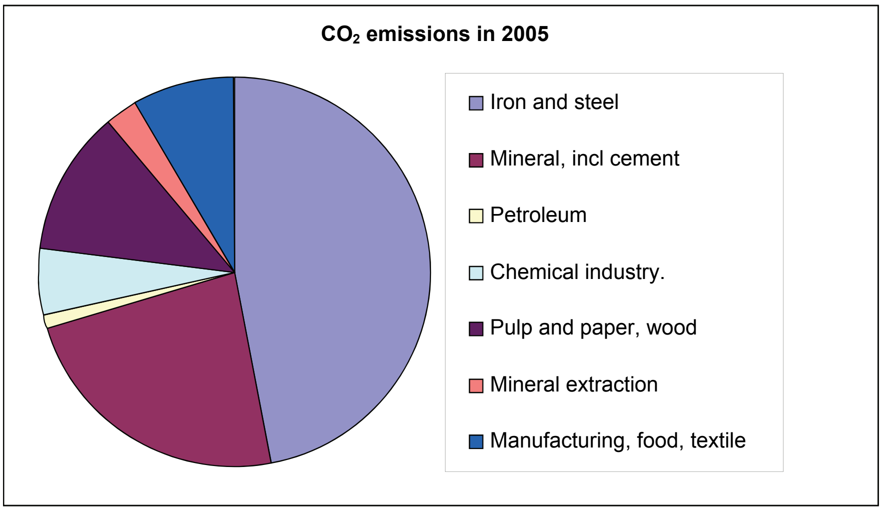

Figure 4. Fossil CO_2 emissions in 2005, classified by industrial sector. Total emissions are 14.9 Mt CO_2.

3.2 Methodology

In general, the methodology follows the procedures described in Chapter 2. However, here are some clarifications specifically regarding the industry sector. In calculating projected energy use for 2050 and CO_2 emissions (before and after measures), we have used the following methodology:

1. Compilation of a data set of sector-specific energy use and process emissions for the year 2005
2. Estimation of growth in energy demand for industry between 2005 and 2050
3. Compilation of a data set of sector-specific energy use and process emissions for the year 2050
4. Application of a set of CO_2-reducing measures for each sector
5. Compilation of a final table showing the resultant low-carbon scenario with projected energy use and CO_2 emissions for 2050, specified for each sector and energy type.

3.3 Energy use and CO_2 emissions per sub-sector

3.3.1 Energy use and CO_2 emissions in Swedish industry sectors 2005

For each sector, based on statistics from the Swedish Energy Agency, use of fossil and renewable fuels has been compiled for 2005 (Swedish Energy Agency, 2006). Based on this data, fuel-related CO_2 emissions have been calculated using official Swedish emission factors (Swedish Environmental Protection Agency, 2010). Process-related emissions, mainly from steel and cement production (SCB, 2009) have been added to the data set. Energy and fossil carbon dioxide emissions related to production or use of electricity and district heating are not included in the industry sector. The energy demand and emissions for electricity and district heating are presented in the specific chapters below. A summary of this data set is shown in Table 1.

Table 1. Energy use and CO_2 emissions for Sweden industry for the year 2005, sorted by energy type and sector.

	Industry total		**Iron and steel**		**Mineral, including cement**		**Petroleum**		**Chemical ind.**		**Pulp and paper, wood**		**Mineral extraction**		**Manufacturing, food, textile**	
	TWh	Mt CO_2	TWh	Mt CO_2	TWh	Mt CO_2	TWh	Mt CO_2	TWh	Mt CO_2	TWh	Mt CO_2	TWh	Mt CO_2	TWh	Mt CO_2
Non-steel processes		2.3		0		2.1		0.2		0.1		0		0		0
Steel processes and other use of coal, coke	14	5.0	11	3.7	2.5	0.9	0	0	0.1	0	0.3	0.1	0.7	0.3	0.2	0.1
Coke oven gas	2.0	0.3	2.0	0.3	0	0	0	0	0	0	0	0	0	0	0.1	0
Blast furnace gas	1.7	1.8	1.7	1.8	0	0	0	0	0	0	0	0	0	0	0	0
Peat	0.2	0.1	0	0	0	0	0	0	0.2	0.1	0	0	0	0	0	0
Oil	12	3.3	1.6	0.4	1.4	0.4	0	0	0.8	0.2	5.3	1.4	0.6	0.2	2.4	0.6
Natural gas, gasworks gas	4.3	0.9	0.4	0.1	0.2	0	0	0	1.8	0.4	0.3	0.1	0	0	1.6	0.3
Propane	4.7	1.1	2.4	0.6	0.3	0.1	0	0	0.4	0.1	0.7	0.2	0	0	0.9	0.2
Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wood, solid biofuels	17	0	0	0	0	0	0	0	0.4	0	16	0	0	0	0.4	0
Black liquor	38	0	0	0	0	0	0	0	0	0	38	0	0	0	0	0
District heating	4.4	0	0.3	0	0	0	0	0	0.5	0	0.8	0	0	0	2.8	0
Electricity	56	0	8.5	0	1.0	0	0	0	7.3	0	26	0	2.6	0	10	0
Total incl. processes	**154.8**	**14.9**	**27.4**	**7.0**	**5.5**	**3.4**	**0.1**	**0.2**	**11.5**	**0.9**	**87.9**	**1.8**	**3.9**	**0.4**	**18.6**	**1.2**
of which fossil	**39.3**	**14.9**	**18.6**	**7.0**	**4.4**	**3.4**	**0**	**0.2**	**3.3**	**0.9**	**6.6**	**1.8**	**1.3**	**0.4**	**5.0**	**1.2**

3.3.2 Projected energy use and CO_2 emissions in 2050

The projected total energy demand in industry in 2050 is based on the Swedish Energy Agency's long-term scenarios for the year 2030. These scenarios are based on GDP economic growth of 2.25% per year for the Swedish economy as a whole and economic growth of 3.45% per year for the industry sector (Swedish Energy Agency, 2009a). According to their scenario, energy efficiency improvement and restructuring in the industry sector are almost of the same magnitude as economic growth. Energy demand in the industry sector will therefore increase only slightly between 2005 and 2030. This extrapolated growth rate gives a total growth in energy demand in industry of 12% between 2005 and 2050 (about 0.25% per year). We further assume that the percentage of individual energy carriers in total energy use remains the same as in 2005, which is obviously a simplification. In summary, based on the 2005 data set of energy use in industry and an energy demand growth factor of 12%, a new set of sector-specific energy use and CO_2 emissions data has been calculated for 2050. This data set is then used as a basis for the emission reduction measures, presented below.

3.4 Measures for reduction of carbon dioxide emissions

The following types of CO_2 emission reduction measures have been applied:

- Efficiency improvement measures. The calculated energy demand for 2050 includes efficiency improvement measures in both energy use and processes. These efficiency improvement measures are of almost the same magnitude as economic growth (3.45% per year). The net effect of economic growth and efficiency improvement measures results in an increase in energy demand and process emissions of 12% over the period 2005 and 2050. For simplification, we assume that this energy demand growth value is the same for each sub-sector.

Based on the projected energy use in 2050, which includes efficiency improvement measures, the following CO_2 reduction measures have been applied:

- Use of fossil fuels for heating purposes is replaced by biofuels: solid, liquid or gas.
    - However, we estimate that emissions related to industrial processes will be difficult or very expensive to substitute. This mainly concerns the use of metallurgical coal and coke in the steel industry, the release of CO_2 from cement production and certain fugitive emissions from the chemical industry. These emissions related to processes have been assessed separately for each sector and in some cases subject to CO_2 reductions.
- Some of the residual carbon emissions from the steel and cement industries are assumed to be captured and stored using CCS technology.

The following use of fossil energy is sustained:

- Process emissions from small and fugitive sources are sustained.
- The use of propane gas for cutting is sustained.

3.5 Results for the industry sector

The energy demand in 2005 and in 2050 before and after measures is summarised in Table 2 and Table 3. Indirect emissions from production of electricity used in the industry sector are not included.

Table 2. Energy use and CO_2 emissions from each industry sub-sector 1) in 2005, 2) projections for the year 2050 before measures and 3) projections for the year 2050 after measures. Values for "2050 before measures" include a general economic growth factor, energy efficiency improvement measures and re-structuring of industry between the years 2005 and 2050.

	2005, before measures			**2050, before measures**			**2050, after measures**				**Residual**
	TWh total	TWh fossil	Mt CO_2	TWh total	TWh fossil	Mt CO_2	TWh total	TWh fossil	Mt CO_2, excl CCS	Mt CO_2, incl CCS	
Iron and steel	27	19	7.0	31	21	7.8	31	19	7.0	4.5	process, NG, propane
Mineral, incl. cement	5.5	4.4	3.4	6.1	4.9	3.9	6.1	0.3	2.4	2.3	process, propane
Petroleum	0.1	0	0.2	0.1	0	0.2	0	0	0	0	
Chemical ind.	12	3.3	0.9	13	3.7	1.0	13	0.5	0.2	0.2	process, propane
Pulp and paper, wood	88	6.6	1.8	98	7.4	2.0	98	0	0	0	waste
Mineral extraction	3.9	1.3	0.4	4.4	1.5	0.5	4.4	0	0	0	
Manufacturing, food, textile	19	5.0	1.2	21	5.6	1.4	21	0.1	0	0	process
Industry total	**155**	**39**	**15**	**173**	**44**	**17**	**173**	**20**	**9.6**	**7.1**	

The steel sector (2050 before measures: 30.7 TWh, 7.8 Mt CO_2). The major part of the emissions originates from two sites where iron ore is reduced to metal iron in blast furnace processes using coal and coke as reduction agents. The production of coke generates coke oven gas, which is mainly consumed internally in the steelworks. The blast furnace process produces blast oven gas (BOF gas), which is partly consumed at the steelworks. A significant portion of the BOF gas is sold to nearby CHP plants for the production of electricity and heat. Since emissions from the use of coal, coke, coke gas and BOF gas are strongly related to the metallurgical process, we judge that it is difficult or very expensive to reduce these emissions. In our low-carbon scenario for 2050 we estimate that natural gas can be used to replace coal and coke in the reduction process. This substitution reduces the use of coal/coke but increases the use of natural gas. Since natural gas has a lower CO_2-emission factor than coal, this results in a net CO_2 reduction (0.9 Mt CO_2). We further assume that all fossil oil is replaced by liquid biofuels (0.5 Mt CO_2 reduction). We assume that propane (0.6 Mt CO_2), mainly used for cutting, is not replaced. In this report, we have used estimates from McKinsey showing that 2.5 Mt of the remaining CO_2 can be reduced by CCS. This appears to us to be a conservative estimate since the residual CO_2 emissions from the steel industry after all the assumed measures will be approx. 4.5 Mt CO_2.

Table 3. Energy use and CO_2 emissions from the industry sector classified per energy carrier 1) in 2005, 2) projections for the year 2050 before measures and 3) projections for the year 2050 after measures (the Biofuel 2050 scenario). Valuesfor "2050 before measures" include a general economic growth factor, energy efficiency improvement measures and re-structuring of industry between the years 2005 and 2050.

	2005, before measures		**2050, with efficiency improvement measures only**		**2050, after all measures (Biofuel 2050 scenario)**	
	TWh	Mt CO_2	TWh	Mt CO_2	TWh	Mt CO_2
Industrial processes, excluding iron and steel		2.3		2.6		2.4
Coal, coke, including steel processes	14	5.0	16	5.6	9.2	3.3
Coke oven gas	2.0	0.3	2.3	0.4	2.3	0.4
Blast furnace gas	1.7	1.8	1.9	2.1	1.9	2.1
Peat	0.2	0.1	0.3	0.1	0	0
Oil	12	3.3	14	3.7	0	0
Natural gas, gasworks gas	4.3	0.9	4.8	1.0	3.0	0.6
Propane	4.7	1.1	5.3	1.2	3.5	0.8
Waste	0	0	0	0	0	0
Solid biofuel	17	0	19	0	24	0
Black liquor	38	0	43	0	43	0
District heating	4.4	0	4.9	0	4.9	0
Electricity	56	0	63	0	63	0
Liquid biofuels	0	0	0	0	14	0
Biogas	0	0	0	0	6.1	0
Total incl. processes, excl. CCS	**155**	**15**	**173**	**17**	**173**	**9.6**
Of which fossil	**39**	**15**	**44**	**17**	**20**	**9.6**
Total including process, CCS						**7.1**

The **Mineral sector**, including cement (2050 before measures: 6.1 TWh, 3.9 Mt CO_2). Main emissions (2.3 Mt CO_2) originate from the production of cement, where limestone, $CaCO_3$, is processed into CaO, emitting CO_2 in the process. In our low-carbon scenario for 2050, we estimate that part of these process-related emissions can be captured and stored (CCS). Based on McKinsey, approximately 0.1 Mt CO_2 can be reduced by CCS. However, we note that the potential for reduction should be significantly greater. Second to the process-related emissions are emissions from fuels for the cement ovens, mainly from coal and oil. We have assumed that these fuels can be replaced by biofuels. The residual CO_2 emissions from the mineral industry after all the assumed measures will be approx 2.3 Mt CO_2.

Pulp and paper, wood, graphic industry (2050 before measures: 98 TWh, 2.0 Mt CO_2). This sector is by far the most energy-consuming, which is due to the use of large quantities of forest residues and black liquor, but also due to extensive use of electricity. While the share of fossil fuels in the total energy use is low (7.4 TWh), the sector still has significant CO_2 emissions (2.0 Mt). In our low-carbon scenario for 2050, we assume that all fossil fuels (oil, propane, natural gas and coal) are replaced by biofuels and biogas. Taken together, the residual CO_2 emissions from the pulp and paper industry will be close to zero.

Chemical industry (2050 before measures: 12.9 TWh, 1.0 Mt CO_2). Main emissions originate from the use of natural gas, oil, propane and peat. This sector is highly diverse and complex, and a detailed analysis of each subsector is beyond the scope of this report. In our low-carbon scenario for 2050, we have assumed for simplicity that all use of oil, natural gas and peat can be replaced by biofuels, while the use of propane is sustained. Together with some minor process emissions, the residual CO_2 emissions from the chemical sector will be 0.2 Mt CO_2.

Petroleum refineries (2050 before measures: 0.1 TWh, 0.2 Mt CO_2). Since our main energy scenario assumes that all fossil fuels in the transport sector are phased out, there will be little need for the domestic production of these fuels. In our low-carbon scenario for 2050, we therefore assume that refineries are re-structured into biofuel refineries and that all fossil fuel production is phased out. This is however, a simplification, since refineries could, for instance, still be used for the production of fossil fuels used abroad and for international transport. For simplicity, we assume no residual emissions from petroleum refineries in 2050.

Extraction of minerals (2050 before measures: 4.4 TWh, 0.5 Mt CO_2). Emissions are mainly due to the use of coal and oil. In our low-carbon scenario for 2050, we assume that these fossil fuels are replaced by biofuels, leaving no residual CO_2 emissions from this sector.

Manufacturing and other industries (2050 before measures: 21 TWh, 1.4 Mt CO_2). Emissions are mainly due to the use of oil, natural gas, propane and to a lesser extent coke and coke oven gas. There is also a minor portion of process-related emissions. In our low-carbon scenario for 2050, we assume that all fossil fuels are replaced by biofuels, except for the use of coke oven gas, which is a result of the steel-making process. Due to process emissions and use of coke gas, the residual CO_2 emissions from this sector are 0.01 Mt CO_2.

Table 4: CO_2 emissions from the industry sector 1) in 2050 before measures and 2) in 2050 after measures (the Biofuel 2050 scenario). Values are classified by sector. Values for "2050 before measures" include a general economic growth factor, energy efficiency improvement measures and re-structuring of industry between the years 2005 and 2050

Sector/ Industry	**Emissions 2050 before measures [Mt CO_2]**	**Main origin of emissions**	**Measures**	**Emission 2050 after all assumed measures [Mt CO_2]**
Steel	7.8	Use of reduction agents coal and coke in blast furnace process; combustion of BOF gas; use of oil and propane	CCS; Natural gas partially replacing coal; substitution of oil for biofuels	4.5
Mineral	3.9	Limestone, $CaCO_3$ is heated to produce CaO and CO_2; Fossil fuels for the lime ovens	CCS; biofuels replacing fossil fuels	2.3
		Coal, oil	Biofuels	
Petroleum	0.2	Process related	Biofuels replace fossil	0
Chemical	1.0	Diverse uses of oil, propane, natural gas and peat	Partial substitution for biofuels	0.2
Paper & pulp, wood, graphic	2.0	Oil for heat and electricity production	Substitution for biofuels and biogas	0
Mineral extraction	0.5	Use of coal and oil	Substitution for biofuels	0
Manufacturing	1.4	Oil,natural gas,propane and limited use of coke and coke oven gas	Substitution for biofuels	0.1

3.5.1 Feasibility of mitigation options and costs

The costs of CCS are, according to McKinsey (2008), below SEK 700/tonne reduced CO_2.[12] Apart from CCS, we have not estimated the cost or feasibility of the suggested measures, as this would require extensive sector studies beyond the scope of this study. It should be noted that the assumptions made in this study requires that CCS is a mature and accepted mitigation technology in 2050.

A summary of CO_2 reduction measures in the "Biofuels 2050" scenario is given in Figure 5. Only reductions in direct emissions are included, while indirect emission reductions (e.g. from reduced use of electricity and district heating) are not included. The industry sector does not change in the alternative scenario ("Fossil fuels + BECCS 2050") compared to the main scenario ("Biofuels 2050")

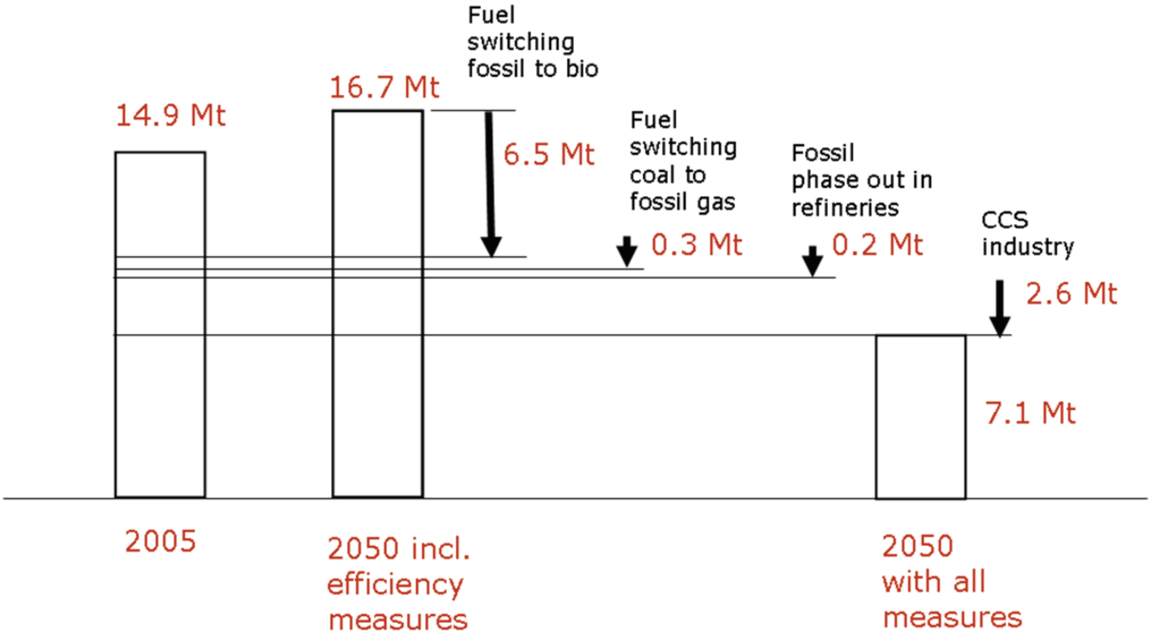

Figure 5: Summary of CO_2 reduction measures in Swedish industry for the Biofuel 2050 scenario. The reductions are identical in the alternative scenario for the industry sector.

3.6 Conclusions

With the suggested measures we conclude that:

- Total energy demand increases from 155 TWh year 2005 to 173 TWh year 2050. This includes efficiency improvement measures of almost the same magnitude as the economic growth
- Total **fossil** fuel demand decreases from 39 TWh to 20 TWh
- Emissions decrease from 14.9 Mt year 2005 to 9.6 Mt CO_2 year 2050, without CCS, or 7.1 Mt CO_2 with CCS

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[12] McKinsey (2008) estimates that in 2020 CCS will have an abatement cost of 600-1000 SEK/tonne reduced CO_2. However, they also predict that with a future positive technology development of CCS, the abatement cost may decrease to below 500 SEK/tonne reduced CO_2.

- Main residual emissions, 9.6 Mt CO_2, originate from processes related to the steel industry (5.8 Mt CO_2); processes from the cement industry (2.4 Mt CO_2); usage of natural gas in the steel industry (0.6 Mt CO_2); and propane use (0.8 Mt CO_2).
- With CCS these emissions can be reduced by 2.6Mt CO_2 resulting in total CO_2 emissions from industry in 2050 of 7.1 Mt CO_2.

3.7 Discussion

We note that there are large point sources of CO_2 at the two blast furnace sites and at the three clinker production sites in Sweden. Process-related emissions from these sites could be as large as 6 Mt CO_2 and total emissions, including both process and fuel-based emissions from these five sites, could be as large as 10-11 Mt CO_2. In this study, the total potential for CCS in industry has been estimated to be 2.6 Mt CO_2, based on the McKinsey study. In the light of the large point sources in steel and cement, this seems to us to be a conservative estimate, and we think that there could be potential for increased use of CCS in the year 2050.

We have assumed that all solid and liquid fossil fuels and a large part of natural gas can be replaced by biofuels. This raises two issues. Firstly, will the production and distribution capacity for biofuels be sufficient to satisfy this substitution in the year 2050? Secondly, an assessment needs to be done on a sectoral level if such fuel replacement can be done while maintaining the quality of the industrial processes.

We have assumed that a major part of the propane cannot be replaced. Our rationale for this is that when propane is used in processes that require high temperatures, such as cutting steel slabs, we assume that the propane gas cannot easily be replaced by a renewable gas. However, propane is also used for more trivial purposes such as heating. In these applications there should be potential for substituting some of the propane with renewable energy sources. We have not made this analysis since it would require a more in-depth assessment of propane use in each sector.

4 Residential and service sector

4.1 Description of the sector

The sector constitutes residential buildings (detached houses and apartment buildings), commercial premises, holiday homes, land use[13] and services[14]. The energy use in these various sub-sectors is shown in Figure 6. The scenario involves measures and assumptions for residential buildings, commercial premises, holiday homes and services. The use of transport fuels for land-use purposes is addressed in the transport sector. Other energy use in the land use sub-sector is not handled in this study.

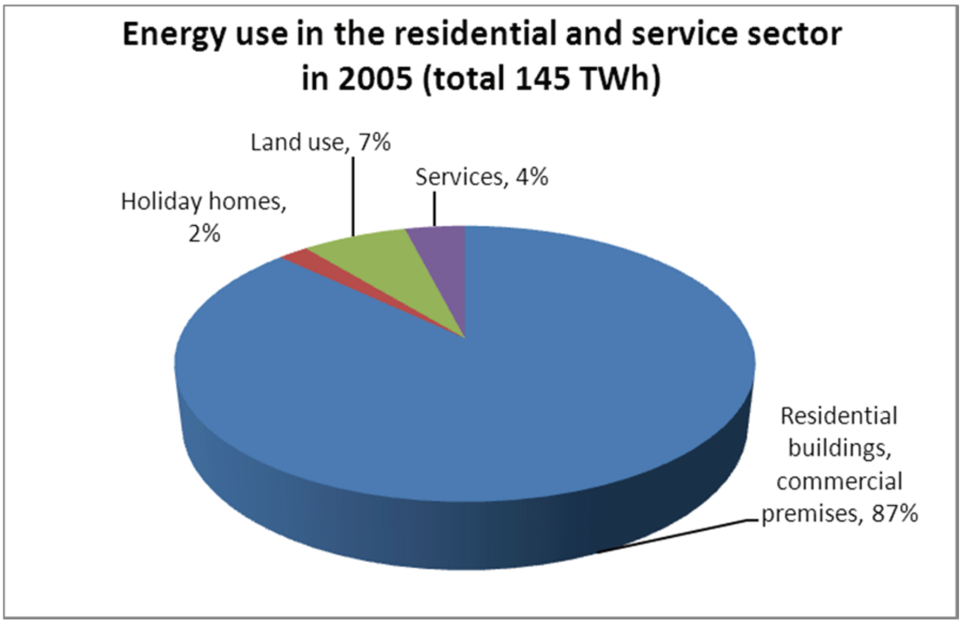

Figure 6. Breakdown of energy use in the residential and service sector in 2005 (data from the Swedish Energy Agency, 2006). Total energy use is 145 TWh.

To facilitate the analysis of potential measures for reduction of fossil fuel use and CO_2 emissions, residential buildings and holiday homes are broken down into detached houses and apartment buildings.

4.2 Detached houses – assumptions and measures

The assumptions about population growth (+17%), energy efficiency (-30% on space-heating demand) and climate change (-11% on space-heating demand, cooling demand will increase) are in accordance with Gode and Jarnehammar (2007). The heat demand for hot water is assumed to be

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[13] Land use includes agriculture, forestry, horticulture and fisheries.

[14] Services include e.g. the building sector, street lighting, sewage treatment and electricity and waterworks.

20% of the total heat demand in the reference case and is assumed to be constant in the future scenarios.

4.2.1 Electricity for household purposes (not for heating)

As well as space and tap-water heating, households use electricity for electric appliances such as lighting, washing machines, dishwashers, stoves and ovens, refrigerators, freezers, computers, air conditioning and TV. The efficiency of electric appliances has improved and continues to improve. In our scenarios we assume that the electricity demand for electric appliances will reduce by 30% in 2050 compared to 2005. The motive behind this assumption is that we believe that technology development will yield high-efficient electric appliances and lighting, partly as a result of the targets in eco-design directives and corresponding regulations of phasing out light bulbs (Directive 2005/32/EC and Commission Regulation (EC) No 641/2009). This means that the efficiency improvement of electric appliances must be stronger than the electricity demand resulting from increased used of different electric appliances. A previous study (Bennich, 2008) has examined how the use of electricity in homes changed between 1994 and 2007. The conclusion from that study was that the efficiency and increased number of appliances more or less balanced each other out during 1994-2007 and as a consequence that electricity consumption per household is kept fairly constant. Our assumption is thus pushing even further towards energy efficient appliances.

4.2.2 Heating

Electricity is an energy carrier that can be used for several purposes, whereas district heating, for example, can mainly be used for heating. Furthermore, district heating is very flexible regarding fuel input and can be based on waste energy resources that cannot be used for efficient electricity production. Direct electric heating (not for operating heat pumps) in that perspective is an inefficient way of using electricity. We therefore assume that direct heating based on electricity will be eliminated by 2050. There are several potential options for replacing direct electricity heating, but no given solution. The applicability of different options depends for instance on costs, potential and technology development. Possible solutions include solar heating, district heating, heat pumps and bioenergy. However, in our scenario a large amount of bioenergy is needed for the transport sector. Consequently, we assume that the electricity used for direct heating will be replaced by solar heating (60%), district heating (20%) and heat pumps (20%). Solar heating and heat pumps are used where district heating is not realistic.

We assume that existing (2005) use of **heat pumps, district heating, and bioenergy** for heating will remain in 2050. However, the energy use from the existing (2005) sources will decline in relation to the change in the overall heating demand to 2050. Heat pumps and district heating will gain market shares as a result of conversion from electric heating and oil. The market share for bioenergy will remain constant.

The use of **oil** for space and tap-water heating has declined substantially as a result of high world market prices, high taxes and conversion subsidies in combination with the expansion of district heating. The competition from oil will continue and we assume that the use of oil for heating in residential buildings will decline to zero. The options for conversion from oil heating are the same as for electricity. Oil is assumed to be replaced by solar heating (60%), district heating (20%) and heat pumps (20%). Solar heating and heat pumps are used where district heating is not considered realistic.

Use of **natural gas and gasworks gas** for heating is assumed to decline to zero by 2050. Gas-heated houses have an existing infrastructure for their gas supply and use and we therefore assume that all fossil gas is replaced by synthetic natural gas, SNG (50%) and biogas from anaerobic digestion (50%). The conversion from fossil to renewable gases may be a natural consequence of high future fossil fuel prices and carbon dioxide tax.

4.3 Apartment buildings – assumptions and measures

The assumptions about population growth (+17%), energy efficiency (-45% on space heating demand) and climate change (-11% on space-heating demand, cooling demand will increase) are in accordance with Gode and Jarnehammar (2007).

4.3.1 Electricity for household purposes (not for heating)

The same assumption on the use of electricity for household purposes (excluding space and tap-water heating) has been used for apartment buildings as previously for detached houses. Electricity consumption (excluding space and tap-water heating) is assumed to decrease by 30% between 2005 and 2050.

4.3.2 Heating

The use of direct **electricity** for heating is assumed to be eliminated for the same reason as for detached houses. District heating is easier to install in apartment buildings, and it is therefore assumed that direct electricity heating is replaced by district heating (70%) and by solar heating (30%) in areas not covered by district heating. The same is valid for **oil**.

Apartment buildings using **district heating** are assumed to continue to use district heating.

The use of **natural gas and gasworks gas** will decline to zero with the same arguments as for housing above. It will also be replaced by SNG (50%) and biogas (50%).

4.4 Commercial premises – assumptions and measures

The assumptions about population growth (+17%), energy efficiency (-30% on space-heating demand) and climate change (-11% on space heating demand, cooling demand will increase) are in accordance with Gode and Jarnehammar (2007).

4.4.1 Electricity for common purposes (not for heating)

The use of electricity for common purposes (excluding electricity for heating) in commercial buildings shows a continuing increasing trend. It will probably also increase in the near future. However, we assume that efficiency improvements will reduce demand to the same level in 2050 as in 2005. With population growth taken into account, this means that a slight energy efficiency improvement is assumed. This level of energy efficiency improvement may be hard to achieve without powerful policy measures and incentives.

4.4.2 Heating

The use of **direct electric heating** is assumed to decline to zero, based on the same arguments as for detached houses. We assume that direct electric heating is replaced by district heating (70%) and by solar heating (30%) in areas not covered by district heating. The same assumptions are also valid for **oil-**based heating. Buildings using **district heating** at present (2005) are assumed to continue to use district heating.

The use of **natural gas and gasworks gas**is assumed to be replaced by SNG (50%) and biogas (50%).

4.5 Services – assumptions and measures

The sub-sector services include the building sector, street lighting, sewage treatment and electricity and waterworks. The use of oil for transport purposes is treated in the transport sector and the remaining energy use is very small, about 4% of the residential and service sector. Furthermore, energy statistics are quite scarce regarding the energy flows in this sub-sector. Therefore, we have not made any detailed assumptions of potential mitigation options. We assume that today's electricity use remains constant, that the use of oil is used for transport purposes (and consequently treated in the transport sector), that the use of natural gas and gasworks gas is replaced by SNG and biogas (50% each) and finally that separate use of bioenergy remains constant.

4.6 Cooling – assumptions and measures

It has not been possible to distinguish cooling demand and cooling production for the different subcategories in the residential and service sector. Cooling demand and cooling production are therefore described as a total for the whole residential and service sector.

Cooling demand will increase to 13 TWh with economic growth and changing climate. The increase in cooling demand has been estimated by Gode and Jarnehammar (2007). Cooling can be produced with low environmental impact from heat with no alternative use. District heating using waste heat and heat from solar heating can produce cooling by absorption-driven cooling. Cooling demand is assumed to be met by absorption cooling (50%, which of 35 percentage points with district heating and 15 percentage points by solar heating), free cooling (40%) and electric cooling machines (10%).

4.7 Results

In the scenario, end-use of energy in the residential sector decreases by a total of 16% from 2050 to 2050. The district heating demand in the residential and service sector decreases somewhat in the scenario. The use of biofuels decreases as well, by 16% and electricity use decreases by almost 30%. Use of solar heat is assumed to increase to 12 TWh, while the use of oil, natural gas and gasworks gas disappears.

District heating takes market shares for heating at the expense of direct electric heating in particular. District heating is also used for the production of absorption cooling. The use of district heating nevertheless does not increase, as energy efficiency improvement and climate change result in a reduced total need for heating.

The use of energy for the residential and services sector in 2005 and in the 2050 scenario is presented in Table 5.

Table 5. Energy demand in the residential and service sector today and in 2050 according to the main scenario. Source: Swedish Energy Agency (2009a) for 2005, and this report for 2050.

	2005	**Biofuel 2050 scenario**
Electricity	72	52
District heating	43	42
Oil	11	0
Natural Gas, gasworks gas	2.2	0
SNG / Biogas	0	1.6
Solid biofuels	14	11
Solar heat	0	12
Total	**142**	**119**

4.8 Discussion

The measures assumed for the residential and services sector are mainly based on existing technologies. The most important group of measures is energy efficiency improvement actions both for heating and electric appliances. These measures are often very cost-effective measures that will reduce the energy bills for the owner of the house or service facility. There is therefore a risk of what are known as rebound effects, where the improved economy due to energy efficiency improvement may lead to increased energy utilisation. For instance, when energy costs decrease, households may raise the indoor temperature or buy new electricity-consuming appliances.

It is a challenge to decrease the electricity demand to the degree indicated in the scenario. The use of direct electricity for heating will decrease, and it is not unrealistic that it will disappear by 2050 (except for heat pumps). However, a larger proportion of the residential buildings could very well be heated by heat pumps than is assumed in our scenarios. The reduction in use of electricity for household electric appliances will probably also be difficult to achieve. Even if energy efficiency increases for the existing types of appliances (lighting in particular has great efficiency improvement potential), new electric appliances tend to be developed constantly.

In the scenario above, solar heat is assumed to expand significantly. The realism in this assumption can, of course, be questioned but there is some rationale for this idea. However, this is a long-term scenario and the extensive demand for transport biofuels may require high utilisation of solar energy. Another solution could be more extreme assumptions about energy efficiency improvement. The potential for solar heat production, if looking at available house roofs at the right angle, is large (Kjellsson, 2000). 11.8 TWh solar heat is not an unrealistic assumption and can be produced by using available roof area.

The solar heat will mostly be used in buildings that cannot be reached by district heating and will be a back-up form of energy for biofuels and heat pumps for heating. By storing some of the heat from the solar heaters in the ground during the summer, the efficiency of the heat pumps can be improved. The technologies for producing cooling from heat is assumed to improve and will be commercially available for small-scale applications in buildings and not just for large-scale district cooling production, as is the case today. Thus, solar heat can be used for cooling as well.

Climate change and increased comfort requirements will increase cooling demand. Cooling can be produced efficiently in district cooling systems that can use free cooling as well as absorption cooling. It is assumed that most cooling demand can be met by district cooling systems. The cooling demand that cannot be met with district cooling is assumed to use absorption cooling from solar heat and to some degree electric cooling machines. This is not unrealistic, because most cooling demand will still exist in commercial and official buildings that in most cases could have access to a district cooling network.

5 Transport sector

5.1 Description of the sector

The transport sector can be divided into road, railway, aviation and shipping (see Figure 7). These sub-sectors can be further divided into goods and passenger transport. However, lack of information and statistics at sub-sub-sector level has limited the prospects of detailed separation and analysis. Aviation and shipping can both be divided into domestic and international transport. Our scenario covers domestic transport only[15].

The transport sector uses a very high proportion of fossil fuels compared to other sectors. Finding solutions to reduce the dependency of fossil fuels in the transport sector is thus very important to reduce the carbon dioxide emissions. However, the abatement costs for reduction of fossil fuel utilisation and carbon dioxide emissions are high in the transport sector compared to other sectors (McKinsey&Company, 2008).

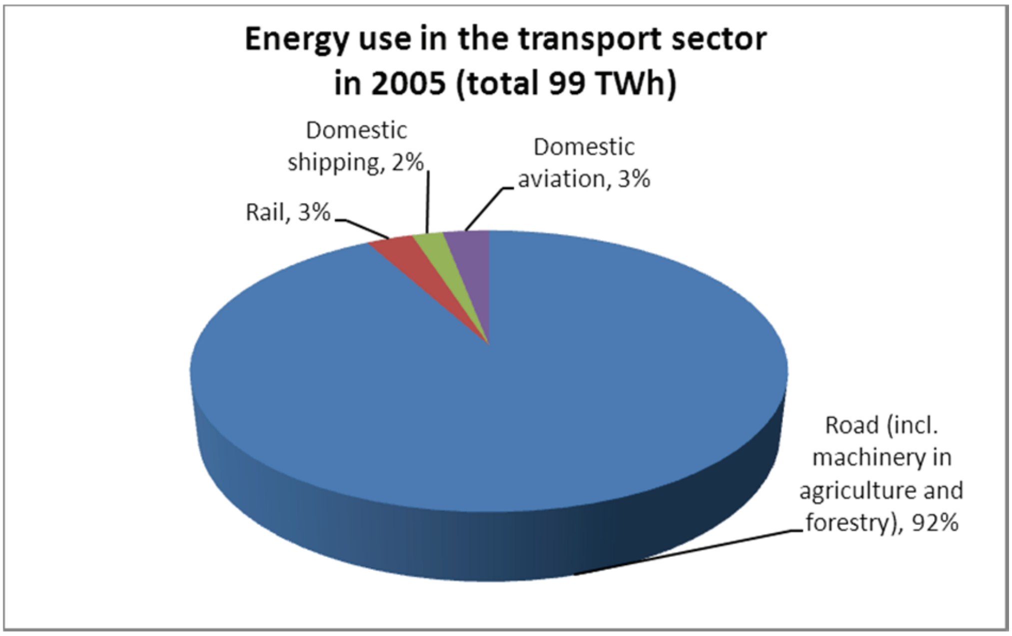

Figure 7. Breakdown of the transport sector in 2005. If international shipping (23 TWh) and international aviation (7.6 TWh) are included the figure for the Swedish transport sector would be 122 TWh.

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[15] International transport is neither included in the reporting of greenhouse gas emissions under the Kyoto Protocol. However, it should be noted that energy use for international transport and the related greenhouse gas emissions are increasing very rapidly.

5.2 Methodology

In general, the methodology follows the procedures described in Chapter 2. However, here are some clarifications specifically regarding the transport sector. The methodology involves the following five steps (all steps are explained in more detail in the chapters to follow):

1. **Energy demand in 2005 (see chapter 5.3.1).** Compilation of a data set of energy use (energy carriers and demand) for the year 2005, based on energy statistics (Swedish Energy Agency, 2006) and long-term energy projections (Swedish Energy Agency, 2009a)
2. **Calculated *baseline* energy demand in 2050 (see chapter 5.3.2).** By baseline we refer to the energy demand in 2050 when assuming the same powertrains as today and extra-polating growth from the period 2010-2020up to 2050. The extrapolation is based on data from 2010-2020 in the Swedish Energy Agency (2009a).
3. **Measures for reduction of fossil fuel utilisation and carbon dioxide emissions (see chapter 5.4).** The applied measures are explained in Chapter 5.4 below.
4. **Resulting *scenario* energy demand in 2050 (see chapter 5.5).** Final energy demand in the transport sector in 2050 after applying abatement measures on baseline energy demand.

5.3 General assumptions

5.3.1 Step 1. Energy demand in 2005

Energy statistics (Swedish Energy Agency, 2006) and energy projection data (Swedish Energy Agency, 2009a) has been used to present energy supply and demand for the transport sector in 2005. The results are shown in Table 6.

Table 6. Energy demand for transports in 2005. Source: Swedish Energy Agency (2006) and Swedish Energy Agency (2009a)

Energy for transports	2005
Electricity	3
Oil	94
Natural gas	0.2
Biogas (digestion)	0.2
Synthetic natural gas (SNG)	0
Ethanol and FAME	1.8
Dimethyl ether (DME)	0
Total	**99**

5.3.2 Step 2. Calculated *baseline* energy demand in 2050

Data from the Swedish Energy Agency's (2009a) long-term energy projection has been used to estimate *baseline* energy demand for transports in 2050, representing a transport sector with the same powertrains as today. This baseline scenario is needed for applying abatement measures in the next step. Therefore, the *baseline* energy demand must represent a case *without* introduction of abatement measures assumed in our scenario (i.e. without introduction of plug-in electric hybrids, biofuels and massive shift from road to rail transport of goods). However, in the Swedish Energy Agency's (2009a) projections to 2030, biofuels and plug-in hybrids are to some degree already included. A direct extrapolation of the projected development from 2005-2030 up to 2050 is therefore not possible. Instead these elements have been quantified and excluded based on a reference case for 2020 in the Swedish Energy Agency (2009a).

Furthermore, calculation of the *baseline* energy demand in 2050 requires assumptions of transport growth up to 2050. This has been done by extrapolating the Swedish Energy Agency's projections of growth from 2010 to 2020. These projections (2010-2020) show an annual increase in demand of 0.6% for liquid and gas fuels and 1.6%[16] for electricity. The results show a *baseline* demand for liquid and gas fuels of 127.2 TWh in 2050 (including use of fuels for domestic shipping and aviation, which is assumed to be constant between 2030 and 2050[17]), and a *baseline* electricity demand of 5.8 TWh in 2050.

5.4 Step 3. Measures for reduction of fossil fuel utilisation and carbon dioxide emissions

The abatement measures assumed in this study are described and quantified in the following chapters. To summarise, the assumed measures for the main scenario ("Biofuels 2050") are:

- 50% of the liquid and gas fuels in the extrapolated *baseline* scenario (step 2 above) are replaced by electricity. Conversions are made in both passenger and goods transport.
- The remaining 50% of the liquid and gas fuels in the extrapolated *baseline* scenario (step 2 above) are replaced by biofuels. Conversions are made in both passenger and goods transport. The biofuels used are dimethyl ether, DME (50%) biogas from anaerobic digestion (25%) and synthetic natural gas, SNG (25%).
- Domestic aviation and shipping are assumed to be run on dimethyl ether (DME).

5.4.1 Introduction of plug-in hybrid cars and shift to rail transport

In both the "Biofuels 2050" scenario and the "Fossil fuels + bio CCS 2050" scenario (see chapter 11.2), 50% of the liquid and gas fuels are assumed to be replaced by transport systems using electricity for plug-in hybrid cars and rail. 50% is an assumption based on extensive introduction of plug-in hybrids and other electric transport systems for passenger transport and a massive shift from goods transport by road to rail. The realism of this assumption has not been examined.

Electric hybrids cars, which have both an electric motor and an internal-combustion engine, have been commercially available for more than 10 years. Many of the large car manufacturers have presented plans to produce plug-in hybrid cars. These improved electric hybrid cars have better battery capacity which makes it feasible to charge the car from the mains and to drive longer distances without using the internal-combustion engine. We assume that all cars will be plug-in hybrid cars in 2050 even if there may be other competitors. Plug-in cars will still need some fuel (liquid or gas) for long distances.

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[16] This could be compared to 0.8% increase per year between 1990 and 2005 and projected increase of 2.1% per year between 2005 and 2010.

[17] This is reasonable according to the Swedish Energy Agency long-term scenario to 2030 where the use of fuel for domestic aviation and shipping decreases from 4.7 TWh in 1990 and 4.2 TWh in 2005 to 3.7 TWh in 2030.

Lorries cannot convert to plug-in technology as easily as cars. Batteries cannot meet the great need for energy for long-distance transport. However, existing lorries will probably be more efficient with electric-hybrid technology. The most realistic way to electrify goods transport is to shift from goods transport by road to rail. In our scenario one third of the goods transport by road[18] is assumed to be shifted to rail. Massive investments in railway infrastructure are necessary to put this assumption into effect. It is not examined in this study whether it is possible to expand the railway infrastructure to the level used in the main scenario for 2050.

When electricity is used instead of liquid or gas fuels, either in a plug-in hybrid or for goods transport by rail instead of by road, end-use energy demand decreases. The average decrease in end-use energy is assumed to be 67% for the element of transport that is "converted" from liquid and gas fuels to electricity. This is based on the information in the Swedish Energy Agency (2009a) long-term scenario, where 0.51 TWh petrol in an ordinary car corresponds to 0.17 TWh electricity in a plug-in hybrid. This reduction could very well be larger. Elforsk (2009) assumes that the reduction is slightly more than 70% when converting from ordinary fuels to electric cars. Shifting from freight transport by road to rail will probably result in an even greater reduction[19]. We have chosen to assume a reduction of 67% according to the Swedish Energy Agency (2009a). The motives for choosing a lower reduction than stated by Elforsk (2009) are as follows:

a) An efficiency improvement for the petrol and diesel engines is already included in the scenario that indicates a yearly increase of 0.6% for liquid and gas fuels. It is not evident that electric cars will have the same efficiency improvement.
b) There is a risk of rebound effects, i.e. transport demand increasing when transport is made more efficient and probably cheaper
c) Lack of reliable information about the future efficiency improvement potential.

5.4.2 Introduction of biofuels

Road transport

50% of the liquid and gas fuels in our "Biofuels 2050"are assumed to be converted to biofuels (as mentioned above, the other 50% is converted to electricity based powertrains). These biofuels are assumed to be produced in Sweden[20], for details about biofuel production see chapter 8. The high demand for biomass as raw material in the forest industry and for energy production means that the biofuels have to be produced with high efficiency and with the focus on production from residuals. The biofuels will mostly be used in lorries, and the lorries demand a fuel with high energy density. The biofuels DME, SNG and biogas from anaerobic degestion are assumed to best fulfil these requirements, while the most common present biofuel – ethanol – fails on several points.

The biofuels will be used in lorries and as auxiliary energy in plug-in hybrid cars. Lorries need a fuel with high energy density. DME is a fuel with high energy density and at the same time low emissions of particulates, NOx and SOx. Biogas and SNG are other examples of fuels with low

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[18] Only goods transport run on liquid fuels at present is assumed to be converted to rail.

[19] SIKA 2008 presents calculations that shifting goods transport from diesel lorries to diesel trains reduces the use of diesel with 63%. A shift to electric trains would probably reduce the end-use energy demand even further.

[20] This is probably an overestimation since a large part of present day's biofuels are imported. However, one goal of our scenario is to quantify the possible future demand for Swedish biomass and therefore we make this assumption. Furthermore, it is very likely that the pressure on Swedish biomass will be even larger when EU and the whole world are to reduce the dependency of fossil fuels.

environmental impact. Biogas can be produced from waste from households and agriculture. On this basis it is assumed that 25% of the biofuels needed in the transport sector is produced as biogas from anaerobic digestion, 25% as synthetic natural gas by gasification and 50% as dimethyl ether (DME) by gasification (gasification of black liquor and other biomass). Lorries for long-distance transport will mainly use DME, and lorries for shorter-range transport will mainly use biogas/SNG. Plug-in cars will mainly use biogas/SNG as back-up fuel.

Domestic aviation and shipping
According to the statistics in Swedish Energy Agency (2009a) there have been small changes in energy demand for domestic aviation and shipping in the last few decades. It is therefore assumed that the energy demand for these will be constant up to 2050 from 2030 levels (according to the Swedish Energy Agency (2009a) scenario). This is a decrease from the level in 2005. To increase energy efficiency it is possible that shipping will increase and aviation will decrease slightly, but it is assumed that these changes balance each other out. Aircraft in particular, but also ships, need a fuel with high energy density. It is therefore assumed that domestic aviation and shipping will be run on DME.

5.4.3 Alternative scenario ("Fossil fuels + bio CCS 2050")

As an alternative scenario to the extensive introduction of biofuels in the transport sector, the "Fossilfuels+ bio CCS 2050" scenario has been developed. In this alternative scenario the introduction of plug-in hybrids and the shift to rail transport is the same as in the main scenario ("Biofuels 2050"). However, no biofuels are used in the transport sector in the alternative scenario. Instead this energy need is met by fossil fuels.

To reach the same low carbon dioxide emissions as in the main scenario "Biofuels 2050", an extensive capture and storage is assumed on biogenic carbon dioxide[21] from stationary plants (mainly pulp and paper mills). This alternative scenario is based on other assumptions for the transport sector, as mentioned above. However, as shown in Table 7, this scenario also has other substantial effects. It affects electricity use and production (need for electricity to compress the carbon dioxide in the CCS process chain) and district-heating production (less excess heat and gases from biofuel production).

5.5 Step 4. Resulting scenario energy demand in 2050

Energy use for the transport sector in 2005 and for the main and alternative scenarios in 2050 is presented in Table 7.

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[21] Often referred to as BECCS (bioenergy carbon dioxide capture and storage) or bio CCS.

Table 7. End-use of energy in the transport sector today (2005) and in 2050 for the main scenario and for the alternative scenario. Source: Swedish Energy Agency (2009a) for 2005, this report (scenario 2050). The bioenergy needed to produce the biofuels listed in this table can be found in the Fuel producing sectorchapter below.

	2005	**"Biofuels 2050"**	**"Fossil fuels + bio CCS 2050"**
Electricity	3	26	26
Oil	94	0	65
Natural gas	0.2	0	0
Biogas (digestion)	0.2	15	0
Synthetic natural gas (SNG)	0	15	0
Ethanol and FAME	1.8	0	0
Dimethyl ether (DME)	0	35	0
Total	99	92	92

5.6 Discussion

In our scenario, transport activity is assumed to increase, in accordance with the projections made by the Swedish Energy Agency (2009a). Energy efficiency improvements offset a large part of the increased growth. When assuming the same powertrains in 2050 as today[22], the results nevertheless show an increase of more than 30% in energy demand from 2005 to 2050. However, the switch to plug-in hybrids and a larger proportion of transport by rail assumed in this scenario reduces the end-use energy demand in the transport sector in 2050 compared to 2005. This is due to electric transport demanding less end-use energy than fuel-operated transport[23].

It is a great challenge to phase out fossil fuels in the transport sector. In our main scenario ("Biofuels 2050") we assume a substantial switch to electrical powertrains and biofuels. When a switch is made from fossil fuels to electric drive, a substantial improvement takes place in the end-use of energy. There is uncertainty over how great the improvement in efficiency will be. We have been conservative in our scenario, and it is possible that the efficiency improvement may be even greater. If so, this would significantly decrease the electricity demand in the "Biofuels 2050" scenario. One motive for this conservative assumption is that the change-over to electric propulsion results in lower costs per kilometre. This may lead to an increase in transport mileage unless taxes, for example kilometre tax, are introduced. The potential increase in transport mileage has not been included in the scenario more than a conservative assumption being used for the efficiency improvement potential in switching from fossil fuels to electric propulsion.

In the scenario, we have assumed that dimethylether (DME), synthetic natural gas (SNG) and biogas from anaerobic digestion will be the most important biofuels. However, it is difficult to predict which biofuels will be winners and losers in a long-term perspective. Substantial research is in progress at present to develop and commercialise techniques for first and second-generation biofuels. At present, ethanol is the most commonly used biofuel in Sweden, of which a substantial amount is imported, for example from Brazil. However, a general assumption in our scenario is that non-fossil fuels should primarily be indigenous. One reason for this prerequisite is to allow analysis of demand for Swedish forest biomass. We assume that Swedish first-generation ethanol production will not be competitive environmentally and economically with other biofuel production in

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[22] I.e. comparing the Baseline energy demand in 2050 with present energy use (2005), see Methodology above.

[23] Note that this is valid for end-use energy only. Depending on the performance of the electricity used for transport, primary energy use may differ substantially.

2050. Introduction of second-generation ethanol production instead of DME or SNG would significantly increase the biomass demand, even when taking into account that second-generation ethanol production results in net production of electricity. The future competition of biomass makes ethanol production less realistic. Importing biofuels from other countries (depending on availability of and global market prices for biomass) could be one way of reducing the pressure on Swedish biomass from the forests.

The proposed measures for the transport sector are expensive to implement. The abatement costs are around the level of the present-day carbon dioxide tax (approximately 1000 SEK per tonne carbon dioxide) or higher (IEA, 2008).

6 Electricity production

6.1 Description of the sector

Existing Swedish electricity production is mainly based on hydro power and nuclear power, roughly 45% each. Just under 10% of the electricity is produced by combined heat and power (CHP) inindustry or at district heating plants. Less than 1% is produced by wind power[24]. In 2005 Sweden had net exports of electricity, but this changes from year to year depending, for example, on electricity demand, precipitation and availability of the nuclear power plants.

6.2 Electricity production – assumptions and measures

The Swedish Energy Agency (2009a) shows in its projections that electricity production will increase more than electricity demand to 2030. Net exporting of electricity will therefore grow. Nuclear power plants have a service life of 60 years in these projections and will therefore still exist in 2030. However, it is unclear whether nuclear power will exist in Sweden in 2050. In the beginning of this scenario project there was still a ban on construction of new reactors. However, in June 2010 there was a decision in the Swedish Parliament that new nuclear power plants may be constructed if they replace existing reactors and are built on the same sites.

The results of our scenario show that electricity demand will increase marginally from 2005 to 2050. Present-day production would therefore almost be sufficient to meet the national need for electricity in 2050, according to our scenario. This applies even though assuming an annual growth in GDP of 2.25%. However, if nuclear power is phased out by 2050, remaining electricity production, equivalent to around 75 TWh, needs to be produced from a mix of wind power, expanded hydropower production[25], solar power, wave power and biomass.

The CHP electricity production in industry is assumed to increase from 4.6 TWh in 2005 to 10.6 TWh in 2050, based on the same yearly change as the Swedish Energy Agency (2009a) assumes for 2005 to 2030. The industry's energy demand is changing according to the extrapolation of the Swedish Energy Agency (2009a) scenario (see chapter 3), and it is therefore realistic that the increase in CHP electricity production in the industry corresponds to that extrapolation as well.

The CHP electricity production at district heating systems decreases from 7.3 TWh in 2005 to 5.7 TWh in 2050 in the main scenario because of the increased use of excess heat (mainly from biofuel production) in the district heating system. In the alternative scenario "Fossil fuels + BECCS 2050" CHP electricity production in district heating systems will increase from 7.3 TWh to 7.6 TWh.

The only use of fossil fuels in the electricity sector has been in CHP production. It is assumed that all fossil fuels except excess gases from the steel production will be replaced by biomass or waste. It

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[24] It should be noted that the electricity production from wind power has increased from 0,9TWh in 2005 to 2,0 TWh in 2009. The baseline year of this study is 2005.

[25] In particular as a result of increased precipitation from a changed climate.

is assumed that 50% of the fossil carbon dioxide emissions from the excess gases from steel production that are exported to CHP production can be captured and stored. This is in line with the amount of CO_2 that McKinsey assumes can be captured and stored from steel plants (McKinsey&Company, 2008).

6.3 Results

The end-use of electricity increases from 131 TWh in 2005 to 150 TWh in 2050 (to 154 TWh in the alternative scenario). The increase in the transport sector is almost offset by the decrease in the residential and service sector. Industry increases its electricity demand, especially when CCS is introduced[26].

The electricity production increases from 155 TWh in 2050 to 158 TWh in 2050 (to 162 TWh in the alternative scenario). The differences between production and end-use of electricity are explained by losses in the electricity distribution network, use of electricity in the energy plants in producing electricity and heat, use of electricity in refineries, use of electricity in biofuel production, and imports/exports.

Table 8. Energy supply for electricity production.

Electricity production, TWh				
	2005	**"Biofuels 2050"**	**"Fossil fuels + BECCS 2050"**	**Comment**
Hydro power	72	68	68	The potential assumed for 2050 is based on a "normal" year in 2005.
Wind power	0.9	*	*	
Nuclear power	70	*	*	
Wave power	0	*	*	
Solar power	0	*	*	
Nuclear, wind, increased hydro, solar, and wave power		73	76	
CHP in industry	4.6	10.6	10.6	
CHP in district heating networks	7.3	5.7	7.6	
Condensing power	0	0	0	
Gas turbines	0	0	0	
Total net production	155	158	162	
Import minus export	-7.5	0	0	

* Note:The exact contribution of wind, nuclear, increased hydro, wave and solar power to the electricity production mix in 2050 is not specified.

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[26] Capture and storage of carbon dioxide from the steel, cement and energy sectors increases the use of electricity by 2.1 TWh. In the "Fossil fuel + BECCS 2050" alternative scenario the use of electricity for CCS increases by another 9.5 TWh.

6.4 Discussion

The future electricity mix has not been examined in detail. Consequently, as shown in Table 8 above, the scenarios do not specify the details of the whole electricity production mix. Instead, we assume base production from hydro power and CHP in industry and district heating (varying according to scenario). The rest of the electricity production mix is assumed to be met e.g. by nuclear power, increased hydro power (as a result of increased precipitation in a future climate), wind power, solar power and wave power. The reason for this simplification is that the focus of the study has been on reducing the use of carbon-intensive fossil fuels as well as carbon dioxide emissions. All non-specified energy sources for electricity production (wind, nuclear, increased hydro, wave, solar) are non-fossil/non-carbon-intensive and have low CO_2 emission factor. Specifying the electricity production mix should be an important part of a potential new project.

A scenario with a substantial increase in intermittent power sources, such as wind power and solar power, will require regulating power mainly from hydro power. It is therefore possible that the potential increase in hydro power production due to climate change cannot be fully utilised. On the other hand, a scenario with nuclear power would reduce the demand for regulating power. Wind, solar and wave power can produce significant volumes of electricity, but probably not as much as about 75 TWh, even in a 40-year perspective. Furthermore, electricity from biomass on top of what is already included in the CHP production is not considered plausible.

The costs of combined heat and power, back pressure in industry, nuclear power, expanded hydro power and wind power are judged to be competitive today. Solar power for the time being is expensive and wave power is not yet commercially available. Solar power and wave power may, however, very well be competitive in 2050.

7 District heating production

7.1 Description of the sector

Heat production in district heating systems amounted to approximately 50 TWh in 2005. 40% of the energy supply to districtheating systems is based on bioenergy, about 20% is waste, and 10% excess heat from the industry. The rest is a mix of fossil fuels, peat and heat pumps. See Table 9 for more detailed information.

7.2 District heating – assumptions and measures

The demand for district heating in 2050 is established from the assumptions made and measures taken for three user sectors (transport, residential/service and industry). In addition to this, the sector is also affected by the assumptions on energy supply in other sectors. For example, district heating production is influenced by what assumptions are made on the development of the transport sector. We therefore obtain substantially different results in the main scenario “Biofuels 2050” and in the alternative scenario “Fossil fuels + BECCS 2050”. This is due to the main scenario requiring considerable production of transport biofuels, which generates residual heat that can be used in the district heating sector, while the other scenario does not include use of biofuels in the transport sector. Fossil fuels are used instead, and fossil carbon dioxide emissions are offset by BECCS[27] at paper and pulp mills. On the basis of the result need for district heating and the assumptions on energy supply in the transport sector we have made assessments of possible measures to reduce the sector’s fossil fuel use and carbon dioxide emissions.

We have assumed that in principle all direct use of fossil fuels in the district heating sector is replaced biofuels and waste. The use of residual heat increases sharply. This is principally due to the assumption that the production of transport biofuels takes place in polygeneration plants which generate surplus heat[28] that can be used for district heating and production and that existing use of natural gas could be replaced among other things by residual gases from the production of transport biofuels and synthetic natural gas. The fossil fuels that still remain are residual gases from steel production, but it is assumed that 50% of the carbon dioxide generated could be captured and stored (see the description for electricity production in Chapter 8 above).

We assume that the use of direct electricity and heat pumps for district heating production is replaced by other alternatives (biofuels, waste or residual heat). The fuel mixes for district heating in the main scenario “Biofuels 2050” and the alternative scenario “Fossil fuels + BECCS 2050” are presented in Table 8.

In 2050 it is calculated in the main scenario that 53% of district heating is produced with residual heat and residual gases from industry and production of transport biofuels, of which 3 percentage

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[27] BECCS means capture and storage of biogenic carbon dioxide

[28] We have assumed that transport biofuels are the main product and the heat formed is therefore defined as residual heat. This is to avoid duplicate counting of the primary need for biomass.

points are fossil fuel from use of coal and coke in the steel industry. 21% is produced from waste and the remainder from biofuels.

7.3 Results

District heating demand in 2050 is a result of the assumptions and measures applied to the end-use sectors (see Chapters 3-5). The resulting district heating demand in 2050 is more or less the same as in 2005, see Table 9. A substantial improvement in energy efficiency and climate change reduces demand. However, the decrease is offset by increased market share at the expense of heating with oil and direct electricity and by the assumption that a large proportion of the expected need for cooling could be met by absorption cooling produced using district heating. Aggregate district heating production is thus more or less unchanged (53 TWh in 2005, 51 TWh in 2050).

Table 9. The fuels and energy sources used for district heating production

District heating production, TWh				
	2005	**“Biofuels 2050”**	**“Fossil fuels + BECCS 2050”**	**Comment/assumption**
Oil	3.2	0.0	0.0	Replaced by other fuels
Natural Gas and LPG	2.4	0.0	0.0	Replaced by excess/waste gases from biofuel production and SNG
Coal for energy use, including coke oven gas, blast-furnace gas	3.2,	1.3	1.3	Excess gas from steel industry (using coal) will remain, coal is replaced by other fuels.
Solid biofuels, biofuels, waste, peat, etc.	32	24	36	
of which peat	2.6	0.0	0.0	
of which waste	9.9	11	18	
Excess heat from biofuel and SNG production		14	4.5	From polygeneration plants
Waste gases from biofuel production		3.0	0.8	From polygeneration plants
Electricity (for boilers, not heat pumps)	0.3	0.0	0.0	Replaced by other fuels.
Geoheat to heat pumps	4.4	0.0	0.0	Replaced by other fuels.
Electricity to heat pumps	1.8	0.0	0.0	Replaced by other fuels.
Excess heat from industry, etc	5.4	9.0	9.0	The whole potential in 2009 is assumed to be used in 2050 (The potential according to ÅF (2002))
Total	53	51	51	

7.4 Discussion

The future fuel mix is strongly influenced by what assumptions are made for other sectors. This applies for example to assumptions on energy efficiency improvement and heat supply in the user sectors, but also to what assessments are made on future powertrains in the transport sector. The main scenario “Biofuels 2050” and the alternative scenario “Fossil fuels + BECCS 2050” consequently produce entirely different results for district heating production.

Substantial electrification of the transport sector and large use of transport biofuels are therefore assumed in the main scenario. Production of transport biofuels in turn generates excess heat that can be used in the district heating sector[29]. The basis for district heating is consequently also reduced. The same substantial electrification of the transport sector is assumed in the alternative scenario. However, the transport sector continues to use a large quantity of fossil fuels in this scenario. This has the consequence that production of district heating uses a larger quantity of waste and biofuel combined heat and power to meet the need for district heating.

We have assumed virtually all use of electricity in the district heating sector has been phased out in 2050, This might be a far-reaching assumption as some electricity is needed to pump waste heat and pumps are a good way of utilising heat for example from sewage treatment plants. It is likely that some electricity use will persist. However, this would not appreciably affect total energy use in 2050.

The increased use of residual heat from the production of transport fuels (see Chapter 10 on production of transport fuels below) and industry signifies that the need for fuels for district heating production decreases. Another consequence of this is that the basis for district heating is reduced. Despite the alpha value (the proportion of electricity production per unit of heat production) rising to 0.2, electricity production from the district heating network decreases due to the reduced basis of combined heat and power. An alpha value of 0.2 is perhaps at first glance not that high, but in view of the fact that the base load is covered by residual heat, a large part of the remaining heat base is peak load and less suitable for combined heat and power. This means that 0.2 is a relatively high, but realistic, alpha value for 2050[30].

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[29] As mentioned earlier, it is partly a question of definition whether this heat is termed residual heat or not. We have chosen to do so to avoid duplicate counting of the primary need for biomass.

[30] The average value in 2008 is 0.15 (based on the gross electricity production)

8 Fuel sector

8.1 Description of the sector

In 2005 this sector is dominated by refineries. There is also a very small contribution from indigenous biofuel production. The present transformation losses in the refineries are 18 TWh according to the Swedish Energy Agency (2009a).

In the main scenario, "Biofuels 2050", almost all oil is converted to biofuels and the present Swedish refineries will consequently either have changed their production extensively (e.g. to biofuel production) or have closed down. The closure of the refineries alone saves 18 TWh of fossil fuels (the transformation losses).

In the alternative scenario, "Fossil fuels + BECCS 2050",fossil fuels are still used (although use is decreased compared to 2005) and the losses from 2005 are down-scaled according to fossil-fuel use.

8.2 Assumptions and measures

The description of assumptions and measures below relate to the main scenario "Biofuels 2050". The alternative scenario also uses some biofuels, e.g. in the industry sector. However, biofuel use is much lower in the alternative scenario.

Biofuels are assumed to be produced with the efficiency levels presented in Table 10. The excess heat is assumed to be used to 100% in district heating systems. The excess gases are assumed to be used as fuel in CHP production in the district heating systems. The processes listed in Table 10 are optimised to produce as much biofuels as possible, which implies that extra electricity is needed. The electricity used in the fuel sector is not considered to be an extra end-use of electricity but categorised as losses in transformation in the same way as electricity used in the refineries in the Swedish Energy Agency (2009a) scenarios. However, this electricity is included in the electricity production described in Chapter 6.

Table 10. Efficiencies for biofuels production.

Efficiency	Biofuels	Excess heat	Electricity production	Excess gases	Reference
Biogas (anaerobic digestion)	70%	-7%	-7%	0%	Gode et al, 2008; Berglund and Börjesson, 2003
SNG	71 %	24 %	– 4 %	0 %	Gode et al, 2008
Ethanol	32 %	8 %	13 %	0 %	Gode et al, 2008
DME	65 %	11 %	– 6 %	4 %	Gode et al, 2008

8.3 Results

Table 11 shows the demand of biofuels from energy end-using sectors, as well as the resulting need for biomass and electricity for biofuel production and the excess heat and gases produced.

Table 11. Demand for various biofuels in the main scenario "Biofuels 2050". Note that the table is only valid for the main scenario and not for the alternative scenario.

	Biofuels needed		**Biomass needed to produce the biofuels**	**Excess heat**	**Excess electricity**	**Excess gases**
Biogas (anaerobic digestion)	16.3	19 %	23.2	– 1.6	– 1.6	0.0
SNG	22.3	26 %	31.4	7.5	– 1.3	0.0
Ethanol	0.0		0.0	0.0	0.0	0.0
DME	48.1	55 %	74.0	8.1	– 4.3	3.0
Total	86.7		128,6	14.1	– 7.2	3.0

The need for biofuel for the production of transport biofuels is estimated at 129 TWh, of which 117 TWh as residuals from forestry or energy crops and 12 TWh as waste. In the alternative scenario "Fossil fuels + BECCS 2050", the need for biofuel from the forests is sharply reduced.

8.4 Discussion

There are various ways of optimising biofuel production. For instance, it is possible to optimise production to obtain as much fuel as possible or to obtain as much from total energy carriers as possible. In Table 10 above, the performance levels for the production processes have been selected to represent the cases where fuel production is optimised. As shown in the table, ethanol production has very low conversion to biofuels compared to the other biofuel technologies. On the other hand, ethanol production allows both electricity and heat production as well, whereas the other technologies require electricity. The low performance of fuel production is one of the main reasons why it is assumed that no ethanol production will exist in Sweden in 2050, see Chapter 5 for further information.

9 Forest fuel utilisation

9.1 Present forest fuel utilisation

Sweden is a leading user of renewable energy in the EU as a result of major indigenous resources of renewable energy such as biomass as well as various energy policies. In 2005, the total supply of biomass, peat, waste etc. for energy purposes amounted to 112 TWh. This is used primarily in the forest industry , district heating plants, electricity production, and for heating of residential buildings (Swedish Energy Agency, 2006), see Table 12. As shown in Table 12 the supply of primary forest fuels was 24 TWh in 2005, of which 7 TWh logging residues and 17 TWh round wood. This chapter focuses on future bioenergy potential from logging residues and stumps (i.e. the development of the present 7 TWh logging residues).

Table 12. Swedish supply of bioenergy, peat and waste in 2005 (Swedish Energy Agency, 2006).

Fuel category	**2005 (TWh)**	**Comment**
By-products from forest industry (including processed by-products such as pellets)	73	
Peat	4	
Residential and industrial waste (Refuse)	11	
Primary wood and by-products from forestry and agriculture (wood fuels)	24	Of which • 7 TWh logging residues • 17 TWh round wood
Sub-total	**112**	
Other biofuels	2	
TOTAL	**114**	

9.2 Future forest fuel potential

Future utilisation of forest fuels depends on a large number of factors such as present-day silvicultural management decisions (e.g. fertilisation, clearing ditches etc), ecological restrictions (e.g. leaving dead wood), technical development (e.g. the development of new techniques for harvesting residual fuel, finding more efficient modes of transport etc.) and climate change (e.g. increased growth due to higher temperatures).

There are a number of studies on future potential of bioenergy from the forest, and these studies vary widely in their conclusions. WWF in Sweden (2009) has made a comparison of estimations from e.g. Swedish Forest Agency, Swedish Energy Agency, the governmental commission on oil dependency and SVEBIO. The results show extreme variations of future potential estimates of logging residues (from approximately 25-73 TWh), partly depending on the assumptions about environmental restrictions and concerns and the studied time perspective. These estimations can be compared to the present supply of 7 TWh logging residues. The lower estimations (25 TWh) originate from WWF Sweden (2009) while the higher estimates are extrapolated data from the Swedish Forest Agency (2008b), see explanation in chapter 9.2.1 below.

The estimations of future potential for stumps very even more. WWF (2009) exclude stumps from their future estimations with the motivation that stump extraction it is very uncertain from an environmental point of view. On the other hand the Swedish Forest Agency (2008b) estimates a rather high potential for bioenergy from stumps. As shown in section 9.2.1 below, extrapolated data from the Swedish Forest Agency (2008b) show a potential of 30-108 TWh.

Nor WWF (2009) or the Swedish Forest Agency (2008b) include the current use (17 TWh) of round wood in their future potential estimates. A majority of the present round wood is used by small-scale forest owners for own use (Swedish Energy Agency, 2009c). It is likely that this use will stay fairly constant because of very low energy cost for the forest owners. In our scenarios we have assumed that the use of round wood for energy purposes remains constant at 17 TWh in the future.

9.2.1 Estimations by the Swedish Forest Agency

One of the most extensive studies of future forest fuel potential is presented in The Swedish Forest Agency (2008b). They have estimated the potential energy supply from the forests over the period 2010-2019 (Table 13), based on a "reference scenario" in which existing techniques and silvicultural methods are still used, environmental political decisions are implemented and tree productivity has increased due to climate change. Furthermore, three levels of environmental and economic/technical restrictions were taken into consideration in Swedish Forest Agency (2008b)[31]:

- Level 1: 0% of the logging residue fuel is left during final felling and 0% in thinnings
- Level 2: 12% of the logging residue fuel is left during final felling and 13% in thinnings
- Level 3: 27% of the logging residue fuel is left during final felling and 25% in thinnings

From these three levels The Swedish Forest Agency has estimated future forest potentials (see Table 13). These numbers are based on a conversion factor of 4.9 TWh per 1 tonne dry matter and represent the energy potential excluding flue gas condensation (i.e. the lower heating value)[32]. As shown in Table 13, The Swedish Forest Agency (2008b) estimates a future forest fuel potential of 55-143 TWh during 2010-2019.

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[31] If the Swedish Forest Agency's recommendation on logging residue extraction and ash recycling (2008c) are taken into account, we believe that level 3 appears to be the most realistic scenario.

[32] If energy from flue gas condensation is included (upper heating value) the conversion factor is 5.33. However, in this study we based all calculations on the lower heating value.

Table 13. Total supply of forest fuels in TWh per year over the period 2010-2019 at three different levels of ecological considerations. Data compiled from the Swedish Forest Agency's reference scenario (2008b, Tables 3.22, 3.23, 3.24, 3.25 and 3.26)

TWh/y		Pre-commercial thinnings	Thinnings	Final felling	Total
LEVEL 1	Logging residue fuel	2.2	19.2	36.3	**143**
	Stumps	-	28.0	57.5	
LEVEL 2	Logging residue fuel	2.2	12.9	25.0	**87**
	Stumps	-	13.1	33.7	
LEVEL 3	Logging residue fuel	2.2	8.5	15.5	**55**
	Stumps	-	8.4	20.7	

The data presented in Table 13 show potentials in the near future (2010-2019). The Swedish Forest Agency (2008a) has also calculated best available scenarios of potential future annual fellings. The best available scenarios are presented in the unit Mm^{3}sk (million cubic metres of forest), representing the volume of the tree stem above the stump, including top and bark[33]. The results are presented in Figure 8 (translated from Swedish Forest Agency, 2008a). As shown in Figure 8, the Swedish Forest Agency's (2008a) best available scenarios show a potential annual felling in 2050-2059 of 99 Mm^{3}sk in the "environment scenario", 105 Mm^{3}sk in the "reference scenario" and 120 Mm^{3}sk in the "production scenario". Figure 8 also shows the annual gross felling in 2007 and estimated an baseline for 2010-2019[34]. Based on data from the Swedish Forest Agency (2008a), in comparison to 2010-2019 we have concluded that the future potential in gross felling 2050-2059 would be 4% higher in the environment scenario, 11% higher in the reference scenario and 26% higher in the production scenario (see Figure 8).

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[33] The unit Mm^{3}sk cannot unambiguously be translated to energy terms since the energy content is dependent on the moisture content of the biomass. However, one m^{3}sk in final felling (logging residue fuel) produces about 0.95-1.2 MWh and in thinnings (logging residue fuel) about 1-1.5 MWh (Lehtikangas, 1999). According to The Swedish Forest Agency (pers. comm. Hillevi Eriksson, 2009) 1 m^{3}sk corresponds to approximately 2 MWh.

[34] Note that the documented annual gross felling in 2007 (101 Mm^{3}sk) is not representative for the period 2010-2019, because of the storm Gudrun and the unusually high economic growth in 2007. The Swedish Forest Agency (2008a) argues that 95 Mm^{3}sk per year would be a more realistic baseline value for the period 2010-2019.

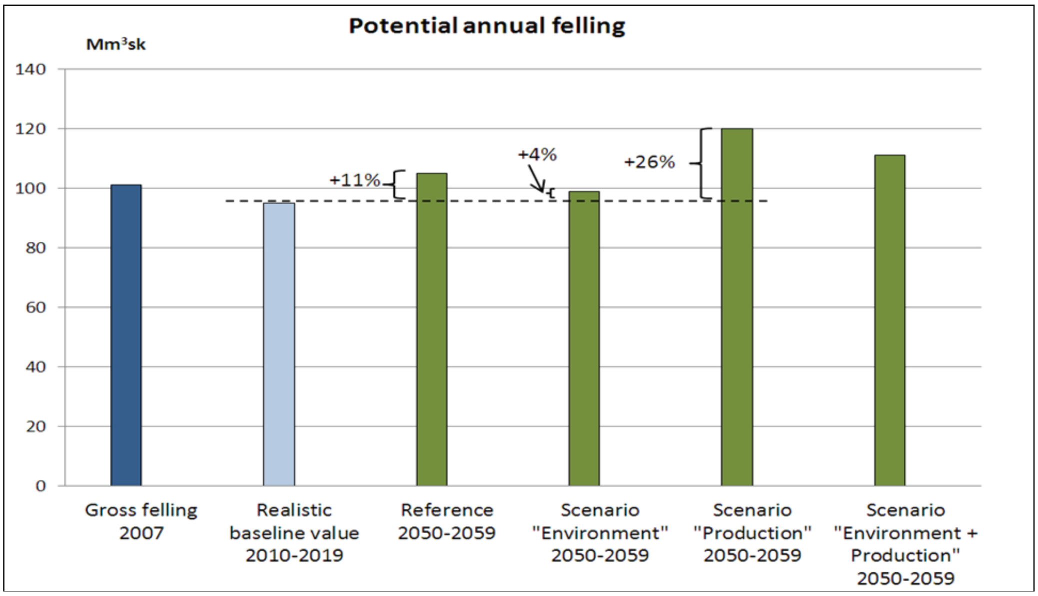

Figure 8. Gross felling in 2007 (dark blue), realistic baseline value for 2010-2019 compensated for the storm Gudrun and high economic growth (light blue) and potential annual felling 2050-2059 (green) in four different scenarios. Data compiled from the Swedish Forest Agency (2008a).

Assuming that the energy supply from forest fuels will increase in a corresponding manner as the annual gross felling according to the Swedish Forest Agency (4%, 11% or 26%) from 2010-2019 to 2050-2059, the total potential energy supply from logging residue fuel and stumps would amount to:

- 57-149 TWh per year, of which 27-60 TWh logging residues and 30-89 TWh stumps (environment scenario 2050-2059, extrapolated data).
- 61-158 TWh per year, of which 29-64 TWh logging residues and 32-95 TWh stumps (reference scenario 2050-2059, extrapolated data).
- 69-180 TWh per year of which 33-73 TWh logging residues and 37-108 TWh stumps (production scenario 2050-2059, extrapolated data).

These values were obtained by extrapolating the data in Table 13 on total forest fuel supply in the near future (2010-2019) by 4% (environment scenario), 11% (reference scenario) respectively 26% (production scenario). These estimations may be compared to the short-term potentials estimated by Swedish Forest Agency (2008b) of 55-143 TWh per year (2010-2019), see also Table 13. All above-mentioned values are based on the assumption that only logging residues and stumps are used for energy purposes[35].

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[35] With the high industrial production growth assumed in this report we believe the stem wood will be needed as raw material for the pulp and paper industry. However, the energy potential of the stem wood in the production scenario (from 95 to 120 Mm3sk per year) corresponds to about 50 TWh (25 Mm3sk per year * 0.4 MTonnes dry matter stem wood * 5 = 50 TWh, personal communication Dr. Hillevi Eriksson, Swedish Forest Agency, 2009).

9.2.2 Conclusion, future forest fuel potential

In conclusion, based on estimations from WWF (2009) and extrapolated data from the Swedish Forest Agency (2008b) the future bioenergy supply from forests may vary substantially. The estimations are summarised in Table 14. As clearly shown by the table, the differences lie mainly in the estimations of bioenergy potential from stumps. WWF considers stump extraction very uncertain from an environmental perspective.

Table 14. Estimations of forest fuel potential made by WWF (2009) and extrapolated data from the Swedish Forest Agency (2008b)

Source	**Logging residue potential (TWh)**	**Stump potential (TWh)**	**Total potential (TWh)**	**Time perspective of estimation**
WWF Sweden (2009)	25	0[a]	25	Not stated
Swedish Forest Agency (2008b), extrapolated data	27-73	30-108	57-180	2050-2059

[a] WWF considers stump extraction very uncertain from an environmental point of view and therefore excludes stumps from the future potential.

In addition to forest fuels other by-products, energy crops, waste fuels or import could contribute significantly to the total bioenergy supply.

9.3 Discussion

Renewable energy plays a more and more important role in the Swedish energy system. The Swedish Energy Agency (2009b) describes a vision with a secure and efficient as well as environmentally sustainable energy supply. The vision points out the importance of efficient production and use of biomass from the forest. Some of the theoretical potentials summarised in this chapter are substantially greater than the levels used today. There are a number of studies on future potential of bioenergy from the forest, and these studies vary widely in their conclusions. There is thus no consensus on future forest-based bioenergy potential, as clearly shown by WWF (2009). Today (2007) the fuel supply of logging residues is 7.3 TWh[36] (Swedish Forest Agency 2008a). The estimations of future potential, made by the Swedish Forest Agency, shows great future potentials for bioenergy supply from Swedish forests, whereas other studies show substantially lower potentials (see e.g. WWF, 2010).

The substantially higher estimations by the Swedish Forest Agency, are motivated by a higher environmental concern in the WWF estimation and the fact that stump is considered doubtful by WWF from an environmental point of view.

The amount of biomass from the forest that can be used for energy purposes will be limited by a number of factors. Ecological and environmental issues in particular will impose restrictions on how much can actually be removed from the forest. There will also be restrictions due to competition with other sectors and countries etc., and the future price of bioenergy will most probably be set on regional or global bioenergy markets. In the future scenario with increased forest growth, the price of biomass will have a great impact on the use of bioenergy. Aspects such as restrictions on possible use because of technical aspects and logistics also impose limits. The bioenergy is very important, and a great deal of effort and research is being put into how to solve

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[36] In Swedish denoted as GROT (grenar och toppar)

the issues of restriction, for example the Forestry Research Institute of Sweden is financing an initiative known as "Effektivare Skogsbränslesystem – ESS" to study more efficient techniques for harvesting etc.

The increased demand for bioenergy implies great challenges for the forest sector. Increased growth in the forest and increased use of agricultural land could reduce the competition. Unused agricultural areas that are not suitable for food production can, for example, be used for cultivation of energy crops and make a significant contribution.

10 Carbon Capture and Storage (CCS)

Carbon dioxide capture and storage (CCS) may be a very important technology for achieving large reductions of carbon dioxide emissions. If applied to biogenic carbon dioxide from e.g. pulp and paper mills or bioenergy plants, net reductions of CO_2 are possible. Below we describe the assumption about CCS in our scenario. For more information about CCS we refer to e.g. Teir et al (2010), Swedish Energy Agency (2010a, 2010b in prep) and Gode et al (2005).

In the main scenario "Biofuels 2050", 4.5 Mtonnes carbon dioxide from coal used in the steel industry, from process emissions in the cement industry, and from excess gases used in energy sector is captured and stored. Compression of the carbon dioxide requires a large amount of electricity, totalling 2.1 TWh.

In the alternative scenario "Fossil fuels + BECCS 2050" where fossil fuels are still used in the transport sector, it is assumed that biogenic carbon dioxide from pulp and paper mills is captured and stored to compensate for the fossil carbon dioxide emissions generated in the transport sector. The captured and stored carbon dioxide emissions from the pulp and paper industry correspond to 20 Mtonnes. These emissions equate to 52 TWh bioenergy. The extra electricity needed for compression of CO_2 is 9.5 TWh.

11 Results

The results of the main scenario (“Biofuels 2050”) as well as the alternative scenario (Fossil fuels + BECCS 2050) are shown in Figure 9 and Table 15. As shown, the total energy demand changes only slightly between 2005 and 2050 when the losses in nuclear power production are excluded. The energy demand in the main scenario (“Biofuels 2050”) is slightly higher than in the alternative scenario (“Fossil fuels + BECCS 2050”). The energy flows between different sectors (supplying as well as end-using sectors) are illustrated in Figure 10.

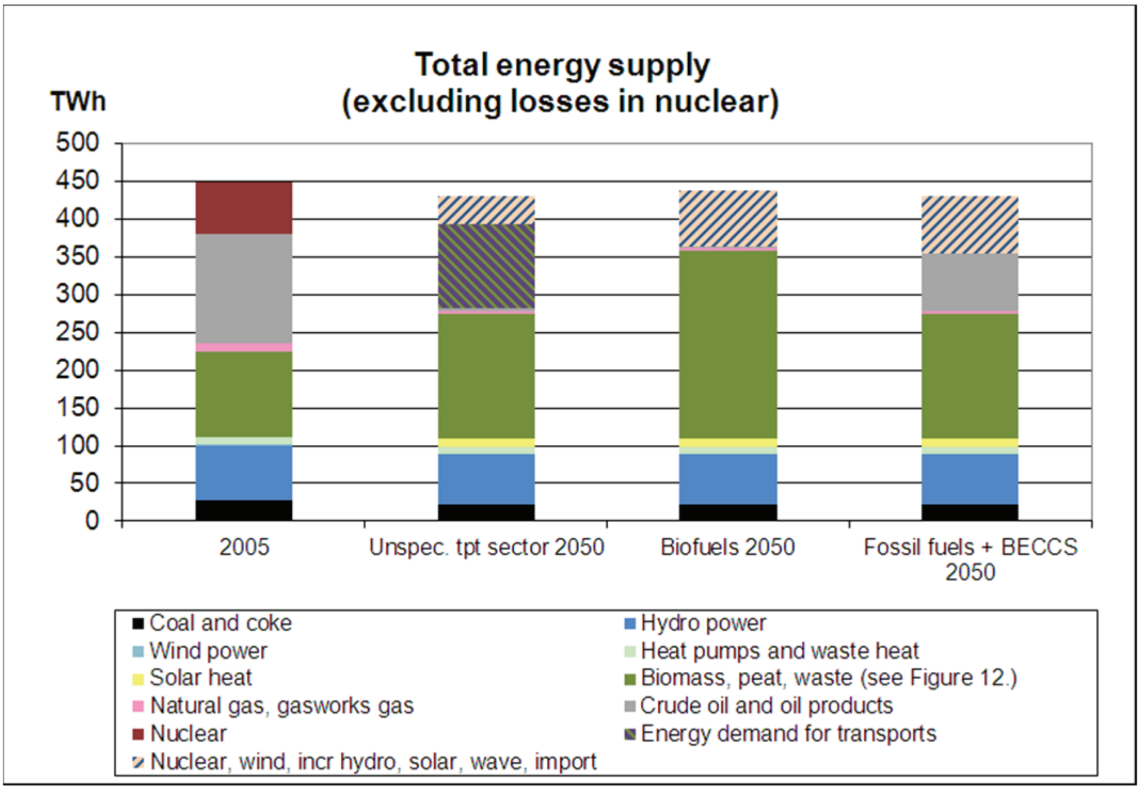

Figure 9. Energy demand in 2005 and 2050 (scenarios). As shown in the three bars for 2050, some of the energy supply for electricity production is not specified (pink/blue striped bars). For further information, see Chapter 6. In the bar marked “Unspec. tpt sector 2050” the energy supply to the transport sector is not specified (the total demand is, however, indicated by the green/purple striped bar). In the main scenario (“Biofuels 2050”), 50% of the energy demand for transports is assumed to be met by electricity and the 50% by biofuels. In the alternative scenario (“Fossil fuels + BECCS 2050”), 50% of the energy demand for transports is assumed to be met by electricity and 50% by oil products. To reach low emissions in the alternative scenario, biogenic carbon dioxide is captured and stored (BECCS) to compensate for the fossil fuel emissions in the transport sector. Note that the bioenergy supply is uncertain, see section 11.1 and Figure 12.

The CO_2 emissions in 2005 as well as the resulting emissions in the various scenarios are shown in Figure 11 and Table 16. Energy end-use efficiency improvement measures (including plug-in hybrid cars and shift in goods transport from road to railway) and fuel shift to biomass (in the main scenario “Biofuels 2050”) are the major carbon dioxide emission reduction measures in the scenarios. Other important measures are CCS in industry, electricity and heat production, and CCS on biogenic carbon dioxide emissions.

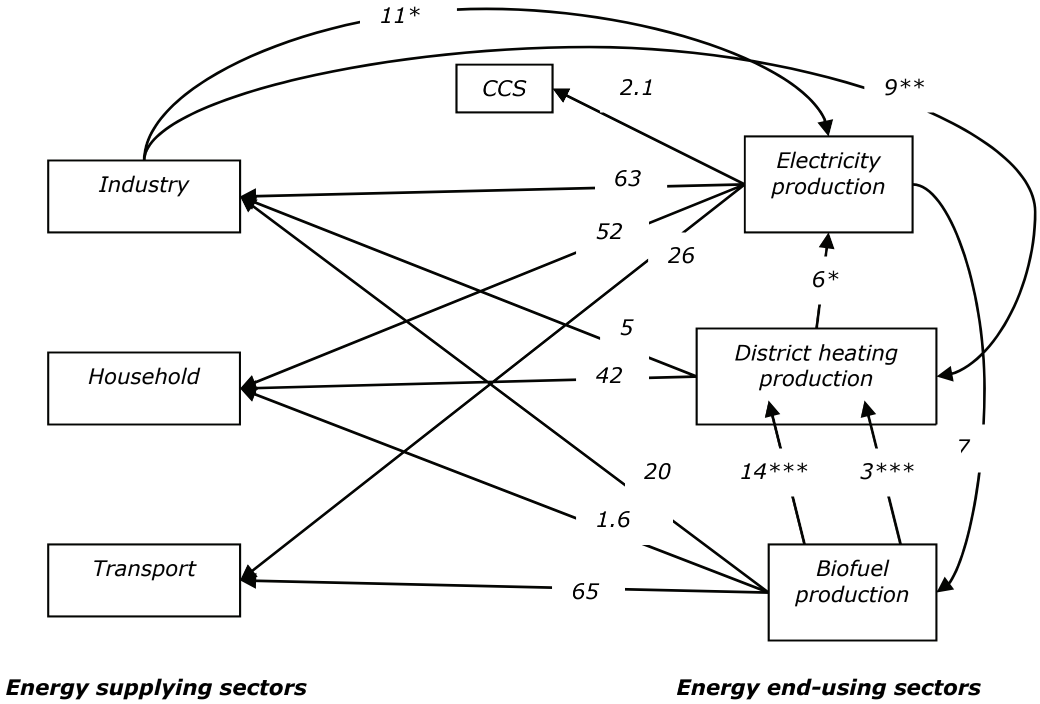

Figure 10. Energy flows between the different sectors in the main scenario. This diagram only includes energy that flows from one sector to another. It does not include use of energy carriers other than electricity, district heating and the biofuels DME, SNG and biogas. Consequently, residuals from the forest industry (sawdust, etc) used in other sectors, for example, are not included.

Notes: * The fuel for electricity production in CHP plants in industry and in district heating systems is allocated to electricity production. ** Fuels that are used in industry and generate excess heat used for district heating are allocated to the industry sector. *** The fuel production sector produces excess heat and excess gases that are used for district heating. The fuels used to produce this excess heat and gas is allocated to fuel production.

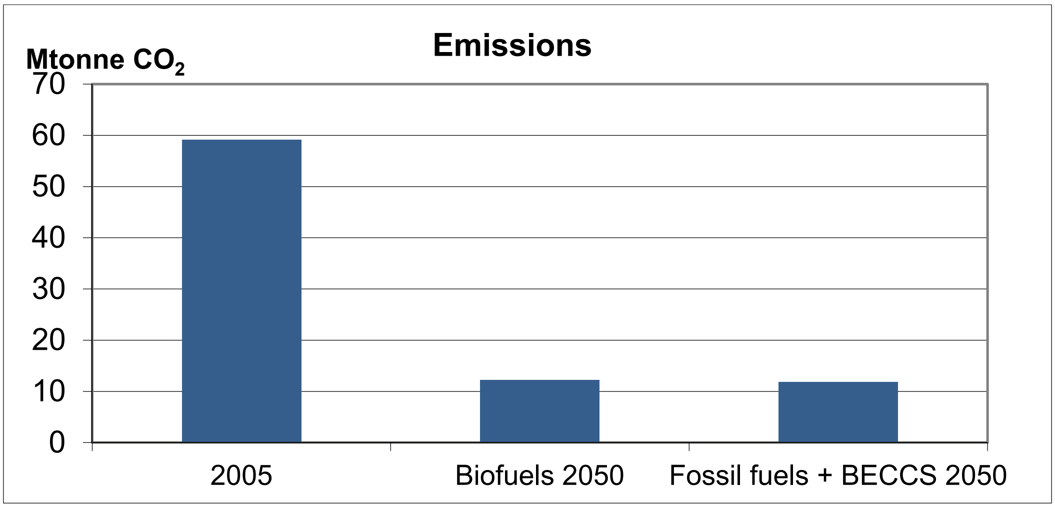

Figure 11. Emissions of carbon dioxide in the scenarios compared to the emissions in 2005.

Table 15. Swedish total energy demand, excluding international aviation and shipping and energy not for energy purposes. Values in TWh.

Total energy supplied	2005	2050	“Biofuels 2050”	“Fossil fuels + BECCS 2050”
Crude oil and oil products	145	3.5	3.5	77
Natural gas, gasworks gas	10	3.0	3.0	3.0
Coal and coke	29	22	22	22
Nuclear	70	0	0	0
Heat pumps and waste heat	10	9.0	9.0	9.0
Solar heat	0	12	12	12
Hydro power	72	68	68	68
Biofuels, peat, waste, etc	114	165	248	165
of which is peat	3.8	0	0	0
of which is waste	11	20	25	20
Wind power	0.9	0	0	0
Solar power	0	0	0	0
Wave power	0	0	0	0
Energy for the transport sector	0	111		
Nuclear, wind, increased hydro, solar, and wave power	-	38	73	76
Deficit in electricity balance (import minus export)	-7.5	0	0	0
Total	450	432	439	432

Table 16. The carbon dioxide emissions from the different fuels in 2050 in the main scenario (“Biofuels 2050”) and in the alternative scenario (“Fossil fuels + BECCS 2050”).

Mtonne Carbon dioxide emissions	2005	“Biofuels 2050”		“Fossil fuels + BECCS 2050”	
		Without CCS	With CCS	Without CCS	With CCS
Crude oil and oil products	40	1.0	1.0	21	21
Natural gas, gasworks gas	2.1	0.6	0.6	0.6	0.6
Coal and coke	12	10	6.0	10	6.0
Nuclear	0	0	0	0	0
Heat pumps and waste heat	0	0	0	0	0
Solar heat	0	0	0	0	0
Hydro power	0	0	0	0	0
Biofuels, peat, waste, etc	0	0	0	0	-20
of which is peat	1.5	0	0	0	0
of which is waste	1.0	2.3	2.3	1.8	1.8
Wind power	0	0	0	0	0
Solar power	0	0	0	0	0
Wave power	0	0	0	0	0
Nuclear, wind, increased hydro, solar, and wave power	0				
Not energy related process emissions in the cement industry	2.3	2.5	2.4	2.5	2.4
	0	0	0	0	0
Total	59	17	12	37	12

11.1 Bioenergy demand in 2005 and 2050

The bioenergy demand in 2050 is presented in Table 17, whereas the supply is shown in Figure 12. Table 17 clearly shows the extreme increase in demand for round wood and logging residues, from the present 24 TWh to 67-145 TWh depending on scenario. It is not evident that this demand can be met by indigenous resources. As described in section 9, there are uncertainties about future forest fuel potentials. The same is true for energy crops. Estimations of future logging residue potential show variations from 25-73 TWh and stump potential from 30-108 TWh[37].

As shown in Table 17, there is also a substantial supply of round wood at present (17 TWh). The majority of the round wood is used by small-scale forest owners for own use (Swedish Energy Agency, 2009c). It is likely that this use will stay fairly constant because of very low energy cost for these forest owners. In our scenarios we have assumed that the use of round wood for energy purposes remains constant at 17 TWh in the future as well. We have not estimated future round wood potential as we believe that most of the round wood will be needed in the pulp and paper industry.

As described above and in chapter 9 estimations of future forest fuel potential vary substantially. The data on bioenergy supply in 2050 in Figure 12 is therefore based on conservative estimations of primary wood fuel potentials[38] to clearly show the future uncertainty. The shaded areas in Figure 12 illustrate that, depending on future scenario, some 25-100 TWh have to be met by e.g. increased utilisation of logging residues, stump extraction, energy crops, by-products, round wood or import.

Table 17 Bioenergy demand in 2005 and in 2050 scenarios.

	2005	”Biofuels 2050”	“Fossil fuels + BECCS 2050”
Industrial forest by-products (incl. processed by-products such as pellets)	73	78	78
Peat	4	0	0
Residential and industrial waste (Refuse)	11	25	20
Primary wood fuels – forest and agriculture	24	145	67
of which logging residues (and stumps)	*7*	*128*	*50*
of which round wood	*17*	*17*	*17*
Sub-total	**112**	**248**	**165**
Other biofuels (2005)	2	0	0
TOTAL	**114**	**248**	**165**

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[37] WWF (2009) states that stump extraction is too doubtful from an environmental point of view and thus regards the potential as zero.

[38] I.e. 25 TWh of logging residues as estimated by WWF Sweden (2009), no utilisation of stumps and present supply of round wood (17 TWh).

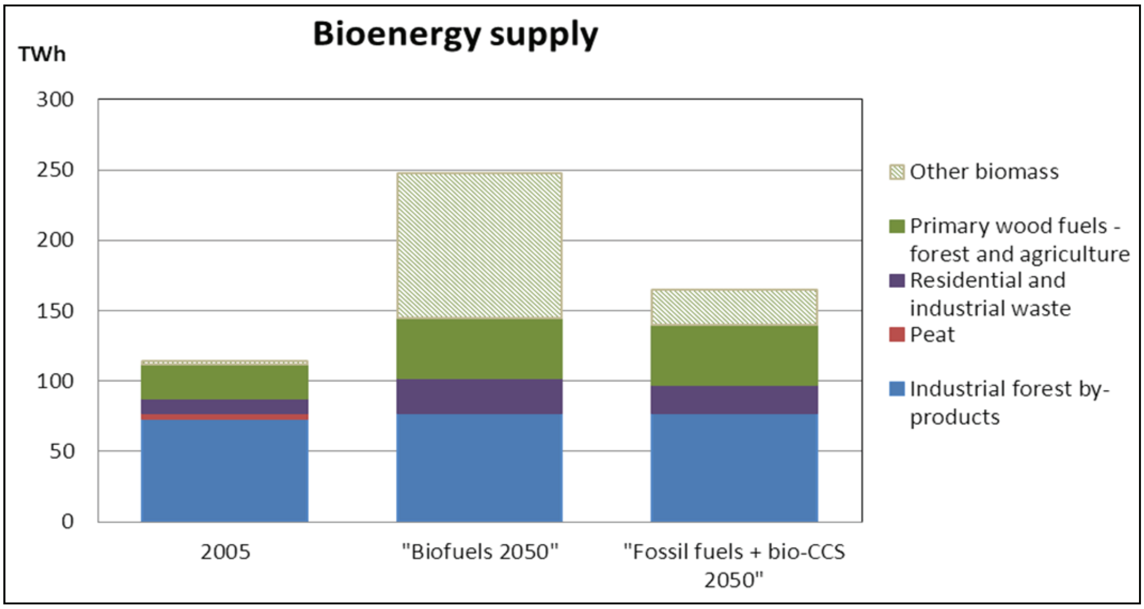

Figure 12. Bioenergy supply in 2005 and in the 2050 scenarios. "Industrial forest by-products" include black liquor and other by-products from sawmills and pulp and paper mills including pellets. "Primary wood fuels – forest and agriculture" includes biomass from the forest and energy crops grown on agricultural land, based on 17 TWh of round wood and conservative estimations of logging residue potential (see section 9). "Other biomass" (the shaded areas) refers to other biofuels in 2005 resp. additional future biomass demand in 2050, e.g. extended use of primary wood fuels, waste, energy crops or import.

11.2 Alternative scenario (Fossil fuels + BECCS 2050)

The alternative scenario ("Fossil fuels + BECCS 2050") may serve as a sensitivity analysis of the main scenario. The alternative scenario is to a large extent based on the main scenario, but with an assumed alternative development of the transport sector. Instead of using biofuels to reduce the fossil carbon dioxide from the transport sector, continued use of fossil fuels is assumed. To reduce fossil carbon dioxide emissions in the alternative scenario, capture and storage of biogenic CO_2 emissions for example from pulp and paper mills is assumed.

The alternative scenario provides an increase in the use of fossil fuels of 74 TWh compared to the main scenario ("Biofuels 2050"), at the same time reducing the use of biofuels by 83 TWh. The reason why these values do not equate is higher losses to produce biofuels than fossil fuels (even if the biofuels are produced in poly-generation plants). The use of electricity increases in the alternative scenario by 4.0 TWh where 1.4 TWh is produced in combined heat and power. The capture and storage of CO_2 from pulp and paper mills requires electricity, 9.5 TWh. At the same time the electricity demand for transport biofuel production decreases by 5.5 TWh.

The demand for primary biomass as well as by-products from forestry and agriculture is naturally lower in the alternative scenario, as a result of lower biofuel production.

12 Discussion and conclusions

There is a strong link between economic welfare and energy use. Economic growth usually leads to increased use of energy. It is not uncommon, especially in certain stages of economic development, for the growth of energy use to be as fast as economic growth. This is currently the case, for example, in China, which is in a stage of economic growth where heavy industrial production is growing very rapidly (for example the development of the energy-demanding steel industry). By taking energy efficiency improvement measures the energy use can be decoupled from economic growth, which means that energy use does not grow as fast as the economy. This does not mean that energy use decreases, merely that it does not increase as fast as economic growth.

Another way of decoupling energy use from economic growth is to restructure the economy, for example from heavy industry production to a more service-oriented or value-creating economy. If, for example, higher intellectual knowledge can be included in products, their value increases without an increase in energy use.

The energy use in the scenarios of this report is based on projections made by the Swedish Energy Agency (2009a) to 2030 for energy use. These are based on economic projections made by the National Institute of Economic Research[39], indicating that the Swedish economy will grow by 2.25% per year in average, somewhat faster in industry. There will be a restructuring of industry, where heavy industry will grow slower than manufacturing industry. The Swedish Energy Agency (2009a) projections show that energy use will continue to grow, but at a much slower rate than the economy. This is partly because they predict a restructuring of the economy and the high energy prices they assume will lead to implementation of energy efficiency improvement measures. Our scenarios estimate fairly constant energy use between 2005 and 2050, despite the slight increase predicted by the Swedish Energy Agency (2009a). The motive is that this increase is offeset by increased end-use energy efficiency in the transport sector with the implementation of plug-in hybrid cars, a shift for goods transport from road to railway, and with higher energy efficiency implementation in the residential and service sector.

The Swedish Energy Agency's (2009a) projections include energy efficiency improvements from restructuring of the economy and from assumptions on high energy prices. In our scenarios, energy efficiency improvement measures in the transport and residential/service sectors have also been included. Increasing the energy efficiency level even more would be in line with the 2050 goals of low use of fossil energy and fossil carbon dioxide emissions. Scenarios presented by other organisations often have higher energy efficiency levels. However, it could be difficult to judge the total effects of efficiency improvement measures, due to so called "rebound effects", i.e. that reduced energy at one place in the economy may increase energy use somewhere else. One example of a rebound effect is that more efficient cars will decrease the cost per km (assuming constant fuel prices), thereby maybe resulting in increased average distance driven. Rebound effects may be significant but are also very hard to predict. Another rebound effect, in the same example, may be if the money saved is used for something else that increases the energy demand. Energy efficiency improvement measures are important because they increase our prosperity, but we should also be aware of the limitations of energy efficiency improvement measures. Our scenarios are therefore based on moderate to high (but not extreme) assumptions of energy efficiency improvement. More

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[39] In Swedish: Konjunkturinstitutet

could perhaps be implemented, but there is also a risk that energy use will increase somewhere else instead. Strong political incentives may be necessary to limit the rebound effects.

Reducing the use of fossil fuels reduces carbon dioxide emissions. Another way to reduce Sweden's climate impact could be to buy international carbon credits. This could be done on an international carbon market, and the result would be that the reductions are made in another country. However, in 2050 greenhouse gases has to be reduced to very low levels and it is likely that there will be very high demand for international carbon credits and that these will be very expensive. It is therefore assumed in this report assumed that it is not possible to buy international carbon credits.

One exception could be if electricity or biofuels that in our scenario are used in Sweden could bring about more reductions abroad. For example, fossil-free electricity production may be used to replace coal power production in Europe instead of being used for plug-in hybrids, and bioenergy could perhaps be used in a more climate-efficient way in replacing some of the coal in coal-fired power plants than in producing biofuels. In this case emissions globally would decrease, but the emissions in Sweden would increase. It would then be more realistic to buy international carbon credits to offset the emissions in Sweden.

Another way to reduce Sweden's climate impact could be to capture and store biogenic carbon dioxide (BECCS) from e.g. pulp and paper mills. Research on CCS especially for fossil power plants is in progress in many places around the world, and it is likely that the technology will be commercially available around 2030, although some hope that it will go faster. Using CCS for bioenergy is probably more difficult and also requires incentives for sequestering biogenic carbon dioxide. However, it is not unrealistic that BECCS[40] will be available by 2040-2050. In a Swedish perspective BECCS from e.g. pulp and paper mills is an interesting solution since these plants are often rather large point sources compared to e.g. Swedish CHP plants. On the other hand, in comparison with large coal-fired power plants in other parts of Europe the Swedish point sources are relatively small. Due to the uncertainties about BECCS, we have not included this measure in the main scenario ("Biofuels 2050"). It is, however, included in the alternative scenario "Fossil fuels + BECCS 2050", where it is assumed that biogenic carbon dioxide from pulp and paper mills (52 TWh bioenergy in 2050) is captured and stored to compensate for the carbon dioxide emissions from over 73 TWh of fossil fuels. With a positive development of BECCS technology as well as implementation of supporting policy intruments, BECCS could be a very important future technology. Applying BECCS to the main scenario would naturally yield even higher emission reductions.

In our future scenarios, the demand for primary wood from logging residues (and stumps) increases from 7 TWh to 50-128 TWh depending on future scenario[41]. As described in section 9 there are uncertainties about future forest fuel potentials. For example, extrapolated data from the Swedish Forest Agency show a potential of 57-180 TWh (of which 27-73 TWh logging residues and 30-108 TWh stumps), whereas WWF Sweden (2009) estimates a potential of 25 TWh logging residues. One reason for the large differences is that WWF does not include stumps as they believe stump extraction is doubtful from an environmental viewpoint. It is interesting to note that WWF's estimation of logging residue potential (25 TWh) is close to the lower estimation of the Swedish Forest Agency (27 TWh). It is obvious from the estimations of the Swedish Forest Agency that

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[40] BECCS means capture and storage of biogenic carbon dioxide, thus resulting in net reduction of carbon dioxide emissions

[41] These numbers, 2005 as well as 2050, do not include the use of round wood (17 TWh in 2005 and the same assumed for 2050).

stump extraction has a large potential. However, increased use of waste fuels, energy crops from agriculture as well as import may also contribute significantly to reducing the pressure on forest fuels.

12.1 Main overall conclusions

- There are measures that sharply reduce Sweden's fuel dependence by 2050. According to the IVL scenario, the energy-related carbon dioxide emissions including process emissions in industry are reduced from 59 million tonnes in 2005 to 12 tonnes in 2050, a reduction of 79%. Without CCS emissions in 2050 are approximately 17 million tonnes, a reduction of 72%.
- The reductions are achieved in the IVL scenario through both known technologies and technologies under development. Energy efficiency improvement and fuel conversion are examples of existing technologies which we have to a great extent based ourselves upon. Technologies under development are principally plug-in hybrid technology, second-generation transport biofuels[42] and carbon capture and storage (CCS).
- In the energy scenario we have assumed increased GDP growth of 2.25% per year with increased industrial production, increased transport and an increased population. However, substantial improvement in energy efficiency means that the final use of energy is maintained at roughly the same level in 2050 as in 2005. We regard the assumed level of energy efficiency as reasonable, but consider that powerful political incentives can probably raise the degree of energy efficient improvement further. A factor militating against further energy efficiency improvement is the so called rebound effects, i.e. that lower energy costs lead to increased energy use.
- It is a great challenge to make the transport sector fossil-free. Despite extensive improvement in efficiency and a switch to electric drive, the transport sector will need a large quantity of transport biofuels in 2050 according to our scenario. This also applies if the whole passenger car fleet is converted to electricity. It is estimated that in this scenario transport biofuels will be principally used for goods transport and as "back-up fuels" for plug-in hybrid cars. The demand for transport biofuels remains high despite us having anticipated a relatively substantial switch of goods transport from road to rail.
- A large quantity of fossil fuels can be replaced by renewable ones in the industry sector. However, industrial process emissions are considered to be difficult or very expensive to replace completely with renewable alternatives. This applies principally to carbon dioxide emissions that originate from the use of metallurgical coal in the steel industry, from cement production and from fugitive emission sources (particularly from the petrochemical industry). Some of these process emissions can be captured and stored in the scenario, but despite this there will be a certain quantity of remaining process emissions.
- Assumed measures in the residential and service sector are principally based on existing technology such as energy efficiency improvement. We have assumed substantial energy efficiency improvement with regard to both heating and electricity for household purposes and electricity for common purposes in buildings. Climate change is also assumed to contribute to a reduced need for heating, but on the other hand demand for cooling will increase. Reducing the need for electricity in the sector to the level we have assumed may

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[42] Production of DME and synthetic natural gas (SNG) from residues from forestry or equivalent.

pose a challenge. We have assumed substantial expansion of solar heat in Sweden in the scenario. Although the assumption is regarded as realistic, it may present a challenge.

- The need for electricity from the end-user sectors increases in the scenario by 7% by 2050 in comparison with 2005. This includes electricity needs for capture and storage of process emissions. The reason why the increase is not greater despite a sharp increase in the need of the transport sector for electricity is extensive energy efficiency improvement in the residential sector, which reduces the use of electricity for heating.
- Present-day electricity production of around 150 TWh is principally based on hydro power, nuclear power, combined heat and power and industrial back-pressure. The present-day level of production would thus almost be sufficient to meet the national need for electricity in 2050, even assuming growth in GDP of 2.25% per year. However, in a possible phase-out of nuclear power there is a need for new electricity production equivalent to around 75 TWh. The scenario does not specify how this is met, but it may be met for example through a mix of wind power, expanded production of hydro power[43], solar power, wave power and bioenergy.
- Virtually all use of fossil fuels in the district heating sector is replaced in the scenario by renewable alternatives and residual heat. A large proportion of the residual heat in the main scenario for 2050 consists of excess heat from the production of transport biofuels which is assumed to take place in polygeneration plants. Because of the sharply increased potential of residual heat (partly from the production of transport biofuels, partly from industry), the basis for combined heat and power decreases in the main scenario.
- Our scenarios rely on a substantial increase in the use of forest biomass in order to meet long term climate targets and visions as well as increased growth in the end-using sectors. Consequently, bioenergy demand increases substantially in the "Bioenergy 2050" scenario compared to 2005. It is very uncertain whether this increased demand can be met by indigenous resources. Previous estimations of future forest fuel potential vary significantly. For example, WWF Sweden (2009) estimates a future potential of 25 TWh logging residues, compared to the present use of 7 TWh. On the other hand, extrapolated data from the Swedish Forest Agency (2008b) indicate a potential of 27-73 TWh of logging residues and to this could be added a potential of 30-108 TWh from stumps (extrapolated data from Swedish Forest Agency, 2008b, see chapter 9). Increased use of waste fuels, energy crops, by-products, round wood and even import may be necessary in order to reduce the pressure on Swedish forests.
- We suggest that other alternatives to reduce carbon dioxide emissions are investigated. One such alternative, is to capture and store biogenic carbon dioxide for example from chemical paper and pulp mills. This is investigated in an alternative scenario ("Fossil fuels + BECCS 2050"), where the bioenergy demand decreases by just over 80 TWh. However, the electricity demand increases by 4 TWh (electricity is needed for compression of CO_2 in the CCS process).
- Exports of electricity and biomass to the Continent may also possibly provide greater global climate benefit than Sweden using them itself, as has been assumed in this scenario. This applies on condition that the exported electricity and the biofuels replace fossil fuels[44].

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[43] In particular as a result of increased precipitation from a changed climate.

[44] Obviously without CCS in order to achieve greater climate benefit.

13 References

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