THE IVL SCENARIO:

Energy Scenario for Sweden 2050

Based on Renewable Energy Technologies and Sources

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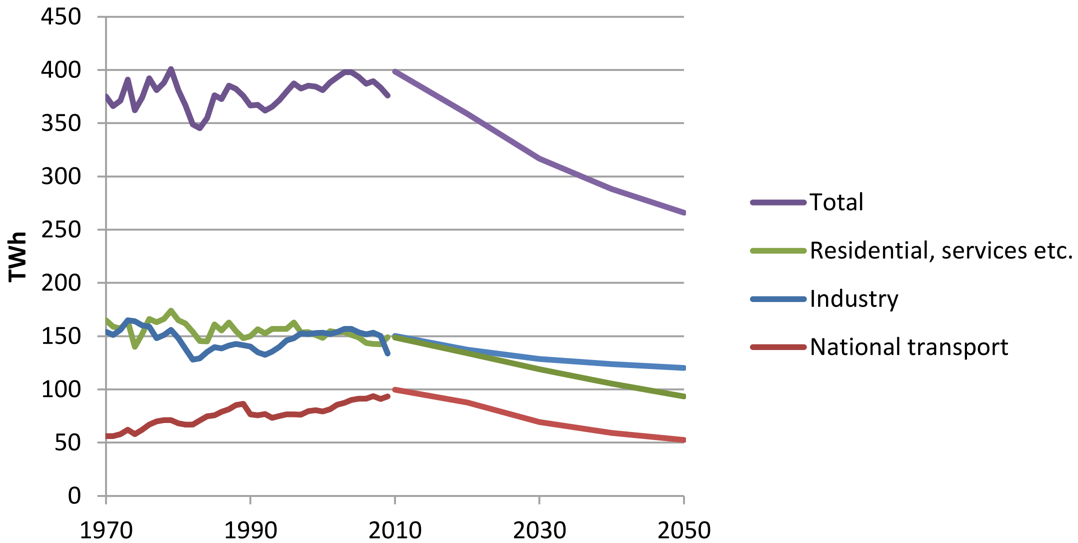
Summary

The report presents an energy scenario for Sweden aiming at providing close to 100% of the energy by renewable energy sources. Renewable resources should be produced with a high level of environmental concern and within the carrying capacity of the ecosystems. As a consequence biomass becomes a limited resource, especially since the transport sector in Sweden relies on fossil energy which needs to be substituted with domestically produced renewable fuels, and electricity is produced with renewable energy technologies.

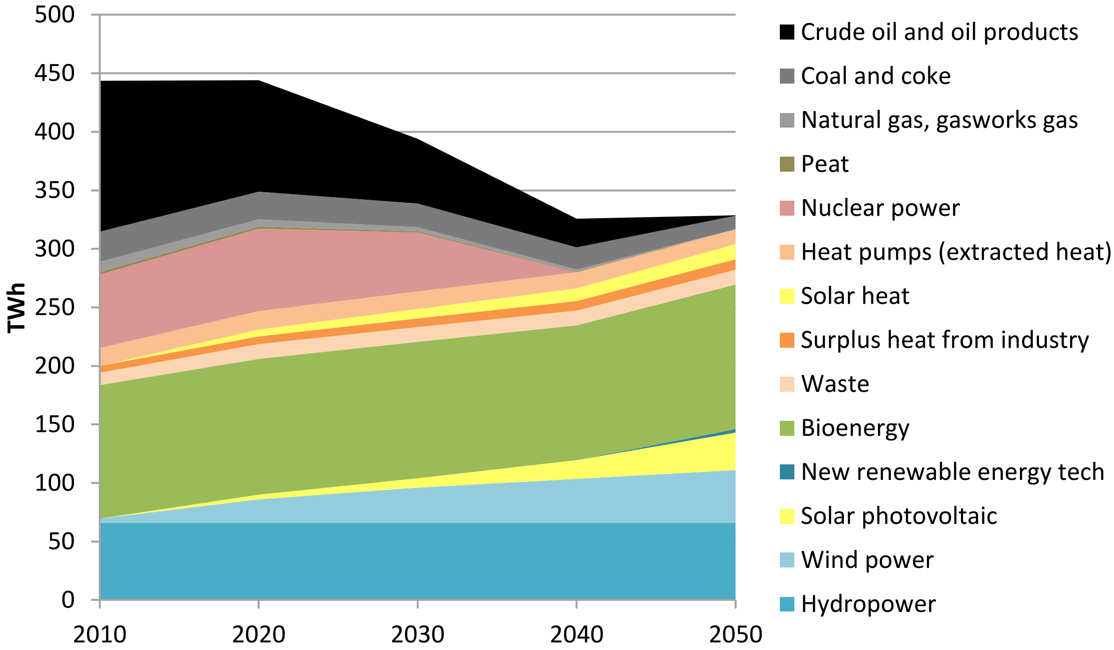
In order to reach the goal of the energy scenario, efficiency measures are needed on the demand side in all of the three energy sectors. The scenario builds on the idea that the energy services needed in society can be delivered in more efficient ways. For example in terms of transport, personal transports for long journeys in Sweden are considered to be done by train to a greater extent than today. Still, cars and individual transport means are important for fulfilling transport needs in areas where there is no public transport infrastructure. Cars will operate on biofuels to a great extent for long journeys, while short journeys can be powered by electricity. Plug-in hybrid cars are an option that will be able to provide both these services.



The paper and pulp industry will, according to the scenario continue to play a key role in both biofuel and heat production. The scenario builds on the idea that biorefineries can supply a range of energy and industry products based on biomass resources. The biorefinery can do this in an efficient manner provided that excess heat and residues are handled properly.

Hydropower, bioenergy, wind and solar power (both heating and photovoltaic) form the basis for energy supply in this scenario. Nuclear power as well as energy conversion based on non-renewable energy sources is phased out. New renewable energy technologies, such as bio algae, play a part in the scenario only in the run-up to 2050. An increased share of intermittent power will be seen in the electricity system. This will pay increased attention to securing regulating capacity in the power system, as well as ensuring transmission capacity within the country and abroad.

The supply curve of the Swedish energy system according to this scenario, excluding losses in nuclear power, is displayed below (TWh).



Hydropower is kept at the current production level. The increased production anticipated through climate change will be used to improve the environmental status of running water in Sweden. Wind power will increase to 20 TWh in 2020 and 30 TWh in 2030 and reach 45 TWh in 2050. A similar increase is seen in solar photovoltaic, reaching 32 TWh in 2050.

Reducing the demand will however represent the most important input to the scenario. Energy efficiency improvement of the magnitude that we anticipate will require a range of new approaches in order to be realized at the levels assumed in this scenario. The barriers to be overcome are among other things found in promoting available technology in society and making energy efficiency a central variable in assessing investment options. Systematic efforts to prevent rebound effects from counteracting the reductions in demand must be initiated. The scenario builds on a constant phasing out of non-renewable energy sources and thus if a surplus is present there should be driving forces in place to ensure that this surplus is deducted from fossil and non-renewable sources. It can be seen as investing the surplus created by energy efficiency improvement in natural capital.

When assuming renewable energy sources as zero GHG-emitters, the reduction of carbon dioxide emissions from the energy sector will keep pace with the phasing out of fossil energy sources. Compared to 1990 greenhouse gas emissions in Sweden the reductions are almost 30% by 2020 and will be halved by 2030. These emission levels can further be reduced by pushing harder for introducing biofuels or other alternative renewable fuels as a substitute for fossil fuels in the transport sector.

The scenario has studied dynamic emissions of carbon dioxide, including terrestrial carbon, linked to the fuel category tops and branches. The results show that if substituting oil, tops and branches will reduce the global net carbon dioxide emissions significantly. Still, biomass resources if used as a fuel will result in substantial emissions of terrestrial carbon dioxide and there are reasons to consider this when creating support structures and regulations for various biofuels. For example, there might be biomass alternatives that are more beneficial for climate mitigation than others.

The report also evaluates costs associated with the scenario's main trends. The results point to reasonable costs and increasing benefits of the investments required to follow the scenario. Most of the measures are identified as mature technologies.

The energy scenario presented in this report provides one scenario of what an energy scenario based on renewable energy could look like. Sweden and the energy system here is not isolated, but rather part of a Nordic energy system, as well as the European and global systems. This national energy scenario provides input and the basis for discussion on how to integrate and work with scenarios that include larger systems. For example there is a need to ensure that the process of initiating and creating support structures for energy efficiency improvement is started promptly. Investments in renewable energy technologies are already made but new capacity must replace old capacity based on non-renewable sources. This study shows one scenario where a Swedish energy system based on renewable energy sources, produced within the carrying capacity of the ecosystems in Sweden, is possible.

Foreword

The energy scenario presented in this report is based on a backcasting scenario of the Swedish energy system between 2010 and 2050. The point of departure has been to see whether energy demand in Sweden can be covered by renewable energy resources available in the country at the same time as the resource utilization is kept *within the carrying capacity of the ecosystems*. In order to approach this last issue we have based the assumptions on limits on biomass output, bioenergy, hydropower, wind power, solar photovoltaic and solar heat potentials on a dialogue process with WWF Sweden. The result was a list of potentials which were then applied as resource limits in the energy scenario. It must be pointed out that these potentials should not be seen as policy or clearly defined sustainable potentials in Sweden but rather as a pragmatic approach to set some boundaries in terms of available biomass and renewable energy resources in Sweden. The scenario represents one possible system under a certain set of inputs, and it should be seen as a point of departure for discussion and planning. The outset, in terms of technological change, is relatively conservative as most technologies that are applied in the model are available today. At the same time a number of not-so-conservative changes will have to happen, possibly the most acute is getting energy efficiency improvement initiatives to be realized. At present there is much talk on the issue of energy efficiency improvement, but unfortunately little happens.

The work was to some extent based on the work reported in "Swedish long-term low carbon scenario – Exploratory study on opportunities and barriers" (Gode et al. 2010). The present project has improved the model and created a number of milestones between present and 2050. In addition the present study has a focus on using renewable resources and potential climate impacts were then analysed based on the results.

This project was carried out by IVL Swedish Environment Research Institute and lead authors are Mathias Gustavsson (project leader), Erik Särnholm, Peter Stigson and Lars Zetterberg. A number of people have contributed with inputs and valuable comments during the course of developing the scenario. Lisa Bolin and Martin Jerksjö at IVL have provided some data on energy efficiency improvement in buildings and transport data. A continuous dialogue with WWF Sweden has provided input and constructive comments on energy and environmental issues. This project was co-funded by WWF Sweden and the Foundation for IVL Swedish Environmental Research Institute (SIVL) via grants from the Swedish Environmental Protection Agency and the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas).

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Abbreviations

CCS	Carbon Capture and Storage
CHP	Combined heat and power production, cogeneration
COP	Coefficient of performance
DME	Dimethyl ether
EE	Energy efficiency
EO1	Oil quality (light fuel oil, similar to diesel)
EO2-4	Oil quality (fuel oil, thicker quality contains more sulphur than EO1)
EU-ETS	European Emission Trading Scheme
EV	Electric vehicles
FAME	Fatty acid methyl ester
GHG	Greenhouse gases
ICT	Information and Communication Technologies
IVL	IVL Swedish Environmental Research Institute
LPG	Liquefied Petroleum Gas
PFE	Program for Improving Energy Efficiency in Energy Intensive Industries
pkm	person kilometre
PV	Photovoltaic
RES	Renewable energy source
RD&D	Research, development and demonstration
SNG	Synthetic Natural Gas. The gas can have an origin in both renewable sources as well as fossil. Here SNG relates to synthetic gas that originates from organic matter hence a renewable SNG.
tkm	tonne kilometre
UNFCCC	United Nations Framework Convention on Climate Change
WWF	Name of a global environmental organization. Previously it was an acronym for *World Wildlife Fund* and *World Wide Fund for Nature* but stands as the name of the international organization today. Known in Sweden as WWF Sweden.

1 Introduction

This report describes what the energy demands could be in a resource efficient energy system in Sweden. These energy demands were then analysed in the light of available energy resources in Sweden. This last step shows that a possible energy balance based on renewable energy resources, available in Sweden extracted within the environmental carrying capacity is possible. The report also includes an evaluation of the costs associated with the scenario's main trends. This includes a discussion on stakeholders and policy perspectives in terms of which actors will bear which costs and how the required investments can be promoted.

The energy systems that we see today in European countries rely heavily on fossil- and non-renewable energy sources. The energy systems are the result of many decades of development, and optimization towards being competitive and safe in terms of operation and delivery of the services that the systems supply. Changes can occur in terms of what type of fuels used, technologies used to generate, and transfer energy as well as technologies used to transport people and goods. Society can develop a number of instruments to support, stimulate or force changes in certain directions.

The use of fossil resources in the energy system has been a main contributing factor to the increase in greenhouse gases (GHG) in the atmosphere (IPCC 2007a). The challenges presented by climate change pose a great risk that may threaten the very existence of the human society (Lynas 2008).

Climate change cannot be seen in isolation to other environmental and societal challenges. Rockström *et al* (2009) argue that there are a number of planetary boundaries that we have to consider when shaping and planning our society. In this framework the challenges of climate change are accompanied by those of loss of biodiversity and human interference with the nitrogen cycle. Time series since the 70's shows substantial losses of biodiversity (WWF 2010) and it has been shown that biodiversity plays a central role in keeping ecosystems services intact and thus also creating the foundation for our societies (Millennium Ecosystem Assessment 2005).

Large parts of the world's population do not have access to modern energy sources while other people use energy without having to consider whether it is sustainable or not. As an example, developing countries use about half of the world's energy but hosts more than 80% of the global population (World Bank 2011). Access to modern energy sources has a number of positive impacts on human well-being, such as improved health due to improved in-door climate, the ability to take advantage of information and communication technologies (ICT) and reduce time and money spent on collection and purchasing traditional energy sources (Modi et al. 2005; UNDP 2005).

On a global scale there is a need both to expand and facilitate the access to modern energy sources for many people, while in other cases there is need to reduce the use of energy (World Bank 2010). OECD countries will generally have to make more efficient use of energy, while access to modern energy sources in developing countries will have to increase. This is not the same thing as to argue that in countries where energy use should decrease, a reduction in living standards or economic activity will occur. Energy is often discussed in terms of energy units and this is a practical way of presenting and analysing the energy system and this is also done in this report. Energy is linked to economic growth in countries, as more production generally means that there is need for more use of energy. As a consequence increased use of energy has normally meant that there is also economic growth (IEA 2010). At the same time it is not the energy *per se* that creates or pushes development, but rather what the energy is used for. Services created from energy use are often referred to as energy services. The same energy service can be obtained from different energy sources, as well as different amounts of energy units. How to decouple economic growth from energy use and economic growth is being discussed. The operationalisation of this in areas with high energy use, and the implementation of energy efficiency improvement activities are of great importance.

Energy use is a global issue and there is no simple, single solution. However, one thing is certain, changes in the energy systems will occur whether we like it or not. Climate changes will alter weather conditions and affect ecosystems, hydrological cycles and a whole range of ecosystem services that are linked to energy systems (Ebinger and Vergara 2011). In addition there is growing evidence that the fossil oil era is coming to an end as we now likely have passed what is referred to as the peak-oil (Aleklett et al. 2010)[1]. Even though we have seen a moving 30-year respite in terms of available oil reserves since the Rome club report in 1972 (Meadows et al. 1972) we seem now to have reached a point where the known reserves of oil do not grow at the same pace as the demand for oil, a situation not known previously.

Still it is vital to understand that these challenges, even though they may sound dystopic, do not imply that the end of the world is coming. A key report presented by Sir Nicholas Stern (2006) argues that a transition towards a more sustainable society would require substantial investments but would not necessarily act as a cap on the capacity for economic growth. The worst scenario, according to the report, is to do nothing.

The current report presents an energy scenario for Sweden where the use of fossil and non-renewable energy sources has been reduced to a level less than 5% of the total energy use in the country. This is reached in 2050. In order to achieve this, a number of steps and changes will have to be seen in the energy system, infrastructure, and regulating/supporting mechanisms and institutions. The global challenges are all relevant to the Swedish case. There is need to reduce the use of resources and to attain more efficient energy services. Sweden has a high *primary energy* use per person and, as will be shown, vast improvements can be made[2]. Further on, aspects of environmental concern in the exploitation of natural resources can be strengthened. All options of energy generation and extraction of natural resources will have environmental impact and in this scenario a high level of environmental restrictions have been applied.

1 Peak oil describes a point in time when the production rate of oil products reaches its maximum. The point is defined through analysing the known production in individual oil wells in combination with known oil reserves. Reaching the peak oil sets focus on a decrease in oil production and subsequently increased oil prices.

2 Primary energy is the actual energy resource use. In the case of energy carriers such as electricity, there is a range of unseen losses.

1.1 Other scenario studies

There have been a large numbers of studies produced in recent years focusing on global energy systems and possible pathways forward (some examples are Delucchi and Jacobson 2010; EREC 2010; Jacobson and Delucchi 2010; PWC 2010; Teske et al. 2010b; Deng et al. 2011; IPCC 2011b; Jeffries 2011; UNEP 2011). These studies were motivated by needs to mitigate the rising GHG levels in the atmosphere, counteract effects that will occur as the cost of oil increases, prevent the loss of biodiversity, minimize negative effects on local livelihoods and human well-being and tackle unequal distribution of wealth in the world.

The scenarios all indicate a reduction in GHG emissions and a shift towards more renewables in the energy system. A whole range of efficiency measures are taken into account in order to reduce energy use. However, there are also a number of optional technologies that are found in some scenarios, but not used in others. For example nuclear power is a technology, defined as non-renewable, which has low GHG emissions compared to fossil energy-based technologies. Another technology found in some scenarios, while not in others is Carbon Capture and Storage (CCS) and similar technologies such as Bio-energy with Carbon Capture and Storage (BECCS). In a recent study of the IPCC working group on renewable energy they conclude that the global technical potential of renewable energy is always substantially higher than global energy demand (Edenhofer et al. 2011). There is a whole range of technology options that may develop in the future, but it is difficult today to assess whether or not their potentials will be realized. There are assumptions made in all scenarios regarding the technologies and usage patterns that will evolve, and outcomes are based on these assumptions. Technical breakthroughs, and societal changes could make the transition to the sustainable use of resources come much quicker.

The present study is limited to the Swedish energy system and in that sense connects to the long range of energy pathways that have been studied and presented for Sweden. In 1980 there was a referendum in Sweden concerning the future for nuclear power and linked to this referendum an intensive debate took place on how the energy system would look in the future. Focus was generally on electricity and to some extent also heating, while energy for transport was rarely discussed. One reason was that climate change had not become a prioritized political issue at that time. The decision on the future of nuclear power in Sweden in 1980 was that it should be phased out in parallel with the introduction of new production capacity based on renewable energy technologies. The process of phasing out nuclear power in Sweden was, however, slow and today only two reactors have been shut down and 10 are still in operation.

During the 90s several studies of energy futures were carried out (Meyer et al. 1993; Haegermark 1996; Azar and Lindgren 1998). The discussion on nuclear power also continued and an official report by the Swedish government concerning the energy system and future development was presented in 1995 (SOU 1995). In 1996 a special initiative was launched that looked at transport (Kommunikationsforskningsberedningen). This initiative led to research and studies were carried out on sustainable transport systems (Åkerman et al. 2000).

The global work looking at pathways for energy futures and how to tackle climate change have stimulated development within the EU of the climate package also referred to as the

2020 targets (COM 2008) as well as the Renewable Energy Directive (RED) (European Parliament 2009). Several studies and energy scenarios were also designed and presented in Sweden (Herland 2005; Åkerman et al. 2007; Bryntse and Mattison 2010; Gode et al. 2010; Profu 2010; Svensk Energi 2010)[3]. Most of these look at different ways to make the energy system in Sweden independent on fossil energy sources. In 2008 the Swedish Government presented goals and visions linked to energy and climate issues (Regeringskansliet 2008b; Regeringskansliet 2008a). According to these documents Sweden should not be a net emitter of GHG in 2050 and the transport fleet should not be dependent on fossil energy sources in 2030[4]. In terms of the more immediate actions, Sweden, as all EU member states have ventured on a National Renewable Energy Action Plan (NREAP) stating how the goals set in the RED will be met by 2020 (Regeringskansliet 2010; Beurskens and Hekkenberg 2011). The goals set by Sweden in its NREAP are not very ambitious considering the resources and energy system found in Sweden today. The goal of 49% renewable energy will be met on a business-as- usual scenario. Energy efficiency improvement stands out in terms of vagueness and is not considered in the NREAP and the route forward to realize the goals set in the 2020 targets. In 2010 and 2011 the goals related to the energy efficiency improvement in the 2020 targets was presented in a little more detail by the European Commission (European Commission 2010c; European Commission 2010a). Energy efficiency improvement activities are carried out in Sweden and a number of programmes have been implemented by the Swedish Energy Agency to support energy efficiency improvement in for example the Program for Improving Energy Efficiency in Energy Intensive Industries (PFE) and also support for energy efficiency improvement work in municipalities and county councils. Many would, however, argue that there are vast untapped potentials for energy efficiency improvement that have not been realized yet (McKinsey&Company 2008; Nilsson 2008; Ågren et al. 2008; Nilsson and Wolf 2011).

1.2 Approach

The Swedish energy system is interlinked and part of the Scandinavian energy system, the European energy system and also a part of a global energy system. There are many energy visions, pathways and scenarios for each of these levels; global (WEC 2007; Shell 2008; C.I.R.E.D et al. 2009; Delucchi and Jacobson 2010; IEA 2010; Jacobson and Delucchi 2010; Teske et al. 2010b; Deng et al. 2011; Jeffries 2011), regional EU 27 (EREC 2010; Odenberger and Johnsson 2010; PWC 2010; Teske et al. 2010a; EWEA 2011), regional Nordic (Illum 2006; Melgaard 2006) and Swedish (Haegermark 1996; Azar and Lindgren 1998; Akhtarzand et al. 2003; Åkerman et al. 2007; Bryntse and Mattison 2010; Profu 2010). The reports mentioned above are interlinked both between scales and between the same scale in for example neighbouring countries. For instance, a number of the Danish scenarios make use of the regulating capacity in the Swedish and Norwegian electricity systems when planning their energy scenarios (see for example Mathiesen et al. 2009). In such cases it is vital to know of whether there is or will be in the future competition for the regulating capacity that makes it possible to balance moment by moment demand and supply of electricity. Another example is the

3 There are also some examples of studies made of a Scandinavian energy system, see for example Illum (2006) and Melgaard (2006).

4 Flex-fuel engines are acceptable according to this goal as these engines can run on renewables.

biomass used to produce energy carriers to substitute fossil energy such as petrol and diesel, how much of this biomass will be domestically sourced and how it will be used within the national energy system.

These national energy scenarios are planning tools and inevitably include assumptions and normative judgments. Many of these assumptions are linked to define system boundaries and here defining a geographical border is useful. Sweden is part of the European Union (EU) and as such we cooperate and take part in EU processes to reduce CO_2 emissions and preserve environmental values. Some things we cannot decide by ourselves, such as the internal market, but there are several other issues that we can decide upon. For example the regulations on buildings, strategic work on energy efficiency improvement and support structures linked to this, as well as how to consider environmental values such as biodiversity in our management of forests and other land uses.

The scenario developed in this report is based on a backcasting method (Robinson 1982; Dreborg 1996). The backcasting method in terms of scenario making takes a point of departure in a desired vision and from this vision a path linking the vision to present day is described. Linking the vision with the present is an iterative process where actions are described that will push changes in the system in a direction that will end with the vision. Backcasting is a normative method and is useful for exploring and creating an understanding of future opportunities and structures of society and in strategic planning (Naturvårdsverket 2005; Börjeson et al. 2006). The method has been applied in a range of studies and often within a sustainability context (Azar and Lindgren 1998; Holmberg and Robért 2000; Åkerman et al. 2000; Svenfelt et al. 2010).

A backcasting is different from a forecast approach where present day situation and trends are drawn further into the future, adjusting the development in relation to price adjustments, possible innovations and regulations. A Swedish example of a forecast is the long-term energy forecast presented by the Swedish Energy Agency (Energimyndigheten 2009). A forecast could be broadly described as a possible, relatively near future, while the backcasting is formed around a desired future or examined vision in a more distant future.

2 A Swedish 2050 energy scenario based on renewable energy

The energy scenario presented in this report is based on a backcast. The energy system investigated for 2050 should fulfil a set of desired conditions related to the sustainable use of existing resources.

2.1 Assumptions for the situation desired in 2050

The energy system for 2050 investigated in this energy scenario could be described as a resource-efficient energy system, based on local resources managed with a high level of sustainability concern. The scenario is geographically limited to the energy system in Sweden and includes supply and demand in the transport, industrial, household and service sectors.

The supply should be provided with renewable resources produced or present within Sweden. This does not mean that imports and exports of renewable energy sources are not allowed, but there should not be an import of a resource, for example biofuels, that exceeds the export of domestic production. This precondition is based on the realization that Sweden's energy use is dependent on imported energy resources to a high degree[5] and at least Sweden should be able to provide renewables to meet its own needs. At the same time renewable energy sources are not cornucopias where an endless amount of energy can be tapped in every second. In fact renewable energy sources are limited to the regeneration capacity of the source and this will necessitate management of the source sustainability or it will be depleted. The levels of use of for example biomass were based on a dialogue with WWF. This dialogue has resulted in a number of potentials that are given in the report. The levels indicated are based on assessments made on environmental considerations but do not represent a policy statement.

The energy system should be based on renewable energy technologies and resources in 2050. There is, however, one exception concerning coal used in steel processing. This coal has not been fully substituted with renewables in the scenario. In other industries the transition from fossil sources to renewable sources is accomplished by 2050 and thus almost all excess heat and electricity production is based on renewables.

The approach to limit the scenario to the Swedish geographic area is pragmatic in the sense that the energy system in Sweden is part of a Scandinavian energy market for electricity (NordPool) and also in that Sweden is part of the European Union and takes an active part in the implementation of the Union's goals concerning related areas. For example, according to the European Commission (2010b) there is a need to develop a pan-European energy market and thus Swedish energy conversion and energy use would be interlinked with other countries' energy systems. The scenario is, however, based on a balance between the domes-

5 According to the European Union (2010) imported energy amounts to 17% of the total gross inland consumption of energy. If nuclear energy is included in imported energy (there is no commercial mining of uranium in Sweden) this dependency on imported energy reaches almost 70%.

tic energy needs and existing domestic energy conversion and generation, which does not exclude export and import as long as this balance is kept.

The scenario also stipulates that a high level of concern is taken in the management of forest and other land uses. The level envisioned goes beyond the RED sustainability criteria (European Parliament 2009) and will need a range of changes in present forest governance and management in order to be operationalised. This report takes its point of departure in assessments of the potential available biomass, but does not include a detailed discussion of the changes that this would require in terms of policy and regulations within the sector.

Consumption and energy use linked to the resources used for this production that take place outside Swedish borders, is not included in this scenario. Carlson-Kanyama et al. (2007) made assessments of emissions of GHG linked to Swedish consumption and the resulting GHG emissions which also included emissions in other parts of the world. This was then compared to official statistics. The result showed that emissions varied to a high degree (57-109 Mton CO_2 per year) if these emissions were included or not. The official statistic for a comparable period was 54 Mton CO_2 per year (Carlsson-Kanyama et al. 2007). Similar results are also found in Minx et al. (2008) and Naturvårdsverket (2010)

The resources used in international air travels by Swedish people are not part of this scenario. This is considered consumption outside the Swedish borders and hence excluded. Based on the same reasoning domestic air travel and transport is part of the scenario. Similar exclusion is made for international shipping while domestic boat transports are included in the scenario. For a global approach to a renewable energy scenario, where international air and boat traffic is also included, see for example Deng et al. (2011)

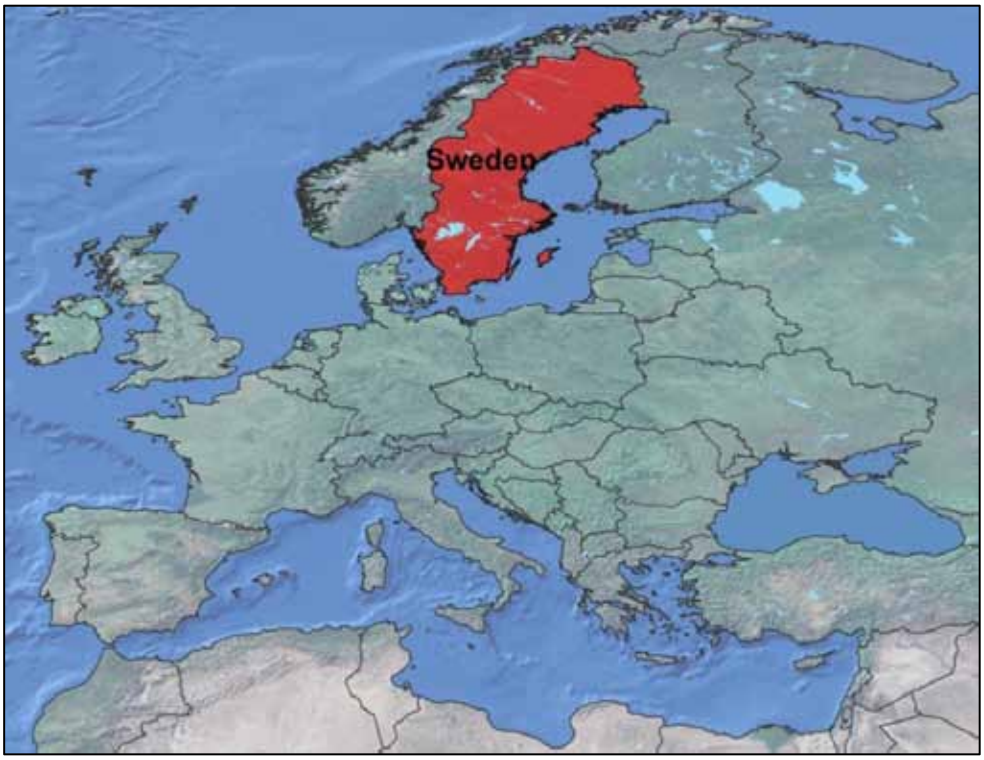
The scenario does not include CCS as an option to reduce emissions of carbon dioxide. An energy scenario based on renewable resources is the point of departure – CCS (or BECCS) would not affect the energy mixes other than through for example efficiency losses in the capture technologies. Nuclear power is not a renewable source of energy and is thus also phased out before 2050. All fossil fuels are assumed to be faced out gradually from 2010 to 2050 except parts of the coal used in the steel industry. It is assumed that a renewable source is used where such exists, thus substituting the non-renewable.

The number of people that live and work in Sweden will have an impact on the resources required in the energy system. Population growth is based on Statistics Sweden (SCB 2011) and the population in Sweden will reach 10.7 million people in 2050 (Table 1).

Table 1: Population growth in Sweden (million people)

	2005	2010	2020	2030	2040	2050
Population (million)	9.05	9.42	10.00	10.36	10.55	10.73
Population Growth (% per year)		0.81%	0.60%	0.36%	0.18%	0.18%

The scenario takes its point of departure in the economic growth assumed for Sweden from 2010 to 2030 (National Institute of Economic Research). That economic growth is used in the Swedish Energy Agency (Energimyndigheten 2009) and the other forecasts used in the scenario. That has resulted in increased demand of production in industry, increased activity of transport and increase demand for e.g. cooling in the residential and service sectors. The scenario assumes a lower increase in transport activity compared to official forecasts and high energy efficiency improvement implementation. Economic growth is assumed to be constant at 2.2% per year due to the large investments needed for energy efficiency improvement implementation.



Area: 450,000 km²

- Forests: 53%
- Mountains: 11%
- Cultivated land: 8%
- Lakes and rivers: 9%

Longest north-south distance: 1,574 km
Longest east-west distance: 499 km
Capital: Stockholm
Population 2010: 9.4 million inhabitants
Most important export goods: Machinery, electronics and telecommunication, paper, pharmaceuticals, petroleum products, iron and steel, and foodstuffs
Most important imported goods: Electronics and telecommunication, machinery, foodstuffs, crude oil, textiles and footwear, chemicals, pharmaceuticals and petroleum products

(Source: Sweden.se 2011)

2.2 Functions of the energy model applied

In order to investigate the road to 2050, a model of the energy system in Sweden has been applied. The energy system was analysed with respect to energy supply, energy conversion and energy end-use in the three energy demanding sectors i) industry, ii) transport, and iii) household and service, see Figure 1. Bunker fuels (international flight and shipping), energy for uses other than energy purposes, and losses in nuclear were not included in the methodology.

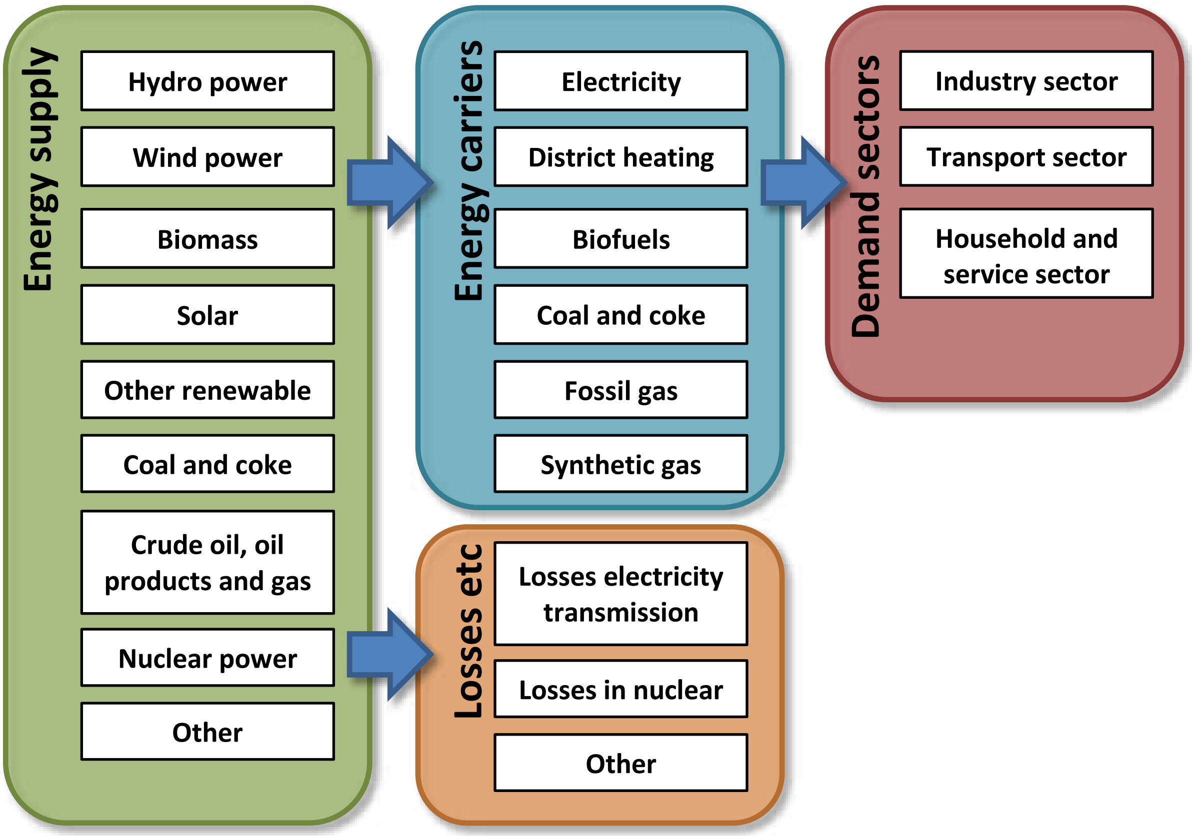


Figure 1: Illustration of the energy system studied, from energy supply to energy end-use without import and/or export by energy carriers (other than fossil fuels).

Energy demand and supply are analysed for the following sectors:

1) Energy end-using sectors
   a) Industry
   b) Transport (excluding international aviation and shipping)
   c) Household and service

2) Energy converting/supplying sectors:
   a) Power production
   b) Heat production
   c) Fuel production

The model is based on fulfilling energy service demands. There is an iteration taking place in order to see that the demands can be fulfilled by the supply side, and that the supply side is also within the set of potentials described as being within the carrying capacity of the ecosystems in Sweden. The methodology used can be divided into 3 stages for the end-using sectors:

1. Determine the activity level, e.g. need of transport, square meters heated, and how it trends in the future. These activities are based on demand of energy services and are not limited to energy units.
2. Find specific energy use per unit activity and how it trends in the future. This variable is an operationalisation of technology development and initiatives that push for more efficient energy use in supplying each specific energy service.
3. Assess and determine the energy carriers and technologies that are applied in the model.

Each of these steps was taken for 2010, 2020, 2030, 2040 and 2050. There are no calculations between these points. The diagrams presented are generally made as area diagrams as these are easily understood. In the diagrams a straight line connects the different decades, while in fact the process described and anticipated in the scenario takes place mostly at the end or beginning of the period. The reader is asked to bear this in mind when interpreting the diagrams. The gradient in the line between 2010 and 2020 does not account for the actual situation in the preceding years. This means that considering the progress we see in the energy demand today in Sweden, there is a challenge to shift this trend from slight increase to decrease in energy use.

The values for 2010 are based on calculations. Due to the economic crisis that was experienced in Sweden (and globally) 2007-2010 the connections between calculated numbers for 2010 and real values display gaps in some cases.

Activity levels are based on official forecasts or the extrapolation of historical trends even though the increase in activity has been reduced for the transport sector. The assessments of specific energy use per unit activity are based on literature or in some cases IVL assumptions based on experience. References are given in the text to make the sources transparent. The scenario assumes a rapid implementation of energy efficiency improvement activities in all sectors. The assumptions also include development of the technology found in the energy system, both on the supply side as well as the demand side. The energy carriers and technologies used in the future have been selected with regard to reaching the overall goal of a renewable future in 2050 within the carrying capacity of the ecosystems with regards to energy supply.

In the case of the industry sector it has not been possible to separate the two first stages (except for the pulp and paper industry). The use of energy in each sub-sector was instead based on the Swedish Energy Agency long term scenario (Energimyndigheten 2009) and extrapolated to 2050 with an assumption of increased energy efficiency.

The Swedish Energy Agency long term scenario and the other forecasts used in the scenario are based on an economic growth rate of 2.2% per year (National Institute of Economic Research, Konjunkturinstitutet). The impact of the decreased activity in the transport sector and the energy efficiency improvement measures implemented on economic development are not analysed in the report. At the same time all the required investments will stimulate economic development and not decrease economic activity. A more detailed discussion of the economy of the scenario is provided in Chapter 6.

The methodology used for supply differs between the different sectors. Biofuel production and the district heating sectors produce the biofuels and heat demanded by the end-using sectors. Biofuel production uses bioenergy and electricity to produce biofuels as well as heat and energy resources and in some processes yield electricity. District heating systems produce electricity by combined heat and power and use surplus heat and energy from biofuel production and industry beside waste, heat pumps and bioenergy. Electricity production is determined by the electricity production potentials and during some decades potential production is much larger than the electricity demand in the scenario.

Figure 2 illustrates energy interactions between the different sectors that are operationalised in the model. 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.

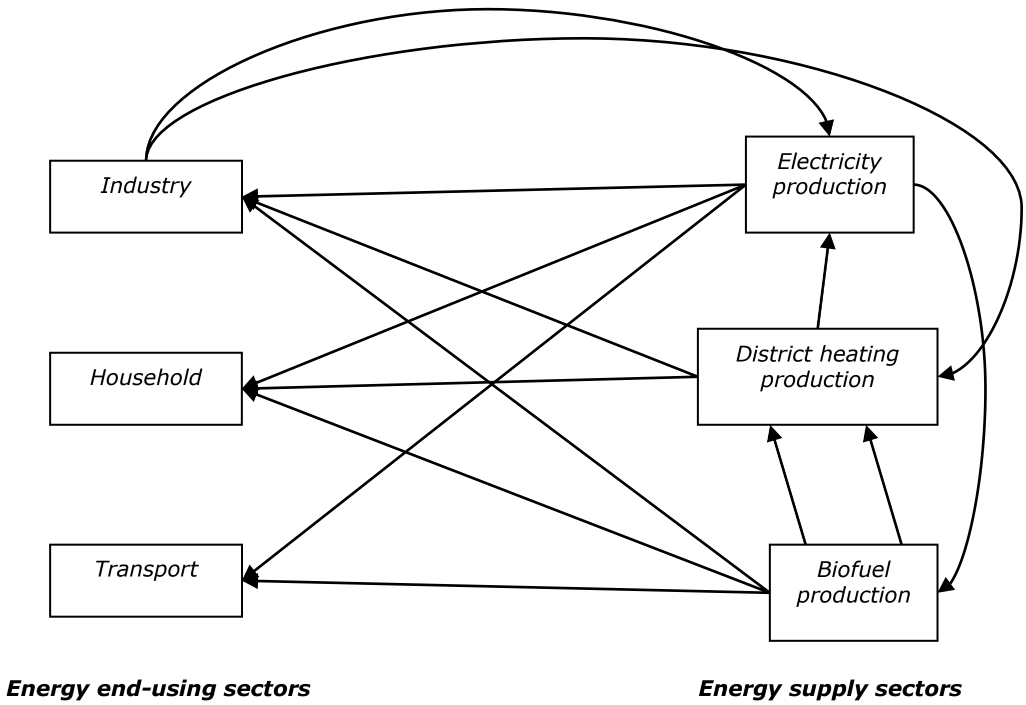


Figure 2: Energy flows between the different sectors included in the model.

Figure 2 illustrates only the 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, Synthetic Natural Gas (SNG)[6] and biogas.

The technical pathways displayed in the scenario are to a great extent based on an analysis of attractive, feasible technical solutions found at present. This is perhaps most illustrative for the case of biofuels and this scenario's relatively heavy reliance on DME production in biorefineries. This is a technical route that combines keeping an existing industry (paper and pulp industry) and receiving a range of needed products for the energy system. The biorefineries will, apart from the pulp, also produce biofuels, electricity and heat, all of which have productive uses in the energy system. If other technology options emerge in the future that display similar efficiency in resource use, those can be applied. The focus on specific energy carriers, such as DME, should thus be interpreted as one route toward realizing the energy system for 2050. This accounts for DME, FAME and ethanol, and the authors are well aware that new options will emerge.

6 In this scenario SNG refers to a synthetic gas produced from renewable sources and is thus a renewable source; the mix is presented in section 3.2.5.2 The source for the gas used in transport sector.

3 Demand side in Sweden

In this chapter the demand side of the energy system is presented, which includes background data and assessments of the changes towards 2050 required to meet the desired energy scenario in 2050. The demand side is divided into the three sectors, i) industry, ii) transport and iii) household and service sector.

3.1 The industry sector

The yearly growth of the total energy use for each industry sub-sector[7] is reduced by 0.5% per year compared to the yearly growth used in the Swedish Energy Agency forecast between 2005 and 2030 (Energimyndigheten 2009) and (Lagerquist 2011). In the Swedish Energy Agency forecast only adopted policy instruments are included and in this scenario we assume that the pressure to increase energy efficiency will increase by e.g. new policy instruments. The same yearly change in energy demand for each sector between 2005 and 2030 is also used for 2030 to 2050.

A number of measures to reduce the use of fossil fuels in the industry sector are included in the scenario. The measures are about the same as in Gode et al. (2010):

- The solid fossil fuels (except the coal used for processes in the steel industry – see below) are replaced by solid bioenergy.
- Diesel, oil and liquefied petroleum gas (LPG) are assumed to be replaced by liquid biofuels produced in the biofuel sector. The biofuel used will depend on how research for different biofuels develops. A biofuel must be chosen in order to perform calculations for the scenarios in which biofuels will be used, and in this scenario dimethyl ether (DME) was selected as the biofuel used in industry. However, other biofuels may well dominate in the future.
- Natural gas is assumed to be replaced by gaseous biofuels. In the calculations it is assumed that the gaseous biofuel is Synthetic Natural Gas (SNG). The SNG introduced in the scenario will have a renewable origin.
- Some of the coal for the steel process is shifted to wood charcoal. The volume that could be replaced is described by McKinsey & Company (2008). They say that the coal could be replaced by natural gas. However, according to the research programme (ULCOS 2011) it will probably be possible to use wood charcoal in the steel-making process in the future. Even more of the coal could according to ULCOS be replaced by wood charcoal. As a consequence of limited access to biomass we assume that 45% of the coal and coke in the steel industry in 2050 can be replaced by bioenergy. This also affects the surplus coke gases used for electricity and heat production that partly will have renewable origin.

7 Except for the pulp- and paper industry where the energy efficiency potentials are examined more carefully.

Table 2 shows the implementation rate of the different measures to reduce fossil fuels. For all measures 100% means that all fossil fuels are replaced. All measures except the measure for reducing coal and coke in the steel industry reach 100% to 2050.

Table 2: The implementation rate of the different categories of measures introduced in the industry sector to reduce the use of fossil fuels.

	2005	2010	2020	2030	2040	2050
Substitution of solid fossil fuels to solid bioenergy	0%	0%	25%	50%	75%	100%
Substitution of oil with liquid bioenergy (e.g. DME)	0%	0%	25%	50%	75%	100%
Substitution of natural gas with e.g. SNG	0%	0%	25%	50%	75%	100%
Substitution of LPG with e.g. DME	0%	0%	25%	50%	75%	100%
Direct reduction (coal and coke is replaced by charcoal from bioenergy)	0%	0%	0%	0%	0%	45%

3.1.1 Pulp and paper industry

The pulp and paper industry in Sweden uses about half of the energy used in the industry sector. The pulp and paper industry is also a large user of bioenergy and has the potential to be an important producer of biofuels for the transport sector. Therefore more careful examination of the future potentials of the pulp and paper industry was conducted in this report.

In 2007, the baseline for the pulp and paper industry was a year with very high production (large global demand) and with high levels of available wood because of the storms "Gudrun" in 2005 and "Per" in 2007. The use of wood in Sweden in 2007 was far above the level of wood production in 2020-2050 according to the WWF adjusted scenario. If the pulp and paper industry is to rely on wood from the Swedish forests and the same imported volume of pulp wood as in 2007 the production volume of pulp has to decrease over the next two decades in order to ensure supply of feedstock for production of biofuel for the transport sector. During these decades the energy sector will use some of the biomass that is today used as pulp wood. In total this means that pulp production will decline by 1.1% per year to 2020 and 0.5% per year from 2020 to 2030. After that the industry can start to grow again because of increased wood availability in the forests and reduced use of pulp wood for energy purposes. The increase is 0.5% per year from 2030 to 2040 and 0.80% per year from 2040 to 2050.

The statistics for 2007 from Wiberg (2007) were used for the pulp and paper industry and include specific details of the energy flows and production volumes. The historical average total specific energy efficiency improvement in kWh/ton produced paper and sold pulp was 0.5% to 1% per year during the period 1979 to 2007. The lower number is according to (Skogsindustrierna 2011) and the higher number from calculations based on Wiberg (2007). (Skogsindustrierna 2011) has the goal of improving the specific energy efficiency by 15% by 2020. Based on this information it is assumed that the future specific energy efficiency will improve by 1% per year (from 2007 to 2050) for all parts of the pulp and paper industry except for the steam needed for the chemical pulp production.

The specific steam needed per ton chemical pulp is assumed to fall by 1.7% per year. The best available technology in the future for chemical pulp production is a steam demand of 7 GJ per ton pulp produced for a pulp production not integrated with paper production according to Alvfors et al. (2010). The average steam demand in chemical pulp production not integrated with paper production in 2007 is 14.6 GJ/ton[8] pulp produced. A reduction from 14.6 GJ/ton in 2007 to 7 GJ/ton in 2050 results in a specific energy efficiency improvement of 1.7% per year. The same specific energy efficiency improvement is assumed for the chemical pulp production integrated with paper production. In these industries steam demand decreases from 19.0 GJ/ton (an average Swedish integrated chemical pulp mill according to (Alvfors et al. 2010) to 9.1 GJ/ton in 2050. 1.7% per year in specific energy efficiency improvement is a very high rate. It could be compared with the average value for steam demand between 1979 and 2007 of 0.6% per year (Wiberg 2007).

Decreased steam demand results in oversupply of black liquor and bark in the chemical pulp mills. These fuels are difficult and expensive to transport to e.g. district heating plants. There are examples already today where there is an excess of bark and the bark is then used for electricity production in condensing mode or used for producing pellets (which are more economical to transport). There are different pathways in which the pulp and paper industry could develop to improve the output from the surplus black liquor and bark, some of which are described in (Jönsson and Algehed 2009). Two of the most probable developments in the long term are increased electricity production and DME-production respectively. These two pathways are examined in Grahn et al (2010). The mill could either build a new recovery boiler with higher steam data that will increase the electricity production or it could build a new recovery boiler that integrates DME-production. Electricity and DME-production performance will depend on steam demand; refer to Alvfors et al. (2010) for further information.

The black liquor production per ton pulp produced (5.84 MWh per ton pulp) in the example mill illustrated in Alvfors et al. (2010) is higher than in the statistics by Wiberg (2007), (4.80 MWh per ton pulp). To be able to use the example by Alvfors et al. (2010) black liquor production per ton pulp has been reduced by 18%. Electricity and DME-production per ton pulp in that example have been reduced by the same factor. However, bark production has been increased by 24% to include other wood residuals and to fit with the energy statistics in Wiberg (2007) from 0.66 to 0.82 MWh per ton pulp.

The implementation rate of recovery boilers for increased electricity production and DME production is described in Table 3.

8 The calculation is based on Wiberg (2007) with 90% efficiency in steam generation.

Table 3: Share of black liquor used in recovery boilers

	2007	2010	2020	2030	2040	2050
Share of the black liquor used in new recovery boilers for DME-production	0%	0%	10%	40%	70%	90%
Share of the black liquor used in new recovery boilers for high electricity production	0%	0%	10%	10%	10%	10%

The electricity and black liquor use for DME production is allocated to the biofuel production sector. Black liquor and bark used for electricity production are allocated to the electricity production sector.

3.1.1.1 Wood available from forests

The Swedish Forest Agency (Skogsstyrelsen 2008b) has created scenarios for future available wood from forests. Their forecasts are presented along with an adjusted WWF scenario in Table 4. These calculations assume positive growth responses in Swedish forests due to climate change. However, due to projection difficulties, no account has been taken of possible increases in forest damage resulting from e.g. pests, storms and fires. Hence, volume availability may prove to be overestimations. WWF's adjusted scenario (WWF 2011) has reduced round wood availability compared to the SKA-08 environmental scenario[9], by assuming a further increase in protected areas by 3.5% and another 7.5% of the total area to be used as continuous cover forestry. Continuous cover forestry is assumed to reduce the availability of round wood volume on average by 35% (optimistic 15%, pessimistic 40%). In total, the reduced round wood volume is 5.75% compared to the SKA-08 environment scenario (Skogsstyrelsen 2008b).

9 The SKA-08 environmental scenario is an interpretation made by the Swedish Forest Agency on what will be needed to fulfill the environmental objectives adopted by the Swedish Parliament.

Table 4: Biomass output from forests based on different management regimes (Million cubic meters standing volume incl. bark, Mm³sk)

	2010-2019	2020-2029	2030-2039	2040-2049	2050-2059
Reference scenario (Skogsstyrelsen 2008b)	91	88	90	95	102
Production scenario (Skogsstyrelsen 2008b)	91	90	95	104	115
Environment scenario (Skogsstyrelsen 2008b)	85	84	85	88	96
Environment + production scenario (Skogsstyrelsen 2008b)	85	85	89	98	107
WWF adjusted scenario	81	79	79	83	89

The scenarios in Table 4 above describe the potentials in 10-year-intervals, 2010-19, 2020-2029 etc. However, the potentials in 2020, 2030, etc. have to be calculated as the average of the potentials in the 10-year interval before and after the actual year. For example, to calculate the potential in 2020 the average of the potentials for 2010-2019 and 2020-2029 is calculated. The recalculated potentials are presented in Table 5. The potentials discussed and assessed in dialogues with WWF are used in the project.

Table 5: Recalculated potentials of biomass output from forests based on different management regimes (Million cubic meters standing volume incl. bark, Mm³sk)

	2020	2030	2040	2050
Reference scenario	89	89	93	99
Production scenario	90	93	100	110
Environment scenario	85	84	87	92
Environment + production scenario	85	87	93	102
WWF adjusted scenario	80	79	81	86

The scenario potential can be divided into different categories of available fractions according to historical values. Table 6: The shares saw timber and pulp wood of net felling are averages from 2004 to 2009 according to Swedish Forest Agency (Skogsstyrelsen 2010). Net wood felling in Mm3sk is the WWF potentials.Table 6 shows the share of each fraction of the available wood.

Table 6: The shares saw timber and pulp wood of net felling are averages from 2004 to 2009 according to Swedish Forest Agency (Skogsstyrelsen 2010). Net wood felling in Mm³sk is the WWF potentials.

	2020	2030	2040	2050
Net wood felling (Mm^3sk)	79.9	79.2	81.1	86.2
Net wood felling (Mm^3fub)	66.6	66.0	67.6	71.9
whereof saw timber (Mm^3fub)	33.0	32.7	33.6	35.9
whereof pulp wood (Mm^3fub)	27.2	26.9	27.6	29.5
whereof wood for domestic energy use (Mm^3fub)	5.9	5.9	5.9	5.9
whereof other (Mm^3fub)	0.5	0.5	0.5	0.5

Mm^3sk = million m^3 standing volume incl. bark
Mm^3fub = million m^3 solid volume under bark

50% of the saw timber used in the saw mills becomes by-products (Skogsstyrelsen 2007a). 2/3 of the by-products are used in the pulp and paper industry and 1/3 is used for heat and electricity production (Skogsstyrelsen 2007a).

3.2 The transport sector

The transport sector uses mainly fossil energy in satisfying existing energy demands. There are a range of alternatives to fossil fuels, many of which can be used in already existing technology and infrastructure. The transport sector is divided into goods transport, and passenger transport. Another division is made between short and long distance transport/journeys. A short distance transport/journey is less than 100 km.

3.2.1 Goods transport

3.2.1.1 Activity data

Wikström et al. (2009) have made forecasts of goods transported in Sweden up to 2020. According to their scenario "Energy efficient-scenario - investment" road transport tkm will increase by 0.74% per year between 2006 and 2020. The corresponding level for rail transport is 1.92% per year (Wikström et al. 2009). The inland transport with shipping is difficult to measure. However, statistics show that 8 billion tkm were produced during 2005 by domestic shipping (SIKA 2009b). Assuming domestic shipping to be constant the total activity increase in goods transport in Sweden measured in tkm is 1.04% per year from 2005 to 2020.

It is difficult to reduce the growth in transport work. However, a reduction of the need of goods transport will be necessary to limit the increasing energy need for transport. There are methods and technologies to reduce the need of transport and with strong policy instruments growth in transport may be slowed down. In the scenario IVL has assumed that the growth rate of 1.04% per year as described above is reduced to half. A yearly growth of 0.52% is assumed to be valid for the whole period 2006 to 2050.

For road transport the km driven by lorries increase more rapidly than the transported volume in tkm (Wikström et al. 2009). This is explained by larger growth in distribution lorries than in long distance road transport. In the scenario it is assumed that policies are introduced so that driven distances increase at the same pace as the transported volume measured in tkm. Table 7 shows the forecast by Wikström et al. (2009) and the transport volumes in the scenario. The volume of transported goods is larger in Wikström et al. (2009) than in SIKA (2009). In the scenario the volume is based on SIKA (2009) and the discussion about growth rate is based on Wikström et al. (2009).

Table 7: Transport volumes categorized by transport option in Wikström et al. (2009), SIKA (2009b) and the IVL scenario assumptions

	(Wikström et al. 2009)		(SIKA 2009b)			IVL assumptions		
	2006	**2020**	**2005**	**2010**	**2020**	**2030**	**2040**	**2050**
Transported goods (billion tkm)	74	85	68	70	74	78	82	86
Growth per year compared to the preceding column		1.04%		0.52%	0.52%	0.52%	0.52%	0.52%
Transport share:								
Rail transport	30%	34%	31.8%	33.1%	33.4%	38.5%	44.0%	48.6%
Road transport	59%	57%	56.5%	55.6%	55.4%	50.4%	44.9%	40.0%
Domestic shipping	11%*	9%*	11.7%	11.1%	11.1%	11.0%	11.0%	11.3%
Domestic air	0.1%**	0.1%**	0.1%**	0.1%	0.1%	0.1%	0.1%	0.1%

** The numbers for shipping in Wikström et al (2009) include all shipping to and from Sweden including international transport. Therefore the figures for domestic shipping from SIKA (2009) for 2005 are used.*
In the reference scenario domestic is assumed to be constant measured in tkm even if total goods transport grows.
*** The figures for air transport are not included in Wikström et al (2009) or SIKA (2009). The values are calculated based on energy use statistics in Swedish Energy Agency (Energimyndigheten 2010c) and on IVL assumptions.*

In the scenario the share of national shipping is constant even if it was assumed that the volume of transported tkm by domestic shipping was constant in the calculation of total transported volume, the reason being that policies will be introduced to enforce energy-efficient domestic shipping.

3.2.1.2 Transport work efficiency (Wh/tkm)

Transport work efficiency is operationalised in the model through the variable energy per tkm (Wh/tkm). The development of energy efficiency in goods transport work is shown in Table 8.

Table 8: Energy efficiency for goods transport (Wh/tkm)

	2005	**2010**	**2020**	**2030**	**2040**	**2050**
Rail	53	51	46	41	37	34
Lorries	667	638	584	534	489	448
Domestic shipping	50	48	43	39	35	32
Domestic air	1 064	1 012	915	828	749	677

The energy efficiencies for 2005 (except for domestic shipping) are calculated by combining the data from SIKA (2009b) for tkm transported and from Swedish Energy Agency (Energimyndigheten 2010c) for energy use per transport category. The report by Transport Analysis (Trafikanalys 2010) is used for energy use in the rail sector. The methodology used by the

Swedish Energy Agency to calculate energy use is based on personal and goods transport by registered vehicles and not all vehicles. This may result in numbers that are too low for the energy efficiency levels used.

The energy efficiency for domestic shipping could be calculated from the same sources of information as above. However, according to Erik Fridell (pers com Fridell 2011) the statistics for domestic shipping are of very bad quality. The domestic shipping energy efficiency values for 2005 come from Åkerman et al. (2007).

The energy efficiency for goods transport by road (percentage reduced energy need per tkm) up until 2050 is based on (Löfgren and Wänn 2009) and reduce energy need per tkm by 30% for long distance transport and 40% for short distance transport up to 2040. This gives a yearly reduction of 0.9%. This corresponds with the assumptions made by Åkerman et al. (2007). The energy efficiency improvement for the other categories is assumed by IVL to be 1% per year.

3.2.1.3 Railway goods transport – energy carriers

Share of tkm performed by different energy carriers for railway goods transport is found in Table 9. Electricity is the major energy carrier used. However, other energy carriers are needed where rail routes are not electrified.

Table 9: Share of goods transported by rail by different energy carriers

	2005	2010	2020	2030	2040	2050
Transported goods (billion tkm)	22	23	25	30	36	42
Electricity	84%	84%	86%	88%	90%	92%
Diesel	16%	16%	12%	8%	4%	0%
Gas*	0%	0%	2%	4%	6%	8%

** The share of gas that has fossil and renewable origin respectively can be found in section 3.2.5.2.*

The figures for 2005 are based on data by Transport Analysis (Trafikanalys 2010). The numbers for 2010 to 2050 are estimations made by IVL.

3.2.1.4 Road goods transport – energy carriers

The required energy for road transports differs between long and short-distance journeys. The boundary between long and short distance is generally set at 100 km (see for example Åkerman et al. 2000; Åkerman and Höjer 2006). From a general point of view the energy requirements for long-distance road goods transports are lower than for short distance travels. The share of tkm performed by different energy carriers for short distance goods transport on roads is found in Table 10.

Table 10: Goods transported and share of tkm performed by different energy carriers for goods transport on roads (short distance)

	2005	2010	2020	2030	2040	2050
Transported goods (billion tkm)	7	8	8	8	7	7
Electricity	0%	0%	5%	20%	35%	50%
Petrol	9%	9%	5%	3%	0%	0%
Diesel	91%	91%	79%	52%	25%	0%
Biofuels, e.g. ethanol	0%	0%	0%	0%	0%	0%
Gas*	0%	0%	3%	10%	20%	30%
Biofuels, e.g. FAME	0%	0%	3%	5%	5%	0%
Biofuels, e.g. DME	0%	0%	5%	10%	15%	20%

** The share of gas that has fossil and renewable origin respectively can be found in section 3.2.5.2.*

The share of tkm performed by different energy carriers for long distance goods transport on roads is found in Table 11.

Table 11: Goods transported and share of tkm performed by different energy carriers for goods transport on roads (long distance)

	2005	2010	2020	2030	2040	2050
Transported goods (billion tkm)	31	31	33	32	30	28
Electricity	0%	0%	0%	0%	0%	0%
Petrol	9%	9%	5%	3%	0%	0%
Diesel	91%	91%	85%	63%	29%	0%
Biofuels, e.g. ethanol	0%	0%	0%	0%	0%	0%
Gas*	0%	0%	2%	4%	6%	10%
Biofuels, e.g. FAME	0%	0%	3%	5%	5%	0%
Biofuels, e.g. DME	0%	0%	5%	25%	60%	90%

** The share of gas that has fossil and renewable origin respectively can be found in section 3.2.5.2.*

The figures for 2005 were only calculated for the sum of the short and long distance transport by road. These figures are based on Swedish Energy Agency (Energimyndigheten 2010c). The figures for 2010 to 2050 are estimates by IVL. Electricity is assumed to be easier to implement in short distance goods transport by road than in long distance where biofuels such as DME will be the alternative to fossil fuels.

3.2.1.5 Domestic shipping goods transport

Table 12 shows the share of tkm performed by different energy carriers for goods transport by domestic shipping. The energy required per tkm for shipping is generally the lowest of all types of transport means even though rail transport can come close for certain types of journey.

Table 12: Goods transported and share of tkm performed by different energy carriers for domestic shipping

	2005	2010	2020	2030	2040	2050
Transported goods (billion tkm)	8	8	8	9	9	10
EO1 (low content of sulphur)	22%	22%	37%	49%	52%	0%
EO2-5 (different degree of sulphur content)	78%	78%	63%	31%	8%	0%
Biofuel, e.g. DME	0%	0%	0%	20%	40%	100%

The shares for 2005 were calculated by the Swedish Energy Agency (Energimyndigheten 2010c). The numbers for 2010 to 2050 are estimates by IVL.

3.2.1.6 Domestic goods transport by air

Domestic transport of goods by air is included in the scenario. Aviation fuel makes a transition from kerosene to DME during the period 2010 to 2050. The numbers presented in Table 13 are assessed by IVL.

Table 13: Goods transported and share of tkm performed by different energy carriers for goods transport by domestic air transports

	2005	2010	2020	2030	2040	2050
Transported goods (billion tkm)	0.1	0.1	0.1	0.1	0.1	0.1
Kerosene	100%	100%	100%	70%	50%	0%
Biofuels, e.g. DME	0%	0%	0%	30%	50%	100%

3.2.2 Passenger transport

3.2.2.1 Activity data

Löfgren and Yngström-Wänn (2009) have made forecasts of passenger transport in Sweden to 2020 and to 2040. In their forecast the increase between 2006 and 2020 is 0.97% per year and between 2020 and 2040 the increase is 0.95%. This scenario assumes that the growth is 0.49% per year for the period 2006 to 2020 and 0.48% per year for the period 2020 to 2040. The annual growth between 2020 and 2040 is assumed to be the same between 2040 and 2050. The reduced increase in the growth rate of passenger transportation is largely due to the high penetration of Information and Communication Technology (ICT). Ecofys and WWF judge that this has great potential for reducing the need for personal transport (Ecofys and WWF 2008).

The transported volumes and the shares between different transport categories differ between Löfgren and Yngström-Wänn (2009) and SIKA (2009b) for 2005/2006. Löfgren and Yngström-Wänn (2009) include less travelling, but a larger share of rail transport. In this report we have based the scenarios on the transported volumes in SIKA (2009b) for the year 2005.

In the scenario IVL has assumed that high-speed rail transport grows as well as metro and tram. This decreases the share of people transported by car. The other transporting categories are assumed to be fairly constant.

Table 14: Personal transport volumes divided on transport option in Wikström et al. (2009), SIKA (2009b) and the IVL scenario assumptions

	(Löfgren and Yngström-Wänn 2009)			(SIKA 2009b)	IVL assumptions				
	2006	2020	2040	2005	2010	2020	2030	2040	2050
Total transport of people (billion pkm)	112	128	155	126	130	136	143	149	157
Yearly growth of personal transports (pkm)		0.97%	0.95%	1.0%	0.49%	0.49%	0.48%	0.48%	0.48%
Transport share:									
Rail	9%	12%	12%	7.1%	7.8%	9.2%	12.1%	15.5%	18.2%
Metro, tram and other tracks	4%	5%	4%	1.6%	1.7%	1.7%	2.6%	3.9%	4.5%
Cars	71%	70%	70%	77.0%	77.2%	76.3%	72.4%	66.4%	62.5%
Buses	9%	8%	8%	6.9%	6.7%	6.1%	6.2%	6.8%	7.0%
Shipping				0.6%	0.7%	0.6%	0.6%	0.7%	0.7%
Air	3%	2%	2%	2.6%	2.6%	2.4%	2.4%	2.6%	2.6%
Walking, cycling	3%	3%	3%	3.5%	3.5%	3.6%	3.7%	4.2%	4.4%

3.2.2.2 Passenger transport work efficiency (Wh/pkm)

Transport work efficiency is operationalised in the model through the variable energy per person kilometre (Wh/pkm). The development of energy efficiency in personal transportation work is presented in Table 15.

Table 15: Energy efficiency for passenger transport (Wh/pkm)

	2005	2010	2020	2030	2040	2050
Rail	127	121	109	99	89	81
Car	498	456	383	321	268	225
Bus	280	256	215	193	173	155
Metro and tram	123	117	106	96	87	78
Domestic ferries	1 435	1 365	1 234	1 116	1 010	913
Domestic air	793	750	672	601	538	482

The energy efficiency improvement presented in Table 15 does not include the end-use efficiency of converting the vehicles from fuels to electricity. This improvement is added to the model afterwards.

The figures for 2005 are in most cases based on statistics in Sweden. Energy use in different sub-sectors of the transport sector was collected from Swedish Energy Agency (2010c). Statistics from SIKA (2009b) were used for pkm travelled. The division into sub-categories is not exactly the same in the two sources, therefore some of the efficiencies are a little uncertain.

Efficiency improvement potentials for cars are estimated at 45% between 2005 and 2040 (Löfgren and Yngström-Wänn 2009) excluding the energy efficiency improvement by converting from fuels to electricity. That reduction is extrapolated to 2050 and reaches 55% compared to 2005. The yearly energy efficiency improvement from 2005 to 2050 is between 1.7 and 1.8% per year. Åkerman et al. (2007) and Deng et al. (2011) assume even higher energy efficiency rates in their scenarios.

The efficiency improvement when driving on electricity instead of fossil fuels is assumed to be a factor 3 for petrol and 2.5 for diesel which means that a car running on electricity only uses one third of the end use energy of a car using petrol (Energimyndigheten 2009). The improvement is very difficult to estimate. Åkerman et al. (2007) estimate the improvement level to increase by a factor of around 2, while assuming a higher efficiency level for fuel-driven cars than that assumed by this report. The performance of electric cars is probably then about the same in Åkerman et al. (2007) and in this report.

Buses are assumed to have an efficiency improvement of 1.7% per year between 2005 and 2020, and an efficiency improvement of 1.1% per year between 2020 and 2050. This corresponds to efficiency levels for lorries. However, buses have a larger share of short distance travel and the yearly improvement is therefore larger for buses than lorries.

Domestic air has an efficiency improvement of 1.1% per year which correspond to the 40% reduction between 2005 and 2050 as projected by Åkerman and Höjer (2006). Deng et al. (2011) use 50% reduction.

The other categories are assumed to have an efficiency improvement of 1% per year between 2005 and 2050.

3.2.2.3 Railway passenger transport – energy carriers

The share of pkm performed by different energy carriers for rail passenger transport is found in Table 16. Electricity is most common. However, some traffic takes place on non-electrified routes and therefore other energy carriers are needed.

Table 16: Passengers transported and share of pkm performed by different energy carriers

	2005	2010	2020	2030	2040	2050
Passengers (billion pkm)	9	10	12	17	23	28
Electricity	95%	95%	95%	95%	95%	96%
Diesel	5%	5%	4%	2%	1%	0%
Gas*	0%	0%	1%	3%	4%	4%

* The respective shares of the gas with fossil and renewable origins can be found in section 3.2.5.2.

The figures for 2005 are based on data by Transport Analysis (Trafikanalys 2010). The figures for 2010 to 2050 are estimations made by IVL. Rail passenger transport is to a high degree based on electricity already today. The rate is assumed to increase a little up to 2050. The larger change from today to 2050 is the fuel switch from diesel to gas (e.g. biogas and SNG).

3.2.2.4 Cars – energy carriers

A relatively large share of all person transport is made by car, more than 75% (Table 14). It is a challenge to make shifts towards more efficient technologies that are mainly represented in the scenario by plug-in hybrids. Pure electrical cars are assumed to have limited potential of becoming an attractive solution for long distance travel. The share of energy carriers for short distance car travels is found in Table 17.

Table 17: People transported by car and the share of pkm performed by different energy carriers (short distance)

	2005	2010	2020	2030	2040	2050
Passengers (billion pkm)	81	82	85	84	79	77
Electricity	0%	0%	15%	60%	80%	90%
Petrol	90%	90%	35%	5%	0%	0%
Diesel	9%	9%	40%	20%	5%	0%
Biofuels, e.g. ethanol	0%	0%	5%	5%	0%	0%
Gas*	1%	1%	5%	10%	15%	10%
Biofuels, e.g. FAME	0%	0%	0%	0%	0%	0%
Biofuels, e.g. DME	0%	0%	0%	0%	0%	0%

** The respective shares of the gas with fossil and renewable origins can be found in section 3.2.5.2.*

The shares of energy carriers for long distance car travels are found in Table 18.

Table 18: People transported by car and share of pkm performed by different energy carriers for people transported by car (long distance)

	2005	2010	2020	2030	2040	2050
Passengers (billion pkm)	17	18	19	19	20	21
Electricity	0%	0%	0%	10%	15%	20%
Petrol	90%	90%	30%	15%	0%	0%
Diesel	9%	9%	60%	45%	35%	0%
Biofuels, e.g. ethanol	0%	0%	5%	5%	0%	0%
Gas*	1%	1%	5%	10%	10%	10%
Biofuels, e.g. FAME	0%	0%	0%	0%	0%	0%
Biofuels, e.g. DME	0%	0%	0%	15%	40%	70%

** The share of gas that has fossil and renewable origin respectively can be found in section 3.2.5.2.*

The transport share of pkm by cars for different energy carriers is assumed to be equal for short and long distance travel in 2005. The figures for 2005 were calculated by using Swedish Energy Agency statistics (Energimyndigheten 2010c). The potential for implementing electric cars and plug-in-hybrids is much greater for short distance traffic. Long distance car travel depends to a larger degree on biofuels, e.g. DME and to some extent gas. The figures for 2010 to 2050 are assumed by IVL.

In 2005 the number of short distance travel was about 5 times as large as long distance travel measured in pkm.

3.2.2.5 Metro and tram – energy carriers

Metros and trams only use electricity per definition.

3.2.2.6 Buses – energy carriers

Shares of pkm performed by different energy carriers for passenger transport by bus are shown in Table 19.

Table 19: Passengers and share of pkm performed by different energy carriers for passenger transport by bus

	2005	2010	2020	2030	2040	2050
Passengers (billion pkm)	9	9	8	9	10	11
Electricity	0%	0%	0%	5%	8%	10%
Diesel	100%	100%	90%	70%	42%	0%
Biofuels, e.g. ethanol	0%	0%	5%	5%	0%	0%
Gas*	0%	0%	5%	10%	25%	30%
Biofuels, e.g. FAME	0%	0%	0%	0%	0%	0%
Biofuels, e.g. DME	0%	0%	0%	10%	25%	60%

** The share of gas that has fossil and renewable origin respectively can be found in section 3.2.5.2.*

The figures for 2005 were calculated from data from the Swedish Energy Agency (Energimyndigheten 2010c). The figures for 2010 to 2050 are assumed by IVL. The assumptions are based on those for lorries. A minor proportion of pkm are powered by electricity in 2050 and the major proportion by biofuels, e.g. DME. However, the part driven by gas is assumed to be higher for buses due to more local traffic.

3.2.2.7 Domestic shipping – energy carriers

Ferries are found throughout Sweden. Today the energy carriers are generally either oil of the quality EO1 or EO2-5. During the period 2010 to 2050 a transition to biofuels, e.g. DME will be made for this whole sector.

Table 20: Passengers and share of pkm performed by different energy carriers for passenger transport by domestic shipping.

	2005	2010	2020	2030	2040	2050
Passengers (billion pkm)	0.8	0.8	0.9	0.9	1.1	1.2
EO1 (low content of sulphur)	48%	48%	60%	65%	50%	0%
EO2-5 (different degree of sulphur content)	52%	52%	40%	30%	0%	0%
Biofuels, e.g. DME	0%	0%	0%	5%	50%	100%

The figures for 2005 are based on data from the Swedish Energy Agency (Energimyndigheten 2010c). The figures for 2010 to 2050 are assumed by IVL.

3.2.2.8 Domestic passenger air travel

Domestic passenger air travel is included in the scenario. Aviation fuel makes a transition from kerosene to DME during the period 2010 to 2050.

Table 21: Passengers and share of pkm performed by different energy carriers for passenger transport by air.

	2005	2010	2020	2030	2040	2050
Passengers(billion pkm)	3.3	3.3	3.2	3.4	3.9	4.1
Kerosene	100%	100%	100%	100%	70%	0%
Biofuels, e.g. DME	0%	0%	0%	0%	30%	100%

The numbers for 2005 are based on data from the Swedish Energy Agency (Energimyndigheten 2010c). The numbers for 2010 to 2050 is assumed by IVL.

3.2.3 Other transport

In Swedish Energy Agency (Energimyndigheten 2010c) the energy needed for personal and goods transport for different transport categories are specified. However, there is a large part of the delivered energy to the transport sector that is not included in that specification. This is because the specified statistics in (Energimyndigheten 2010c) only include passenger and goods transport by registered vehicles and not all vehicles, and that not all transport can be divided into passenger and goods transport, e.g. working machines and leisure boats.

The energy volume that is included in "other transport" as presented in Table 22 is the difference between delivered energy to the transport sector (Energimyndigheten 2010c) and the sum of the specified energy use for the different categories for passenger and goods transport above. The growth rate of energy use (excluding the final energy use savings from electrification) considers the same increase in the activity as for goods transport and assumes 1% energy efficiency improvement per year. The yearly growth in energy demand then decreases by about 0.5% per year during the period 2005 to 2050.

Table 22: Energy volumes linked to transport categorized as "other transport" and share of energy carriers linked to the transport work.

	2005	2010	2020	2030	2040	2050
Use of energy (TWh)	10	10	10	9	9	8
Yearly growth in the use of energy	2.7%	–0.5%	–0.5%	–0.5%	–0.5%	–0.5%
Share of the energy needed covered by:						
Electricity	5%	5%	10%	20%	50%	50%
Petrol	30%	30%	30%	0%	0%	0%
Diesel	64%	64%	59%	70%	20%	0%
EO1 (low content of sulphur)	1%	1%	1%	0%	0%	0%
Biofuels, e.g. ethanol	0%	0%	0%	5%	5%	0%
Gas*	0%	0%	0%	5%	10%	20%
Biofuels, e.g. FAME	0%	0%	0%	0%	0%	0%
Biofuels, e.g. DME	0%	0%	0%	0%	15%	30%

** The share of gas that has fossil and renewable origin respectively can be found in section 3.2.5.2*

The shares of different energy carriers for 2005 in "other transport" are also determined according to the difference in the delivered energy to the transport sector according to (Energimyndigheten 2010c) and the sum of the specified energy use for personal and goods transport above. The shares for 2010 to 2050 are assumed by IVL.

3.2.4 Transport in the household and service sector

In Swedish energy statistics, e.g. (Energimyndigheten 2010a) some of the transport fuels are allocated to the household and service sector. These are fuels used e.g. in machines used for agriculture or forestry, in fishing boats, or at building sites (Nilsson 2011). The energy allocated to the transport sector is energy used for transport and not for other means. However, measures that are possible to implement for transport fuels used in the household and service sector are very similar to those in the transport sector. Therefore these fuels are allocated to the transport sector in this report.

The industrial sector also uses transport fuels for such things as transport at the industrial sites. These could have been allocated to the transport sector in this report. However, because it is more difficult to know which industrial sector fuels should be transferred to the transport sector, these fuels are treated in the industry sector.

Table 23: Energy volumes linked to transport in the household and service sector and share of energy carriers linked to the transport work.

	2005	2010	2020	2030	2040	2050
Use of energy (TWh)	11	10	10	9	9	9
Yearly growth in the use of energy		-0.5%	-0.5%	-0.5%	-0.5%	-0.5%
Share of the energy needed covered by:						
Electricity	0%	0%	2%	10%	20%	30%
Petrol	0%	0%	0%	0%	0%	0%
Diesel	100%	100%	85%	70%	45%	0%
EO1 (low content of sulphur)	0%	0%	0%	0%	0%	0%
Biofuels, e.g. ethanol	0%	0%	8%	10%	5%	0%
Gas*	0%	0%	5%	10%	15%	15%
Biofuels, e.g. FAME	0%	0%	0%	0%	0%	0%
Biofuels, e.g. DME	0%	0%	0%	0%	15%	55%

** The share of gas that has fossil and renewable origin respectively can be found in section 3.2.5.2*

The amount of transport fuel used in the household and service sector is calculated as the diesel oil in the household sector and service sector in Swedish Energy Agency (Energimyndigheten 2010b) that is not specified in Swedish Energy Agency statistics for the subsectors detached houses (Energimyndigheten 2011c), apartments (Energimyndigheten 2011b), or non-residential premises (Energimyndigheten 2011a). The shares in 2010 to 2050 are assumed by IVL.

3.2.5 Other parameters

3.2.5.1 Low blending

The blending of biofuels in diesel and petrol fuels for transport is done today to various degrees. As a result of the low blend a certain share of biofuels are found in the diesel and petrol categories in Table 16 to Table 23. The blending share for petrol and diesel is found in Table 24.

Table 24: Input parameters in the model of low blend in petrol and diesel fuels

	2005	2010	2020	2030	2040	2050
Low blending of ethanol in petrol	3%	5%	10%	10%	10%	n/a*
Low blending of FAME in diesel	0.2%	5%	5%	5%	5%	n/a*.

* No fossil fuels used in 2050.

In 2005 a maximum of 5% biofuels mixed into petrol and diesel was permissible. This was changed to a maximum of 10% on May 1, 2011. IVL assumes that the higher level will be used for ethanol mixed into petrol. However, the FAME mix into diesel is assumed by IVL to remain at 5% because of an assumed limited supply of FAME in Europe.

3.2.5.2 The source for the gas used in transport sector

The gas used in the transport sector can have a range of origins. At present natural gas (fossil gas) and biogas are relatively common while the share of SNG with origins in renewable resources is zero. The transition towards exclusively renewable origins in the gas used in the transport sector is found in Table 25.

Table 25: The source of gas in the transport sector

	2005	2010	2020	2030	2040	2050
Share of natural gas	55%	43%	25%	5%	2%	0%
Share of biogas	45%	57%	60%	60%	40%	30%
Share of SNG	0%	0%	15%	35%	58%	70%

The shares of origins for the gas for 2005 are calculated from the statistics in Swedish Energy Agency (Energimyndigheten 2010c). The shares for 2010 to 2050 are assumed by IVL. Natural gas declines, whereas biogas increases. After 2030 biogas is partially replaced by SNG (Synthetic Natural Gas) produced by the gasification of biomass.

3.2.5.3 The source of the ethanol used in the transport sector

The scenario does not opt for introducing ethanol on a broad scale. Production of ethanol from cellulosic raw material still needs development in order to reach a high level of total efficiency. If there are some technical breakthroughs this technology could prove important to support the transition towards a renewable energy system. Some ethanol remains in the scenario and the technologies to produce it will shift a little towards second-generation technologies; see Table 26.

Table 26: Technology generation to produce ethanol used in the scenario

	2005	2010	2020	2030	2040	2050
1st generation	100%	100%	90%	75%	75%	n/a.*
2nd generation	0%	0%	10%	25%	25%	n/a.*

** No ethanol used in 2050.*

3.3 The household and service sector

The presentation of the household and service sector has been divided into activity data (use of space), energy efficiency (use of energy per square meter heated), and energy carriers used for heating. In addition, electricity consumption (not used for heating) is analysed separately. As is the case with the transport sector, the household and service sector also has a part of the energy supply that is not specified in detailed statistics and must therefore be treated as "Other energy use".

3.3.1 Activity data

Energy demand in the household and service sector is operationalised in the model through a number of variables linked to heating and the space each person uses. The input variables are found in Table 27.

Table 27: Activity data for detached houses, apartments and non-residential premises 2009, 2010-2050.

		2009	2010	2020	2030	2040	2050
Detached houses	millions m^2 heated	272	273	284	296	309	322
	Increase in m^2 heated	1.5%	0.4%	0.4%	0.4%	0.4%	0.4%
	m^2 per person in Sweden	29	29	28	29	29	30
Apartments	millions m^2 heated	173	174	183	193	203	214
	Increase in m^2 heated	-0.5%	0.1%	0.5%	0.5%	0.5%	0.5%
	m^2 per person in Sweden	18	18	18	19	19	20
Non-residential premises	millions m^2 heated	134	135	142	150	158	166
	Increase in m^2 heated	-1.2%	0.1%	0.5%	0.5%	0.5%	0.5%
	m^2 per person in Sweden	14	14	14	14	15	15

The area heated will grow by about 0.5% per year as shown in Table 27. Growth is calculated based on the pace of new building and the pace of demolition as shown in Table 28, 29 and Table 30 below. The number of square meters grows more rapidly than the population increase in Sweden which results in larger areas per person in Sweden.

3.3.2 Efficiency for space and tap water heating (kWh/m²)

Operationalisation of energy efficiency improvement measures in housing and buildings is done in the model through the variable efficiency for space and tap water heating and this variable is measured in kWh/m².

For detached houses, apartments and non-residential premises the energy saved through renovation is calculated based on a 50% reduction of energy use (Boverket 2008)[10] and assumptions by IVL about the number of buildings rebuilt per decade. It is assumed that buildings are renovated every 40 years (Erlandsson and Levin 2005). In the model all existing buildings will therefore be renovated once between 2010 and 2050. The Swedish Energy Agency (Energimyndigheten 2011c) provides information about energy performance for buildings renovated each decade. The pace of renovation is high. However, the historical proportion exceeds 2% per year (Deng et al. 2011).

The pace of demolition is historically close to zero (SCB 2010). This may change in the future. However, it is assumed that the demolition rate will remain close to zero. Demolished houses are assumed by IVL to use 50% more than the average house 10 years earlier.

3.3.2.1 Detached houses – background parameters

The background parameters linked to the space and tap water heating for detached houses is found in Table 28.

Table 28: Background parameters for space and tap water heating in detached houses

		2009	2010	2020	2030	2040	2050
Energy use in newly built stock	kWh/m²		110	40	40	40	40
Energy saved in rebuilt stock	kWh/m²			98	88	86	77
Energy use in demolished stock	kWh/m²		234	233	199	165	132
Pace of new building	%/a	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
Pace of rebuilding	%/a	n/a.	n/a.	1.9%	2.2%	2.3%	2.5%
Pace of demolition	%/a	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

The passive house standard for detached houses of 40 kWh/m² for heating and tap water is assumed to be reached in 2020 for new buildings. This level is assumed to remain the same up to 2050 even though further improvement can be expected.

10 Deng et al (2011) assumes 60%. However, it can be assumed that buildings in Sweden have a higher performance than the current global average and the improvement potential in Sweden is therefore lower.

3.3.2.2 Apartments – background parameters

The background parameters linked to space and tap water heating for apartments are found in Table 29.

Table 29: Background parameters for space and tap water heating in apartments houses

		2009	2010	2020	2030	2040	2050
Energy use in new built stock	kWh/m^2		110	35	35	35	35
Energy saved in the rebuilt stock	kWh/m^2			78	75	72	70
Energy use in demolished stock	kWh/m^2		230	230	193	159	128
Pace of new buildings	%/a		0.6%	0.6%	0.6%	0.6%	0.6%
Pace of rebuilding	%/a	n/a.	n/a.	2.3%	2.3%	2.3%	2.1%
Pace of demolition	%/a	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

The passive house standard for apartment buildings of 35 kWh/m² for heating and tap water is assumed to be reached in 2020 for new buildings. This level is assumed to remain the same up to 2050 even though further improvement can be expected.

3.3.2.3 Non-residential premises – background parameters

The background parameters linked to the space and tap water heating for non-residential premises are found in Table 30.

Table 30: Background parameters for space and tap water heating in non-residential premises

		2009	2010	2020	2030	2040	2050
Energy use in new built stock	kWh/m^2		110	35	35	35	35
Energy saved in the rebuilt stock	kWh/m^2			72	70	66	63
Energy use in the demolished stock	kWh/m^2		215	215	205	171	145
Pace of new buildings	%/a	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%
Pace of rebuilding	%/a	n/a.	n/a.	2.3%	2.0%	2.3%	2.4%
Pace of demolition	%/a	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

The passive house standard for apartment houses of 35 kWh/m² for heating and tap water is assumed to apply to non-residential premises as well and is assumed to be reached in 2020 for new buildings. This level is assumed to remain the same up to 2050 even though further improvement can be expected.

3.3.2.4 Summary of energy efficiency improvements for space and tap water heating

Table 31 shows a summary of the pace of change in energy efficiency linked to heating and tap water heating in detached houses, apartments and non-residential premises.

Table 31: Summary Energy efficiency improvements for space and tap water heating in detached houses, apartments and non-residential premises

		2009	2010	2020	2030	2040	2050
	kWh/m²	156	154	129	105	83	63
Detached houses	%/year	-0.7%	-1.1%	-1.8%	-2.0%	-2.4%	-2.7%
	The share of tap water	20%	20%	20%	25%	30%	35%
	kWh/m²	154	152	125	101	80	63
Apartments	%/year	-2.2%	-0.2%	-1.9%	-2.1%	-2.3%	-2.3%
	The share of tap water	20%	20%	20%	25%	30%	35%
	kWh/m²	144	142	132	109	91	73
Non-residential premises	%/year	0.4%	-0.2%	-0.7%	-1.9%	-1.8%	-2.1%
	The share of tap water	20%	20%	20%	25%	30%	35%

Statistics by Swedish Energy Agency (Energimyndigheten 2011c; Energimyndigheten 2011b; Energimyndigheten 2011a) are used for calculating energy use values for 2009. However, Swedish Energy Agency does not include heat extracted by heat pumps from air, the ground or lakes. The heat extracted by heat pumps in the household and service sector has been estimated at 11 TWh in 2009 (about 10% of the heating demand for space and tap water heating) based on (Nilsson 2011). This calculation is relatively close to the 13 TWh for 2009 that the Swedish heat pump association assume (Bertenstam 2011). The heat extracted by heat pumps has been added to the Swedish Energy Agency official statistics before calculating the figures presented in Table 31. As a consequence the figures are higher for 2009 than usually presented. This energy is however used for heating purposes and should thus be included in the model.

3.3.2.5 Improvement of heat pumps

Sweden already has relatively large numbers of heat pumps installed in the energy system. Heat pump efficiency is represented by the coefficient of performance (COP) factor. The development of this factor is presented in Table 32.

Table 32: Improvement of COP values for heat pumps

	2005	2010	2020	2030	2040	2050
Average COP for heat pumps	2.7	2.8	3.3	3.8	4.3	4.8

Based on numbers by (Nowacki 2011) the average COP for heat pumps is calculated to 2.7 for 2009. According to the Swedish heat pump association the improvement for new heat pumps is an increase of 0.05 per year according to historical data (Bertenstam 2011). How rapid the average increase is depends on the performance of the scrapped old heat pumps and the rate at which they are scrapped as well as the performance of the new heat pumps. IVL has assumed that the increase in performance is on average 0.05 per year during the period 2005 to 2050.

3.3.2.6 Change in heating demand depending on climate change

According to Gode and Jarnehammar (2007) heating demand will decrease by almost 11% compared to 2005 because of the changing climate. Gode and Jarnehammar (2007) calculate the decrease of heating demand by assuming that the change in heating demand due to climate change is linear between the average for the period 1961-1990 and the average for the period 2041-2070. Climate change will have an effect on heating demand. The level of change in heating demand is shown in Table 33.

Table 33: Change in heating demand as a function of climate change

	2005	2010	2020	2030	2040	2050
Changed heating demand because of changed climate compared to 2005	0	-1.2%	-3.6%	-6.0%	-8.5%	-10.9%

3.3.3 Energy carriers used for space and tap water heating

Energy demands for tap water and heating purposes stand for a large share of the energy demands for housing. The energy carriers used to satisfy these energy demands can vary. In Sweden there is a very low dependency of oil within this sector at present.

3.3.3.1 Detached houses

Detached houses will have varied types of heating technologies to secure space and tap water heating. The energy carriers used and the changes over the period 2010-2050 are found in Table 34.

Table 34: Energy carriers used for space and tap water heating in detached houses

	2009	2010	2020	2030	2040	2050
District heating	12%	12%	16%	20%	22%	24%
Electricity (direct use)	23%	23%	17%	11%	6%	0%
Oil	4%	4%	0%	0%	0%	0%
Heat pumps	31%	31%	31%	31%	31%	31%
Biofuel	31%	31%	25%	22%	19%	16%
Natural gas	1%	1%	0%	0%	0%	0%
Solar heat	0%	0%	11%	16%	23%	29%

The shares for 2009 have been calculated from statistics by Swedish Energy Agency (Energimyndigheten 2011c) complemented with information about heat extracted by heat pumps based on information from (Nilsson 2011). Oil has decreased rapidly over the last decade and it is assumed that oil and natural gas will disappear by 2020. Electricity for direct heating use is an inefficient way of using electricity and it is assumed that this is no longer found by 2050. The share of biofuel decreases to conserve these resources for other more valuable needs. Heat pumps are assumed to be constant, and district heating almost doubles its market share because it is an important recipient of surplus heat from industry and biofuel production. Solar heat grows significantly and becomes the second largest energy carrier for detached houses. District heating is used at all detached houses close to district heating networks; solar heating, together with biofuels and/or heat pumps is used in almost all detached houses not using district heating.

3.3.3.2 Apartments

In the scenario apartments are to a great extent connected to a district heating network to secure space and tap water heating. The energy carriers used and the changes over the period 2010-2050 are found in Table 35.

Table 35: Energy carriers used for space and tap water heating in apartments

	2009	2010	2020	2030	2040	2050
District heating	88%	88%	88%	89%	90%	91%
Electricity (direct use)	3%	3%	0%	0%	0%	0%
Oil	2%	2%	0%	0%	0%	0%
Heat pumps	6%	6%	6%	6%	5%	4%
Biofuel	1%	1%	1%	1%	1%	1%
Natural gas	1%	1%	1%	0%	0%	0%
Solar heat	0%	0%	4%	4%	4%	4%
Other fuel	0%	0%	0%	0%	0%	0%

The shares for 2009 have been calculated from statistics by Swedish Energy Agency (Energimyndigheten 2011b) together with information about heat extracted by heat pumps based on information from (Nilsson 2011). For the period 2010 to 2050 it is assumed that the high market share for district heating will grow a little replacing the use of oil, natural gas and electricity for direct use, all of which disappear before 2030. It is also assumed that solar heating increases and heat pumps decrease. Some further solar heating is introduced through district heating systems and is thus not visible in Table 35. Consequently, the share of solar energy is higher than in Table 35.

3.3.3.3 Non-residential premises

In non-residential buildings the trend is to use either heat pumps or district heating. The energy carriers, technologies used are seen in Table 36.

Table 36: Energy carriers used for space and tap water heating in non-residential premises

	2009	2010	2020	2030	2040	2050
District heating	73%	73%	77%	79%	81%	82%
Electricity (direct use)	5%	5%	0%	0%	0%	0%
Oil	4%	4%	0%	0%	0%	0%
Heat pumps	13%	13%	17%	15%	14%	13%
Biofuel	3%	3%	3%	3%	1%	0%
Natural gas	2%	2%	0%	0%	0%	0%
Solar heat	0%	0%	3%	3%	4%	5%
Other fuel	0%	0%	0%	0%	0%	0%

The shares for 2009 have been calculated from statistics by the Swedish Energy Agency (Energimyndigheten 2011a) together with information about heat from heat pumps based on information from (Nilsson 2011). For the period 2010 to 2050 it is assumed that the high market share for district heating will grow a little replacing the use of oil, natural gas and electricity for direct use, all of which will disappear before 2020. It is also assumed that share of heat from heat pumps is roughly constant. Some solar heating is assumed in these buildings.

3.3.4 Use of cooling

The cooling demand will increase as a consequence of for example climate effects, improved building envelopes in combination with increased numbers of heat producing appliances in our homes as well as increased demands on controlled indoor climate. The change in cooling demand in buildings is found in Table 37.

Table 37: Need of cooling in household and service sector and share of cooling technology applied

	2009	2010	2020	2030	2040	2050
Need of cooling (TWh)	1	1	4	7	10	13
Share of cooling covered by:						
Absorption cooling produced by district heating	20%	20%	24%	28%	31%	35%
Absorption cooling produced by solar heat	0%	0%	4%	8%	11%	15%
Free cooling	20%	20%	25%	30%	35%	40%
Electric cooling machines	60%	60%	48%	35%	23%	10%
Average COP for electric cooling machines	2.5	2.5	2.9	3.3	3.6	4.0
Average COP for absorption cooling	80%	80%	80%	80%	80%	80%
Electricity for pumps as share of cooling production	5%	5%	5%	5%	5%	5%

The cooling production and market shares between the technologies to produce cooling are assumed by IVL for 2009, due to lack of statistics. The cooling demand in 2050 is estimated by Gode and Jarnehammar (2007). The cooling demand development between 2010 and 2050 is assumed to be linear. The development of the market shares is assumed by IVL. The high share of absorption cooling depends on the high share of surplus heat (from industries and biofuel production), use of waste and solar heat in district heating production that provide cheap heat during summer. Absorption cooling by solar heat is also assumed to be possible to produce locally.

3.3.5 Use of electricity (not for heating or cooling purposes)

The household and service sector uses electricity for a number of purposes other than for heating and cooling, e.g. for electrical appliances and lighting. The variable is operationalised in the model as electricity use in the baseline plus a yearly change. The electricity use for detached houses, apartments and non-residential premises are found in Table 38.

Table 38: Electricity use in detached houses, apartments and non-residential premises

		2009	2010	2020	2030	2040	2050
Detached houses	TWh	8.2	8.1	7.3	6.6	6.0	5.4
	(%/a)		-1.0%	-1.0%	-1.0%	-1.0%	-1.0%
Apartments	TWh	11.3	11.2	10.1	9.1	8.3	7.5
	(%/a)		-1.0%	-1.0%	-1.0%	-1.0%	-1.0%
Non-residential premises	TWh	32	31.4	28.4	25.7	23.2	21.0
	(%/a)		-1.0%	-1.0%	-1.0%	-1.0%	-1.0%

Electricity for purposes other than heating has historically increased rapidly (Energimyndigheten 2010b) with an increased requirement of ventilation (especially for non-residential premises) and increased use of electric appliances, e.g. computers. Even if there is a rapid improvement in efficiency for example for refrigerators and washing machines, the increased number of appliances has increased the use of electricity. However, since 2001 demand has stabilized (Energimyndigheten 2010b). In the analysis of electricity use in 400 Swedish households it was concluded that large electricity savings are possible (Zimmermann 2009). Based on this, IVL assumes that a reduction in electricity use of 1% per year is possible.

3.3.6 Other energy use in the household and service sector

In Table 39 energy demand for other energy uses is displayed, along with corresponding energy carrier. It is unclear how this energy is used and to what purposes. However, IVL assumes that it is used for similar purposes as the rest of the household and service sector.

Table 39: Other energy use in the household and service sector

		2009	2010	2020	2030	2040	2050
Energy use	TWh	9.7	9.7	8.3	7.1	6.0	5.1
Yearly growth of energy use	%/y		0.0%	-1.6%	-1.6%	-1.6%	-1.6%
Share of energy use covered by:							
Electricity	%	42.6%	43%	43%	43%	43%	43%
District heating	%	35.4%	35%	41%	46%	46%	46%
Oil	%	0.0%	0%	0%	0%	0%	0%
Natural gas	%	10.5%	10%	5%	0%	0%	0%
Biofuel	%	11.5%	12%	12%	12%	12%	12%
Solar heat	%	0.0%	0%	0%	0%	0%	0%

Energy for the household and service sector 2009 presented in (Energimyndigheten 2010b) but not specified in the Swedish Energy Agency publications for detached houses (Energimyndigheten 2011c), apartments (Energimyndigheten 2011b), and non-residential premises (Energimyndigheten 2011a) is described in Table 39, except for oil fuels which are treated in the transport sector above.

The change of energy use is of the same magnitude as in the detached houses and apartments subsectors above. An activity level increase of about 0.5% and an efficiency level just over 2% result in a total decline of energy use by 1.6% per year from 2010 to 2050.

The shares of most energy carriers used are assumed to be unchanged because it is difficult to know how this will develop owing to uncertainty as to exactly where these fuels are used. Fossil gas used for heating is assumed to be replaced by district heating.

4 Supply

In the model the energy supply is generated from existing demands. An iterative process has been used to ensure that the demands are found within limitations defined in this backcasting scenario. This chapter presents input variables that are used in the model. The variables define for example performances, availability and also in some cases actual expanding power production from a specific source. In a number of cases the model will give results and inputs in terms of available resources. For example residues from the industry used for DME production, will result in inputs both for electricity and heat generation and needs.

4.1 Biofuel production

Biofuels can be produced by different technologies from different biomass materials. It is difficult to assess which biofuels will be produced in the future. In this scenario an outset has been to utilize the biomass resource as efficiently as possible as it is a limited resource. Hence a resource-efficient process has been sought for. The available resource in the Swedish case is to a great extent solid biomass and that has also resulted in choosing a technology trajectory based on biorefineries within the existing paper and pulp industry. In recent years the biorefinery concept has received increased attention and also application in Sweden.

In a biorefinery a range of products can be obtained from the biomass and losses are reduced substantially. The technology applied in the scenario will produce either DME or FAME and the production specifications are specific in terms of the output that will be received from the input resources. In Table 40 the performances for the biofuel productions that are included in the project are shown. All future biofuel is assumed to be produced in poly-generation plants with several outputs to improve efficiency.

Table 40: Energy efficiency for producing (+) or using (-) biofuels, heat, electricity and other by-products compared to bioenergy input.

	Efficiency compared to input energy			
	Biofuel production	**Heat use (-) / heat prod (+)**	**Electricity use (-) / prod (+)**	**Usable by-products**
Biogas *,**	70%	-7%	-7%	0%
SNG *	71%	24%	-4%	0%
Ethanol 1st gen *	55%	-19%	-3%	39%
Ethanol 2nd gen *	32%	8%	13%	0%
FAME *	67%	-12%	0%	0%
DME *	65%	11%	-6%	4%

** (Gode et al. 2008)*
*** (Berglund and Börjesson 2003)*

In the scenario it is assumed that a major part of the biofuels in the future will be DME complemented with biogas and SNG based on renewable sources. DME is assumed to be produced partly from gasification of black liquor in the pulp and paper industry and partly by gasification of solid biomass elsewhere. How much DME is produced from black liquor is determined by developments in the chemical pulp industry and the implementation of DME production facilities at pulp mills, see section3.1 The industry sector3.1 The industry sector. The volume of biofuels produced is determined by the demand specified in the sectors above. The performance of DME produced by black liquor gasification depends on the steam demand at the chemical plant and varies during the period. In most cases this production is more efficient than other DME production.

4.2 District heating production

Table 41 shows the energy supply to the district heating plants and the share of each fuel. District heating systems are (today) relatively local and only in larger cities interlinked between communities.

Table 41: District heating production and energy carriers (technologies) (TWh)

	2005	2010	2020	2030	2040	2050
Oil	3.8	3.3	2.5	0.0	0.0	0.0
Natural gas	3.0	2.7	2.0	1.3	0.7	0.0
Coal	3.1	2.8	2.1	0.0	0.0	0.0
Bioenergy	22.3	23.3**	19.0**	17.6**	10.4**	2.8**
Peat	3.3	2.9	2.2	1.5	0.7	0.0
Waste	10.6	10.6	12.6	12.6	12.6	12.6
Surplus coke gases	2.6	2.8**	2.2**	0.7**	0.7**	0.4**
Surplus heat from biofuel production	0.0	-1.2**	-0.8**	0.8**	3.5**	6.0**
Surplus energy from biofuel production	0.0	1.8**	2.8**	1.7**	0.8**	1.1**
Electricity boilers	0.3	0.0	0.0	0.0	0.0	0.0
Heat pumps (extracted heat)*	4.4	4.4	4.8	5.3	5.7	6.2
Heat pumps (electricity)	1.8	1.8	1.8	1.8	1.8	1.8
Surplus heat from industry	5.4	5.8	6.6	7.4	8.2	9.0
Solar heat	0.0	0.0	1.0	2.0	3.0	4.0
Total	**60.6**	**61.0**	**58.8**	**52.7**	**48.1**	**43.9**

** The COP for heat pumps in district heating systems increases from 3.4 in 2010 to 4.4 in 2050. It is a slower increase than for heat pumps for domestic use. The reason is higher temperatures needed in the district heating system and a lower investment rate.*
*** These numbers are calculated within the model and are the results from the scenario*

The energy used for electricity and heat production in combined heat and power plants and in heat boilers for 2005 is presented in Table 41 and is based on Swedish Energy Agency statistics (Energimyndigheten 2009). The energy use for each energy carrier listed in Table 41 for 2010 to 2050 is assumed by IVL. Fossil fuels, peat and electricity boilers decline to zero, heat from heat pumps increases slightly (but with constant electricity demand due to increased performance), waste is assumed to increase a little, and solar heat is introduced to some extent.

The waste directive (European Parliament 2008) stipulates that a desired development for management of wastes is to strive for re-use and recycling of resources rather than burning them for energy recovery. This is far from the actual situation today where waste is a mixed resource with both renewable/organic and fossil origins. Improved separation of the waste fraction, and also a shift in resources used in the production of plastics, etc. will have an impact here. Assuming that there is a general shift towards phasing out fossil resources globally waste will become increasingly renewable/organic. The amount of waste used for energy purposes in Sweden is supposed to be held constant from 2020 onwards. It would obviously make much sense to reduce the amount of waste even further.

Surplus coke gases depends in this scenario on the production level in the steel industry, and surplus heat and energy from biofuel production depend on the production level of biofuels and the production technologies used. Bioenergy used in district heating plants to produce heat and electricity is calculated as the difference between the demand of fuels (depending on the demand for district heating) and the potential from the other fuels, heat production technologies and surplus energy and heat per decade.

The electricity produced in district heating plants is determined by the alpha values for each fuel in 2005. The alpha value is defined by dividing the electricity production with the heat production. The alpha values were calculated as Swedish averages based on data from Svensk Fjärrvärme (2011) and the Swedish Energy Agency (Energimyndigheten 2009). The alpha values are listed in Table 42.

Table 42: Alpha values for electricity production in district heating systems

	2005
Oil	0.11
Natural gas	0.36
Coal	0.36
Bioenergy	0.14
Peat	0.25
Waste	0.07

The alpha values will probably be possible to increase in the future. However, since biomass is a limited resource in this scenario the alpha values have been kept at a static level.

4.3 Electricity production

The generation of electricity is secured through a number of different energy technologies. In 2050 all non-renewable energy sources have been replaced by renewable energy technologies. Table 43 shows electricity production in 2005 according to the Swedish Energy Agency (Energimyndigheten 2009). In Table 43 values for 2050 are based on the assessment made by IVL and is discussed in more detail under each technology section below.

Table 43: The production of electricity by different technologies (TWh)

	2005	2010	2020	2030	2040	2050
Hydropower	72	66	66	66	66	66
Wind power	0.9	3.5	20	30	38	45
Solar photovoltaic	0	0	4	8	16	32
New renewable energy tech	0	0	0	0	0	3
Nuclear power	70	63	70	50	0	0
Electricity production at district heating plants	7.3	5.9*	5.9*	5.1*	3.9*	2.9*
Electricity production in industry	4.6	6.6*	5.6*	4.4*	3.2*	1.9*

** These numbers are calculated within the model and are the results from the scenario*

4.3.1 Hydropower

The hydropower production was higher in 2005 than in a normal year due to more rainfall than average. A normal year results in a production of 66 TWh. Climate change is predicted to lead to increased rainfall which would result in an increase in hydropower production. This increase is used to improve the natural capital in running water and around the water catchment areas. The process of implementing the European water directive (European Parliament 2000) in Sweden is currently under way and changes in regulation regimes and management of running water will be needed to realize it. There are a number of ways to improve the existing hydropower to reduce negative impacts.

In the energy system hydropower acts as a regulating capacity, compensating for both short- and long-term changes in electricity demand. It may regulate the intermittent production from for example wind and solar technologies. There are, however, two types of hydropower stations in Sweden, reservoir hydropower stations and run-of-the-river stations. The run-of-the-river type of hydropower only has very limited regulating capacity. A regulating capacity is vital in order for the system to be operational and in the Nordic electricity system hydropower is the main regulating capacity.

4.3.2 Wind power

In Sweden the amount of electricity generated from wind power has developed from less than 1 TWh in 2006 to 3.5 TWh in 2010. The Swedish Energy Agency has a planning target of 30 TWh in 2020 set in the energy policy laid out by the government in 2008 (Regeringskansliet 2008a). The planning target means that the Swedish energy system should be ready to handle this expansion, but is not responsible for its actual taking place. The planning target says that 20 TWh should be land based, and 10 TWh offshore. This scenario does not push the wind power expansion rapidly enough to reach 30 TWh by 2020 but will achieve this level in 2030. The main reason for this is the importance of expanding with consideration for the local environment.

During the period between 2030 and 2050 replacement of old wind turbines takes place which increases production without increasing the number of sites. Recent years' expansion of wind power in Sweden has highlighted the challenges in terms of gaining acceptance for new wind power projects. From an environmental point of view there are a number of variables to take into consideration when assessing the impact of a wind power station on the local environment. It is not only the turbine structure that has an effect but also the infrastructure needed to service the wind turbines, and maintain and distribute the power generated. An expansion in the magnitude of 30 TWh will necessitate that a high level of environmental consideration be taken regarding the locations of the wind turbines and associated infrastructure.

The scenario does not divide the energy generated from offshore and on-shore wind turbines. Offshore is presently more costly in terms of investments than for on-shore locations. However, it is reasonable to argue that in a not-so-distant future wind power will stand out as a commercial technology. Today, new projects depend on electricity certificates in order to be profitable.

4.3.3 Solar power

Solar photovoltaic (PV) will increase rapidly from 2020 and onwards to reach 32 TWh in 2050. Experiences from other European countries have shown that the expansion of solar photovoltaic technology has the potential to make an impact in the energy system. The technology has historically been expensive but the learning curve of PV has displayed a significant decrease in cost per installed unit of power. Solar PV technology can potentially be expanded to even higher electricity outputs than the 32 TWh in the scenario.

PV technology has the advantage of being possible to integrate in house construction and other unused surfaces. In global energy scenarios PV technology stands out as a major contributor (Deng et al. 2011). Because current PV technology requires a number of rare earth minerals, large expansion of production capacity it might lead to a shortage of these materials in the future. We anticipate there will also be an increased focus on research and development within this sector.

4.3.4 New renewable energy technologies

New renewable energy technologies refer to technologies such as wave power, bioenergy from algae, and so forth. The assumption has been to introduce these on a relatively low scale within this scenario as the scenario is mainly based on available technologies. This could be disputed as it is very likely that there will be technical breakthroughs within the area of energy systems and technologies before 2050. However, this backcasting scenario is motivated by analysing the needs for change in demand structures and to see the strategically important changes in energy supply in terms of reaching these demands.

4.3.5 Nuclear power

Nuclear power generates a relatively large share of the Swedish electricity (~45%). Availability, i.e. time outside scheduled and non-scheduled maintenance and repair, of the reactors is a central variable in terms of the production from the power plants. During 2005, nuclear power in Sweden had a higher availability than the 80% that has been assumed in the model. According to plans within the nuclear power sector there will be new turbines with higher power output from 2020 in a number of the nuclear power stations. This has been included in the scenario.

Nuclear power represents a non-renewable energy source and will be phased out before 2050 according to this scenario. The lifetime for each nuclear reactor in this project is set at 50 years and by 2030 five reactors have been phased out and in 2040 all nuclear reactors in Sweden have been decommissioned.

4.3.6 Electricity production in industry and district heating systems

Electricity production in industry and in district heating systems 2010 to 2050 is determined by developments in industry and district heating demand and the technologies used. Most of the electricity produced in industry is generated in the pulp and paper industry. The electricity production decreases during the period with the assumed focus on DME-production in the pulp and paper industry and decreased pulp production. Electricity production at the district heating systems decreases as well because of decreased demand for district heating and the increased use of surplus heat and solar heat for district heating production. The increased supply to district heating of surplus heat and solar heat decrease the possible production of CHP.

Electricity production in industry and district heating systems will still use some fossil fuels in 2050 as a consequence of coke gases from the steel industry being used for the producing of electricity and heat. The oil industry that currently provides heating to district heating in a number of cities in Sweden will not use fossil resources in 2050 and as a consequence the excess heat from these industries will be renewable in origin.

4.3.7 Losses in transmission and distribution

There are a number of losses linked to the transmission and distribution of electricity, as well as in the generation of electricity. The levels of the losses are summarized in Table 44.

Table 44: Losses linked to electric power production

	2005	2010	2020	2030	2040	2050
Losses in transmission and distribution (share of electricity production)	8%	8%	7%	6%	6%	5%
Efficiency in fuel based electricity production (CHP)	90%	90%	90%	90%	90%	90%
Efficiency in fuel based power production	40%	40%	40%	40%	40%	40%

Losses linked to hydro, wind and solar power are not operationalised in the model other than through technical innovations and advancements. In terms of for example hydropower there are a number of efficiency-increasing changes that can be made to the hydropower station, which mainly are linked to improving the turbines and generators.

4.4 Bioenergy, waste and peat

Biоenergy is a major contributor in the Swedish energy system. The contribution in terms of energy in 2009 was more than 110 TWh (Energimyndigheten 2010b). Bioenergy in the Swedish energy system displays remarkable growth. Since the early 90s the use of biofuels in the energy sector has almost doubled (Energimyndigheten 2010b). At the same time this has resulted in a growing pressure in forestry and more and more of the biomass is extracted from the forest ecosystems to be used as a source for energy or as other types of products. There are several studies made on the impacts seen in the ecosystem and forests as well as the magnitude of these (see for example Dahlberg et al. 2006; Skogsstyrelsen 2008a; de Jong and Lönnberg 2010).

In the scenario the ambition is to use resources as efficiently as possible. As a consequence of turning solid biomass into different types of energy carriers that can be used to provide energy services, the biomass used is often a residue or by-product from an alternative production (e.g. saw mill, paper and pulp industry etc). Table 45 shows the various potentials.

Table 45: Bioenergy waste and peat potentials in the scenario (TWh)

	2010	2020	2030	2040	2050
Bioenergy from paper and wood industry residues*	67	60	57	60	65
whereof black liquor*	41	37	35	37	40
whereof tree bark from pulp mills*	9	8	7	8	8
whereof residues from saw mills*	18	15	15	16	17
Bioenergy tops and branches (GROT)	19	17	19	20	21
Pulpwood not used for paper*	0	0.4	4.2	1,9	0
Bioenergy round timber and small wood for domestic use	16.5	13.5	13.5	13.5	13.5
Bioenergy from agriculture and perennial crops (e.g. salix)	1	15	15	15	15
Bioenergy from agriculture used for biogas production	0	5	5	5	5
Wastes and sewage used for biogas production.	1.4	1.5	1.5	1.5	1.5
Wastes used in incineration	10.6	12.6	12.6	12.6	12.6
Peat	3	3	2	1	0
New innovations e.g. algae biomass	0	0	0	0	5

** These figures are calculated within the model. These numbers are to be considered as results from the scenarios and not potentials.*

The bioenergy levels presented in Table 45 are based on a forest management that would include more protected forest area and extensive forestry than the SKA 08 environment scenario (Skogsstyrelsen 2007b). The level of concern has been developed by WWF and considers both the protection of biodiversity in accordance to the decisions by the tenth meeting of the Conference of the Parties to the Convention on Biological Diversity in Nagoya, Japan 2010 and in addition introduction of continued cover forestry practice on certain land areas.

In Sweden the fuel category 'tops and branches' is usually referred to as GROT. GROT includes tops and branches from for example final fellings and thinnings, but does not include stumps. In the WWF adjusted scenario tops and branches is not to be removed from thinnings and hence the potential have been adjusted in accordance.

Peat is a non-renewable resource and decreases gradually to zero in 2050. The potential for the categories calculated in the model is determined by the production volumes in the forestry industry. The production in the forestry industry is mainly determined by the available wood from forest for industrial purposes.

The potentials for bioenergy from agriculture are perennial crops, bioenergy from agriculture used for biogas production, waste and sewage used for biogas production, waste used in incineration and innovations e.g. algae biomass.

5 Results from the energy model

The supply of primary energy sources is based on the demands in the different sectors calculated considering different technology mixes applied and the progress of introducing renewable energy technologies. For example, the introduction of biorefineries on a large scale is first seen after 2020. The demands are based on the assumptions and processes described in section 2.2 Functions of the energy model applied. and chapter 3 Demand side in Sweden. The supply side is also dependent on the variables and inputs to the model presented in chapter 4 Supply.

In Figure 3 the demands in the different sectors are presented along with actual statistics 1970-2009 (Energimyndigheten 2010b). In 2008 and 2009 the economic recession gave effects in the energy demands which are seen in the actual figures for those years. The scenario takes its point of departure in the Swedish Energy Agency long term scenario (Energimyndigheten 2009) which does not account for the recession and thus there is a gap between actual figures and scenario demand figures.

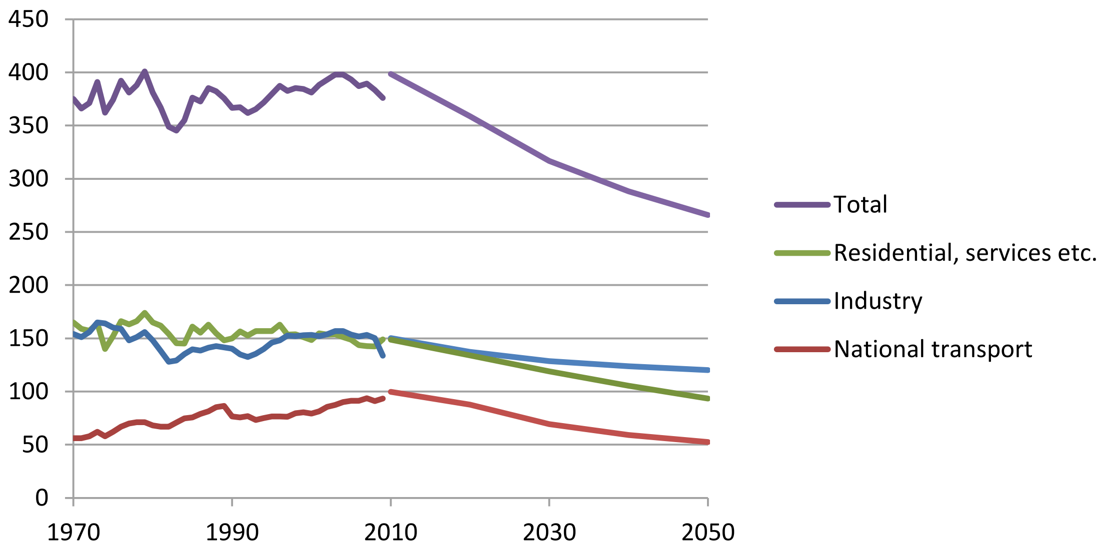


Figure 3: Sector-wise change in energy demands, actual 1970-2009 and scenario 2010, 2020, 2030, 2040 and 2050 (TWh).

The demand trend needs to show a decline in all sectors in order for the scenario to fulfil the targets for 2050. As was described previously there is a certain growth in terms of energy services used, while the primary energy needed to provide these energy services is reduced. The demand side is further discussed in section 5.2.

5.1 Supply

There is a need to start to increase the share of renewable energy as well as to establish industries that can produce biofuels in order to be able to reach the sustainable energy system in 2050. Several of the initiatives that are anticipated will take time to implement. The strategic focus must be on support and the creation of incentives for this to be realised.

The supply curve does not necessarily match the demand curve exactly but in the design of the scenario, there is no time when the demand curve is higher than the supply. The Swedish energy system is interlinked with other countries both in terms of trading fuels and energy carriers such as electricity. The scenario has been developed to cover the demand in Sweden with supply on a yearly basis in terms of each energy carrier (biofuels, electricity and heat).

The curve in Figure 4 represents the primary energy supply in the Swedish energy system 2010-2050 excluding losses from nuclear power but including other losses in the energy system.

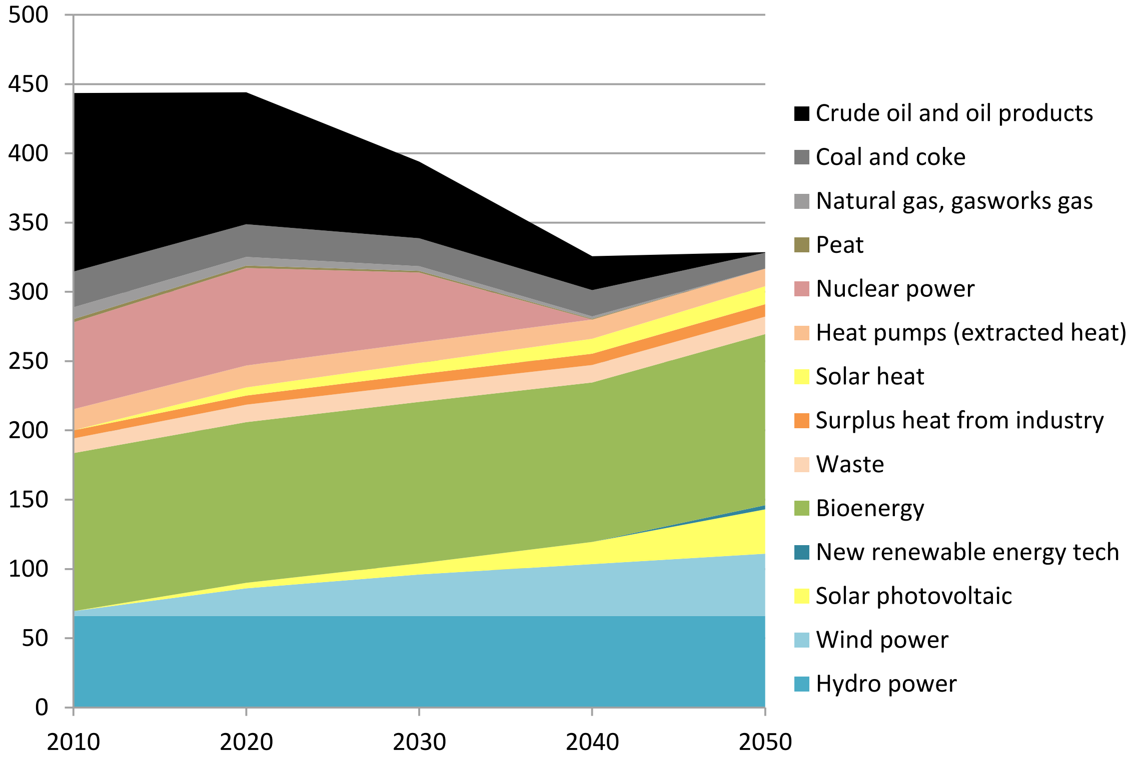


Figure 4: Total Energy supply, excluding losses in nuclear (TWh)

The fossil and non-renewable energy sources are phased out and represent less than 5% of the primary energy supply in 2050. In 2050 coal and coke is still used in the steel industry and the resulting by-products and heat are used to fill demands and thus there is a remnant of fossil energy in the system. There are mainly two processes that could speed up the removal of non-renewable energy sources in the Swedish energy system. The first one is the phasing out of nuclear power. In the scenario, the lifetime of the existing nuclear power plants is set to 50 years but this is an estimation and could be carried through earlier.

Another option for reaching a higher share of renewables in the Swedish energy system is to replace more of the fossil energy used in the transport sector at an earlier stage. The transport sector is heavily dependent on fossil energy today and the transition towards more renewables in this sector will take off as production of biofuels in Sweden starts on a large scale, which is anticipated to take place after 2030. This is not scheduled earlier as the introduction of biorefineries takes time.

The energy carriers *electricity* and *district heating* are used in the demand curves as resources to meet demand. These energy carriers will however have an origin that will change over time along with the change in the energy balance and technologies present for energy generation. In order to understand the demand curves and the resources used to generate the electricity and district heating the energy carrier fuel mix is presented below.

5.1.1 Electricity

The supply of electricity is part of a Nordic market and the connections are interlinked. However, this scenario is restricted to the production capacity in Sweden. There are a number of processes that take place in Europe in order to harmonize the electricity markets to take advantages of synergetic effects as well as security in power supply. The scenario is designed to consider national demands and to be able to fulfil these with production within the geographic border of Sweden. The electricity demand is found in Figure 5.

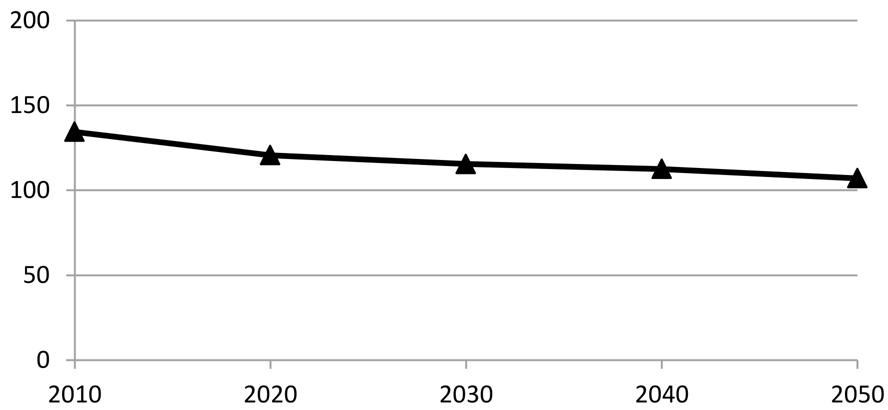


Figure 5: Demand of electricity in the Swedish energy system 2010-2050 (TWh)

In Figure 6 the electricity production per energy source is shown.

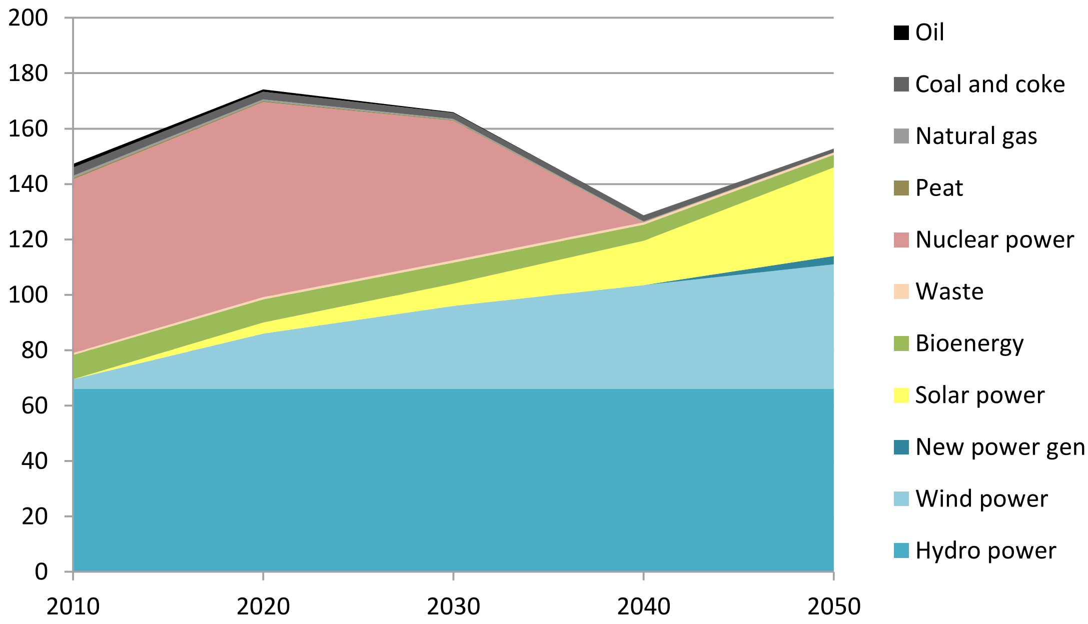


Figure 6: Generation of electricity in Sweden 2010-2050 (TWh)

Nuclear is phased out after its technical life time which is set at 50 years in this scenario. This means that during the period towards 2040 there is both a push for installing new renewable electricity production capacity at the same time as there is production in the nuclear power plants. As a result there will be a surplus of electricity produced in Sweden during this period (Table 46).

Table 46: Electricity production and demand (TWh)

	2010	2020	2030	2040	2050
Primary energy allocated to electricity production	147	174	166	129	153
Losses in transmission and distribution	11	12	11	7	8
Losses in fuel-based electricity production (co-generation)	3	2	2	2	2
Electricity demand	134	121	116	113	107
Import (+) / export (-) potential	**1**	**-39**	**-37**	**-7**	**-36**

In the demand curves presented in section 5.2 Energy demands in Sweden the mix for each year should be used. The share of renewable sources in the production mix is steadily increasing but slows in momentum when reaching close to 100% in 2040.

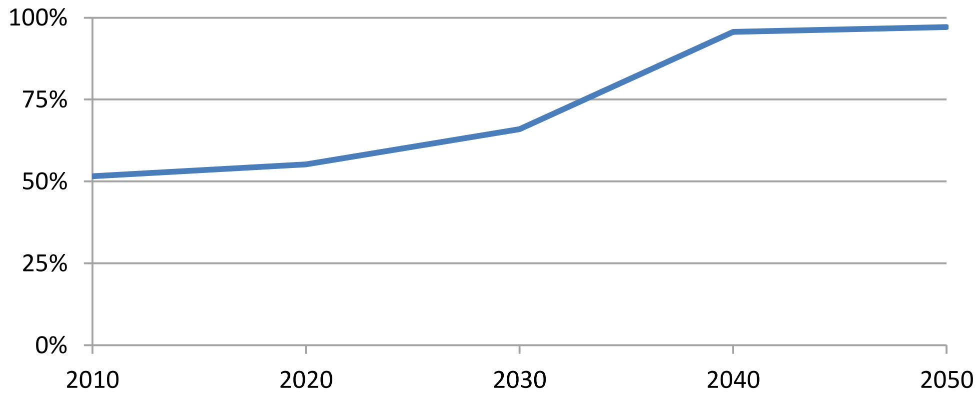


Figure 7: Share of renewables in the electricity production mix in Sweden

The share of renewables in the energy mix could be increased by phasing out nuclear before reaching the lifetime (50 years) now set in the energy scenario. In 2030 there is a nuclear power input of 50 TWh and a surplus electricity production of 37 TWh.

The share of intermittent power increases to slightly more than 50% in 2050. The issue of handling the large share of intermittent power is discussed in more detail in for example Lund (2010). The regulating capacity in hydropower resource should be prioritized over power production. Smart grids, including the management of power peaks by managing demand loads (for example, plan certain recurring events such as the start of large compressors at certain times), are also needed to manage the increase of intermittent power in the electricity supply.

5.1.2 District heating

Compared to the global WWF energy scenario (Deng et al. 2011) district heating has been promoted as a discrete energy carrier as it fills such a central role in this scenario. In the scenario presented here, full advantage of the possibilities from this kind of energy distribution is taken. At the same time the demand in energy units for district heating will decrease during this period as a consequence not only of energy efficiency improvement measures in buildings, but also due to reduced need for heating as a consequence of global warming. In parallel the need for cooling will increase. The source mix of district heating is displayed in Figure 8.

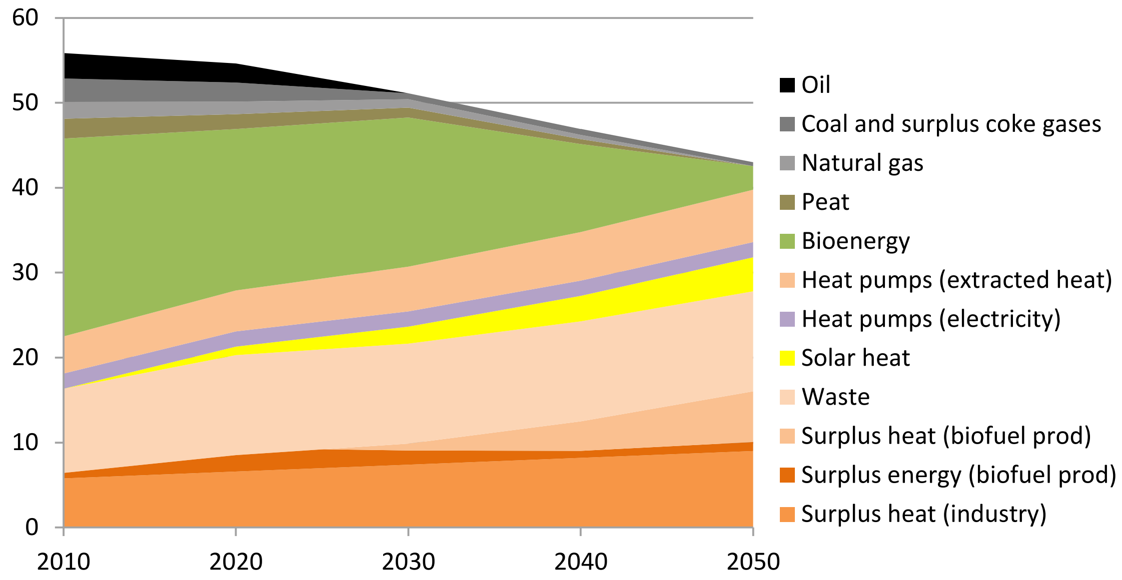


Figure 8: District heating, sources (TWh)

In the demand curves presented in section 5.2 Energy demands in Sweden the mix for each year should be used in order to interpret the mix of fuels in district heating.

The district heating systems are anticipated to be used to distribute heat from industries and from biofuel production. This is especially important after 2030 when the scenario anticipates increased volumes of DME and SNG production to substitute fossil transport fuels. In Figure 8 surplus energy refers to energy sources such as gas and other fuels, while surplus heat refers to heat.

The ability to utilize district heating creates good opportunities to efficiently distribute and make use of excess heat from industrial processes and biofuel production. The scenario will require that further expansion of district heating systems in Sweden are made, as well as reducing the energy losses in these distribution systems. Compared to many countries in Europe Sweden has the advantage of having district heating systems in many of its cities and towns. Utilizing these to distribute excess heat to various demands is an efficient route towards a renewable energy system. The ability to manage and operate the energy system in an efficient way and also to track environmental impacts and recycle ashes, etc. is improved through a more centralized production.

5.2 Energy demands in Sweden

The demand curve results from calculating the energy services assessed and existing technology in the model. The demands curve does not necessarily correspond exactly with the supply curve. The non-overlapping parts of the supply curve are surpluses and could for example be exported. The demand curve for the Swedish energy system is presented in Figure 9.

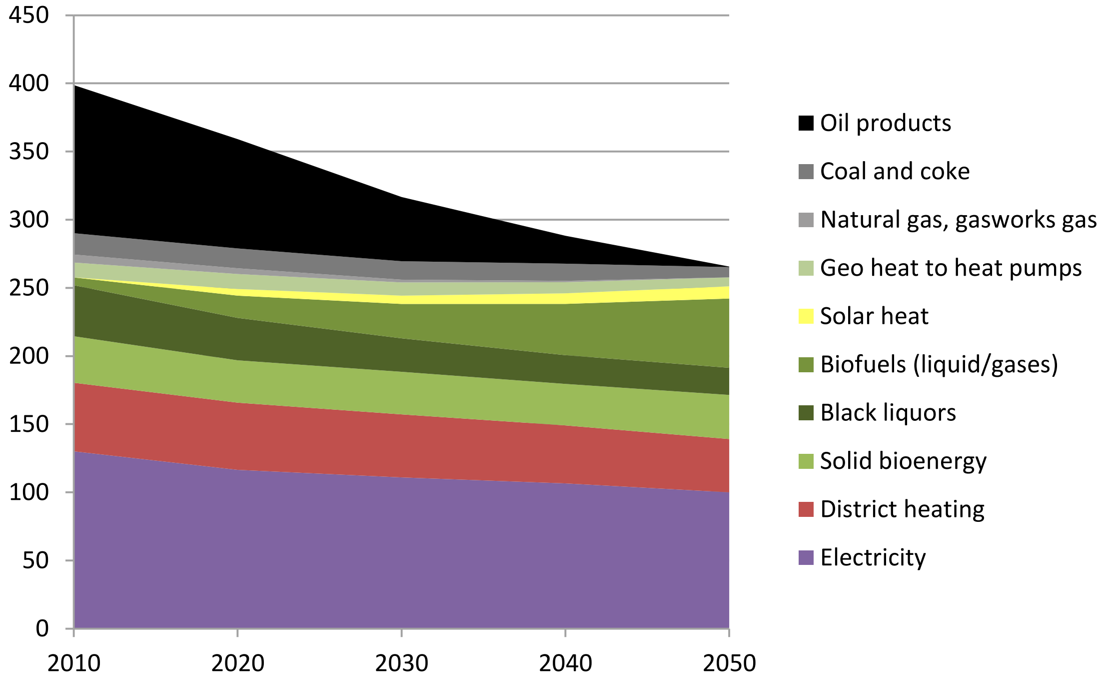


Figure 9: Total final energy demand in the Swedish energy system 2010-2050 (TWh)

District heating and electricity are energy carriers and the mix in each of these two is presented in Figure 6 and Figure 8. The gradient in point 2010 does not account for the trend seen in previous years. Figure 3 displays the relatively steady energy demand in Sweden, and the decrease will represent a major break in the trend. It should, however, be pointed out that this break, operationalised through the energy efficiency improvement target of 20%, is set in European policy (European Commission 2010a). Final energy demand in Sweden will be reduced by 33% according to the scenario.

5.2.1 Demand in the industry sector

In the industry sector a number of initiatives for energy efficiency improvement have taken place, but the scenario pushes this even further in order to reduce the energy needed without reducing production. The demand curve for the industry is found in Figure 10.

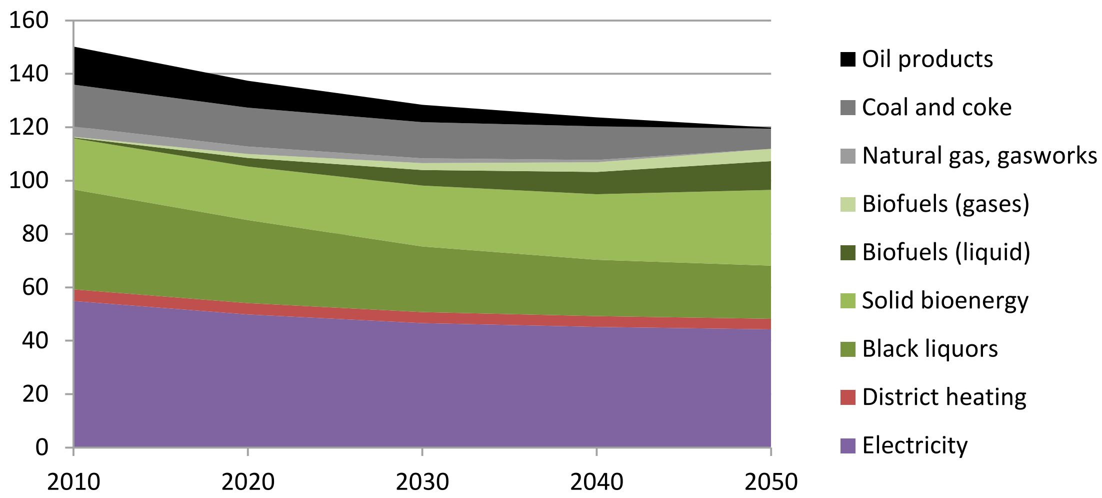


Figure 10: Total final energy demand in the Swedish industry sector 2010-2050 (TWh)

District heating and electricity are energy carriers and the mix in each of these two is presented in Figure 6 and Figure 8.

The industrial sector in Sweden has a number of energy-intensive industries. In the scenario we have not considered major changes in the production mix. Changes and shifts in the type of production found in Sweden, for example that the paper industry shuts down, would have great consequences for society and also the demand and supply side of the energy system. The paper and pulp industry is energy intensive with a high energy demand. But these industries also generate electricity and surplus heat is sometimes fed into district heating systems. In the scenario it is proposed that biorefineries be introduced in the paper and pulp industry. The solution proposed includes utilizing the surplus heat for district heating hence the industries will become highly integrated with the energy system. In order for this option to be feasible there is a need to mutually ensure security in terms of energy deliveries, as well as price mechanisms.

5.2.2 Demand in the transport sector

The transport sector displays a high dependence on fossil fuels today. This means that in order to reach the targets for 2050 a number of transitions in terms of sources of energy are needed. In addition the transportation technology options display large variations in terms of need for energy to supply the same energy service i.e. the transport of an item from a to b. Thus to supply a certain transport a shift from technologies that require a high input of energy per transport work to more efficient is desired. Some types of transport are, however, difficult to shift as the infrastructure is not present or it is not technically feasible. The energy demands in the transportation sector are found in Figure 11

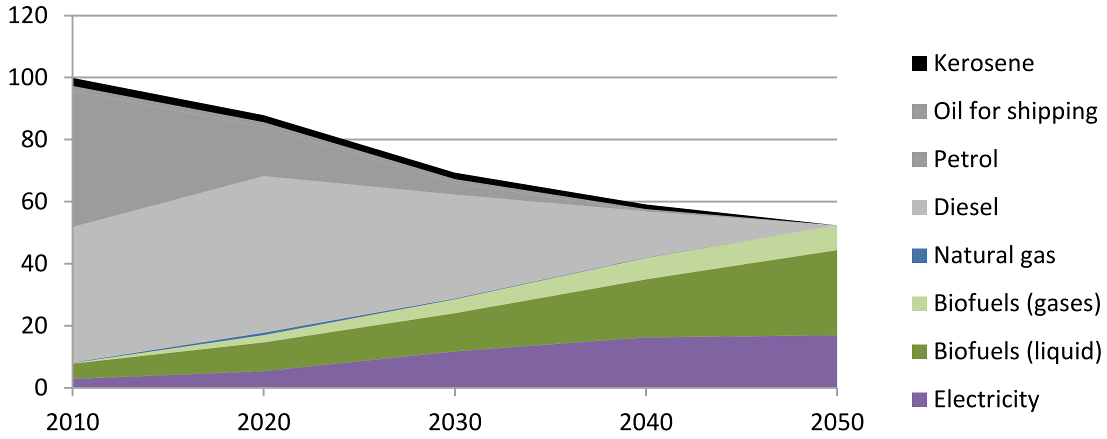


Figure 11: Total final energy demand in the Swedish transport sector 2010-2050 (TWh). Petrol and diesel categories are here pure fossil sources, the low-blend content is found in biofuels (liquid).

The supply mix found in electricity is presented in Figure 6. In Figure 11 the categories petrol and diesel are in a pure form and the low-blend content with renewable origin is found in the category biofuels (liquid).

The policy goal of a fossil-independent transportation fleet in Sweden in 2030 (Regeringskansliet 2008a) is interpreted as meaning that vehicles at this point use flex fuel and could therefore be operated on biofuels where these are present. The production of biofuels in Sweden has, according to the assumptions in the scenario, not really taken off at this point. The reason is that the technical route for biofuel production anticipated involves large investments in the pulp and paper industry. In the process of achieving these investments there are a number of challenges linked to create business models that handle the complexity of biorefineries.

The scenario does not include cars and other vehicles operating on hydrogen, e.g. by using fuel cells. We do not exclude this technology trajectory as a solution in the future (for a review of backcasts and forecasts towards a hydrogen economy see McDowall and Eames 2006). Electricity is considered as being used in the process of producing the hydrogen, so the hydrogen cum fuel could be seen as storage for electricity. If the technology becomes accessible and the infrastructure the production and distribution of hydrogen is developed then this option might play a role in supplying transport services (a discussion of the hydrogen economy and EU is given in Bleischwitz and Bader 2010).

The available statistics in Sweden on the transport of people are divided into long distance journeys and short distance journeys (less than 100 km) (Åkerman et al. 2000; Åkerman and Höjer 2006). In the scenario all journeys that are included are within the Swedish border. Long distance journeys are to a great extent made by train, while car journeys in terms of person km are kept at present day levels (Table 14). Car journeys for short distance decrease, while there is still need to keep cars as an option for long distance journeys. Long distance journeys here are those travel services that cannot be satisfied through other, more energy-efficient, transport technologies.

5.2.3 Demand in the household and service sector

A steady reduction of energy demand in the household sector is needed to reach the targets for 2050. The household and service sector is already in 2010 not very dependent on fossil energy sources. Oil for heating has been reduced drastically since the 70s and compared with many other European countries heat pumps contribute a substantial part of heating in the sector.

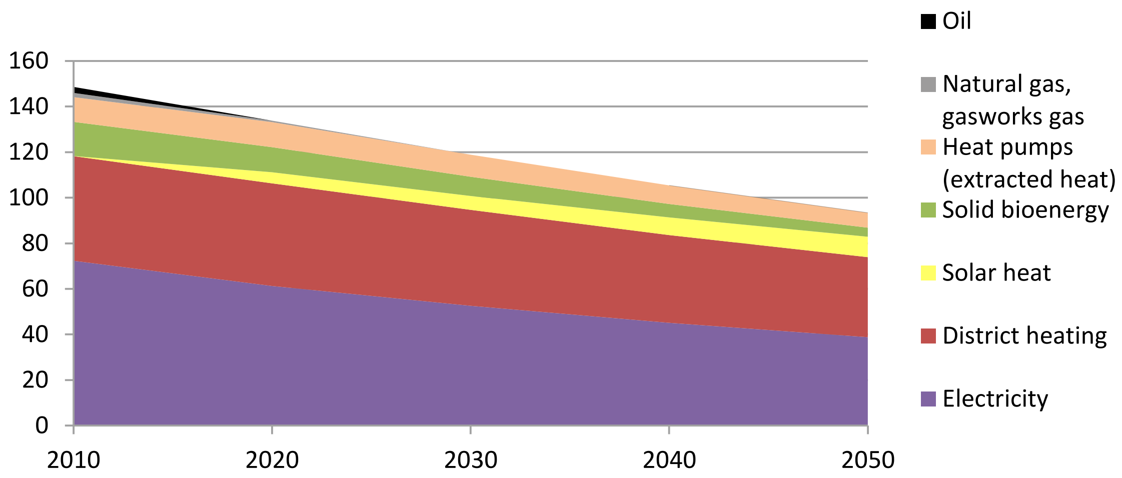


Figure 12: Total final energy demand in the Swedish household and service sector 2010-2050 (TWh)

District heating and electricity are energy carriers and the mix in each of these two is presented in Figure 6 and Figure 8. The category labelled "heat pumps (extracted heat)" in Figure 12 is the heat that is extracted from the heat sink used by the heat pump. This category is seldom found in statistics as it is free energy. As a consequence going from direct electric heating to heat pump would look like a reduction in energy demands in the house for heating as less electricity is used. In fact no change in energy demand for heating has been made, but the technology to supply the energy service has changed. The suggested path is to both look into reduction of energy demand in the house *and* to apply an efficient technology to supply the required energy service. In Figure 12 the electricity used for operating the heat pump is part of the electricity demand.

5.3 Emissions of greenhouse gases

From the supply scenario it is possible to calculate the corresponding emissions of GHG. The curve in Figure 13 is based on static emission factors linked to each source.

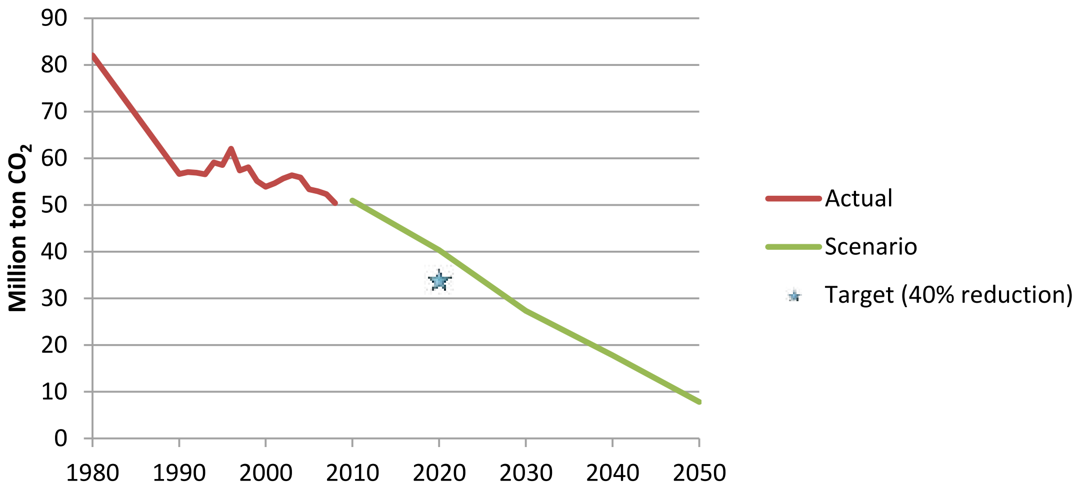


Figure 13: Total energy-related carbon dioxide emissions, actual emissions 1980-2009 (Energimyndigheten 2010b) and scenario emissions based on static emission factors (Naturvårdsverket 2011) (Million ton CO_2)

When not accounting for carbon dioxide emissions from renewable energy sources, i.e. these are assumed as zero emitters, reduction in emissions follows the reduction in use of fossil energy in the energy system. In 2050 the emissions are dominated by the emissions from coal and coke in the steel industry. In 2030 the reduction, compared to 1990 emissions levels, has been halved and in 2050 the carbon dioxide emission is about 8 million ton CO_2.

In Sweden the environmental movement have argued that drastic cuts in emissions are needed by 2020 in order to avoid climate effects that would result in temperature rise above 2°C (Naturskyddsföreningen 2007; WWF 2007a; WWF 2007b). The proposed level of emissions reduction has been 40% domestic reduction by 2020. This is in line with what the international environmental community, a range of scientists and others argue to be a minimum level for developed countries in order to be able to tackle the climate effects (WWF 2007c; CAN International 2009). In the scenario the reduction will be almost 30% in 2020 as compared to 1990 emission levels. This means that another 6 million ton (mega ton) of CO_2 in domestic emissions needs to be further cut by 2020 to reach this goal. The focus on this report and scenario has been on achieving 100% renewable energy within the Swedish ecosystem capacity by 2050 at the latest and not specifically on how to reduce emissions 40% by 2020 compared to 1990. Based on the scenario there are some general comments and suggestions on how to stimulate a process that would also reach this 40% reduction goal. For example there is need for pushing introduction of new technologies, innovation and alternative energy carriers, as well as stimulating changes in consumption (the demand side).

Fossil fuels are predominant in the transport sector and the industry sector and it is here that targeted short-term actions are needed. In the transport sector a stronger push to create a domestic biofuel production with targeted actions to substitute fossil energy would have impact on emission levels. The 6 Mton reduction is roughly equal to substituting 20 TWh of fossil oil (30% of the fossil energy used in the transport sector 2020 according to the scenario). The industry (including steel industry) could also push for emission savings in different ways. For example bring investments in new and more efficient processes and implement energy efficiency work earlier in time would have an impact. It could be tempting to solve the target of 40% reduction with an increased import of biofuels while waiting for a domestic production to be established. This would, however, result in a substantially increased ecological footprints from Swedish consumption in other parts of the world (WWF 2010) which is not in line with the point of departure in this scenario.

However, changes, especially decreased transport, demands would generally result in a decreased use of fossil energy. The scenario considered changes in these variables towards more efficient transportation means, but not considered drastic cuts in the demand of transport services. There lies a large potential towards reaching the ambition of the scenario in adjusting the demand side. This would, however, create a number questions linked to how this would effect, or be affected by, changes in production and economic activities in general. Further work with stimulating introducing energy efficient technology and energy efficiency work would have an effect. The scenario already assumes relatively high levels of reductions in energy demand per service demand.

The emissions described in Figure 13 are based on a static calculation method. This approach to carbon emission assessment is beginning to be disputed as it will not encompass the whole complex of effects that will occur as a consequence of changing the land use to start or expanding the production of biofuels (Fargione et al. 2008; Olsson 2009; Olsson 2010; Zanchi et al. 2010; McKechnie et al. 2011).

For renewable energy sources one of the consequences of the static approach is that the carbon accumulated in the biomass (terrestrial carbon) will per default be seen as re-accumulated in the standing biomass in the end of the time, hence resulting in a zero net emission. It is well known, however, that emissions tend to change over time. In the case of bioenergy this is an issue for concern as the rotation times can be long and substantial amounts of carbon is stored in the biomass, especially forests. Depending on how the biomass resources are managed the net emissions of carbon to the atmosphere as well as the accumulated carbon in the atmosphere will change.

A special assessment of the emissions linked to the solid biofuel category branches and tops based on a dynamic perspective were carried out for the energy scenario presented in this report (detailed calculation and background is found in appendix 1).

The solid biomass resource will to a great extent be used to substitute diesel and petroleum in the transport sector. Thus comparing the dynamic emissions with oil is representative.

Based on calculated emissions and the decay function, the remaining amount of atmospheric carbon is calculated and presented in Figure 14, expressed in Mton CO_2 (see appendix 1 for a detailed presentation of the calculations).

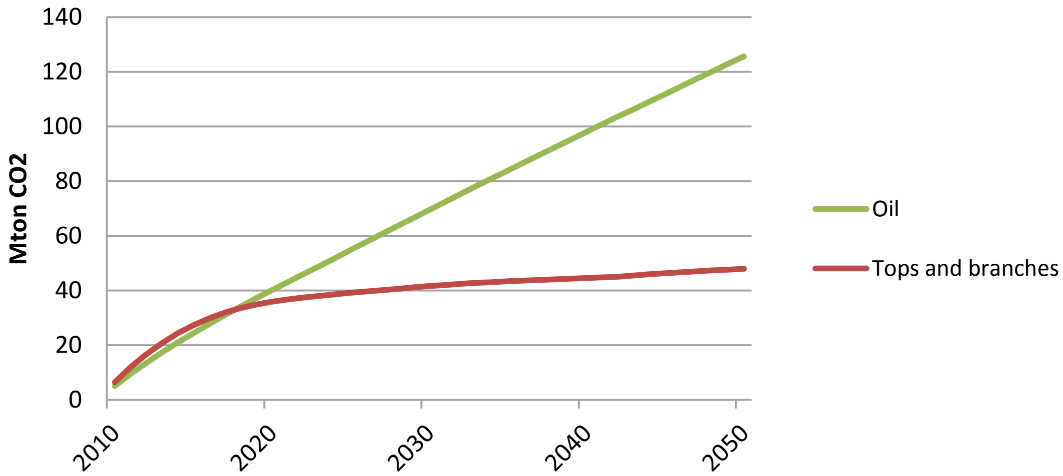


Figure 14: Remaining carbon dioxide in the atmosphere based on the tops and branches variable in the renewable energy scenario. Oil is used as a comparison.

A consequence of using bioenergy or oil will be an increase in the atmospheric concentrations of CO_2. Using tops and branches for energy instead of leaving them on the ground to decompose leads to net emissions of carbon dioxide to the atmosphere. The reason for this is the time lag between combustion-related emissions compared to the emissions from decomposition. If tops and branches begin to be used in 2010 and follow the scenario presented in section 4.4 Bioenergy, waste and peat, remaining atmospheric carbon will be 48 Mton CO_2 in the year 2050. If oil is used instead as a comparative source for energy throughout the whole period, remaining atmospheric carbon will be 126 Mton CO_2 in the year 2050. Using forest residues such as tops and branches leads to an increase in atmospheric carbon dioxide, but using oil would increase atmospheric carbon dioxide significantly more. The important thing to remember here is that the calculations above describe a situation of change (from zero use of tops and branches to 19 TWh in 2010) which causes the rapid increase in the first years. If the aim is to tackle climate change and to reduce carbon emissions, changes in use of bioenergy will have impacts as described above. Different bioenergy will have different characteristics and the calculations here are valid for tops and branches from Swedish forestry specifically.

Using tops and branches as a bioenergy source will have an impact on the net emissions of carbon dioxide to the atmosphere. However, if substituting oil, tops and branches will reduce the global net carbon dioxide emissions significantly. Still, biomass resources if used as a fuel will result in substantial emissions of terrestrial carbon dioxide and there are reasons to consider this when creating support structures and regulations of various biofuels. There might, for example, be other biomass alternatives that are even more beneficial for climate mitigation. For instance, the establishment of new forest on earlier crop land is likely to reduce atmospheric carbon and would have a net cooling effect (Zetterberg and Chen 2011).

5.4 Rebound effects

The scenario is dependent on energy efficiency improvement activities taking place in the whole community. To put it in simple terms – the demand side peg does not fit into the supply side hole. There is thus a need to reduce the demand for energy in society and in production. To do this, energy efficiency improvement is promoted in all sectors. Most of this is made on market conditions, some of it will require support and regulation in order to happen but there is no doubt a huge potential.

Energy efficiency improvement is often linked with the concept of the rebound effect (Gillingham et al. 2006; Herring 2006; Sanne 2006; Herring and Roy 2007; Gillingham et al. 2009; Madlener and Alcott 2009; Ehrhardt-Martinez and Laitner 2010; CAN Europe 2011). Rebound effects are effects that happen as a consequence of resources being made available after applying the energy efficiency improvement measure. Some of these rebound effects could reduce the positive impacts that the efficiency measures resulted in. There are both indirect and direct rebound effects; only the direct effects are possible to measure (Sanne 2006). The discussion on the rebound effects tends on the one hand to address the matter from a theoretical point of view, and on the other hand based on empirical evidence. According to a review by Gillingham et al. (2006) the tendency was that criticism of the efficacy of energy efficiency improvement related to appliance standards was based on theoretical reasoning, while empirical studies tended to support the positive impacts from appliance standards. Sorrel et al. (2009) conclude that the direct rebound effects in energy efficiency improvement within household energy services in the OECD should in general be less than 30%. The problem is to assess the magnitude of the rebound effects in relation to the energy efficiency improvement effect and to minimize these effects.

To minimize the rebound effects there is need for targeted actions. The driving force that results in the rebound effect is that the saving creates a surplus of resources compared to the previous situation. For example, if you save on fuel costs as a consequence of a more efficient car, the result according to the rebound effect would be that you drive longer with your car and thus the saving from the energy efficiency improvement in the transport work is not as large as it could have been. Sanne (2006) discusses how to manage and minimize rebound effects and puts this into the context of handling surplus. Sanne puts forth four different approaches that are interlinked but which focus on different aspects of the ability to manage surplus:

1. Regulate with money: Stimulate consumption towards a less damaging direction through monetary regulations.
2. Remove resources, distribution of wealth: Remove resources from the own economic system in order to reduce the negative impacts from increased consumption. One example is increased development assistance.
3. Invest in sustainable development: Use surplus to invest in strengthening the natural capital and improving ecosystem services to support long-term sustainability.
4. Societal norms and values: Stimulating and steering production to become more sustainable and create human wellbeing rather than economic growth.

These aspects are problematic in the sense that they conflict with general assumptions on economic growth and the creation of wealth. At the same time they focus on the need to link management of the surplus with energy efficiency improvement activities. In the case of the scenario presented in this report, the surplus is used to invest in sustainable development. Hence the energy that is "freed up" through energy efficiency improvement work is used to substitute fossil energy, as well as to manage the renewable energy sources within the carrying capacity of the ecosystem. This cannot be achieved unless regulations and stimulation of these processes are present.

In this report the focus is set on the input parameters in terms of energy needed to perform a certain energy service. The technology options, societal structures and feedback structures to users and producers are qualitative aspects linked to this variable. In the scenario rebound effects are supposed to be strategically managed in order to take advantage of the decrease in demand that the energy efficiency improvement creates. The assumption is that there is no direct surplus in the system, but rather a push to decrease the demand. Societal regulations and driving forces are needed in order to make this happen.

6 Cost and policy overview

This section aims to evaluate costs related to the measures put forth in the scenario, with a focus on the investments required to realize the scenario's main trends[11]. The cost of each trend is compared to other costs in the sector that can be related to, and in some instances avoided by, realizing the scenario. It also includes a brief discussion on policy aspects of promoting these investments. The evaluation does not aim to include a comprehensive analysis of the total costs associated with realizing the required investments, but the overview is rather aimed at providing a reflection on the reasonability of the scenario from a financial and economic point of view. Hence the focus on the main trends, which puts an emphasis on the costs of increasing energy efficiency (EE) in the industry and building sectors, increasing the use of biofuels in the industry sector, increasing rail transports and new road vehicles, and biofuels and renewable energy sources (RES) on the supply side (Figure 15).

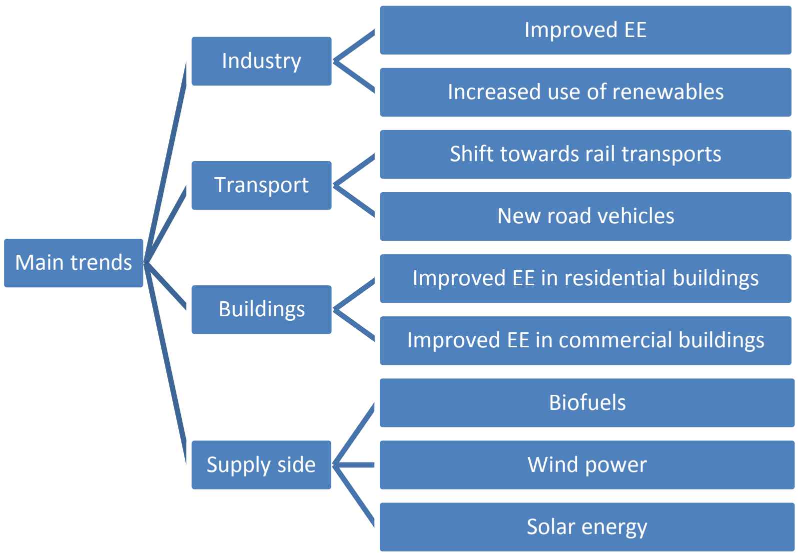


Figure 15: Main trends in the scenario for the transition towards a fossil-free society

An important question in this section is who will carry the costs of the energy system's transition. This includes the question of whether these investments are motivated and feasible for those who will implement them. An aspect equally as important as the monetary evaluation, within the scope of this section, is therefore whether the measures include commercial technologies or are associated with public spending on research, development and demonstration (RD&D). This introduces the question of which policy instruments will be required to provide financing and incentivisation so as to promote the necessary measures and investments.

11 Exchange rates used: SEK/USD = 7; SEK/Euro = 10.

6.1 Costs

The overview of costs has been carried out similarly to that of the WWF's international analysis (Deng et al. 2011), so as to provide a possibility for comparisons. This includes, *inter alia*, that the analysis mainly account for costs during the year in which the investments occur, thus excluding the financial analyses commonly associated with long-term decision-making. The two differ, however, in the sense that this report focuses on an overview of main trends, while the counterpart carried out a cost analysis for all costs and savings. Moreover, it should be highlighted that the calculations herein do not provide an analysis of the most cost-efficient way to reach the scenario. Furthermore, as the project has focused on producing a scenario on required measures and not a business-as-usual scenario, the cost evaluation does not include potential savings due to development. However, costs are compared to other relevant costs for each main trend.

Other aspects of the evaluation are that we do not include any costs for the decreased use of any particular energy carrier. We disregard the influence of policy instruments as the effect, or even presence, of these up to 2050 is deemed to be associated with too large uncertainties. We do not calculate for any changes in industrial or building energy use until existing technologies have reached their economic life-time, i.e. no costs are associated with *reducing* the use of a specific fuel in these sectors.

While we have aimed at finding Swedish data for the calculations, this has proven difficult. The results should therefore be interpreted with international differences in mind.

6.1.1 Industry

Industrial energy efficiency improvements do not affect the use of electricity to any great extent but rather reduce the need to introduce RES as replacing existing use of fossil fuels. Regarding economic evaluations of energy efficiency improvement investments, they commonly indicate easily-obtained gains and cost-negative or cost-neutral measures (i.e. having positive or neutral economic effects for the company). Calculating costs for energy efficiency improvements for Swedish industry is difficult in the light of a large array of measures that can be carried out. Nevertheless, the SEK 708 million invested under PFE has resulted in savings of 1.45 TWh, pointing to an average energy efficiency improvement cost of 0.5 SEK/kWh. While this corresponds to the electricity tax avoided and consequently must be considered from this economic perspective, it points to significant energy efficiency improvement potential at low costs.

WWF's international energy scenario estimates that the increased costs arising from easily-obtained gains and decreased costs due to learning effects will level each other out, which would mean that this cost situation would be constant. However, the Swedish industry sector is often regarded as having high energy efficiency compared to its international counterparts, which could point to a different situation in Sweden. Yet technological development is seen to provide continuous cost efficiency potentials, which is also supported by an expected development where fuel prices and environmental policy instruments increase the benefit of energy efficiency improvement investments.

The introduction of additional RES in the industry sector is seen as mainly associated with heat production, even though other RES are needed for the industry in addition. The costs for this transition are based on IEA's Energy Technology Perspectives, which over the period to 2050 identify the costs of different options as constant in the range 0.10-0.48 SEK/kWh (IEA 2008). No learning effects are included that exceed this price range. As drawn from a global energy technology outlook, the figures do not specifically represent the costs in Sweden but may nevertheless be seen as relevant in light of a diverse national industry sector.

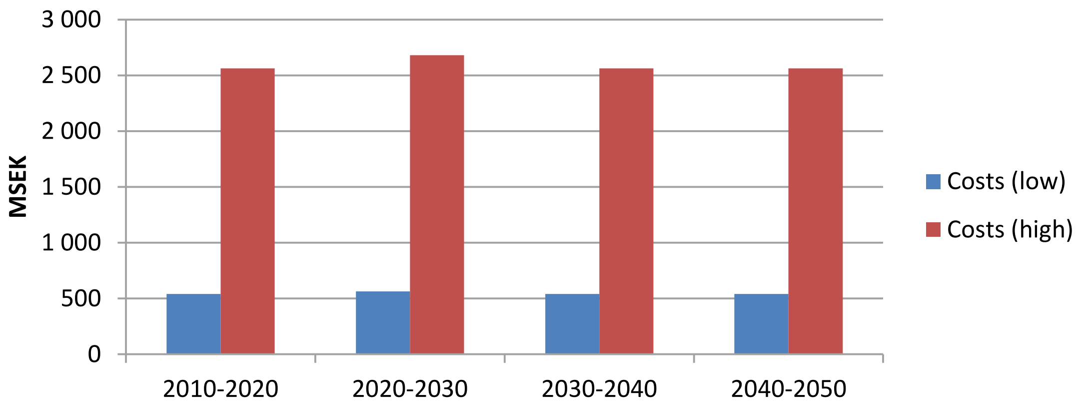


Figure 16: Costs of increasing biofuels in industry per decade

The total costs for the industrial transition would range between 2,200 MSEK and 10,000 MSEK with an average cost range *per annum* of 55-250 MSEK (Figure 16).

In a comparison to the industry sector's carbon dioxide taxes during 2008 of 2,000 MSEK (SCB 2011), switching to RES provides economic benefits for the industry sector (Figure 17). This situation is further improved if taking lower prices for biofuels than fossil fuels into account. Moreover, while industry currently receives carbon dioxide tax subventions, the sectors that are not included under the European Emission Trading Scheme (EU-ETS) will see these subventions decrease and face full taxes from 2015. However, the trading sectors will receive a full tax deduction and only face the emission rights prices of the EU-ETS. Nevertheless, as many reports point towards increasing emission rights prices, the overall picture is that the industrial benefits of fuel-switching will improve.

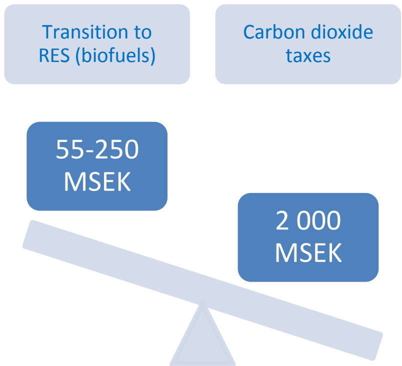


Figure 17: Cost comparison between a transition to RES (biofuels) and carbon dioxide tax costs per annum

6.1.2 Transport

The main transport trends of the scenario are increased rail transports as well as the introduction of electric vehicles (EVs) for person transports and a transition towards renewable fuels, such as DME or equivalent, for goods transports by lorries, as well as air transport and shipping. The costs for increased rail transports are calculated based on SIKA statistics of today's costs for rail investments plus operations and maintenance, and the increase in ton kilometres (tkm) and passenger kilometres (pkm) (SIKA 2009a). Increasing the rail transports is not seen to include the deployment of non-commercial technologies at any large scale.

The costs for freight rail transport (i.e. tkm) are calculated based on the share of tkm on railways while the costs for pkm are based on the share of rail transports not associated with tkm (which for example includes trams and metros), so as to accurately reflect the increase and nature of freight versus person transports. This division is an assumption as the relative costs for these transports may differ.

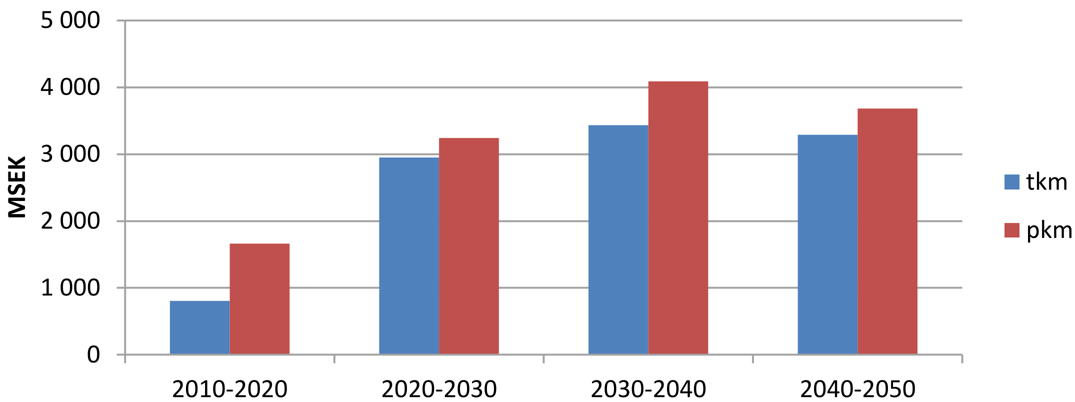


Figure 18: Costs of increasing rail transports per decade

The result is a total operational cost increase of SEK 23,000 million over the period and an average of SEK 600 million per year. This can be compared to the total costs of operating the rail system in 2008 of SEK 18,000 million (SIKA 2009a). Seeing that the costs for truck transports are typically three times that of rail transport, an increase in capacity, flexibility and reliability of the rail system should be the preferable development for transport consumers.

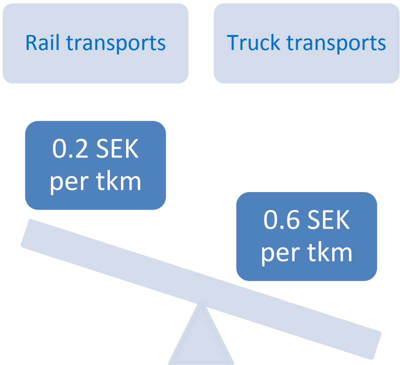


Figure 19: Cost comparison between rail and truck transports per ton kilometre (tkm)

Regarding road traffic, the scenario assumes a constant number of cars (4.3 million), while EVs assume a gradually larger share of the fleet. Based on estimations of EV cost developments in the IEA Energy Technology Perspectives, the additional cost is SEK 175,000 per vehicle in 2015 and about SEK 54,000 per vehicle in 2030–2050 (IEA 2008). There is consequently an expectation of large learning rates in the introduction of EVs, which similarly implies large variations in costs depending on which rates are assumed.

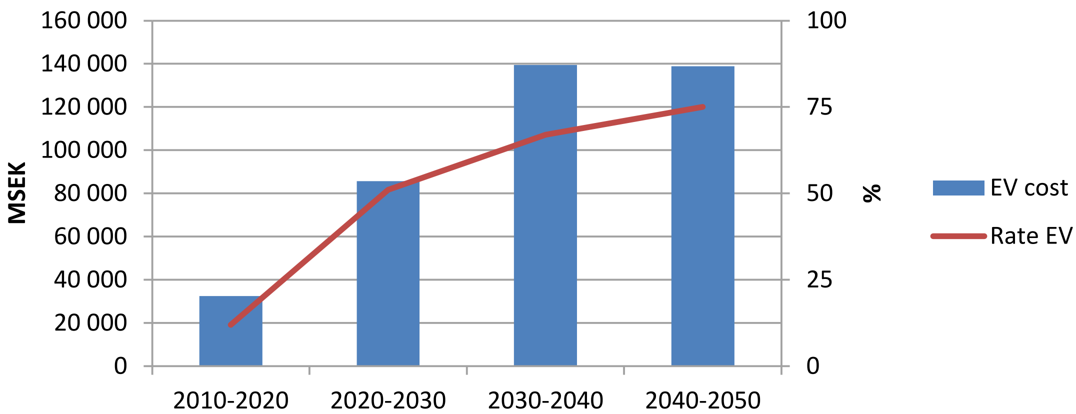


Figure 20: Costs per decade of introducing electric vehicles

The additional costs of introducing EVs are thus about SEK 400,000 million and the average yearly cost is SEK 10,000 million, where the latter figure has large variations and uncertainties over time due to the expected cost decrease (Figure 20). The costs can be compared to the current yearly spending on fuel, which at present prices (approx. 14 SEK/litre) reach about SEK 14,000 million. Seeing that the fuel costs for EVs should typically be significantly lower than current fuel costs and even lower than future costs of diesel and petroleum, the additional vehicle purchasing costs are expected to be increasingly offset.

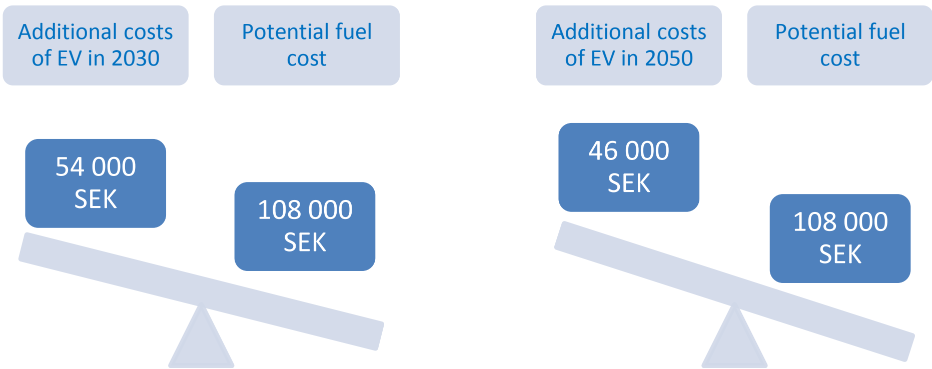


Figure 21: Cost comparison between additional investment costs of EVs and ten-year spending on fuels in different scenarios

One way of looking at the costs on the level of vehicle owners, is that the additional costs per vehicle in 2030 is less than half of the spending on fuels over a ten-year period, if calculating with a yearly transport length of 1,500 km, an improved fuel consumption of 0.4 l/km and a future fuel price of 18 SEK/l (Figure 21). The cost spread would naturally increase with longer transports and higher fuel prices and similarly decrease with lower fuel consumption. An alternative scenario may for example include increased fuel costs due to higher oil prices. Assuming that fuel prices in 2050 are 24 SEK/l, i.e. double that of current fuel prices, and a fuel efficiency improvement to 0.3 l/km, ten-year fuel spending would be equal to the previous scenario. However, this should then be compared to an expected additional EV price of SEK 46,000. The additional costs for EV vehicles can consequently be regarded as offset under varying scenarios. An additional example is that fuel consumption at a fuel price of 18 SEK/l must fall to 0.21 l/km to balance the additional costs for EVs in 2030.

The scenario puts forth that fuel consumption in goods transports by lorries will develop towards lorries using a larger share of DME in particular and to a lesser extent electricity, gas and FAME. We do not include any particular additional costs associated with this development, but rather that the replacement of trucks will follow a general transition on the market towards models equipped with engines using these other fuels. The cost benefits are also seen to follow a positive trajectory under the assumption that the price of fossil fuels will increase relative to that of biofuels. Electrified lorries are, similarly to the private car example above, seen to be economically viable in the future under a range of scenarios.

6.1.3 Buildings

The third sector included the main trends is energy efficiency improvement in buildings, divided between residential and commercial buildings. At present, residential buildings represent an 80% share of the total energy consumption in the building sector, which is expected to remain roughly constant to 2050. During the same period, the average energy consumption per m² is expected to be cut in half in both building sectors. Hence, the largest efforts are to be made in residential buildings. The costs of accomplishing these savings are calculated through the average costs of increasing energy efficiency in the two building sectors (Deng et al. 2011). Learning effects are seen to reduce costs by 10% each ten-year period. As in the industry case, the increased costs arising from easily-obtained gains and the decreased costs due to growth functions are estimated to level each other out.

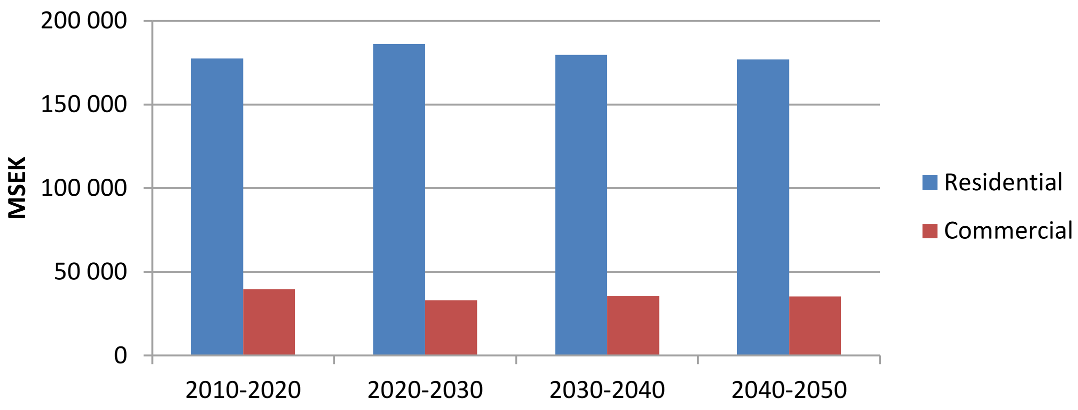


Figure 22: Investments per decade to increase energy efficiency in the building sector

Thus the total additional costs for increasing energy efficiency in the building sector over the period amount to SEK 890,000 million (Figure 22). The average annual cost is about SEK 22,000 million (Figure 23). The cost can be compared to the expenses on energy that are saved as a result of the efficiency measures. Energy demands in electricity and heat (fig 12) are demands that will have a cost associated to them. The extracted heat in heat pumps and solar heat are part of energy efficiency measures. The energy removed through the energy efficiency measures are compared to the baseline (2010). Over the 40 year period the demand is reduced with of almost 1,100 TWh. The annual saving in energy expenses is thus SEK 27,000 million per year. This points to potential cost benefits of realizing the scenario as the energy efficiency improvement measures, in contrast to electricity purchases, is a single investment cost (Figure 23).

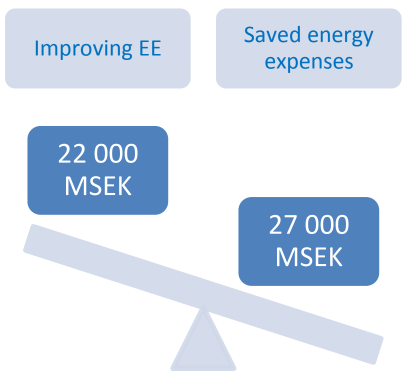


Figure 23: Cost comparison of energy efficiency improvement investments and electricity costs in buildings per annum

Realizing the technical and economic energy savings potential in the building sector has however proved to be difficult due to various market failures and barriers. It is therefore important to implement policies that provide information, incentives or rules in order for all stakeholders in the building sector to invest in and demand more energy efficient buildings despite a potentially higher investment cost.

6.1.4 Supply side

The final sector included in the main trends is the transition towards an increased share of RES in the electricity supply sector. The cost for this transition is based on the individual increased production costs per MWh, added production capacity in MWh, and learning rates. Cost estimations for these technologies vary (see for example Henryson 2010) and we have used an average of several sources, which roughly corresponds to that of the IPCC Special Report Renewable Energy Sources (IPCC 2011a)[12]. We have set the current costs for wind power production at SEK 645/MWh (based on one-third being offshore and two-thirds being onshore) and photovoltaic at SEK 2,000/MWh. Similar to the other trends which include technologies that are currently under development, the costs on the supply side will depend on how fast the technologies develop. We have set the learning rates for the technologies included to 0.9 for wind, and 0.8 for solar power.

The increase in production is given by the scenario. The technical and economic life is set to 20 years. As a consequence, the increase of wind and solar power seen in the period 2010-2020 will have to be replaced with new energy generating capacity in 2030-2040, this has been taken into account in the calculations.

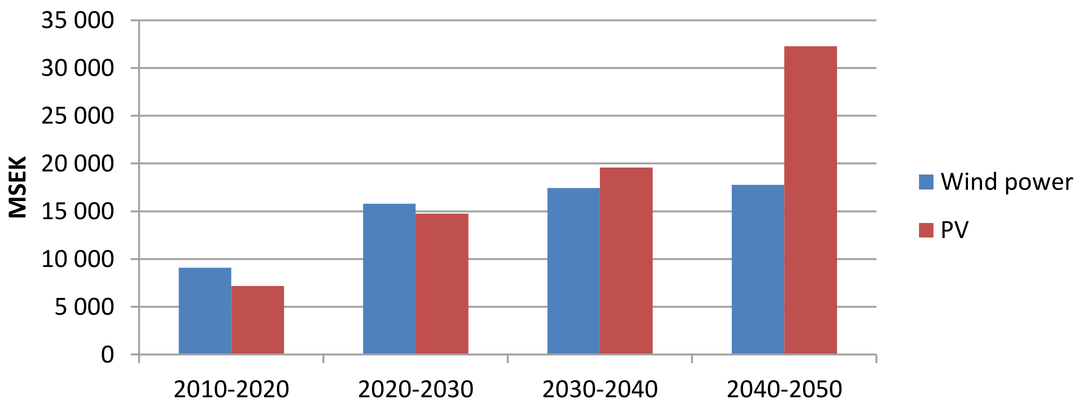


Figure 24: Costs per decade of increasing production of electricity production by wind and photovoltaic

The total costs for the increased electricity production from wind and solar power during this period amount to SEK 110.000 million, with an average annual cost of SEK 2,800 million.

12 Cost estimates available in the literature are produced using a variety of methods. The estimates in the IPCC special report are levelised cost of energy, i.e. representing the cost of generating energy from different sources over their lifetimes. It is calculated as the per-unit price at which energy must be generated from a specific source over its lifetime for the investment to break even. It includes initial investment, operations and maintenance, cost of fuel, and cost of capital. It excludes downstream costs such as costs of delivery to end-user, integration or environmental externalities. Effects of economic policy instruments credits are not included.

The costs associated with producing biofuels will not only depend on the maturity of the technology but among other things also the cost of feedstock used in the process. Learning curves linked to the production cost of advanced biofuels, excluding taxes, could already in 2030 level the production cost of the same quantity of petrol and diesel (see for example IEA 2011). A rough estimate of the production cost of all petrol and diesel used in Sweden 2010 was SEK 40,000 million (9,500 million litres and SEK 4.2/litre, the figure excludes taxes but includes the production marginal at the refinery).

6.2 Policies

The main trends analysed above point to significant costs of dealing with the transition that the scenario put forth. However, the examples also elucidate that the costs are reasonable given the comparisons and that many measures can be argued as profitable. Moreover, as we neither include external environmental costs and benefits of the transition nor the effects of policy instruments, the economic benefits of the transition should typically be larger than those shown in this overview.

A key aspect in the overview is that the technologies which are the main energy suppliers up to 2050 consist chiefly of mature technologies. Hence, the expansion of these technologies could predominately be made on market terms and not result in any significant public costs in support of technology development. This is further supported by a small role for bridging technologies and energy sources. The economic situation would, of course, be quite different in a scenario that includes public support for large scale commercialization of new technologies.

A large portion of the scenario's costs will thus be put on the private sector, which emphasizes the need for policy instruments to catalyse investment and bridge market failures. These instruments should, seeing the role of mature technologies, include a focus on incentives for investments (e.g. subsidies, subventions, taxes and a carbon price). However, parallel to incentive policies there is also a need for policies that provide financial support for technology RDD&D, seeing that some specific technologies that are not yet mature also play a significant role in specific sectors. It is also important that potential policy barriers for investments (such as short-term policies) are dealt with in order not to delay investments.

A key point is that the final costs for the transition will mainly be borne by society, seeing that the increased costs of deploying these technologies by means of policies and other market forces eventually will be put on the end consumers. The question of whether the scenario is economically feasible would then be answered by the purchasing power of the end-consumers and the profitability of choices in low-carbon solutions. As is shown above, one could easily postulate that many of these choices would have an economic rationale; especially in a scenario where, for example, oil prices and environmental policy instruments increasingly affect the pricing of those choices.

7 Conclusions

The aim of this report was to present a backcasting scenario that describes an energy system based on renewable energy sources. The supply of energy sources should be secured within Sweden and produced with a high level of environmental concern. The results from the backcasting exercise shows that it is possible to reach an energy system based closely to 100% on renewable energy. The scenario developed is based on the final goal in 2050 and between the present and 2050 there are three checkpoints (2020, 2030, and 2040).

The scenario indicates that electricity is not the limiting factor in the Swedish energy system. Provided that energy efficiency improvement activities and the expansion of new renewables take place there will be a substantial electricity surplus during the period 2020 and 2030. In 2040 the surplus has been reduced as a result of nuclear phase-out, however net surplus picks up again in 2050.

One of the major challenges is to substitute the fuels used in transport. The transport sector is heavily reliant on fossil-based fuels. The transition from fossil fuels to renewables requires a production capacity for biofuels in Sweden. The scenario has opted for biorefineries where a high level of efficiency can be reached. Heat from these industries can be distributed through district heating: electricity and biofuels are important energy carriers. The scenario has strong measures for limiting the use of primary bioenergy feedstock due to environmental concerns. In some cases the scenario has opted for a route where electricity is used to provide heat through heat pumps as well as pushing for transport methods that use electricity in order to reduce demands for bioenergy.

District heating demand is anticipated to decrease as a consequence of energy efficiency improvement measures and global warming. At the same time the market share for district heating will increase and a large proportion of the future cooling demand is produced by district heating by absorption cooling. It is vital that the district heating sector can contribute to recover the surplus heat from industry and future biofuel production.

Even though energy efficiency improvement measures take place in all sectors of society, the scenario has not taken full advantage of these opportunities. There are a number of efficiency measures that are linked to for example city planning that would result in changes in need for transport and a range of information and technology options that would also have an impact on the need for transport. Changes in consumption patterns, daily routines and aspirations will have major impacts in the demand side of the energy system. It is important that we become more efficient in our way of living in general.

In order for energy efficiency improvement processes to be initiated there will be a need for incentives and regulations. The scenario acknowledges the challenges that reside in avoiding high levels of rebound effects as the energy demands are reduced and a surplus is created.

The scenario has taken its point of departure in using existing technologies. Even though the technology is available today, and the knowledge of the need to act is present, progress is slow and there is a need to initiate these processes of change promptly. Research and development is needed not only on technologies and production processes, but also on business models and how to create strong and cost-effective regulations and incentives for change to happen.

The scenario is based on the Swedish energy system and demand in Sweden. Still, this energy system is interlinked with Nordic and European energy systems. Many of the resources that we use in the energy system today are purchased on a global market and originate from all around the globe. The scenario presented in this study acts as an input to discussions on these higher levels. Pinpointing the crucial aspects in order to reach a renewable energy system based on accessible resources will make the identification of areas where the need for cooperation and harmonization of the energy and support systems one step closer.

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Appendix 1: Impacts on carbon emissions and atmospheric carbon from using branches and tops for energy

This chapter is a special focus on carbon emissions from the use of forest residues, specifically *tops and branches from final felling*[13]. The objective here is to estimate the impacts on emissions and atmospheric carbon from using tops and branches in the Swedish energy scenario 2010-2050 presented in this report. As there are long rotation times in boreal forests some of the diagrams and results here have a time frame of 100 years.

1. Why do tops and branches have a climate impact?

When biofuels are combusted the carbon that once was bound in the growing forest is released, thus closing the biogenic carbon cycle. For this reason biofuels have been considered carbon neutral. For instance, in the EU emission trading system, carbon emissions from biofuels are not accounted for (European Commission 2003). However, Eriksson and Hallsby (1992) showed that using logging residues for energy, instead of leaving them on the ground, could lead to lower carbon storage in litter and soils. However, this effect is of transient character. If the residues were left on the ground, they would decompose and release carbon to the atmosphere. Using tops and branches for energy can therefore be seen as shifting the emissions earlier in time compared to the reference case of leaving them on the ground to decompose (Zetterberg and Hansen 1998; Lindholm et al. 2010). Figure 25 shows an example of estimated net emissions from using branches for energy, based on simulations of carbon stock changes in Southern Finland (Repo et al. 2010).

13 Tops and branches are usually referred to as GROT in Swedish. GROT does not include stubs but can include tops and branches from for example final fellings but also thinnings. In the WWF adjusted scenario tops and branches cannot be removed from thinnings.

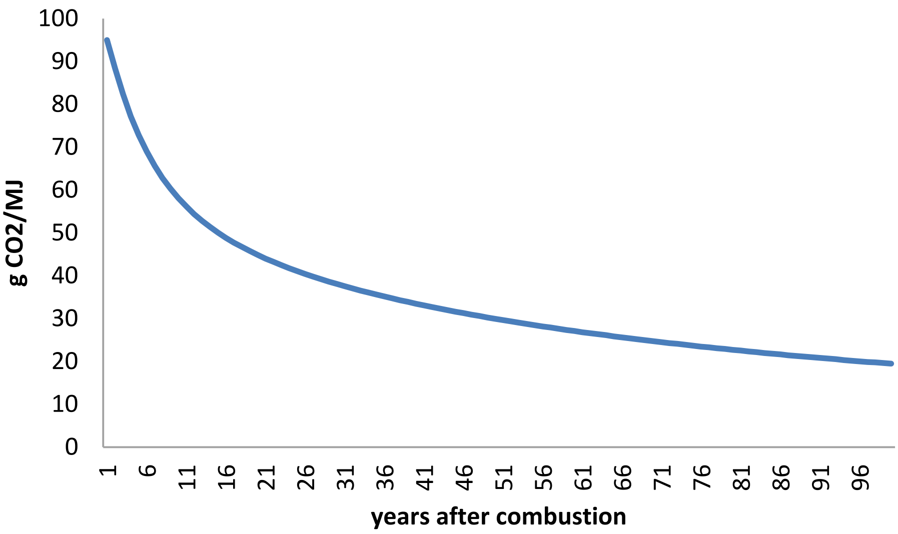

Figure 25: An example of net emissions from using branches (2 cm) for energy. Data is based on simulations of carbon stock changes from using spruce branches (2 cm) in Southern Finland (Repo et al. 2010). The initial emission pulse from combustion is reduced over time due to avoided reference case emission (leaving the branches on the ground to decompose).

2. Emissions

Emissions are calculated based on data on biogenic carbon stock changes. We define the *net* emissions from a biofuel as the emissions from the case of utilization minus the emissions from a reference case:

$$E_{net} = E_U - E_{Ref} \quad (1)$$

This follows the recommendations by Schlamadinger et al. (1997) and is applied by for instance Lindholm et al (2010), Kirkinen et al (2008), Zetterberg and Hansén (1998) and Hagberg and Holmgren (2008).

Emissions, *E*, are calculated based on carbon stock change data, *SC*. If we assume that a reduction of carbon stock results in an immediate emission, *E*, to the atmosphere, the emissions, *E(t)*, will be equal to the time derivative of the carbon stock change, with opposite sign:

(2)

where the prime symbol is used to signify the time derivative. Using (2) into (1) the net emissions, E_{net} will be:

$$E_{net} = SC'_{Ref} - SC'_U \quad (3)$$

3. Remaining CO2 in atmosphere

A pulse emission of CO_2 results in an increase of atmospheric CO_2. However, the remaining mass from this emission pulse decreases over time, as in figure 2.

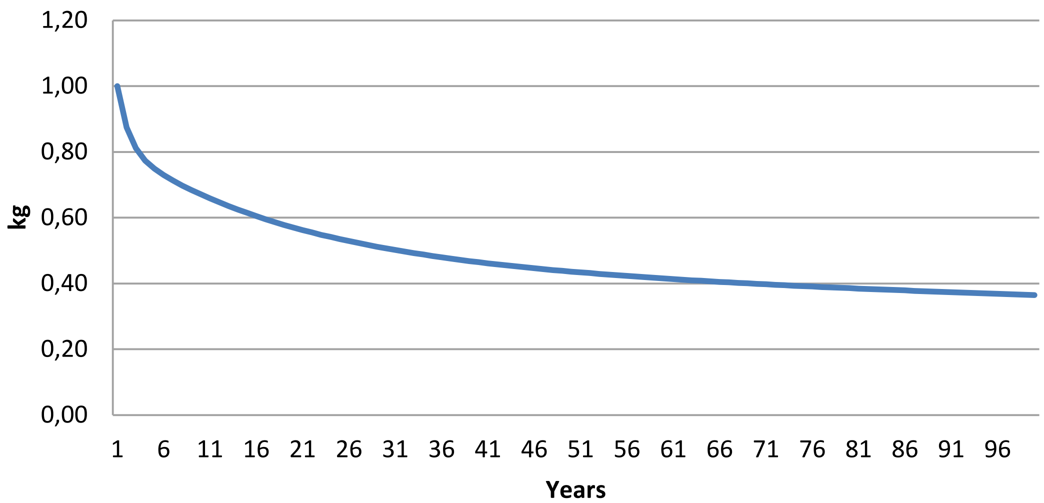

Figure 26: Remaining amount of CO2 after a 1 kg pulse emission at t=0. Data from IPCC (2007b)

The "decay" of atmospheric carbon is due to a number of processes that transport carbon from the atmosphere to other carbon pools, including uptake in ocean surface water and transport from surface water to deeper ocean.

The Intergovernmental Panel on Climate Change, IPCC (2007b) has presented a carbon decay function as a combination of several exponential decay functions:

$$CO_2(t) = CO_2(t=0)^* [0.217 + 0.259 * e^{-t/172.9} + 0.338 * e^{-t/18.51} + 0.186 * e^{-t/1.186}] \qquad (4)$$

4. System boundaries

In this study we investigate the impact on carbon emissions due to using tops and branches as a fuel in a Swedish energy system. We have only considered fluxes of biogenic carbon associated with growth, combustion, decomposition and changes of biogenic carbon pools in trees and soil. We have not included emissions from (fossil) fuel used in equipment for logging, collection, transport, refining and storage of fuels. Nor have we considered energy conversion losses, for instance in the production of electricity, heat or transport fuels. We have not considered substitution effects, such as the emissions avoided when biofuels replace fossil fuels. We have not included other greenhouse gases than CO_2. Furthermore, possible effects on subsequent forest growth after removal of tops and branches are not accounted for.

5. Carbon stock changes for use of tops and branches

Emissions data for use of tops and branches are based on numerical simulations of carbon stock changes made by the "Q-model" (Ågren et al. 2010), presented in Figure 27. The data provides carbon stock changes in the ecosystem (soil and trees) for two different management regimes:

- A reference case with no extraction of forest residues (tops and branches);
- Forest residues: 80% of tops and branches are removed at each harvest.

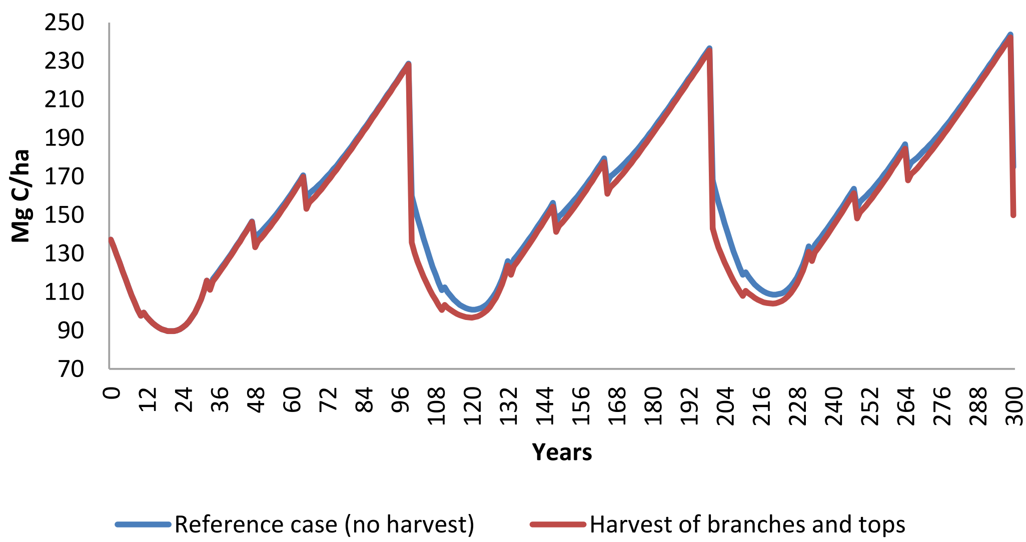

Figure 27: Simulated carbon stock changes in a Swedish spruce forest, assuming two different utilization cases. Data is from Ågren et al. (2010)

The jaggedness of the curve is due to thinning events. We use the second generation data for our calculations, from 100 to 200 years.

6. Energy scenario and emission factors

The energy scenario for utilization of tops and branches is based on the Swedish energy scenario for the period 2010- 2050, which has been developed in this project. We have made the assumption that after 2050 energy use is continued at the same level as in 2050 until the year 2110, see Figure 28

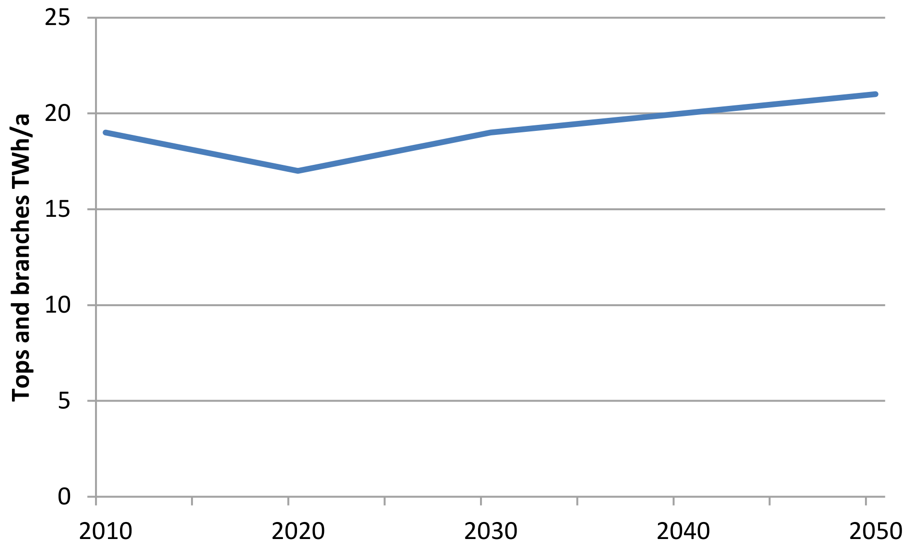

Figure 28: Use of tops and branches in the energy scenario (TWh).

In this report, the combustion-related emission factors are based on Repo et al. (2010) which is 94.4 g CO_2/MJ for tops and branches. For oil, we assume an emission factor of 76.26 g CO_2/MJ, which is the value used in the Swedish national communication to the UNFCCC (Naturvårdsverket 2011).

7. Emissions from using 1 MJ tops and branches at t=0

Net emissions from using tops and branches are calculated as the difference between the two curves in Figure 27, carbon stock changes from using tops and branches minus carbon stock changes from not using them. The resulting net emissions are shown in Figure 29.

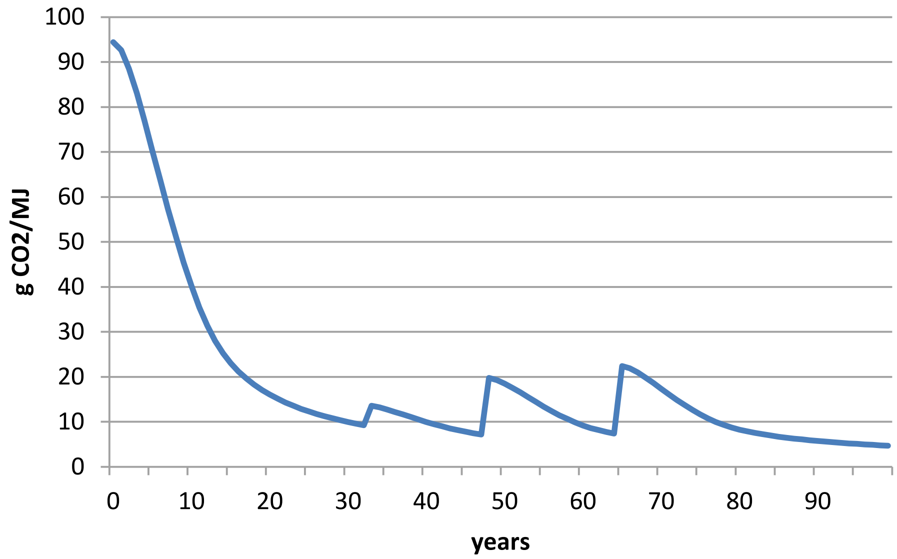

Figure 29: Net emissions from using 1 MJ tops and branches for energy at t=0.

Just after combustion, emissions are 94 g CO_2/MJ. This corresponds exactly to the carbon content of the fuel. However, directly after combustion, the net emissions decrease over time. This is a result of the avoided reference case emissions – leaving the tops and branches on the ground to decompose. This means that in contrast to emission factors of fossil fuels, the emission factor for tops and branches has a dynamic, time-dependent character. After 10 years, emissions from tops and branches are reduced to 40 g CO_2/MJ; after 30 years to 10 g/MJ and after 100 years 5 g CO_2/MJ. For comparison, coal has an emission factor of 93 g CO_2, oil 76 g CO_2/MJ and natural gas 56 g CO_2/MJ (Naturvårdsverket 2011).

The jaggedness of the curve is a result from thinning events at 33, 48 and 65 years. In the energy scenario presented in this report the tops and branches potential does not include resources from thinning. There is no available emission data for that scenario, so thinning is included here and the reader is kindly asked to keep this difference in mind.

8. Calculated emissions for the energy scenario

Based on the net emissions from using one unit of tops and branches for energy (Figure 29), emissions from our energy scenario are calculated and shown in Figure 30, expressed in Mton CO_2. Here we introduce the theoretical concept of an energy source with no net emissions. This is done to show what happens to the accumulated carbon emissions when the emissions cease. Four different scenarios are presented:

1. Tops and branches continued. Here, we assume tops and branches are used throughout the whole period 2010-2109.
2. Oil continued. We assume oil is used throughout the whole period 2010-2109.
3. Tops and branches → emission free. We assume tops and branches are used until the year 2050, and then replaced by an energy source that has no net emissions.
4. Oil → emission free. We assume oil is used until the year 2050, and then replaced by an energy source that has no net emissions.

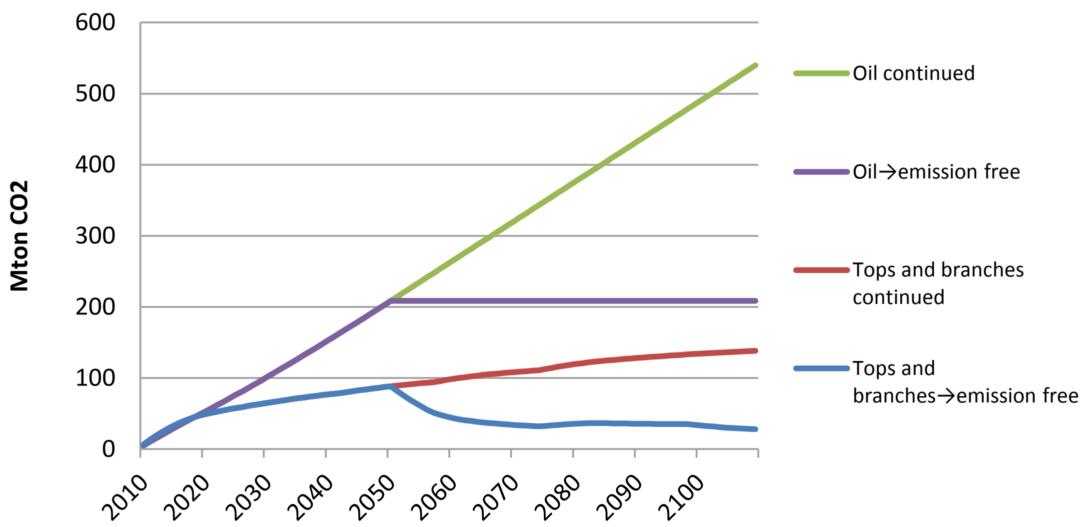

Figure 30: Calculated accumulated emissions for the four scenarios.

All scenarios lead to net emissions. Using tops and branches leads to considerable emissions, but using oil would increase atmospheric carbon significantly more.

Scenario 1. Tops and branches continued. If tops and branches are used as energy throughout the whole period, accumulated emissions from this scenario will be 88 Mton CO_2 in the year 2050 and 139 Mton in the year 2110. This corresponds to 1.4 Mton CO_2 per year during this 100 year period, or 19 g CO_2/MJ.

Scenario 2. Oil continued. However, using oil instead of tops and branches would lead to significantly higher emissions than tops and branches. If oil is used as energy throughout the whole period, accumulated emissions will be 209 Mton CO_2 in the year 2050 and 540 Mton in the year 2110. This corresponds to 5.4 Mton CO_2 per year during this 100 year period, or 74 g CO_2/MJ.

Scenario 3. Tops and branches → emission free. If tops and branches are used 2010-2050 and then replaced by emissions free energy, accumulated emissions will be 28 Mton CO_2 in the year 2110. The sudden decrease in accumulated emissions in the year 2050 is a result from avoided emissions in the reference case of leaving the tops and branches on the ground to decompose.

Scenario 4. Oil → emission free. If oil is used 2010-2050 and then replaced by emission-free energy, accumulated emissions will be 209 Mton CO_2 in the year 2110.

9. Remaining carbon in the atmosphere

Based on our calculated emissions (Figure 30), and the decay function (Figure 29) the remaining amount of atmospheric carbon is calculated and shown in Figure 31, expressed in Mton CO_2.

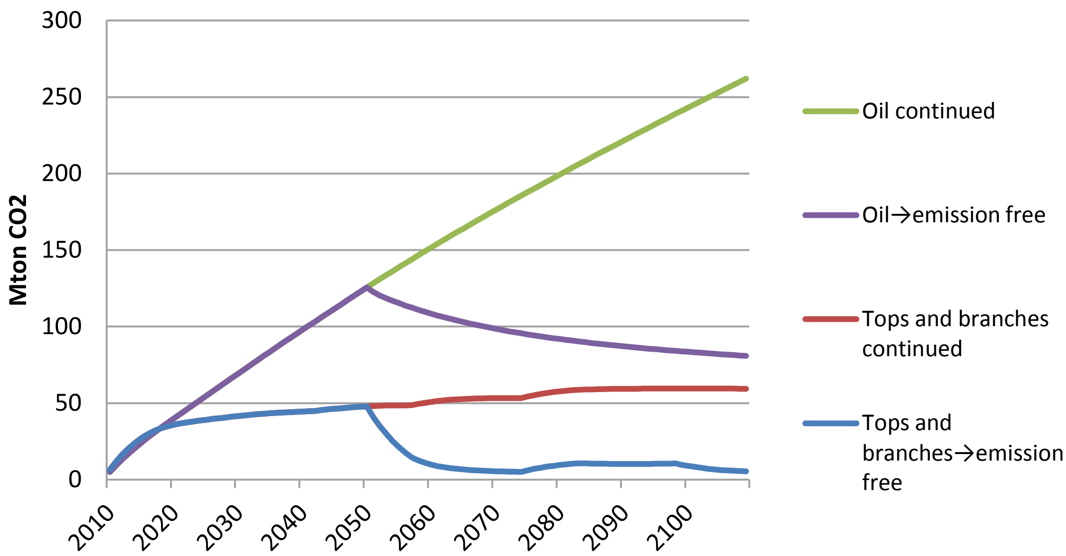

Figure 31: Remaining carbon in the atmosphere from our four scenarios

All scenarios lead to increased atmospheric concentrations of CO_2. Due to the uptake of atmospheric carbon in ocean water and other sink processes about 40-50% of the accumulated emissions remain in the atmosphere after 100 years. Using tops and branches leads to an increase in atmospheric carbon, but using oil would increase atmospheric carbon significantly more.

Scenario 1. Tops and branches continued. If tops and branches are used as energy throughout the whole period, remaining atmospheric carbon will be 48 Mton CO_2 in the year 2050 and 59 Mton in the year 2110.

Scenario 2. Oil continued. If oil is used as energy throughout the whole period, remaining atmospheric carbon will be 126 Mton CO_2 in the year 2050 and 262 Mton in the year 2110.

If emissions cease in the year 2050, there will be a very prompt decrease in atmospheric mass from both the tops and branches scenario (3. Tops and branches → emission free) and the oil-scenario (4. Oil → emission free). The decrease in remaining atmospheric mass from the oil-scenario (4. Oil → emission free) is due to uptake of atmospheric carbon in ocean water and other sink processes. For the tops and branches scenario, the sudden decrease in atmospheric mass is due to two processes; first as a result of avoided emissions from the reference case, and secondly due to the same atmospheric sink processes as in the oil scenario.

Scenario 3. Tops and branches → emission free. If tops and branches are used 2010-2050 and then replaced by emission-free energy, remaining atmospheric carbon will be 5 Mton CO_2 in the year 2110.

Scenario 4. Oil → emission free. If oil is used 2010-2050 and then replaced by emission-free energy, remaining atmospheric carbon will be 81 Mton CO_2 in the year 2110.

10. Concluding remarks on the dynamic perspective of emissions from use of tops and branches

We have investigated the impact on emissions and atmospheric carbon from using tops and branches in a Swedish energy scenario in 2010-2110. This scenario has also been compared with an alternative scenario of using oil instead of tops and branches. We conclude that:

Using tops and branches for energy instead of leaving them on the ground to decompose leads to net emissions of carbon to the atmosphere. The reason for this is the time lag between combustion-related emissions compared to the emissions from decomposition.

Our estimates indicate that using tops and branches for energy at a level of about 19-21 TWh per year for 100 years will lead to net accumulated emissions of approximately 139 Mton CO_2, or 19 g/MJ fuel. We estimate that the remaining amount of atmospheric carbon from the use of tops and branches in this scenario after 100 years will be 59 Mton CO_2. In 2050 the same figure is 48 Mton CO_2. This difference between net accumulated emissions and remaining amount of atmospheric carbon is due to the uptake of atmospheric carbon in ocean water and other sink processes.

However, using the same amount of oil would increase the accumulated emissions by a factor of approximately 4 over the same period, corresponding to 540 Mton CO_2, or 74 g CO_2/MJ oil after 100 years. The remaining amount of carbon in the atmosphere from this emission scenario will be 262 Mton CO_2 after 100 years. In 2050 the figure for oil continued would be 126 Mton CO_2.

If emissions cease in the year 2050, for instance due to changing to a completely emission-free energy source, the impact on atmospheric carbon decreases significantly. For tops and branches, if emissions cease in the year 2050, the remaining amount of atmospheric carbon will be 5 Mton in the year 2110. For oil, if emissions cease in the year 2050, the remaining amount of atmospheric carbon will be 81 Mton in the year 2110.

This study has found that using tops and branches for energy will increase the net emissions of carbon and increase the atmospheric carbon concentrations. However, as compared to using oil, tops and branches will reduce the global carbon emissions significantly. Moreover, in spite of the relative climate benefits of tops and branches there may be other biomass alternatives that are even more beneficial for climate mitigation. For instance, the establishment of new forest on earlier crop land is likely to reduce atmospheric carbon and would have a net cooling effect (Zetterberg and Chen 2011). Above conclusions, however, do not account for emissions in production, transports and conversion losses nor for possible subsequent effects on subsequent forest growth.