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Future Production of Transport Fuel, Power and Heat from Biomass

A Vision of a Large-scale Energy Combine in Göteborg

Julia Franzén

Department of Physical Resource Theory
CHALMERS UNIVERSITY OF TECHNOLOGY
GÖTEBORG UNIVERSITY
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Honor´s Thesis in Environmental Science
with an emphasis on Problem Solving

Göteborg University/Chalmers University of Technology
Department of Physical Resource Theory
Supervisor: Johan Swahn

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Abstract

To reduce the emissions of the greenhouse gas carbon dioxide (CO_2) to the atmosphere different measures can be applied, for example a reduced energy use and a shift from fossil fuels to renewable fuels such as biomass. An energy efficient way of utilising biomass could be for production of transport fuel, electric power and heat in a so-called energy combine. In this report a vision of how a large-scale biomass-based energy combine could be part of a future sustainable energy system in Göteborg has been developed. In order to determine the size of a energy combine, scenarios of the future demand for transport fuel, electricity and heat in the residential and service sector and the transport sector have been made. The method applied is the so-called backcasting approach, which is a method to analyse future options from a sustainability perspective. The sustainability criteria applied are that the energy system should not give rise to net emissions of CO_2, that it is based on renewable energy sources and that it is characterised by efficiency, both on the supply and user side. A population increase of 35% compared with today is also assumed. The image of the future shows a situation where a biomass-based energy combine covers the whole demand for transport fuel and 20% of the electricity demand in the region of Göteborg as well as 95% of the supply of district heat in the municipality of Göteborg. The energy use for heating and the use of electricity is reduced by approximately 50% per capita. The energy use in the transport sector is reduced by more than 70% per capita. The biomass required for the energy combine amounts to 6-8 TWh, which is a substantially extended use of biomass compared with today. The future potentials for biomass utilisation are however large and this aspect is therefore not considered to be an insurmountable obstacle for an energy combine.

Sammanfattning

För att minska utsläppen av växthusgasen koldioxid (CO_2) kan olika åtgärder tillämpas, till exempel minskad energianvändning och en övergång från fossila bränslen till förnyelsebara bränslen såsom biomassa. Ett energieffektivt sätt att använda biomassa skulle kunna vara för produktion av drivmedel, el och värme i ett s.k. energikombinat. I den här rapporten har en vision av hur ett storskaligt biobränslebaserat energikombinat skulle kunna vara en del av ett framtida hållbart energisystem i Göteborg utvecklats. För att bestämma storleken på ett energikombinat har scenarier av framtida behov av drivmedel, el och värme i bebyggelse- och transportsektorn utvecklats. Metoden som har tillämpats är den s.k. backcastingansatsen som är en metod att analysera framtida valmöjligheter ur ett hållbarhetsperspektiv. De hållbarhetskriterier som har tillämpats är att energisystemet inte ska ge några nettoutsläpp av CO_2, att det ska baseras på förnyelsebara energikällor och karakteriseras av effektivitet, både på tillförsel- och användarsidan. En befolkningsökning på 35% jämfört med idag har också antagits. Framtidsbilden illustrerar en situation där ett biobränslebaserat energikombinat täcker hela drivmedelsbehovet och 20% av elbehovet i Göteborgsregionen samt 95% av fjärrvärmetillförseln i Göteborgs kommun. Energianvändningen för uppvärmning och användningen av el minskar med ungefär 50% per capita. Energianvändningen i transportsektorn minskar med mer än 70% per capita. Biomassan som krävs för energikombinatet uppgår till 6-8 TWh, vilket är en kraftig ökning av användningen av biomassa jämfört med idag. De framtida potentialerna för biomassa är dock stora och denna aspekt anses därför inte vara ett oöverstigligt hinder för ett energikombinat.

Acknowledgements

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Julia Franzén

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1. INTRODUCTION

One of the most debated environmental issues today is that of global warming, which is caused by an enhanced greenhouse effect. Even though this issue is connected with large uncertainties, for example regarding the effects a change of the climate might result in, the majority of scientists now agree that global warming is taking place and that it is caused by increased concentrations of the so-called greenhouse gases in the atmosphere.

The temperature of the earth is determined by the process, called the greenhouse effect, in which incoming short wave radiation from the sun is balanced by outgoing long wave radiation of the surface of the earth (e.g. Elvingson, 2001). This balance is for example affected by the absorption of outgoing radiation, which occurs in the atmosphere. Carbon dioxide (CO_2), water vapour (H_2O) and methane (CH_4) are all examples of greenhouse gases absorbing long wave radiation in the atmosphere, hence contributing to a higher temperature at the earth's surface. This natural greenhouse effect raises the mean temperature of the earth by about 33°C. However, increased man-made concentrations of atmospheric greenhouse gases enhance the natural greenhouse effect and thus raise the mean temperature further. The Intergovernmental Panel on Climate Change, IPCC (2001), has estimated that the average temperature at the earth's surface has increased by 0.6°C (with an uncertainty interval of ±0.2°C) during the last century.

The most significant greenhouse gas is CO_2, which contributes to the major part of the global warming. The main anthropogenic source of CO_2 is the burning of the fossil fuels coal, oil and natural gas. Our supply of energy is today to a large extent comprised of fossil fuels, which have resulted in an increased atmospheric concentration of CO_2. The demand for energy has grown steadily the past century and is continuing to grow. At the same time the demand to decrease the use of fossil fuels increases in order to avoid severe consequences due to a changed climate. In order to tackle the climate problem on a long-term basis, the industrialized countries must reduce their greenhouse gas emissions significantly. To do this, different measures can be applied, for example a strongly reduced energy use due to improved efficiencies and a shift from fossil fuels to renewable fuels.

Renewable energy sources have become more and more competitive compared to fossil fuels and nuclear power during the last years and biomass is one example of renewables that have large potentials. In 2000 the Swedish energy supply from biofuels, peat etc. was about 97 TWh, which is more than 15% of the total supply (STEM, 2001). Biofuels are fuels formed in biological processes. The term biofuel is according to Swedish standard defined as fuel where biomass is the original material (STEM, 2003). The fuel can be processed or converted, chemically or biologically. Biomass on the other hand, is defined as material of biological origin, which has not been chemically or biologically converted. The biomass used for energy purposes could be derived from forestry residues, fuel cuttings, non-forest land, forest industry by-products, recovered wood, energy crops and wastes[1]. There are many reasons why

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[1] Wastes include both industrial wastes and wastes handled by the municipality. Municipal waste mainly consists of household waste, out of which 82% is considered to be biomass and 18% to be fossil fuel (Länsstyrelsen, 2001).

biomass appears to be an interesting source of energy. Firstly, it is a renewable resource. Secondly, if biomass is grown sustainably there is no net emission of CO_2 to the atmosphere due to the photosynthesis process. Thirdly, biomass has a large potential, especially in the northern hemisphere. Biomass can thus play a significant role in a sustainable energy system.

The biomass used in Sweden today is used partly for heating and electricity production, partly in different industrial processes (STEM, 2003). An additional usage of biomass could be for production of transport fuels. In order to achieve integration advantages in the production of these energy carriers, they could be co-produced in a so-called energy combine[2]. Gasification of biomass is a technology that transforms solid biomass into syngas for use in advanced conversion technologies and this technique could be the basis of an integrated utilisation of biomass (Overend, 2000). Regarding power production from biomass, the potential advantages of advanced power cycles utilising gasification are increased conversion efficiency compared to the conventional combustion method. This results in reduced feedstock consumption and thus reduced operational costs per generated energy unit. Furthermore, the gasification technology results in reduced emissions of for example nitrogen oxides (NO_x) and particulates. The major advantages of transport fuel production via biomass gasification is that it enables production of different fuels, it results in a high conversion yield and enables low emission levels. By integrating the production of transport fuel, electricity and heat, advantages might be gained since several production factors such as transports and treatment of biomass and electricity and steam in the processes could be planned and used more efficient.

1.1. Current projects

In order to examine how the energy system, including the transport sector, could change to reduce the emissions of CO_2, scenarios for a future sustainable energy use can be developed. This report is conducted within the project GÖTEBORG 2050, which is a research project that works with long-term sustainable images of the future in order to increase the possibilities to reach a sustainable Göteborg in a sustainable world. The main idea behind the project is that working with long-term visions of a sustainable society could motivate a faster development towards sustainability. The objective of the project is to develop, compile and spread knowledge of what a sustainable society could look like and to stimulate research about long-term development. Knowledge and research results are brought out to both societal actors and the public. Other objectives are to provide a basis of municipal and regional planning and strategic development, and that the images of the future will result in the implementation of different demonstration and pilot projects[3].

At present a lot of research and development of gasification technology is in progress and studies regarding energy combines have also been conducted. One example is the BioMeeT project (2000), which is a cooperation between the Trollhättan region and the industry. The purpose of the project has been to investigate the conditions for a biomass-based energy combine in the region of Trollhättan for production of energy

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[2] An energy combine is in this report defined as one or several facilities that co-produce at least three energy carriers.

[3] For more information about the project GÖTEBORG 2050, see www.goteborg2050.nu.

carriers such as transport fuel, fuel gas, electricity, heat and dried solid fuels. This project was preceded by the BAL-Fuels project (1997), which described a methanol plant, self-sufficient of energy, based on biomass gasification. The BioMeeT project has also been followed by BioMeeT II (2003). The objective of this project is to bring stakeholders together in order to prepare for the establishment of the first commercial plant of this kind.

In Göteborg, the municipal energy company Göteborg Energi plans to build a new natural gas-fired combined heat and power, CHP, plant. The plant is planned to be put into operation by the end of 2005 and will be located in the Rya harbour. The project GÖTEBORG 2050 has initiated a research, development and demonstration project where different actors cooperate to develop and demonstrate the gasification technology. In the project the possibilities to connect a facility for biomass gasification to the planned CHP plant in Rya are studied. The gas from the gasification facility could be used partly together with the natural gas in the CHP plant and partly as raw material for production of transport fuel. In this report this thought is taken a step further and a vision of a combine based entirely on biomass is presented.

1.2. Objective and scope of the present study

An important part of a sustainable society is a sustainable energy system. An important part of a future energy system in Göteborg could be a large-scale energy combine based on biomass gasification for production of transport fuel, electricity and heat. The main objective of this report is to develop and analyse a vision of how a large-scale biomass-based energy combine could be part of a future sustainable energy system in Göteborg and thus illustrate an alternative way of achieving a sustainable energy supply. The objective is also to support the project GÖTEBORG 2050's work on developing a vision of a ”Solar City Göteborg 2050”.

In order to estimate the size of an energy combine, scenarios of the future demand for transport fuel, electricity and heat have been developed. As the title of the report implies, the scenarios are limited to Göteborg. In the case of heat, the municipality of Göteborg is regarded since district heat only can be delivered within a limited area[4]. In the case of transport fuel and electricity the whole region of Göteborg, i.e. the municipalities Ale, Alingsås, Göteborg, Härryda, Kungsbacka, Kungälv, Lerum, Lilla Edet, Mölndal, Partille, Stenungsund, Tjörn and Öckerö, is regarded.

The report begins with a description of the methodology applied and then the results, i.e. the image of the future, are presented. The result section starts with a presentation of the criteria for a future sustainable society. Thereafter a survey of potential biomass-based facilities for production of transport fuel, power and heat is conducted and this is followed by a presentation of the scenarios of the future energy demand. The size of the energy combine is then estimated on the basis of the future demand and the biomass required is compared with estimates on future biomass potentials. Finally the relevance of the vision and the possibility to realise it is discussed and conclusions are drawn.

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[4] A limited amount of district heat is also delivered to the neighbouring municipalities Ale, Mölndal and Partille.

2. METHODOLOGY

The method applied in this report to develop an image of the future is based on the backcasting approach. Backcasting means that you develop one or several scenarios by starting in the future and generate one or several images of the future. In order to develop the image of the future, primary information such as scientific articles and statistics has been surveyed. In this section a presentation of the backcasting approach and the data utilised, is made.

2.1. The backcasting approach

The term backcasting denotes a method to analyse future options and has been applied in a number of energy future studies. Today the field of future studies is dominated by the traditional forecasting approach. Since this approach is based on dominant trends, it is unlikely to generate solutions that presuppose the breaking of trends (Dreborg, 1996). In the long run, however, discontinuities are likely to occur and the application of the forecasting approach in the study of complex long-term sustainability problems could therefore be questioned. When issues of this kind are studied, backcasting can be an interesting alternative approach.

Four different types of future studies have been identified (Steen and Åkerman, 1994, acccording to Dreborg, 1996). *Directional studies* investigate different economic and other measures in short-term that will probably work in the right direction towards sustainability. An analysis of how close to sustainability the society reaches is however not addressed. *Short-term studies* take immediate official goals, often political, as a starting point and try to find means of achieving them. Due to their short-term character, these goals are usually just a small step towards sustainability. The third type of future studies is *forecasting studies* or prognoses, which apply a long-term perspective. Usually, restricted presumptions of the possibilities of major change make this approach fail to reach sustainability. *Backcasting studies* are also long-term studies but start with images of future scenarios.

Backcasting is used to develop so-called normative scenarios, i.e. images of the future where the result describes a possible and desirable future where criteria for sustainability are fulfilled. One important difference between prognoses and backcasting studies is that in the former you are trying to find “likely” energy futures while in the latter you are trying to examine how desirable energy futures can be achieved (Swahn et al., 1996). In the three first types of future studies mentioned above there is no comparison of how the predicted change stands in relation to sustainability. There is thus a risk of achieving images of the future that in the long term may lead the development away from the goal of reaching a sustainable society. Steen and Åkerman (1994, according to Dreborg, 1996) have identified different situations where backcasting is of particular interest:

- when the problem studied is complex, hence affecting many sectors of society;
- when there is a need for major change;
- when dominant trends are part of the problem;
- when the problem to a large extent consist of externalities;
- when the time perspective is long enough to allow scope for deliberate choice.

Backcasting should thus be taken into consideration when the subject studied is a major societal problem that needs a solution. Dreborg (1996) argues that there is a need for studies of backcasting type as a basis for a public discussion about sustainability policy.

Backcasting studies generally consist of four steps, which are shown in figure 3.1. The first step is to identify the problem and make a description of the present situation (Eek and Swahn, 2003). Existing trends in the area of focus are also analysed. The second step is to choose criteria, goals and limitations for the study. External factors that might affect the scenario, for example population development and changes of life style patterns, should be taken into consideration. The next step is to develop one or many alternative images of the future on the basis of the goals/criteria chosen in step two. This step is usually considered the core of backcasting studies since it illustrates a solution to a major problem. The fourth, and last, step is to analyse the possibilities to reach the society described in the images. The possible need for a breaking of trends is also discussed. In this report, the ambition is not to perform a complete backcasting study, but merely to conduct the third step and, to some extent, the first and the second step.

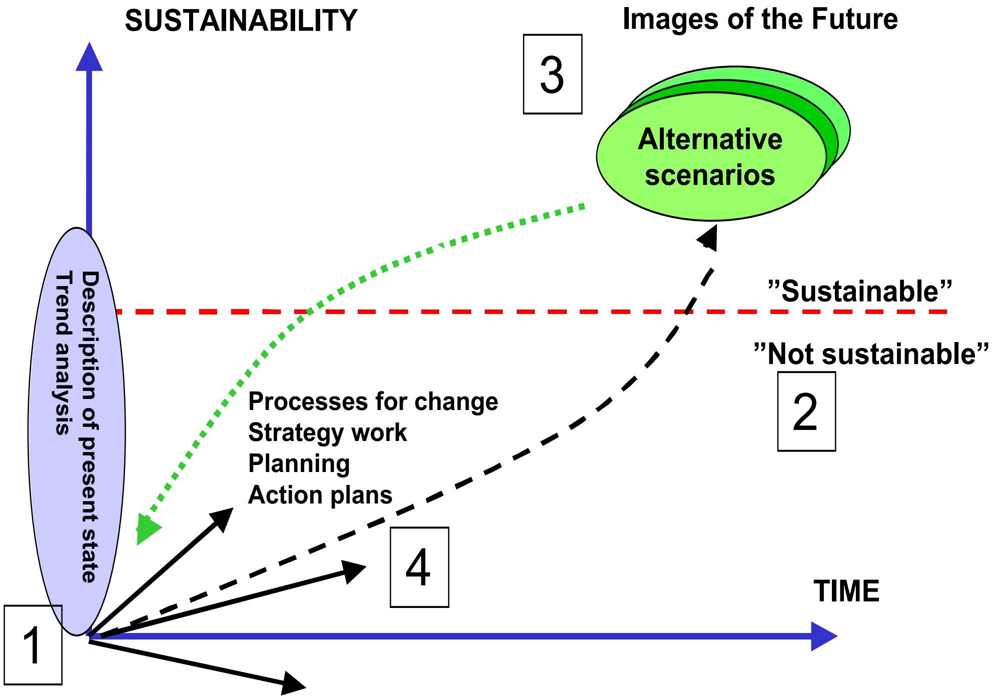

Figure 3.1. *The four steps of the backcasting methodology. The first step includes a description of the present and a trend analysis. In step two criteria and goals, e.g. regarding sustainability, are chosen. In the third step images of the future are developed and in the fourth step an analysis of how to reach the images is made. The figure has been taken from Eek and Swahn (2003).*

2.2. Data

The image of a future large-scale energy combine in Göteborg has been developed as a scenario where different parameters, for example future demand for transport fuel, electricity and heat and future potentials of biomass, have been identified and analysed. In order to describe an energy combine based on biomass gasification for production of fuel, electricity and heat a survey of literature, including scientific articles and reports, on potential technology has been made. Beside information from literature information from experts in the field of chemical engineering has been received to clearify some aspects of the processes of biomass-derived fuel, electricity and heat.

The future demand for electricity and heat has been estimated for the residential and service sector and the future demand for transport fuel has been estimated for the transport sector. The industrial sector has only been briefly considered regaring use of electricity and district heat. The energy situation today is also presented in order to have a base for the analyses of the future energy demand. Data on the present energy use has been gathered from statistics from SCB (2003b) and STEM (2001) and from the municipal energy company Göteborg Energi (2002). In the cases where data has not been available, estimations have been made on the basis of calculations. This is the case for example regarding energy use for heating and the use of domestic and operating electricity in the residential and service sector, where the energy use has been estimated from calculations on total useful floor space and calculations on specific energy use for a national level. The future energy use has been estimated from a number of assumptions, for example regarding efficiency potentials. All assumptions are compared and/or based on other future studies conducted in the respective fields (e.g. Hedberg et al., 2003 and Azar and Lindgren, 1998).

3. RESULTS

In this section the results, i.e. the image of the future, are presented. The section starts with a discussion of the criteria/conditions applied for the sustainable society. Thereafter a survey of possible future biomass-based energy facilities for production of transport fuel, electricity and heat is made. Scenarios of the future demand for fuel, electricity and heat are then presented. Finally a combine is sized on the basis of the demand and a compilation of estimates of future potentials for biomass is made.

3.1. The sustainable society

The term ‘sustainable development’ was spread after the work of the Brundtland commission in 1987 where it was defined as “*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*”(WCED, 1987). This formulation was an important step in the recognition that environmental protection and natural resource management have to be integrated with socio-economic issues like poverty. The definition of sustainable development is however vague and different attempts to interpret the meaning of the term have been made. The most common aspect of sustainable development is the preservation of the environment, which has resulted in the formulation of various principles for ecological sustainability (Steen et al., 1997). For example have Costanza and Daly (1992, according to Steen et al., 1997) defined principles for guidance of anthropogenic production and consumption pattern in order not to exceed the carrying capacity of the ecosystems. These principles are to limit anthropogenic activity to what nature can endure by striving for efficiency through technological innovations, by not using renewable resources faster than they are regenerated, by not emitting more waste than the assimilative capacities of the ecosystems can handle and by not consuming non-renewable resources faster than renewable alternatives are created. Other aspects of sustainable development that are usually included in the interpretations are a fair distribution of resources between present and future generations, a fair distribution of resources within generations and enhanced or maintained life quality (Steen et al, 1997).

The different interpretations of the term sustainable development can be used as a base to generate possible scenarios of a sustainable society. However, they do not give a clear definition that can easily be implemented in practice. In this report, which is limited to the energy use in the residential and service sector and the transport sector, sustainability is interpreted as a future where the energy system is based entirely on renewable resources. Nuclear power, which use non-renewable fuels and generate radioactive wastes, and fossil fuels have been phased out. There is thus no net emission of CO_2 to the atmosphere. The energy system is characterised by efficiency, both on the supply and user side. The future energy use is therefore reduced substantially compared to today, even though the population increases.

In 2000 the municipality of Göteborg had about 467 000 inhabitants and the 13 municipalities in the region of Göteborg had about 845 000 inhabitants (SCB, 2003a). The population in Göteborg municipality is thus the dominating municipality in the region regarding population and constitute more than half of the region’s total population. According to recent population trends an increased immigration to the regions of Stockholm/Uppsala/Mälardalen, the area of Öresund and Västra Götaland will occur, while the rest of the country will have a negative population development (IVA, 2003). In a future sustainable society, however, it is assumed that this trend has changed and that no net immigration to the metropolitan areas occurs. The question of how the migration on an international level will develop is another important and crucial factor for the population development. In 2002 the immigration surplus, defined as the number of immigrants minus the number of emigrants (both domestic and international), was about 4 500 in the region of Göteborg and 2 700 in the municipality (SCB, 2003a). Conflicts and social differences, which today bring about immigration, do not exist in a sustainable world and it is therefore assumed that the net migration is zero. Moreover, it is assumed that the older part of the population will continue to grow. In 2002 the birth surplus was about 2 100 in the region and 1 000 in the municipality (SCB, 2003a). In 2050 the birth and mortality rates are assumed to be of equal size. According to a prognosis conducted by SCB, the population in Sweden will grow with 12% from 2000 until 2050. Since it is assumed that there will be an increased immigration the coming decades, both to the region and the municipality, the population will probably increase more than on a national level. In this report the assumption of a population increase of 35% made by Löwendahl (2003) is applied. This means an increase to about 630 000 inhabitants in the municipality and 1.1 million in the region. Due to the assumption that the difference between the birth and mortality rates and the net migration rate are zero, the population is held constant after 2050.

There are different possible scenarios for how the society and its values will develop in the future. Our society today is, to a large extent, characterised by time strain, a fast tempo and large material consumption. It can be assumed that a continued economic growth, increased prosperity, consumption and travelling will be desirable in the future, but it is not sure that the growth results in material abundance. It is conceivable that our view of happiness and welfare changes in the future, hence making material consumption less important. Perhaps the working hours are shortened and the consumption increase moderate. Perhaps spare time, to a larger extent, is used for garden work, maintenance of dwellings, family and friends etc. It is not unreasonable to assume that the behaviour of the citizens has changed due to a greater awareness of the earth's limited resources. The preferences in this vision of our society's development does not constitute a quantitative tool for the energy scenarios, but rather a qualitative base for certain assumptions regarding for example energy use and standard of living.

3.2. Biomass-based energy facilities

At present there are no existing large-scale bioenergy combines for production of transport fuel, electricity and heat, although some studies of potentials and prospects have been made (e.g. BAL, 1997, BioMeeT project, 2000, BioMeeT II, 2003, Hamelinck and Faaij, 2002 and Wahlund et al., 2002). In the future however, a bioenergy combine could be an energy efficient way to satisfy the demand of transport fuel, electricity and heat and reduce the use of fossil fuels. The demand of these energy carriers varies from country to country and region to region and the aim of a combine should first and foremost be to satisfy the local and regional demands. The facilities described in this report are based on technologies that are available today but not fully developed and/or commercial in large scale. It is assumed that development, demonstration and deployment in the future have resulted in mature technologies and lowered costs, thus enabling large-scale operation of a biomass-based energy combine. The conversion efficiencies mentioned in this section are defined as the energy content of the energy carrier generated divided by the energy content of the biomass supplied. All efficiencies are denoted on a LHV (lower heating value) basis unless otherwise noted[5].

3.2.1. Overview of alternatives

The possible alternatives for biomass-based energy facilities considered in this report are all based on gasification of biomass. Gasification is a conversion process where a solid fuel is reacted with hot steam and air or oxygen (O_2) to produce a gaseous fuel called synthesis gas or syngas. Syngas produced from gasification of wood raw materials consists of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2) and methane (CH_4) as main components (BioMeeT II, 2003). The gas also consists of various contaminants like particulates, tar compounds and dust. Gasification of biomass is interesting from two perspectives, partly as a product gas for synthesis of a transport fuel, partly as fuel gas for combustion in a gas turbine.

In principle, there are many different ways in which an energy combine could be designed, depending on the different types of technologies available (Tijmensen et al., 2002). There are different types of gasification reactors and the gasification can occur at different pressures and with either oxygen or air as gasification medium. Pressurised gasification concepts however have higher overall efficiencies than atmospheric concepts (Tijmensen et al., 2002). Furthermore, gasification with oxygen is only necessary when the syngas produced in the gasifier is used for fuel production, since the synthesis reactor requires a gas of high purity. If the syngas is used directly for power production the gasification can occur with air. On the other hand, the heating value of the gas increases about a factor two when the gasification occurs with oxygen and steam (Maniatis and Millich, 1998). The energy required in the air separation unit might thus be regained in terms of enhanced electricity yields in the power unit.

Different gasification methods can produce a variety of syngas compositions. To receive a composition suitable for the purpose, different gas processing steps can be applied, for example methane reforming and/or a shift reaction. Since syngas derived from biomass gasification contains contaminants the gas needs to be cleaned in order not to destroy the downstream equipment. There are also different routes of cleaning, for example the conventional 'wet' low temperature cleaning and the advanced 'dry' hot gas cleaning, of which the latter might contribute to a better performance (Hamelinck and Faaij, 2002). The technology is however not yet completely proven. The fuel synthesis can also be realised in different reactor types, for example in conventional reactors using fixed bed technology or in liquid phase reactors using slurry technology.

There are also different possible basic configurations of the combine. Depending on the market for each energy carrier, different configurations are suitable. In figure 3.1

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[5] The heating value of a substance is defined as the amount of energy released when a certain amount of the substance is completely combusted and it can be expressed in terms of higher or lower heating value. Higher heating value means that the water from the fuel and the combustion is in liquid phase, while lower heating value means that the water is in vapour phase.

three alternatives are shown. The first option is a so-called integrated gasification combined cycle, IGCC, for production of electricity and heat. The second configuration is a liquid fuel production plant, self-sufficient of electricity. There is however no net production of electricity. This is, on the other hand, the case in the third alternative, where production of liquid fuel, electricity and heat is combined. An additional alternative could be to divert part of the syngas exiting the gasifier in the third alternative directly to the combined cycle.

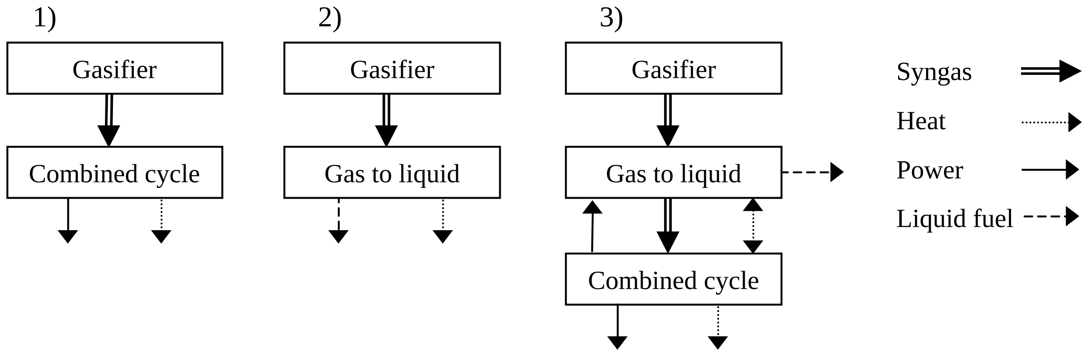

Figure 3.1. *Possible combine configurations for production of liquid transport fuel, power and heat, respectively. The figure is based on Ekbom and Waldheim (2003).*

When liquid fuel is produced the off gas from the fuel synthesis reactor can be partially recycled or be used directly for power production. The concept with recycling is called a “full conversion mode”, aiming at maximised fuel production. This is the case in the second alternative in the figure above where only fuel and heat is produced. The concept without recycling, which is applied in the third alternative, is based on a “once through synthesis” concept. The syngas is thus only brought once through the synthesis reactor. The off gas is then utilised for power production, which means that the fuel production is not maximised. The gas leaving the fuel synthesis is suitable for a variety of gas turbines, for example the combined cycle or the evaporative gas turbine (BioMeeT project, 2000). The fuel synthesis could be modified to include production of different fuels such as methanol, ethanol, dimethyl-ether (DME), Fischer-Tropsch liquid and gaseous hydrogen. In the processes surplus heat that can be used for district heating is also generated. There are thus many ways in which an energy combine could be designed and in the sections below the three different alternatives shown in figure 3.1 are described more in detail.

3.2.2. Co-production of power and heat

For production of power and heat a biomass integrated gasification combined cycle, BIGCC, is a promising option. In this process pre-treatment of biomass, gasification, flue gas cleaning and power generation are integrated. The power-generating unit consists of a combined cycle, which comprise of two power-generating cycles that are combined in a two-stage process, resulting in a high overall efficiency. The IGCC technique was originally developed for fossil fuels, but the principle can also be applied to biofuels. Biomass-based IGCC plants have been demonstrated in small scale in for example Värnamo, Sweden and the ARBRE project, U.K.

The BIGCC process consists of several steps of which the main steps are shown in figure 3.2. First the biomass has to be dried and crushed in order to receive a fuel of right moisture content and properties (Ståhl and Neergaard, 1998 and Sydkraft, 2001). In the pre-treatment step the biomass is screened from metal by magnetic separation and is crushed to the size suitable for the feeding system. After the pre-treatment unit the processed biofuel is transported to the dryer unit. The prepared fuel is then fed to the gasifier where a syngas is produced. The gasification can occur either with air or oxygen and be either atmospheric or pressurised. The gas produced contains various contaminants like particulates, tar compounds and dust, which can corrode the downstream gas turbine. The particulates, which consist of bed materials, particles of unburnt wood and ash, are separated from the gas in the gasifier. The gas exiting the gasifier is then cleaned from tars and other impurities before being combusted in the combined cycle. The clean syngas is supplied to a gas turbine connected to an electricity generator. The exhaust gas that leaves the gas turbine is cooled in a heat recovery steam generator, recovering high-pressure steam. The steam is expanded through a steam turbine connected to an additional electricity generator. The latent heat, i.e. heat of evaporation, in the exhaust steam from the turbine can be used to supply heat to the district heating system via heat exchangers.

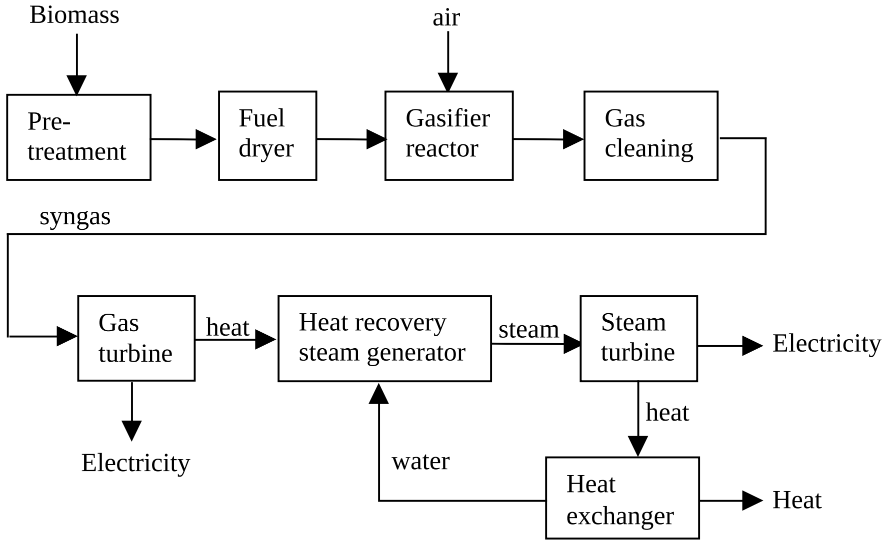

Figure 3.2. *Schematic description of a Biomass Integrated Gasification Combined Cycle, BIGCC.*

A BIGCC plant can be designed in many different ways depending on the application and the demand of electricity and heat, respectively. For example, the steam turbine can be operated in condensing mode in order to maximise the electricity production or be operated in backpressure mode in order to achieve an increased heat production and overall efficiency (BioMeeT project, 2000). Several studies show that well optimised plants based on pressurised gasification, integrated into a combined cycle with a steam turbine operated in backpressure mode, can achieve net electrical efficiencies of 40-50% and an overall efficiency of 85-90% (Sydkraft, 2001).

An additional technology that might be competitive in the future is integration of the evaporative gas turbine cycle, EvGT, with gasification of biomass (Steinwall, 1997 and IVA, 2002a). The EvGT cycle has the advantage that no steam cycle is necessary for using the heat in the exhaust steam from the gas cycle since the heat in this case is recycled directly to the gas turbine. This decreases the capital cost and makes it more suitable for small power outputs, while the electrical efficiency is still competitive with the efficiency in a combined cycle.

3.2.3. Co-production of methanol and heat

Methanol and several other liquid fuels such as ethanol, DME and Fischer-Tropsch and also gaseous hydrogen fuel can be produced from biomass via gasification. In this report, however, the focus is on methanol synthesis. The production process consists of the following basic steps: pre-treatment of biomass, gasification, gas cleaning, shift-reaction, methane reforming, methanol synthesis and purification (BAL, 1997 and Hamelinck and Faaij, 2002). A simplified process diagram of the overall plant is shown in figure 3.3. The three first steps are basically the same as in an IGCC (see section 3.2.2 above). The gasification, however, takes place with oxygen and steam instead of air in order to avoid nitrogen (N_2) dilution. The objective is to produce a syngas with a minimum of methane and a high amount of hydrogen to favour the synthesis of methanol. To receive the required oxygen, an air separation unit is needed. In this unit air is separated into oxygen and nitrogen of high purity. The main part of the oxygen is used as gasification medium, while a minor part is used in the methane reformer step. The nitrogen is used as an inert gas for different purposes within the plant.

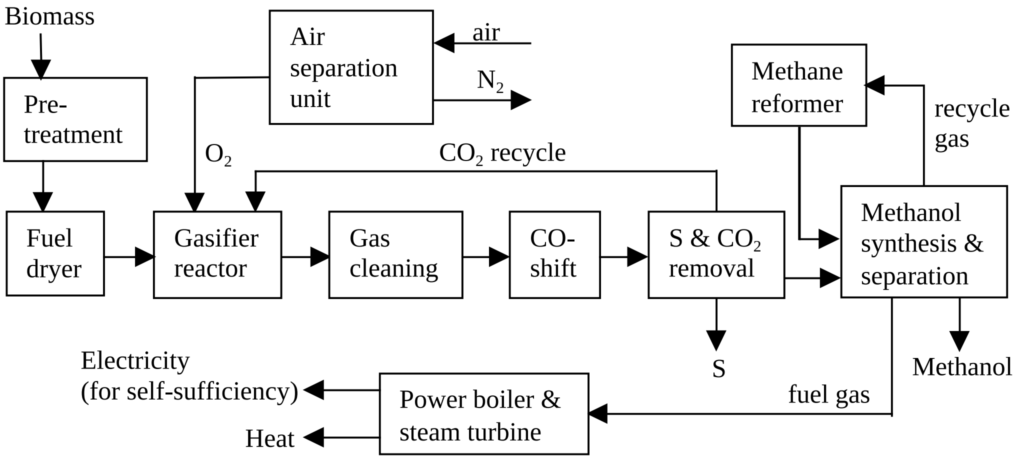

Figure 3.3. *Schematic description of a self-sufficient methanol plant based on the "full conversion" concept.*

After the gas cleaning section the syngas is passed through a shift conversion unit where the hydrogen to carbon monoxide ratio (H_2/CO) of the gas are increased by converting carbon monoxide with steam to hydrogen and carbon dioxide. This is made in order to receive a syngas of optimal relation between hydrogen and carbon monoxide to suit the methanol synthesis, hence maximising the methanol production. To avoid poisoning of the catalyst in the methanol synthesis process, acid gases in the syngas that contain sulphur must be removed. This is done by washing, either with a physical or a chemical solvent, after the carbon monoxide shift conversion (BioMeeT II, 2003). Physical washes dissolve the acid components and chemical washes contain chemicals that react with the components. The sulphur removal step is followed by removal of carbon dioxide. Carbon dioxide has to be removed from the syngas since it is needed as an inertization gas in the fuel feed system and is therefore recycled back to the gasification unit (BioMeeT project, 2000). The carbon dioxide removal also benefits the methanol synthesis in that it is possible to achieve an optimised reaction equilibrium, which results in higher methanol yields, and in that the equipment can be made smaller. The removal process can be based on either physical or chemical absorption.

The cleaned syngas is transferred to the methanol synthesis unit where it is synthesised into fuel-grade methanol. First the feed gas is compressed to suit the pressure requirements of the methanol synthesis and is then further cleaned from possible contaminants. The syngas is thereafter fed into the synthesis reactor, which can be based on conventional gas phase processes or liquid phase processes (Hamelinck and Faaij, 2002). The synthesised methanol leaves the reactor together with unreacted gas and is then passed to a methanol separator where clean liquid methanol is produced by cooling and condensing. In order to maximise the total methanol yield the process is based on the “full conversion” concept. The unconverted gas that remains after the methanol production unit is then recycled back to the methanol synthesis reactor via a methane reformer. In the reformer, methane is converted with steam to carbon monoxide and hydrogen in order to receive a gas of syngas quality.

The unconverted gas exiting the methanol synthesis can still contain a significant amount of chemical energy. Some of this gas can be utilised for power production in order to make the overall plant self-sufficient of electricity. If the heating value of the gas is too low for stable combustion in a gas turbine, it can be fired in a boiler connected to a steam turbine. Steam of various pressure levels is also produced in different units of the process, for example in the methanol synthesis and the methane reformer. This steam is utilised for different purposes within the plant, hence making it self-sufficient in terms of steam as well. In addition, surplus heat available as hot water for the district heating system is produced. The conversion efficiency of methanol in an energy-wise self-sustained plant aimed at maximised fuel production could be around 55% (BAL, 1997, Ahlvik and Brandberg, 2001 and Hamelinck and Faaij, 2002). The yield of heat available for district heating was in the BAL-Fuels project (1997) estimated to be about 12%. This potential is however underestimated (Brandberg, 2003) and here the heat available is assumed to be 15%. This gives an overall efficiency of 70%.

3.2.4. Co-production of methanol, power and heat

A methanol plant, as described above, can be extended to become a net producer of electricity. In order to attain an increased share of power and heat, the process is then based on a “once through synthesis” concept, where the syngas is only brought once through the synthesis reactor. The balance between methanol and power production can however be shifted and some unconverted gas can be recycled in order to enhance the methanol yields (BioMeeT project, 2000). A simplified process diagram of an energy combine for production of methanol, electricity and heat is illustrated in figure 3.4. The design is principally based on the BioMeeT project conducted by Nykomb Synergetics AB and Ecotraffic R&D AB (2000) and Hamelick and Faaij (2002). Beside transport fuel, electricity and heat it is possible to make use of the by-products generated in the processes of the combine and for example receive fuel gas and dried solid fuel as two additional energy carriers (BioMeeT project, 2000). The possibility of delivering fuel gas is however not considered in this report. The potential of receiving dried solid fuel is discussed in section 3.4.1.

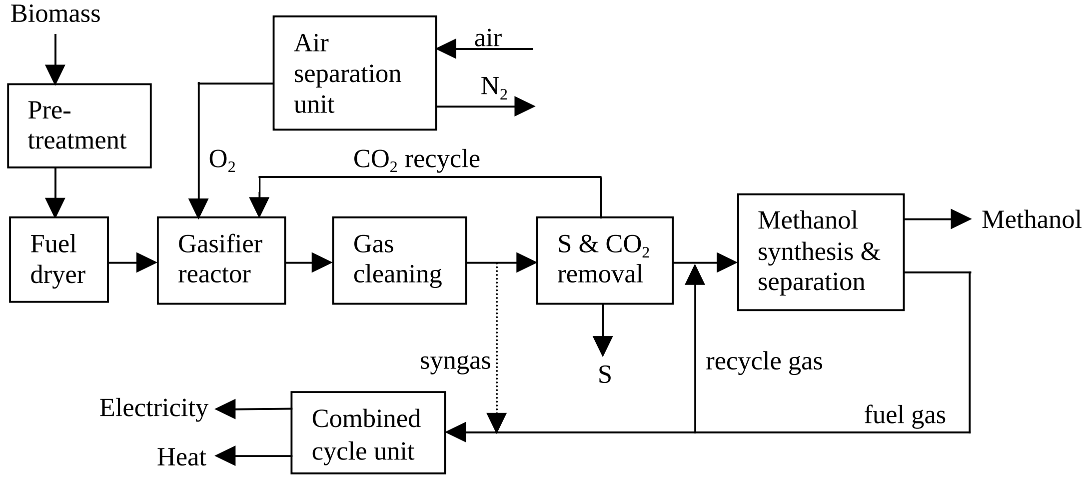

Figure 3.4. *Schematic process description of an energy combine based on a "once through synthesis" concept for production of methanol, electricity and heat.*

The configuration of a plant for co-production of methanol, power and heat are in many ways similar to a methanol plant. There are however some modifications. For example, if the plant is not aimed at maximised methanol production, the methane reformer step can be excluded. Moreover, if a "once through synthesis" concept is adopted the carbon monoxide shift unit can also be found to be unnecessary (BAL, 1997 and Hamelinck and Faaij, 2002). If a liquid phase methanol synthesis is adopted, which might be preferable in a "once through" concept, shifting the gas composition is not necessary since the reactor is flexible towards different compositions. Instead, water can be injected directly in the synthesis reactor, thus allowing a shift-reaction to take place within the reactor itself. After "once through" methanol production the gas still contains enough chemical energy to be combusted in a gas turbine. In order to optimise the gas usage, the gas exiting the methanol synthesis could be combusted in a combined cycle unit, as described in section 3.2.2 above. Some syngas could also be diverted to the combined cycle directly after the gas cleaning section in order to achieve a flow suitable for the gas turbine (BAL, 1997).

By integrating production of fuel, electricity and heat, some advantages might be gained. For example, the exclusion of the methane reforming step results in savings of electricity and heat consumption (BAL, 1997). The supply and demand of heat within the plant might also be better utilised in a combined system, which could increase the overall efficiency. Furthermore, it can be argued that "once through" concepts perform better than "full conversion" concepts due to the lower energy quality of liquid fuel compared to electricity (Hamelinck and Faaij, 2002).

The conversion efficiency of an energy combine of this kind could differ depending on the configuration. In the BioMeeT project (2000) two different cases with production of methanol, electricity and heat were considered. In the first case the electricity production was maximised, resulting in an output of about 25% methanol, 17% electricity and 5% heat. The second case was aimed at increased heat production and resulted in an output of about 25% methanol, 10% electricity and 36% heat. These outputs were however not maximised and could be improved through different modifications in the process. Hamelinck and Faaij (2002) have performed system calculations of different concepts of methanol and power production, aiming at high energy efficiency and/or low costs. Their objective was to identify future prospects for biomass to methanol concepts and the calculations include both commercial and promising non-commercial technologies. This results in various yields depending on the design of the combine. For example, using a pressurised, oxygen-fired gasifier, where the syngas is cleaned by the conventional cooling and scrubbing technology, and the gas is synthesised in a liquid phase methanol reactor with water injection the yield of methanol and electricity was calculated to be about 26% and 24%, respectively, denoted on HHV (higher heating value) basis. In a similar configuration, where the advanced hot gas cleaning technology is used and a methane reforming step is included, the yield was about 40% and 15%, respectively.

An additional configuration for co-production of methanol, power and heat could be a combination of an IGCC and a methanol plant (Ekbom and Waldheim, 2003). After the gasification and gas cleaning sections, a smaller part of the syngas could be diverted directly to a combined cycle unit since the combined cycle does not require a gas of as high purity as the methanol synthesis and the synthesis is a costly procedure (Ekbom, 2003). In this case the methanol plant could utilise electricity from the combined cycle instead of being connected to a boiler and steam turbine in order to be self-sufficient, as is the case in the stand-alone methanol plant described above. Since the syngas is divided between the methanol plant and the combined cycle the net yield of each energy carrier will be proportional to the amount of syngas diverted to the plants, respectively.

By including a dehydration function in the methanol reactor, DME could be produced (BioMeeT project, 2000). This increases the productivity of the reactor and results in more transport fuel and less unconverted gas. The higher efficiency is however obstructed by the less efficient recovery process where gaseous DME must be converted to liquid. Another possibility is co-production of hydrogen. In this case the syngas is modified through reforming and shifting to a hydrogen rich gas, from which it is possible to separate and compress the hydrogen (Hamelinck and Faaij, 2002). There are different methods for hydrogen separation but the most common process in new hydrogen plants today is pressure swing adsorption, PSA. Using this method, recovery rates of 90% and up are achievable and the product purity is as high as 99.999%.

In the sections above a survey of different biomass-based facilities for production of transport fuel, power and heat has been made. As was mentioned, the technologies reviewed are basically available today but not completely developed or commercial in large scale and the efficiencies mentioned are based on literature and pilot-scale operating experiences. This means that the efficiencies might be slightly improved in future facilities that are operated in larger scale. For example, the heat integration of the total plants could be improved, resulting in higher yields (Tijmensen et al., 2002). More development and reasearch are also needed for development of large-scale pressurised gasification systems and also the gas cleaning section should be given attention since it is still uncertain whether it can meet the strict cleaning requirements.

3.3. Future energy demand

In order to determine the size of the energy combine it is necessary to know the future demand of heat, electricity and transport fuel. In this section sustainable energy scenarios for Göteborg in year 2050 are developed[6]. The energy demand is estimated for the residential and service sector and the transport sector. A brief description of the energy situation today in each sector is also made in order to have a base for the subsequent analyses of future energy use[7]. It should however be noted that the calculated energy use, both for today and the future, is approximate for example due to imperfections in statistics, disagreements in data from different sources and inconsistent definitions. The accuracy of the data is however sufficient for the purpose of this report. Moreover, the calculated energy demand only shows the yearly demand and does not consider seasonal variations. The scenarios are constructed on the basis of the principle that energy supply in a sustainable society is renewable. The overall supply is therefore based on biomass, hydropower, solar energy and wind power.

3.3.1. The residential and service sector

The residential and service sector includes residential buildings, non-residential premises, holiday homes, land use applications and other service applications, including the building sector, street lighting, waterworks, sewage treatment plants and electricity works. Almost 90 % of the energy use in the sector is made up of the use in residential buildings and non-residential premises and the scenarios are limited to these only. Residential buildings include detached houses (one- and two-dwelling buildings) and multi-dwelling buildings. Non-residential premises include commercial premises and public buildings like offices, hotels, schools, hospitals etc. Industrial premises are not included since statistics for the extent and energy use of these premises are not available. The industrial sector is only briefly considered regarding total use of district heat and electricity.

The energy use in buildings can roughly be divided between heating, domestic hot water production, ventilation, climate cooling, lighting and the use of electric appliances. On a national level over 60% of the energy use in the residential and service sector is used for heating and domestic hot water production (STEM, 2002). The electricity use in the sector can be divided up into electricity for heating, domestic electricity and operating electricity. Domestic electricity is the electricity used for domestic purposes, for example cooking and washing. Operating electricity is used for equipment in commercial premises and for building service systems, for example ventilation fans and pumps for circulation of water. It also includes electricity use for common spaces like washing rooms, elevators, cellars and entrances. Today the residential sector accounts for 35% of Sweden's total final energy use (STEM, 2002). This high level of energy use makes the residential sector central in the attempts to reach a sustainable development of the society. A reduced environmental impact of the residential sector is thus an important goal, which also requires a long-term perspective since buildings have a long life.

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[6] The year 2050 is a symbolic date, denoting the way to a sustainable society.

[7] The energy situation today is represented by the situation in year 2000.

3.3.1.1. Energy use for heating

The energy use for heating, including hot water production, in detached houses, multi-dwelling buildings and premises in the municipality of Göteborg is today about 4 200 GWh. The energy use has been calculated from figures on specific energy use, i.e. the energy use per m^2, and total heated useful floor space[8]. The specific energy use is assumed to be the same as the average specific energy use on a national level. The total useful floor space today has been calculated from figures on the number of dwellings, 50 400 for detached houses and 188 300 for multi-dwelling buildings (Göteborgs Stadskansli, 2003), and figures on average useful floor space per dwelling, which is about 130 m^2 and 70 m^2 for detached houses and multi-dwelling buildings, respectively (Berghe, 1998). This gives a total useful floor space of 6.6 million m^2 and 13.2 million m^2, respectively. The total utility area for premises was in 1993 about 6.5 millions m^2 (Berghe, 1998). On a national level the heated area in premises has increased by an average of 1% per year the last two decades (Boverket et al., 2002). If this is applied to Göteborg, the area for 2000 is approximately 7 millions m^2. The specific energy use, useful floor space and total energy use today are shown in table 3.1. The energy use denotes the gross energy use, i.e. the energy supplied to the building. Losses in furnaces are thus included.

Table 3.1. Specific energy use, useful floor space and total energy use for heating of detached houses, multi-dwelling buildings and premises today. The energy use denotes gross energy use.

	Spec. energy use (kWh/m^2)	**Useful floor space (million m^2)**	**Total energy use (GWh)**
Detached houses	155	6.6	1020
Multi-dwelling buildings	162	13.2	2140
Premises	144	7.0	1010
Sum			**4170**

Source: The figures on specific energy use have been taken from Hedberg et al. (2003).

There are large potentials to decrease the energy use for heating, for example through improved building techniques (Elmberg et al., 1996). The concepts of reaching a low heating demand are basic and can be realised with technology available today. A low energy requirement can be achieved through good heat insulation in walls, floors and roofs, air proof houses, controlled mechanic ventilation using heat recovery, well insulated windows and good technical construction solutions. These concepts can and should also be applied when existing houses are being renovated in the future. Already today there are houses with extremely low energy use in Lindås, 20 kilometres south of Göteborg (Eek, 2002). By using the best available technology to decrease the energy losses and by good construction work and planning, the houses are kept warm by only using heat radiation from persons, lighting, electric appliances and the sun. Hot water production is managed through solar collectors and electric heating.

In the scenario of this report it is assumed that all newly built buildings from today to 2050 are constructed with the technology utilised in the houses without heating system in Lindås. Existing buildings are assumed to be renovated by 2050 and the specific energy use for remaining buildings is therefore reduced compared with today. The assumptions on future specific energy use are presented in table 3.2.

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[8] Useful floor space includes the residential area and other heated spaces.

According to the reasoning in section 3.1, the population in the municipality is assumed to increase with about 35% until year 2050. The fact that the share of older people is increasing contributes to the present trend of fewer persons per household (Hedberg et al., 2003). This means that the number of households will increase more than the population. It is however reasonable to assume that the useful floor space per dwelling will decrease in the future. On the basis of this reasoning, it is assumed that the total useful floor space will increase with the population. An increase of total useful floor space with the population means an increase from 6.6 to 8.8 million m^2 for detached houses and from 13.2 to 17.8 million m^2 for multi-dwelling buildings. The total utility area for premises is also assumed to increase with the population. With an increase of 35% the area will be about 9.5 millions m^2 in 2050. Furthermore, it is assumed that 10% of the multi-dwelling buildings existing today will be demolished until 2050 (Hedberg et al., 2003). All detached houses are assumed to be remained in 2050. This means that about 30% of the multi-dwelling buildings and about 22% of the detached houses in 2050 are relatively new buildings that are assumed to have been built after low heating demand concepts. Also for premises the assumption that 10% of the existing area will be demolished in 2050, is made. This means that about one-third of the utility area in 2050 is relatively new built.

On the basis of the assumptions made above on specific energy use and total useful floor space, the total energy use in 2050 for heating in residential buildings and premises has been calculated. The result is presented in table 3.2. The total energy use for heating in 2050 is about 2 600 GWh, which is a reduction of 40%. The reduction per capita is more than 50%.

Table 3.2. Specific energy use, useful floor space and total energy use for heating of detached houses, multi-dwelling buildings and premises in 2050. Total energy use denotes gross energy use.

	Spec. energy use (kWh/m^2) remaining[a]	**Spec. energy use (kWh/m^2) new**[b]	**Useful floor space (million m^2)**	**Total energy use (GWh)**
Detached houses	90	25	8.8	650
Multi-dwelling buildings	100	25	17.8	1340
Premises	80	20	9.5	570
Sum				**2560**

Source: The figures on specific energy use for remaining buildings have been taken from Hedberg et al. (2003). The figures for new buildings have been calculated on the basis of the Lindås project (Egnahemsbolaget et al., brochure).

[a] In Hedberg et al. (2003) remaining buildings are divided between renovated and other buildings. For rebuilt buildings the energy use for detached houses, multi-dwelling buildings and premises are estimated to 80, 90 and 70 kWh/m^2, respectively and for other buildings the corresponding figures are 100, 110 and 90 kWh/m^2, respectively. Here the median figures are assumed for all remaining buildings.

[b] The total energy use for heating (hot water production by electric heating and solar collectors) in houses without heating system is 3 000 kWh (Egnahemsbolaget et al., brochure). With the assumption that the average useful floor space area is 130 m^2, the specific energy use is approximately 25 kWh/m^2. The construction technique applied in houses without heating system is assumed to apply to newly built multi-dwelling buildings and premises as well.

3.3.1.2. Energy supply for heating

Today, detached houses are mainly heated by oil or electricity (direct-acting or waterborne), which accounts for approximately 30% and 55%, respectively, of the total energy supply for heating. The main reason for the high proportion of electric heating is that it is cheap to install and simple to run. Only 8% of the detached houses are heated by district heat. The number of detached house customers is, however, increasing and within a few years, Göteborg Energi wants 16 000 detached houses, i.e. about 30% of the houses, to be connected to the system (Göteborg Energi, 2001). A smaller part of the heat supply comes from natural gas and biofuels. For multi-dwelling buildings the most common way of heating is district heating, which supplies about 90% of the dwellings with heat. Oil, together with natural gas, is the second largest source of heat. The use of electric heating in multi-dwelling buildings is relatively low. The main source of heat in non-residential premises is also district heat but fossil fuels and electricity also contribute to a substantial part of the heating.

In a sustainable Göteborg, the use of fossil fuels has been phased out and there is thus no supply of heat from oil or natural gas. It is assumed that no remaining houses or buildings use electricity for heating. The use of electric heating in 2050 is therefore only made up of the use in buildings without heating system. Electricity is assumed to comprise half of the energy supply for heating in these buildings (Egnahemsbolaget et al., brochure). It is assumed that solar collectors have been commercial and are assumed to constitute about 5% of the energy supply in all remaining buildings (Azar and Lindgren, 1998) and half of the energy supply for hot water production in buildings without heating system (Egnahemsbolaget et al., brochure). It is assumed that the heating demand not covered by solar heat and electric heat is covered by district heat, except for a small part covered by small-scale combustion of biofuels/pellets in detached houses. District heating will thus constitute the main part of the heating in the residential sector, amounting to 2 160 GWh, out of which 545 GWh are supplied to detached houses, 1 130 GWh to multi-dwelling buildings and 485 GWh to premises. The energy supply for heating in 2000 and 2050 is shown in table 3.3 and figure 3.5.

Table 3.3. Present and assumed future energy supply for heating of detached houses, multi-dwelling buildings and premises. The figures denote the energy supplied to the buildings. Losses in furnaces are thus included.

	Energy supply (GWh)					
	2000			**2050**		
Source of heating	**Detached houses**	**Multi-dwelling buildings**	**Premises**	**Detached houses**	**Multi-dwelling buildings**	**Premises**
Biofuels	10	0	0	15	0	0
District heat	80	1990	670	545	1130	485
Electricity	560	10	100	30	75	30
Natural gas	50	30	90	0	0	0
Oil	320	110	150	0	0	0
Solar heat	0	0	0	60	135	55
Sum	**1020**	**2140**	**1010**	**650**	**1340**	**570**

Source: The allotment of energy supply for heating in 2000 has been calculated on the basis of Berghe (1998). Berghe's figures are from 1993, but the same allotment is assumed to be valid also for 2000.

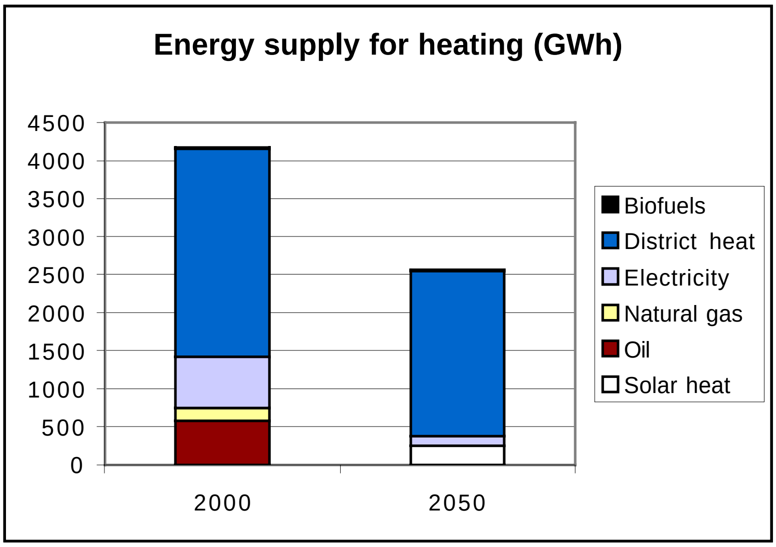

Figure 3.5. *Energy supply for heating in the residential and service sector, today and in 2050.*

The district heating system in Göteborg is today covering almost all of the municipality's area and in 2000, the total supply was about 3 400 GWh (SCB, 2003b). About one third of the district heat is made up of waste heat from the oil refineries, Shell and Preem, and about one quarter comes from Renova's waste incineration plant in Sävenäs (Göteborg Energi, 2002). About 16% of the heat is extracted by heat pumps from cleaned wastewater from GRYAAB's sewage treatment plant. These facilities constitute the base load of the district heating system. During the coldest period of the year they are complemented with heat from combustion plants. The combined heat and power plant located in Rosenlund, where mainly natural gas is used, is contributing to about 6% of the heat. Natural gas and the biofuel pinepitch oil are also used in hot water furnaces in the facilities in Rosenlund, Sävenäs and Rya. Altogether, natural gas accounts for 19% of the supply of district heat and biofuels for about 4%. Oil is only used as a reserve during very cold weather and operation interruptions.

The use of district heat in the residential and service sector in 2050 was above estimated to 2 160 GWh. Beside the residential and service sector, district heat is used by industries. Today the use amounts to 470 GWh (SCB, 2003b) and this amount is assumed to be the same in 2050. The losses associated with the transmission are today about 190 GWh, i.e. 6% of the total supply. These losses are assumed to be of the same size in 2050. Altogether, the supply of district heat will be about 2 800 GWh in 2050. There will thus be a decrease of nearly 20% even though more houses are connected to the district heating system.

In a sustainable Göteborg, there will also be a different mixture of energy sources in the district heating system. Since the use of fossil fuels is phased out, there is no contribution from fuel oil, natural gas and waste heat from oil refineries. District heat production from heat pumps is not considered efficient enough and is therefore not contributing to the district heating in 2050. The main part of the heat will come from biofuels in the form of heat production in an energy combine. It is assumed that the share of households recycling their waste has increased. The recycling system has been further developed and the different fractions of biomass and fossil fuels are separated. This results in a lower amount of heat from waste, but it will still constitute a substantial part of the district heating system. However, the waste will not be combusted in waste incineration plants but is gasified together with biofuel in an energy combine. The share of solar heat is assumed to be about 5%. The supply of district heat today and in 2050 is shown in table 3.4 and figure 3.6. Transmission losses are included.

Table 3.4. The supply of district heat today and the assumed supply in 2050. Losses associated with the transmission are included.

	2000		**2050**	
Energy source	**GWh**	**%**	**GWh**	**%**
Biofuel	140	4	2380	85
Fuel oil	30	1	0	0
Heat pumps	540	16	0	0
Natural gas	640	19	0	0
Solar heat	0	0	140	5
Waste heat (oil refineries)	1150	34	0	0
Waste incineration	880	26	280	10
Sum	**3380**	**100**	**2800**	**100**

Source: The figures for 2000 have been taken from Göteborg Energi (2002) and SCB (2003b).

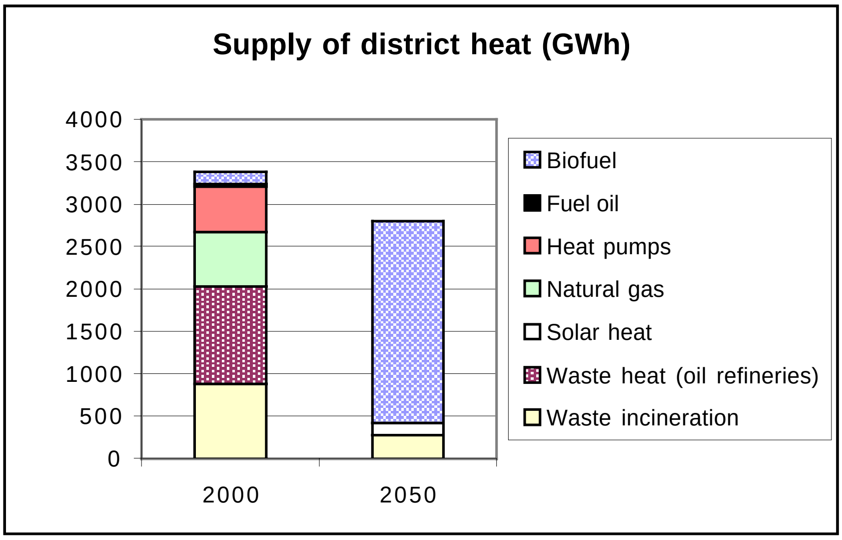

Figure 3.6*. The supply of district heat today and in 2050. Losses associated with the transmission are included.*

3.3.1.3. Use of domestic and operating electricity

The use of electricity for domestic and operation purposes in the region of Göteborg, today amounts to nearly 4 000 GWh. The electricity use has been calculated from figures on specific energy use and useful floor space. The specific energy use is assumed to be the same as on the national level. The total useful floor space for the region has been estimated in the same way as was made for the municipality. The numbers of dwellings in the region are about 151 000 and 240 600 for detached houses and multi-dwelling buildings, respectively (SCB, 2003c and SCB, 2003d). The average useful floor space is assumed to be the same in the region as in the municipality, i.e. 130 m^2 per dwelling for detached houses and 70 m^2 for multi-dwelling buildings. This gives a total useful floor space of about 19.6 million m^2 for detached houses and 16.8 million m^2 for multi-dwelling buildings. According to

Hedberg et al. (2003), the average utility area for premises is a bit over 20 m^2 per citizen. Here, 22 m^2 per citizen is assumed. In 2000 the population in the region was about 845 000. This gives a total utility area of about 18.6 million m^2 for premises. Specific energy use, useful floor space and total energy use are shown in table 3.5.

Table 3.5. Specific energy use, useful floor space and total energy use for domestic and operating electricity in detached houses, multi-dwelling buildings and premises today.

	Spec. energy use (kWh/m^2)	**Useful floor space (million m^2)**	**Total energy use (GWh)**
Detached houses	46	19.6	900
Multi-dwelling buildings	63	16.8	1060
Premises	107	18.6	1990
Sum			**3950**

Source: The figures on specific energy use have been taken from Hedberg et al. (2003).

Also regarding electricity use, there are large possibilities to reduce the energy use for example through more efficient electric appliances. About 80% of the electricity use in dwellings is used for stoves, dishwashers, washing machines, refrigerators, freezers and other household appliances. The potential for energy efficiency for these appliances, using the most energy efficient products available on the market today, are between 40 and 55% (Azar and Lindgren, 1998). The energy use also depends on people's behaviour and a changed behaviour can contribute to further reductions of energy use (Hedberg et al., 2003). Turning off appliances instead of using the stand-by functions and control of lighting by presence-detection are examples that might comprise a substantial part of the reduction of electricity use. It is however reasonable to assume that the number of appliances per household will increase in the future and thus counteract the efficiency potential (Azar and Lindgren, 1998). The potential is therefore assumed to be in the lower part of the efficiency interval, around 45% for electricity use in detached houses and multi-dwelling buildings. The potential for premises is more than 50% and the energy use is estimated to 50 kWh/m^2 (Elmberg et al., 1996 and Hedberg et al, 2003). Since electric appliances have a short lifetime compared to buildings, the efficiency potential can be realised in a relatively short time period. It is therefore assumed that the specific electricity use in 2050 is the same in new and remaining buildings. The assumed future specific energy use for domestic and operating electricity is presented in table 3.6.

The same reasoning about increase of useful floor space and utility area that was made for the municipality of Göteborg is applied to the region. It is thus assumed that the total useful floor space in dwellings and total utility area in premises will increase with the population, i.e. an increase of 35%. This results in an increase to 26.5 and 22.7 million m^2 for detached houses and multi-dwelling buildings, respectively. For premises the area will be about 25.1 million m^2 in 2050. From the above assumptions on specific electricity use and total useful floor space, the future demand for domestic and operating electricity in dwellings and premises has been calculated, see table 3.6. It is shown that the electricity use for domestic and operation purposes is about 2 700 GWh, which is a reduction of about 30%. The reduction per capita is nearly 50%.

Table 3.6. Specific energy use, useful floor space and total energy use for domestic and operating electricity in detached houses, multi-dwelling buildings and premises in 2050.

	Spec. energy use (kWh/m^2)	**Useful floor space (million m^2)**	**Total energy use (GWh)**
Detached houses	25	26.5	660
Multi-dwelling buildings	35	22.7	800
Premises	50	25.1	1260
Sum			**2720**

Source: The figures on specific energy use are based on Elmberg et al. (1996) and Hedberg et al. (2003).

3.3.1.4. Use and supply of electricity

The total use of electricity in the region of Göteborg, is today nearly 10 700 GWh (SCB, 2003b). The electricity is mainly used in the residential and service sector and in the industrial sector. The former constitutes 5 520 GWh, i.e. more than 50% and the latter about 4 180 GWh, which is almost 40% of the total electricity use. The use in detached houses amounts to about 2 130 GWh. This relatively large use can be explained with the large share of electric heating. The electricity use in the transport sector is relatively small, amounting to about 160 GWh. This electricity is being used almost entirely for railborne transports. The losses due to the transmission of electricity constitute 7% of the total supply.

The electricity use for domestic and operation purposes in the residential and service sector in 2050 was in the section above estimated to 2 720 GWh. In 2050, it is assumed that all electricity use in remaining buildings is used for domestic and operation purposes only. The electric heating has thus been replaced in remaining buildings and is only used in new buildings without heating system (see section 3.3.1.1). With the assumption that all new buildings is constructed according to the technique used in Lindås and that 10% of the multi-dwelling buildings and of the premises existing today have been demolished in 2050, the use of electricity for heating amounts to about 90 GWh for detached houses, 90 GWh for multi-dwelling buildings and 80 GWh for premises. The electricity use in the industrial sector is today about 4 180 GWh (SCB, 2003b). In this sector a reduction of 25%, mainly due to a more efficient energy use, is assumed (Azar and Lindgren, 1998). Due to a larger use of railborne public transports and a substantial increase of railborne goods transports the electricity use for transports increases. The transport sector is discussed further in section 3.3.2. The losses associated with the electricity transmission are assumed to be of the same size as today, i.e. about 7% of the total supply. Altogether, the electricity use in 2050 has been estimated to be 6 850 GWh, i.e. a reduction of about 35%. The reduction per capita is about 50%. The present and assumed future use of electricity is shown in table 3.7 and figure 3.7.

Table 3.7. The use of electricity, in 2000 and 2050, divided by sector. The figures for the residential and service sector include domestic and operating electricity and electricity for heating.

	2000		**2050**	
Sector	**GWh**	**%**	**GWh**	**%**
Detached houses	2130	20	750	13
Multi-dwelling buildings	1160	11	890	11
Premises	2230	21	1340	19
Industry	4180	39	3140	46
Transports[a]	160	2	250	4
Losses[b]	790	7	480	7
Sum	**10650**	**100**	**6850**	**100**

Source: The data for all sectors, except for the transport sector, have been taken from SCB (2003b).

[a] For calculations of the electricity use for transports, see section 3.3.2.

[b] Losses associated with the transmission of electricity.

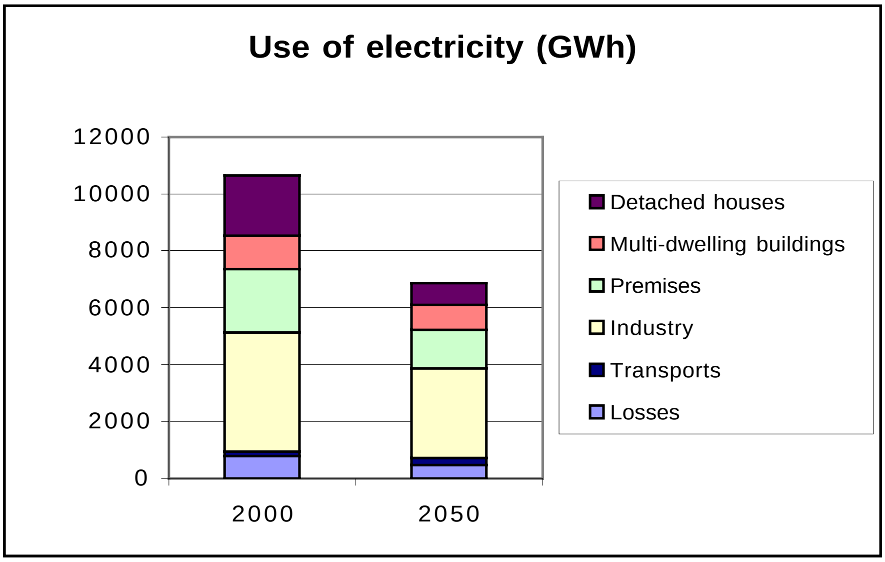

Figure 3.7. *The use of electricity, in 2000 and 2050, divided by sector. The figures for the residential and service sector include domestic and operating electricity and electricity for heating.*

Most of the region's supply of electricity today is imported and is mainly made up of hydro and nuclear power, which comprise more than 90% of the total supply. About 6% is generated from natural gas-fired combined heat and power plants and a small share is produced from wind power. This production mix of electric power is likely to change in the future, mainly because nuclear power is assumed to be completely phased out in 2050. In order to compensate for the nuclear power, increased energy efficiency alone is not sufficient. Other energy sources must be developed and commercialised. The possibility to expand wind power has been explored in different investigations. The Swedish Energy Agency has for example estimated the Swedish potential for 2050 to be 7 TWh from land-based facilities and 22 TWh from sea-based facilities (IVA, 2003). In the region of Göteborg, wind power is assumed to constitute more than 40% of the total supply, amounting to nearly 3 000 GWh. Electricity from solar cells are today not economically viable. However, the installation of solar cells increase by about 30% per year globally and by 2050 they are assumed to comprise nearly 20% of the electricity supply in the region. The use of energy combines for electricity generation will increase in the future due to the high overall efficiency and will account for more than 20% of the supply. The use of fossil fuels will be phased out and natural gas fired CHP plants will thus be replaced. Since hydropower comprise a long-term base in the Swedish electricity production, it is assumed to continue to constitute a substantial, part of the electricity supply. The supply of electricity, today and in 2050, is presented in table 3.8 and figure 3.8. Losses due to the transmission are included.

Table 3.8. The total supply of electricity, in 2000 and 2050, divided by energy source. Losses associated with the transmission of electricity are included.

	2000		**2050**	
Energy source	**GWh**	**%**	**GWh**	**%**
Energy combine biofuel	0	0	1510	22
CHP plant natural gas	640	6	0	0
Hydro power	5805	54.5	1230	18
Nuclear power	4155	39	0	0
Solar cells	0	0	1160	17
Wind power	50	0.5	2950	43
Sum	**10650**	**100**	**6850**	**100**

Source: The electricity mixture in 2000 is assumed to be the same as on the national level and has been taken from STEM (2001). The electricity mixture in 2050 is based on the project Göteborg 2050 (2003).

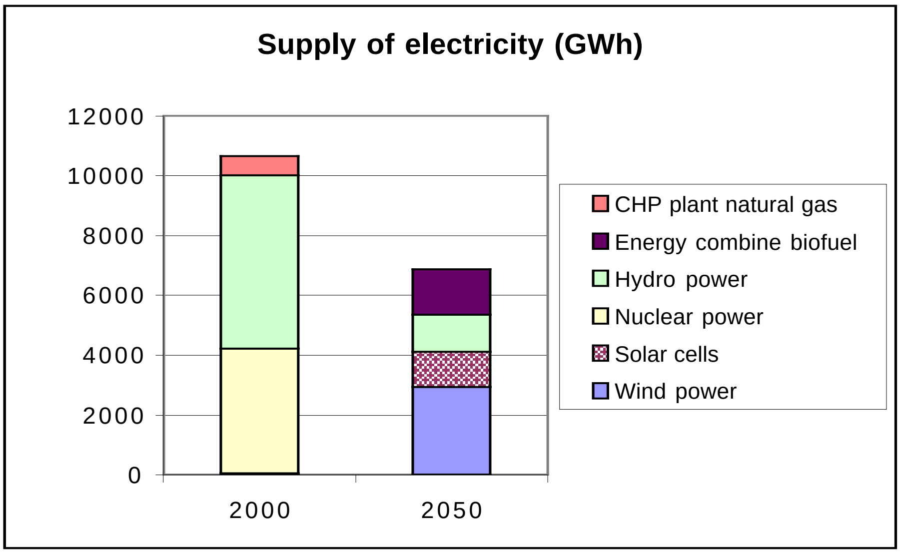

Figure 3.8. *Total supply of electricity, in 2000 and 2050, divided by energy source. Losses associated with the transmission of electricity are included.*

3.3.2. The transport sector

Energy use for transports, excluding foreign maritime traffic, comprise about 23% of the country's total final domestic energy use (STEM, 2002). The energy use in the transport sector consists almost entirely of oil products, mainly petrol and diesel fuel. Since no technology to clean the emissions are commercially available today, the emissions are directly related to the fuel consumption and the choice of fuel. The sector thus contributes to a large share of the emissions of CO_2. In 2000, 35% of Sweden's total CO_2 emissions came from the transport sector. A phase-out of oil products in the sector would thus have a significant impact on the greenhouse gas emissions.

The need of transports has increased the past decades for example due to the economic development. As the economy grow the need of mobility of both people and products increase. The international development, with an increased globalisation and with that an intensified world trade and international travelling, also spur the demand for transports. Other important factors related to the development of passenger transports are the pattern of housing, the household's economy and the allotment between employment and spare time. In total, the domestic passenger transport work has increased by 50% since 1975 and the domestic goods transport has increased by 34% (STEM, 2002). On an average we are travelling 45 kilometres each day. More than every second trip is, however, shorter than 5 kilometres and half of these are made by car (IVA, 2002b). Transports are usually divided between short and long distance transports. Short distance transports are defined as trips shorter than 100 kilometres. Nearly 90% of the energy use for passenger transports is made up of short distance transports, while the energy use for short distance goods transports only constitutes slightly more than 40% (Steen et al., 1997).

3.3.2.1. Passenger transports

Today the total energy use for short distance passenger transports in the region amounts to about 3 660 GWh and the transport work amounts to about 5.5 billion person-kilometres[9]. The total energy use has been calculated from data on transport work and specific energy use, i.e. fuel consumption per person-kilometre. The specific energy use, transport work and total energy use for different modes of transportation are shown in table 3.9. The table shows that about 84% of the total transport work is made by car and only 16% by public transports. Cars, including taxis, run mainly on petrol and buses mainly on diesel. Trams and trains run on electricity. Motorbikes, small private boats and other shipping are excluded because of their small share of the total energy use.

Table 3.9. Specific energy use, transport work and total energy use for different modes of short distance transportation today. Total energy use denotes the energy supplied to the vehicle.

Mode of transportation	Spec. energy use (kWh/pkm)	Transport work (million pkm)	Total energy use (GWh)
Car[a]	0.75	4640	3480
Bus[b]	0.22	500	110
Tram[b]	0.19	230	40
Train[b]	0.16	160	30
Sum		**5530**	**3660**

Source: Löwendahl (2003).

[a] The number of passengers per car is assumed to be 1.38. Taxi cars are included.

[b] A mean capacity use of 50% is assumed.

In a backcasting study on short distance passenger transports in the region of Göteborg conducted by Löwendahl (2003), different scenarios for 2050 have been created. In the so-called complex scenarios in this study, it is shown that the energy use in 2050 for short distance passenger transports can be reduced to less than 10% of today's use. This result is achieved providing certain prerequisites. For example it is assumed that the society is built around a network organisation characterised by so-

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[9] Person-kilometre is defined as the product of the number of people in the vehicle and the transportation distance. The abbreviation is pkm.

called decentralised concentration. The daily activities can thus be performed within a limited geographical area. This results in for example shorter daily travel distance and therefore more transports by bike, cheaper and more energy efficient public transports and increased usage of car pools. Substantial vehicle efficiencies are also assumed in this scenario.

Since the changes of e.g. life style pattern and infrastructure assumed in Löwendahl's complex scenarios, are not applied in the scenario of this report, the reduction of energy use is more modest. Here, the reduction is mainly due to more efficient technology. According to Steen et al. (1997) there is a 75% reduction potential of specific energy use for short distance travels by car until year 2040. The corresponding figures for bus and railborne transports are 60% and 50%, respectively. These potentials are due to, among others, changed engine constructions and lighter vehicles. In this scenario it is assumed that not all measures needed to reach such a low energy use are taken. On the other hand, more people are assumed to travel in each vehicle, for example due to extended use of car pools and increased travelling by public transports. Altogether, the reductions of specific energy use are assumed to be the same as in Steen et al. (1997).

The number of travels made by car, bus, tram and train is assumed to decrease in the future, for example due to a greater possiblity to work from home and an increased use of bicycles. Nevertheless, due to the increased population the total transport work is assumed to increase. The transport work is however not assumed to follow the population increase but is estimated to increase by 20%. Furthermore, the allotment of transport work between the different modes of transportation is assumed to have changed in the future. The share of the transport work made by car has decreased to the favour of travels by public transport and only constitutes 55% in 2050. The share of transport work made by buses and railborne transports accounts for 25% and 20%, respectively[10]. The assumed specific energy use, transport work and the total energy use in 2050 are shown in table 3.10. The total energy use has been estimated to 1 000 GWh, which is a reduction of about 70%. The reduction of energy use per capita is even larger, amounting to nearly 80%.

Table 3.10. Specific energy use, transport work and total energy use for different modes of short distance transportation in 2050. Total energy use denotes the energy supplied to the vehicle.

Mode of transportation	**Spec. energy use (kWh/pkm)**	**Transport work (million pkm)**	**Total energy use (GWh)**
Car	0.20	3650	730
Bus	0.09	1660	150
Tram	0.10	800	80
Train	0.08	530	40
Sum		**6640**	**1000**

The energy use for long distance passenger transports made by car, bus and train in the region of Göteborg, is today nearly 500 GWh. The energy use has been calculated from figures on specific energy use and transport work. On a national level, the transport work for long distance car and bus transports are about 30% of the

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[10] The allotment between the different modes of transportation is based on the scenario "More efficient public transports" in Löwendahl (2003).

corresponding transport work for short distance transports and the transport work for long distance train transports is 25% larger than for short distance train transports (Steen et al., 1997). This has been used to estimate the transport work for long distance passenger transports. The specific energy use, transport work and total energy use is shown in table 3.11. It is shown that 80% of the transport work is made by car and 20% by public transportation.

Table 3.11. Specific energy use, transport work and total energy use for different modes of long distance transportation today. Total energy use denotes the energy supplied to the vehicle.

Mode of transportation	Spec. energy use (kWh/pkm)	Transport work (million pkm)	Total energy use (GWh)
Car[a]	0.32	1390	450
Bus[b]	0.13	150	20
Train[b]	0.11	200	20
Sum		**1740**	**490**

Source: The figures on specific energy use have been taken from Steen et al. (1997).
[a] Two persons per car is assumed.
[b] A mean capacity use of 50% is assumed.

Also for long distance transports there are potentials to reduce the energy use, although not as large as for short distance transports. Steen et al. (1997) have estimated the efficiency potentials to be 65% for transports by car, 40% for bus transports and 50% for train transports until year 2040 and these potentials are applied here. The allotment of transport work between short and long distance passenger transports mentioned above is assumed to be valid in the future as well, which results in an increase of 30% of the total transport work. Also for long distance transports the share of the transport work made by car decreases to the favour of public transports. The future specific energy use, transport work and total energy use is presented in table 3.12. It is shown that the energy use is reduced by 60% to 200 GWh. The reduction per capita is 70%.

Table 3.12. Specific energy use, transport work and total energy use for different modes of long distance transportation in 2050. Total energy use denotes the energy supplied to the vehicle.

Mode of transportation	Spec. energy use (kWh/pkm)	Transport work (million pkm)	Total energy use (GWh)
Car	0.12	1100	130
Bus	0.07	500	40
Train	0.05	660	30
Sum		**2260**	**200**

3.3.2.2. Goods transports

The total energy required for goods transports by road, both short and long distances, is on a national level about 25% of the energy required for short distance passenger transports by car (Steen et al., 1997). This is assumed to be valid for the region of Göteborg as well. The energy use for passenger transports by car today is 3 480 GWh (see above). This means that the energy use for goods transports by road is about 870 GWh. The efficiency potential for goods transports is lower than for passenger transports. One reason for this is that lorries already have been optimised regarding low fuel consumption. The possibilities to reduce the total weight of the vehicle are also considerable less for lorries compared to passenger cars. Steen et al. (1997) have estimated the efficiency potential for goods transports by lorry to be about 40% for short distance transports and about 30% for long distance. In this scenario a potential of 30% for both short and long distances is assumed (Azar and Lindgren, 1998). The total transport work for goods transports by road and rail is assumed to increase with 40% in the future (Azar and Lindgren, 1998). This increase is however assumed to take place by train. The transport work by road is therefore the same as today while the railborne transports more than doubles[11]. The energy use for goods transports by road is thus reduced by about 30% to 610 GWh.

The energy use for railborne goods transports, both short and long distances, constitutes approximately 8% of the energy use for road transports (Steen et al., 1997). The use of electricity for railborne transports today is thus about 73 GWh. A doubling of the transport work and an efficiency potential of 30% results in an increase of 40%. In 2050, the electricity use for railborne goods transports will thus be about 100 GWh.

3.3.2.3. Total energy use for transports

The above transport scenario results in a future demand of 1 050 GWh transport fuel for passenger transports (cars and buses) and 610 GWh fuel for goods transports (lorries). The future electricity use is 150 GWh for passenger transports (trams and trains) and 100 GWh for goods transports (trains). In total, the reduction of energy use is slightly more than 60% compared to today. The reduction per capita is about 70%. However, car transports constitute the largest share of the reduction. Due to increased transport work for public transports and goods transports by rail, the energy use for buses, trams and trains increases compared to today. The total energy use for both passenger and goods transports today and in the future is shown in figure 3.9. In 2050, all cars, buses and lorries are assumed to run on renewable transport fuel. In this report methanol is used as an example of renewable fuel and if all transports by road run on methanol, the total demand in the region amounts to 1 660 GWh.

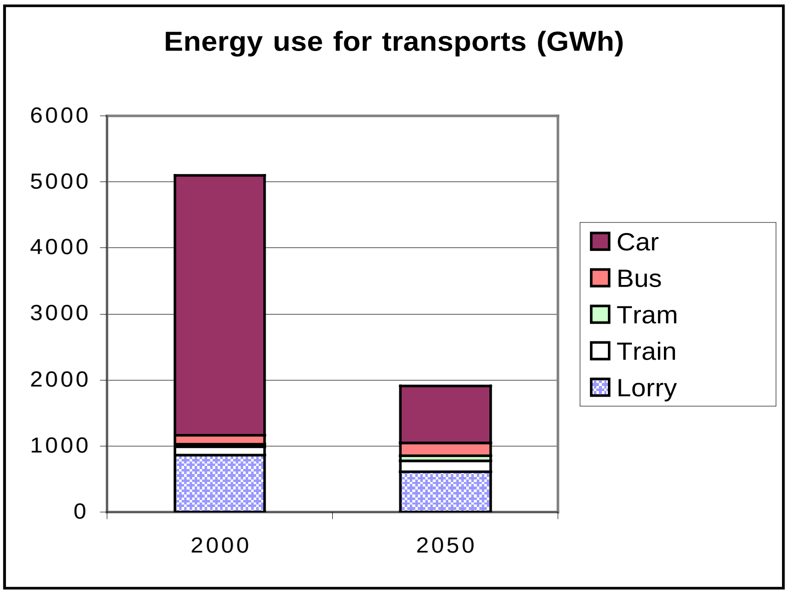

Figure 3.9. *Energy use for passenger and goods transports, today and in 2050.*

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[11] Road transports constitute about 63% of the total goods transport work and railborne transports constitute 37% (Steen et al., 1997). This results in an increase of railborne transports by a factor 2.1.

3.4. Sizing of the energy combine

As was shown in section 3.2, there are a number of possible configurations of biomass-based energy facilities and it is difficult to appoint one particular design to be the most appropriate. The design most suitable depends on various conditions and circumstances. Moreover, some of the process components mentioned are more suitable than others for upscaling which may lead to different "optimal" technology for different capacities (Tijmensen et al., 2002) but this aspect is not considered in this report. There are, however, other aspects that need to be taken into consideration when designing a combine, for example the market demand. A combine should primarily be designed to suit the local demands of the energy carriers produced (BioMeeT project, 2000). In the scenario of this report there is an extensive market demand for biomass-derived transport fuel and also for electricity and heat from biomass. The approximate amount of each energy carrier was estimated to 1 700 GWh methanol, 1 500 GWh electricity and 2 700 GWh district heat. This market base is more than sufficient for a large-scale energy combine in Göteborg.

Depending on the design and on which technologies that are used, different shares of methanol, electricity and heat, respectively, could be produced. Which shares that are optimal depend on different conditions. In the section below two different examples of how the estimated amounts of each energy carrier could be produced from the biomass-based facilities described in section 3.2. To be able to make a comparison between the two examples several facilities are considered in each example in order to produce the amounts estimated. The comparison is then made on the basis of biomass requirement. As was shown in the scenarios, the demand for heat is relatively large compared to methanol and electricity and it is therefore suitable to chose facilities the generate a surplus of heat, which could be utilised in the district heating system. The methanol and power plants mentioned in section 3.2.4 are therefore not considered since there is no net production of heat. For the same reason is neither the first case in the BioMeeT project, which only produces an output of 5% heat, considered. Since the demand for methanol is relatively small and in order for the region to be self-sufficient of transport fuel, a future combine is aimed at covering the total demand for methanol. In the first example the demand for methanol is covered by a methanol plant and in the second example the demand is covered by a facility for co-production of methanol, electricity and heat.

3.4.1. Systems for production of methanol, power and heat

If a methanol plant, as described in section 3.2.3 with an output of 55% methanol and 15% heat, is used to produce 1 500 GWh methanol, about 3 090 GWh biomass would be required. The yield of heat will be about 460 GWh, which means a shortage of 2 240 GWh. In a methanol plant there is no net production of electricity. In the electricity scenario 22%, i.e. 1 500 GWh, of the total demand was estimated to be biomass-based. In order to produce the estimated amount, an IGCC with high overall efficiency could be a promising option. In future IGCC plants, outputs of about 45% electricity and 45% heat are expected (Sydkraft, 2001). This means that a production of 1 500 GWh electricity (and thus 1 500 GWh heat) would require about 3 300 GWh biomass. There would however still be a shortage of heat, amounting to 740 GWh. In order to make the example comparable to the example below this amount of heat is assumed to be produced in a stand-alone heat plant. For this type of plant a conversion efficiency of 90% is assumed (e.g. Azar et al., 2000). The biomass requirement would then be approximately 820 GWh. The total biomass required to produce the estimated amounts of methanol, electricity and heat, respectively, would thus be about 7 200 GWh.

Another option to cover the demand for methanol could be to utilise a facility for co-production of methanol, electricity and heat. Since there is a large demand for district heat, case II in the BioMeeT project (2000) with outputs of 25% methanol, 10% electricity and 36% heat, is chosen. These efficiencies are however not optimised and could be improved by at least 8 percentage points by performing some modifications in the process (BioMeeT project, 2000). Here an improved overall efficiency of 80%, with an output of 28% methanol, 12% electricity and 40% heat, is assumed[12]. To cover the total demand of methanol, 6 070 GWh biomass is then required. The yield of electricity and heat will be 730 GWh and 2 430 GWh, respectively. An addition of 770 GWh electricity and 270 GWh heat is thus required to receive 1 500 GWh and 2 700 GWh, respectively. If an IGCC, with an output of 45% electricity and 45% heat, is sized on the basis of the heat requirement, the biomass needed amounts to 600 GWh. There will however still be an electricity shortage of 500 GWh. To make this example comparable with the example above, the electricity is assumed to be produced in a biomass-based power plant with an efficiency of 50% (Sydkraft, 2001). An additional 1 000 GWh biomass is then required. The total amount of biomass required to produce the estimated amounts of transport fuel, electricity and heat would thus be approximately 7 700 GWh.

If the two examples are compared it is realised that the first example requires a slightly less amount of biomass, 7 200 GWh compared to 7 700 GWh. The amounts are however of the same size and it is difficult to appoint which system that is optimal regarding energy efficiency. The efficiency potentials assumed here might also be higher in future facilities for example due to optimisations of the integration of the processes and a reduction of process steps (e.g. Ekbom, 2003). The biomass-based systems for production of transport fuel, electricity and heat described above should therefore only be seen as possible examples and as indicators of how much biomass that would be required. The heat shortage of 740 GWh in the first example is however not likely to be produced in a stand-alone heat plant. This heat could instead be produced from other sources, for example small-scale heating systems utilising pellets or hydrogen. Neither is the electricity shortage of 500 GWh in the second example likely to be produced in a biomass-based power plant since this electricity perhaps could be produced cheaper from hydropower or wind power plants. If only a methanol plant and an IGCC is utilised in the first example, the biomass requirement would be about 6 400 GWh. If a facility for co-production of transport fuel, electricity and heat in the second example is complemented with an IGCC only, the biomass requirement would be 6 700 GWh. The mixture of energy supply for heating and the electricity mixture presented in section 3.3 would then look slightly different.

It is assumed that several of the facilities that generate heat in the district heating system today, have been closed down in 2050 and the facilities described here constitute a base load in the district heating system. In the examples above, about 2 700 GWh out of a total supply of 2 800 GWh district heat will be produced from biomass. There are however great seasonal variations in the consumption of district

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[12] This estimation was made with help from Simon Harvey (2003).

heat, which means that heat might be wasted during the summer season. To meet this variation in seasonal demand the surplus heat can be utilised for increased drying of the biomass. It might also be possible to establish a side-production of dried storable pellets (BioMeeT project, 2000 and Wahlund et al., 2002). The dryer thus serves as an extra heat sink and thereby enables increased annual operational hours. Furthermore, the consumption of transport fuel for passenger transports is typically higher in the summer than in the winter. In the integrated production of fuel, electricity and heat, it could therefore be advantageous to decrease the methanol production during the winter season in order to reserve more gas to the combined cycle to provide for the demand of district heat.

3.4.2. Biomass potential

The use of biofuels in Sweden today amounts to nearly 100 TWh and consist of wood fuels, such as logs, barks and chips, energy crops, waste, straw, peat and black liquors in pulp mills. As was realised in the section above, great amounts of biomass is required in order to satisfy the demand of biomass-based transport fuel, electricity and heat in the region of Göteborg. Irrespective of the system used, the biomass requirement will be of the approximate size 6-8 TWh. This figure could be compared with the use of wood fuels in conventional combustion facilities in the county of Västra Götaland[13] today, which is about 3.3 TWh (Länsstyrelsen, 2001). It is thus realised that the use of biomass has to be greatly expanded and the question if there is enough biomass is therefore of crucial importance. The future potential of biofuels is however a controversial issue and the estimates differ for example depending on different opinions regarding existing limitations of the supply. Factors that could vary from different estimations are e.g. the definition of biofuels, growth limitations and ecological, economical and technical limitations (Kretsloppsdelegationen, 1998). Below, a summary of different estimations of the potential of biomass from forestry and agriculture, both on a county level and on a national level, is given. The potentials are denoted as energy content of the biomass before conversion. Peat is not considered since it is questionable if it is a renewable fuel. Neither is black liquor considered since it is mainly used in the processes in pulp mills.

Biomass from forestry

This category includes wood fuels, which are fuels from trees that have not been chemically processed. Wood fuels consist of logging residues, stem tops and branches, direct wood fuel cuttings, i.e. wood from thinning, wood without industrial use etc., industrial by-products and recovered wood (Kretsloppsdelegationen, 1998). The county administrative board in Västra Götaland (Länsstyrelsen, 2001) has estimated the potential of wood fuels to be approximately 7 TWh. This figure however only includes logging residues, stem tops and branches. In the BioMeeT project (2000) the biomass potential from forestry in the county of Västra Götaland is calculated to about 12 TWh. This estimation is conducted by the Swedish University of Agriculture and includes all types of wood fuels. On a national level the future potential for wood fuels is in the approximate interval 55-130 TWh (e.g. Azar and Lindgren, 1998 and Kretsloppsdelegationen, 1998). This could be compared with the use of wood fuels today, which is about 40 TWh. In a study conducted by Börjesson et al. (1997) the biomass potential from logging residues and excess stem wood alone

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[13] The county of Västra Götaland consists of 49 municipalities, including all the municipalities in the region of Göteborg, with the exception of Kungsbacka.

was estimated to reach 170 TWh if new forestry management methods such as optimised fertilisation would be utilised.

Biomass from agriculture

Biomass from agriculture includes straw and energy crops cultivated on excess arable land not needed for food production (Kretsloppsdelegationen, 1998). Today there is excess arable land in Sweden and according to different estimates it seems like there will be an excess of land in the future as well. However, the potentials to utilise future arable land vary from different estimates e.g. regarding cultivation method and future import and export of provisions. In the county of Västra Götaland the potential for straw has been estimated to 0.3 TWh by the county administrative board (Länsstyrelsen, 2001). In the BioMeeT project (2000) a potential of nearly 1 TWh is presented. The potential for energy forest has been estimated to at least 0.5 TWh under favourable conditions in the BioMeeT project but is considered marginal by the county administrative. On a national level the potential for straw and energy crops together is approximately 15-60 TWh (Börjesson et al., 1997, Azar and Lindgren, 1998 and Kretsloppsdelegationen, 1998).

Altogether, the estimates of biomass potential in the county of Västra Götaland differ from approximately 7-14 TWh and the potentials for the whole country differ from 70-190 TWh. The use of wood fuels today in the county is about 3.3 TWh. The county administrative board (Länsstyrelsen, 2001) estimates that an addition of nearly 1 TWh wood fuel is required if all planned heat plant projects in the county will be performed. With an additional need of 6-8 TWh biomass for the facilities described above, the total requirement will be about 10-12 TWh. Moreover, it is reasonable to assume that the use of biofuel for production of transport fuel, electricity and heat will increase in other parts of the county as well and there will thus be an even larger pressure on the limited supply. How much the additional use of biomass would be is difficult to predict but it is realised that the nearest surrounding area from Göteborg will probably not be sufficient for the supply of biomass for a large-scale bioenergy combine. Part of the biomass requirement will therefore have to be supplied from other parts of the country, perhaps mainly from Norrland, Dalarna, Värmland and Småland since these provinces are predicted to have an excess of biomass in the future even with an increased biomass utilisation (Kretsloppsdelegationen, 1998).

Furthermore, there is an additional supply of biomass from combustible wastes. The waste combusted in Göteborg today consists of both household wastes and industrial wastes and is a mixture of both biomass and fossil fuel (Länsstyrelsen, 2001). In a future recycling system it is assumed that the fossil fraction is separated from the biomass fraction. Future biomass-based facilities will probably enable different fuels to be mixed and since it is assumed that waste will be better sorted and thus much cleaner in the future, it can be used as a fuel supplement in bioenergy facilities. The contribution from waste was in section 3.3.1.2 estimated to 280 GWh of the total district heat supply. If this heat is produced in an IGCC with an output of 45% heat, there will thus be an addition of about 600 GWh waste to the biomass potential.

4. DISCUSSION

In this report an image of a future energy system in Göteborg based on renewable resources with no net emissions of CO_2 has been developed. Biomass is assumed to play a central role of the energy system, mainly for production of transport fuel, electricity and heat. The time horizon has been set to a “future sustainable society”, which is denoted 2050 throughout the report. This date could signify 50 years from now, but it could also be 100 years. In such a long term it is impossible to tell with certainty how the demand for energy will develop. On the other hand the long time horizon makes it possible for a major change of the energy system. In order to see what role a system of biomass-based facilities could have in a future energy system, scenarios of the demand for district heat, electricity and transport fuel have been created. The scenario shows a future where the energy use for heating and the use of operating and domestic electricity in the residential and service sector are reduced by approximately 50% per capita. The reduction of energy use in the transport sector is even larger, amounting to slightly more than 70% per capita. In the image of the future, biomass-based facilities cover the whole demand for transport fuel and more than 20% of the electricity demand in the region of Göteborg and nearly all heat in the district heating system in the municipality of Göteborg.

Since the scenarios are based on a number of assumptions, the relevance and validity could be discussed. The large reductions of energy use are for example a result of energy efficiency measurements. Regarding the residential and service sector, the pace of technological development and building companies’ adaptation to new construction techniques depend, among other things, on energy prices. It is therefore difficult to indicate levels of efficiency potentials as well as usage of construction techniques from now until 2050. The efficiency potentials assumed in this report are technically possible but they are quite optimistic and in order to realise them an energy-conscious behaviour from both the different actors in e.g. the building sector and the transport sector and the users of energy will be required. The building sector is, however, characterised by certain conservatism so even if there are great potentials to decrease the energy use through rebuilding, it might not be put into practice. Follow-ups of previous future studies, including forecasts, often show that the potentials for reduced energy use are not fulfilled. The assumption that all new buildings from now until 2050 will be built with the construction technique used in the houses without heating system could therefore also be discussed. The low use of energy in the scenarios is also a result of a breaking of trends. For example, the useful floor space per capita is assumed to be constant and the transport work per capita is assumed to decrease. However, the question of how the present trends of increasing floor space and transports will be broken has not been considered in detail.

On the basis of the above discussion, it could be concluded that it is relatively easy to develop images of the future as has been done in this report, but it is more difficult to provide a detailed suggestion of how the image could be realised. How to reach the image developed is the fourth step in a backcasting study (see section 2.1). This step is not considered here but could be the subject of continued studies. However, there is a point of only performing the third step, i.e. to develop images of the future, since it shows what kind of changes that would be required to achieve a future sustainable energy system. This report could thus be seen as a basis of discussions and of continued studies.

However, the question whether the vision presented in the report is a utopia still remains. There are some barriers for a development towards the future energy situation described in the report. The assumptions made regarding efficiency potentials are, as mentioned above, technically realistic even though stronger incentives will be required. The conversion techniques utilised for production of biomass-based transport fuel, electricity and heat are more or less based on technology that exist today. Nevertheless, some of the process steps are not yet fully developed and there are at present no large-scale facilities in operation. However, these barriers could probably be eliminated by further development and demonstration projects in the near future and are therefore not considered long-term. In this report economical aspects of a change of energy system have not been taken into consideration. However, a changeover of this proportion will increase the energy prices but the costs for achieving the vision described here will probably be small since the energy costs in the society constitute a relatively small part of the total costs.

Even though the vision of a large-scale energy combine could be realised from a technical and economical perspective, there might be restrictions regarding biomass supply. As was shown in section 3.4.2, the estimated biomass potentials are large but they differ greatly, e.g. depending on different opinions on how large extractions that are compatible with ecological sustainability. A large part of the future biomass potential is constituted of logging residues and there are uncertainties regarding environmental impact from large-scale extraction. The extraction of logging residues results in nutrient losses in the forest soil, which may cause nutrient imbalances and increased acidification. These nutrient losses could be compensated for by recirculation of the ash produced in the energy conversion process. Recirculation of good quality ash is thus an important aspect of increased biomass utilisation since it could prevent decreases in the long-term productivity of forest soils. However, if the potentials turn out to be in the lower parts of the estimated intervals and if there will be an extended use of bioenergy in the rest of the country as well, there might be a situation where the demand exceeds the supply and where competition between for example the energy sector and other sectors such as the forest industry is created. A large demand and a limited supply could also result in increased biomass prices.

However, the main barrier for reaching the vision is perhaps lack of political will. In order to implement the changes required political decision in the form of regulations and means of control, such as CO_2 taxes and regulations regarding energy use. Incentives for a sustainable energy system and society must be created. The decisions regarding the development of society made today must not prevent or complicate a development towards a future sustainable society. Since there are uncertainties about the future development, social planning therefore needs to be adaptive, i.e. be able to adapt successively to changed conditions.

In the image of the future all transport fuel, nearly all heat in the district heating system and more than 20% of the electricity demand is derived from biomass-based facilities. It is important to note that this vision is just an illustration of one possible future situation. Other alternative scenarios are conceivable. It might for example be more favourable to produce transport fuel, power and heat in other ways than described here. Perhaps these energy carriers will continue to be produced from fossil fuels, utilising CO_2 sequestration. Perhaps we are heading towards a change of system where the main energy carriers are electricity and hydrogen. Perhaps the district heating system has been replaced and each house has its own fuel cell for production of electricity and heat.

Due to the time limit, there are several issues that have not been considered in this report. As was mentioned above, the fourth step in a backcasting study, where suggestions of how to reach the image of the future developed, could be an applicable subject for further studies. Patterns of behaviour do also play a significant role in a changeover to a sustainable society. An analysis of the impact of the individual's behaviour regarding use of energy and the acceptance of changing behaviour and habits, which might be required in order to realise the vision, could also be an interesting subject.

The issue where the biomass-based facilities should be located is another relevant question since both the production facilities and the feedstock require large areas. Biomass-based facilities described in the report are technically advanced and the operation requires a continuous flow of feedstock to the plant. Biomass must thus always be available and in order to secure the supply a large transport system will be needed. The facilities should therefore be located where they could easily be reached by the transport deliveries. How the biomass should be transported is therefore also of importance. Boat and train is more favourable than lorry since larger amounts of biomass per transportation can be loaded, hence reducing the transport intensity. The overall environmental impact of the plant, including the impact from the feedstock transports, could also be considered in future studies.

Further studies could also include alternative visions. One example is a vision of a hydrogen society where fuel cells provide buildings with heat and electricity and transports by road run on hydrogen. Hydrogen could for example be produced from biomass or from electricity produced from solar cells. The possibilities to implement sequestration and storage of CO_2 in the production of transport fuel, electricity and heat from biomass as described here or in the production of hydrogen from biomass is also an important issue that might receive increased impact in the future. The utilisation of biomass would then not only be CO_2 neutral, but would also constitute a carbon sink.

5. CONCLUSIONS

Even though many of the technical components of a biomass-based energy combine for production of transport fuel, power and heat are not yet fully developed they are likely to be commercially practicable in large scale in the near future. There are large potentials to reduce the energy use per capita, both in the residential and service sector and in the transport sector. In a future sustainable Göteborg, characterised by energy efficiency, a biomass-based energy combine could comprise an important part of the energy system. However, the supply of biomass could be a problem for an energy combine of this kind, but the estimated future potentials are large and this aspect are therefore not considered to be an insurmountable obstacle, even though there might be logistical problems regarding biomass transportation. Instead, the main obstacle for an energy combine and an energy system based on renewable energy sources is perhaps lack of political will and the conservatism that characterise for example the building sector. An interesting subject for continued studies would therefore be how the vision presented in this report could be realised.

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