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ALTERNATIVE SOURCES FOR PRODUCTS COMPETING WITH FOREST-BASED BIOFUEL, A PRE-STUDY

Report from an f3 project

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THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

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SUMMARY

Forest biomass is used for many products including paper based products, sawn wood products and solid fuels. The production of forest derived liquid transportation fuels is currently limited but predicted to increase.

Biomass is a renewable resource and therefore of high interest for applications such as new innovative materials, liquid and gaseous fuels. The production of various biofuels for transportation is forecast to increase and Sweden has a goal of a fossil-independent transportation system by 2030. Other, non-material, uses of forest biomass include the so called eco system services biodiversity, fishing, hunting, recreation, berry picking etc. which are also competing for forest biomass.

There is currently a net growth of forest in Sweden, which theoretically could allow for an increased use of this resource. However, the amount of forest biomass is not unlimited and its harvest should not exceed its growth. Therefore, forest biomass should be considered as a limited resource and its use should aim to maximize the environmental benefit compared to the use of fossil resources. For this reason, environmental impact evaluations of forest biomass based products should include alternative sources for products competing with this resource.

The pre-study reported herein included: a review of Swedish forestry and the relationships between different types of forest biomass and fuels; a workshop in which the competition for forest biomass was discussed with experts in the area; a theoretical reasoning around indirect effects and biomass potentials; and two case studies in which the theoretical reasoning is applied. Traditional assessments of environmental impacts of products and processes do not include the aspect of resource scarcity or competition for raw materials. In the case of bioethanol this has been shown to affect the results of such evaluation and the same thing applies also to other forest biomass based fuels.

The main conclusion of the study is that alternative sources for products competing with forest biomass should be taken into account when assessing the environmental impacts of forest biomass derived products. This is, however, complex as indirect effects are difficult to predict and depend on numerous factors including market situations, financial instruments, legislation and policies etc. Nevertheless, the question is important for the development of bio-based substitutes for fossil derived products.

SAMMANFATTNING

Skogsråvara används idag till olika ändamål, som t.ex. pappersprodukter av olika slag, sågade trävaror och energi – huvudsakligen i form av fasta bränslen. Det finns även en viss produktion av drivmedel, men inte i så stor skala som förväntas i framtiden. Utvecklingen av sådan tillverkning är intensiv och biobaserade drivmedel eftersträvas och premieras med b.la. styrmedel och politiska mål.

Biomassa är en förnyelsebar resurs och som sådan mycket intressant för många användnings-områden, som t.ex. nya material och flytande och gasformiga bränslen och drivmedel. Framställ-ningen av biodrivmedel kommer med all sannolikhet att öka under de kommande åren – i synnerhet som Sverige har ett mål om en fossiloberoende fordonsflotta till år 2030. Skogen ska, förutom att vara råvara till ovanstående typer av produkter, också tillgodose behoven av de s.k. ekosystem-tjänsterna, som t.ex. biodiversitet, fiske, jakt, rekreation och bärplockning som därmed också kon-kurrerar om denna råvara.

Idag har Sverige en netto-tillväxt av skog, vilket åtminstone teoretiskt ger utrymme för ökat uttag av skogsbiomassa i Sverige och därmed en ökad tillverkning av produkter därav. Tillgången på skogsbiomassa är dock inte obegränsad eftersom tillväxten måste vara lika med, eller större, än uttaget. Därför måste skogsbiomassa betraktas som en begränsad resurs och dess användning bör vara sådan att den ger maximal fördel jämfört med användning av fossila resurser. Det medför att LCA och andra utvärderingar av miljömässiga konsekvenser av en produkt från skogsbiomassa bör inkludera alternativa råvaror för produkter som konkurrerar om samma råvara.

Denna förstudie omfattar en beskrivning av svenskt skogsbruk och sambandet mellan olika kvali-teter av skogsbiomassa, en workshop vid vilken konkurrensen om skogsbiomassa diskuterades med experter i ämnet, en teoretisk diskussion om indirekta effekter och biomasse-potentialer samt två fallstudier i vilka de teroetiska resonemangen appliceras. Traditionella utvärderingar av produkters miljöbelastning inkluderar inte begränsning av tillgång på råvara eller konkurrens om densamma, vilket, bl.a. för produktionen av bioetanol har befunnits ha stor betydelse. Samma sak gäller även för andra produkter från skogsbiomassa.

Den huvudsakliga slutsatsen av studien är att alternative råvaror för produkter som konkurrerar om skogsråvaran måste inkluderas när den miljöbelastningen av en skogsråvarubaserad produkt analy-seras. Detta är mycket komplext eftersom indirekta effekter är svåra att förutse och beror på många faktorer, som t.ex. marknadslägen, styrmedel, politiska mål etc. Icke desto mindre är frågan viktig för att utvecklingen av biobaserade råvaror ska bidra till en så minskad miljöbelastning som möjligt jämfört med de fossilbaserade motsvarigheterna.

CONTENTS

1 INTRODUCTION

Among the challenges facing the world is the substitution of fossil based products with bio-based equivalences. Biomass is a renewable resource, whose use is associated with lower net emissions of greenhouse gases and overall lower environmental impact compared to fossil-based products. Therefore, it is desirable to substitute fossil-based products with bio-based ones in order to mitigate climate change and decrease the use of finite resources. Many countries have, or are about to, publish national strategies for how to achieve a shift from fossil to bio-based economies, such as the USA (White House, 2012), EU (European Commission, 2012b), Sweden (Formas, 2012) and Germany (National Research Strategy BioEconomy 2030, 2011), which deal with many challenges regarding increased use of bio-based resources. It is a wide-spread forecast that the world will soon face a scarcity not only of fossil resources, but also metals, phosphorous (Cordell, Drangert, & White, 2009), water (OECD, 2012; Postel, 2000), biomass (McKinsey&Company, 2008) etc. With a growing global population, it is a challenge to support everyone with energy, water, food and other basic needs within sustainable frames. The World Business Council for Sustainable Development (WBCSC) has published a vision for 2050: “9 billion people living well within the boundaries of one planet” (World Business Council for Sustainable Development, 2010). The vision includes a roadmap, divided into nine different areas, for how to reach this vision, of which forests are one, thus showing that WBCSC considers this resource as one of the key areas for attaining their vision. One common challenge for all of the areas specified is that resources need to be used wisely in order to get the maximum output of all inputs. This limitation of resource availability is also the key aspect of this pre-study on production of biofuel from forest biomass.

One important question related to the above is how to provide the world with sustainable fuel for transportation. Several technologies are available today for upgrading biomass to solid, liquid and gaseous fuels such as ethanol, synthetic diesel, biodiesel, biogas etc. showing various environmental performances depending on type and origin of biomass and refining technique. Until now, commercial bio-based liquid fuels belong to the so-called first generation biofuels, i.e. mainly produced from sugar rich feedstock. There is, however, an ongoing discussion regarding if and how these biofuels might compete with food production, thereby interfering with global food supply. Second and third generation biofuels refer to biofuels produced from biomass that are not considered to compete with food production in the same way, such as lignocellulosic biomass. Research and development of technologies for such fuels is both advanced and intensive, but as of today, there is no commercial, full scale production of biofuels from such feedstock. However, diesel from tall oil, a by-product from pulp and paper making, is produced and sold on a commercial basis by Sunpine and Preem.

Forest biomass is a highly interesting feedstock as it is suitable for production of biofuels for transportation. There are several kinds of biofuels from forest biomass with production techniques at various stages of development, such as fermentation of cellulose to ethanol, gasification of wood and other forest biomass to syngas, which can be converted to diesel, methanol, methane and other fuels. However, forest biomass can also be used for other purposes. Current products include wood for construction, paper and board. Future products are plastics, composites, textile etc.

Considering the challenge discussed above on future resource scarcity, it is relevant to discuss the impacts of increasing the use of forest biomass for biofuel. In such an impact assessment it is important to expand the system boundaries and consider what happens to the material supply for other products and services in which there could be potential use for forest biomass, i.e., to include the use of alternative sources for the products competing for forest biomass.

The present study is a pre-study based on such reasoning, focusing on Swedish forest biomass.

1.1 AIM AND SCOPE

The aims of this pre-study are as follows:

- Provide a straight-forward overview of Swedish forestry, biomass qualities and the relationship between them and the availability of biomass streams from forestry, pulp and paper mills and saw mills. Such knowledge is crucial for everyone interested in forest biomass as an important raw material and a significant corner stone of a society based on the use of renewable resources for energy and material purposes.
- Discuss the environmental impact of various uses of forest biomass, taking into account alternative uses for the feedstock and the alternative feedstocks for those products/services.
- Describe potential conflicts between interests in forest biomass resources.
- Highlight which areas are the most important to focus on for further research related to the issues dealt with in this report.

1.2 METHODOLOGY AND READING INSTRUCTIONS

The study is divided into two parts. The first part contains a general description of the system, modern forestry and biomass availability. It also examines quantitative and qualitative economical relationships between different biomass types and alternative sources for the biomass-based applications. The second part contains an analysis of the current situation with the help of a workshop, and is further illustrated with case studies (ethanol production and black liquor gasification with subsequent production of DME fuel), in which the reasoning described is applied.

When discussing the use of Swedish forest biomass, it is important to have an understanding of the availability of biomass in Sweden. Therefore, the report presents an overview of Swedish forestry, biomass qualities and the relationship between them, and the availability of biofuels from forestry, pulp and paper mills and saw mills, etc.

At the end of the report, conclusions are presented, research gaps discussed and suggestions for further studies given.

1.2.1 Workshop

A workshop was planned together with f3 and was held in Lund, on November 28th, 2012. The workshop was held in connection to the f3 and LU open seminar on integrated biofuel production on November 29th. f3 partners and the f3 board were invited. Eighteen participants attended (see participant list in appendix A), of whom three are researchers of this project. All participants have expert knowledge in at least some aspects of the issue in focus. They were both researchers in the field and working in companies in the energy sector and in the pulp and paper sector. Several actors and companies in the forestry sector were also contacted and invited, but unfortunately could not attend the workshop.

The workshop aimed to explore three main questions:

1. What are the current and potential future uses of forest biomass?
2. Are there alternative sources of materials or alternative services for these uses?
3. What could the potential environmental impact due to increased use of the alternative sources/services be?

During two sessions the participants were divided into discussion groups to discuss these questions and then report back to the whole group. The participants were also asked to vote for which environmental effects they thought were most important to explore further. The outcome of the workshop is presented in Chapter 5.

1.2.2 Case studies: ethanol and DME from black liquor gasification

The main tools used in the analysis of the case studies are Life Cycle Assessments (LCA), calculation of primary energies and CO_2 emissions using expanded system boundaries. These are used to illustrate the main issue of the study, i.e. the limited availability of biomass and the associated environmental impacts of its various uses.

Ethanol and dimethyl ether (DME) from black liquor gasification were chosen as case studies since these represent two very different types of biomass derived transportation fuels. Bioethanol contributes significantly to both Swedish and international transportation and is therefore a natural choice for a case study. Black liquor gasification with subsequent upgrading of the gas to liquid fuels such as methanol or DME has been pointed out as a promising technique to produce biofuel for transportation and was, at the time of planning the study a technique in focus with a pilot plant running and advanced plans for a demonstration plant at Domsjö mill in Sweden – all which makes it an interesting case study.

1.3 DEFINITIONS OF BIOMASS

This section contains a number of definitions: of biomass per se, biomass categories and types, and biomass energy potentials.

1.3.1 Biomass

Numerous definitions exist for the term biomass. Depending on the background from which they originate, they may differ considerably, e.g. regarding the inclusion or exclusion of a specific material or product. The general biomass definition is found in several European Commission documents on biofuels or bioenergy, e.g. in the EU Renewable Energy Directive. There, biomass is defined as *'the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste'*. This general definition, however, only includes biomass that is actually entering the economic cycle, i.e. when it is either used by agriculture, forestry and related industries or – in the case of industrial and municipal waste – occurring due to economic activities.

A more scientific definition can be found in European Environmental Agency's glossary characterizing biomass as *'all organic matter that derives from the photosynthetic conversion of solar* *energy'*. However, this definition might be too broad, especially when it comes to materials such as peat. Despite having a biogenic origin it actually is a *'fossil secondary product of rotting processes'* (fossil energy carrier) and is therefore excluded from a strict biomass definition. Peat is often referred to as a renewable energy carrier (biomass) in several peat-rich countries. The most suitable definition of biomass in the context of this project is presented in the so-called "Unified Bioenergy Terminology" paper by FAO which aims at unifying and organising currently used terminology and definition of wood fuels and other biofuels (FAO, 2004)

> *'Biomass' means material of biological origin excluding material embedded in geological formations and transformed to fossil*

1.4 LIMITATIONS AND ASSUMPTIONS

The focus of this report is Swedish forest biomass, which is the main contributor to the Swedish bioenergy sector. Other sources of biomass include semi-natural vegetation, agricultural biomass and algae. Agricultural residues are currently used for energy purposes, but not contribute significantly less than forest derived biomass. In 2008, 111 and 1.5 TWh of Sweden's 131 TWh bioenergy energy came from forest and agricultural residues respectively (Bioenergiportalen, 2013). Algae is today an unexploited feedstock for energy and full scale commercial plants in Sweden are, to our knowledge, not realistic in the near future.

Forest management is assumed to be the same as today for the next 100 years, i.e. approximately one growth cycle, (time from seeding to final harvest) in the forest but that there is a potential to increase harvest of other parts of the tree, such as branches and tops and also a certain increase in thinning and pruning. Intensive forestry is addressed but not analyzed in depth. Substitution of current tree species for new ones is also not taken into account. These limitations have been chosen in order to keep the discussions at a comprehensible level.

There are debates on whether Swedish forestry is really taking environmental issues enough into account or not, but that issue will not be discussed in this report. The study mentions the potential of increasing the amount of forest harvested or the introduction of new tree species that can be suitable in a future climate with higher average temperatures but will not go into details on these issues. There are many ongoing projects aimed at increasing forest growth per hectare, which is further discussed in section 10.2. Such increases would permit a greater amount of harvested biomass, although the consequences for such forest management are under debate.

Furthermore, the potential amount of biomass available in the future is discussed. However, the amount is not pivotal for the reasoning in this study: that biomass is indeed a renewable but limited resource, and that use of biomass for one purpose has far reaching effects, that require expanded system boundaries for LCA and other impact studies.

2 BACKGROUND – FOREST AND BIOMASS

2.1 SWEDISH FOREST AND FORESTRY

In this study, we focus on Swedish forest biomass. There are several qualities of biomass extracted from the forest, as is described below. In Sweden today, there are 3000 million m^3 of forest, of which 40% is pine and 41% is spruce. The remaining 19% consists of hardwood and other coniferous trees. The annual growth is estimated to be 120 million m^3 (see Figure 1). Approximately 90 million m^3 forest is harvested annually, which means that there is a net growth of forest. This increase is a result of increased forest volume rather than an increase in net forest area.

Biomass is a renewable feedstock, but it will effectively be a finite feedstock if it is consumed at a higher rate than its renewal. Therefore, a net growth of ≥ 0 is necessary for a long term sustainable forestry.

Almost all Swedish forest is certified to either, or both, of the systems FSC and PEFC.

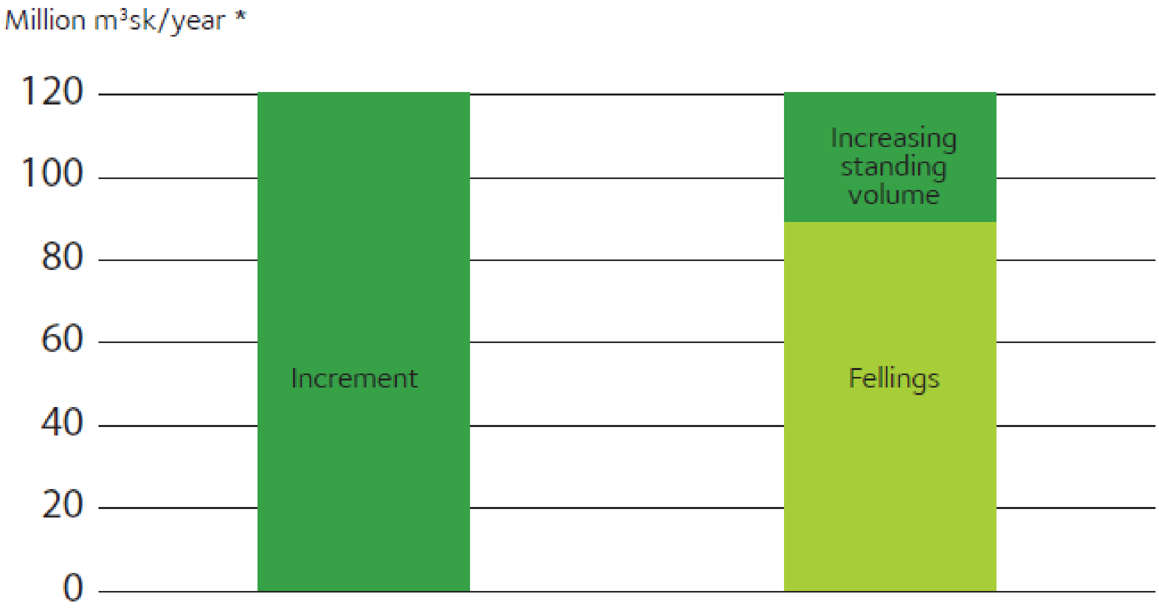

Figure 1. Growth and harvest of Swedish forest (The Swedish Forest Industries, 2012). m3sk = forest cubic meter.

Swedish forest owners include: the state, state-owned companies, forest companies and private owners. Figure 2 shows the distribution of ownership for Swedish forests, which is an important factor for the discussions later in the report. There are more than 300 000 private forest owners in Sweden and the average size of privately owned forest properties varies between 37 ha in southern Sweden, to 73 ha in the northern parts of the country (The Swedish Forest Agency, 2012).

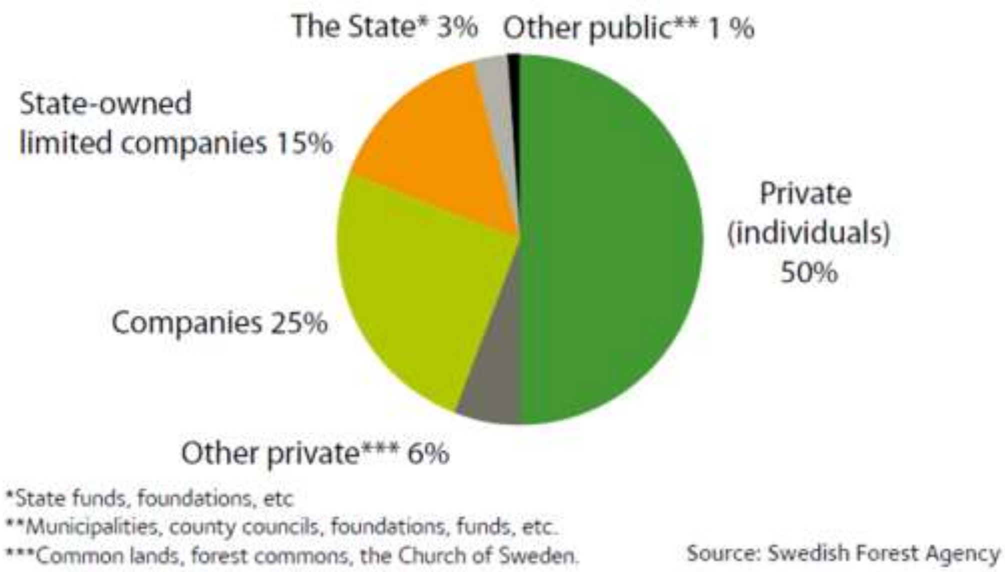

Figure 2. Ownership of Swedish forest land. Source: The Swedish Forest Industries: facts and figures.

An overview of the Swedish wood flow in 2010 is shown in Figure 3 below. The 80 million m^3 of forest harvested result in approximately 72 million m^3 of solid under bark available for utilization. (There are several ways of measuring volumes of trees. Forest m^3 is most commonly used for harvested amounts whereas m^3 solid under bark is the most common for saw mills and pulp mills, 1 forest m^3 equals 0.8 m^3 solid under bark. Detailed information on the relationship between the different volumes can be found on Skogssverige's homepage, www.skogssverige.se.Approximately equal amounts are processed in saw mills and pulp mills. As can be seen in Figures 3 and 4, Sweden is a net importer of round wood, which means that under current market conditions, an increased use of forest biomass is likely to have consequences on the international market of roundwood and other forms of forest biomass. For example, if production of. Biofuel is to be increased, it will probably affect current utilization and/or domestic harvest, import and export.

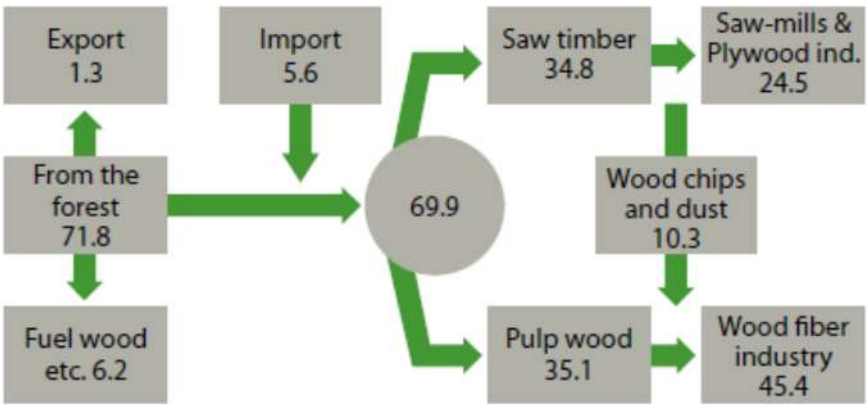

Figure 3. Wood flow in million m^3 under bark 2011. (Figures differ from Figure 1, where volume is given in forest m^3, see explanation in text above.) Source: The Swedish Forest industries: Facts and figures.

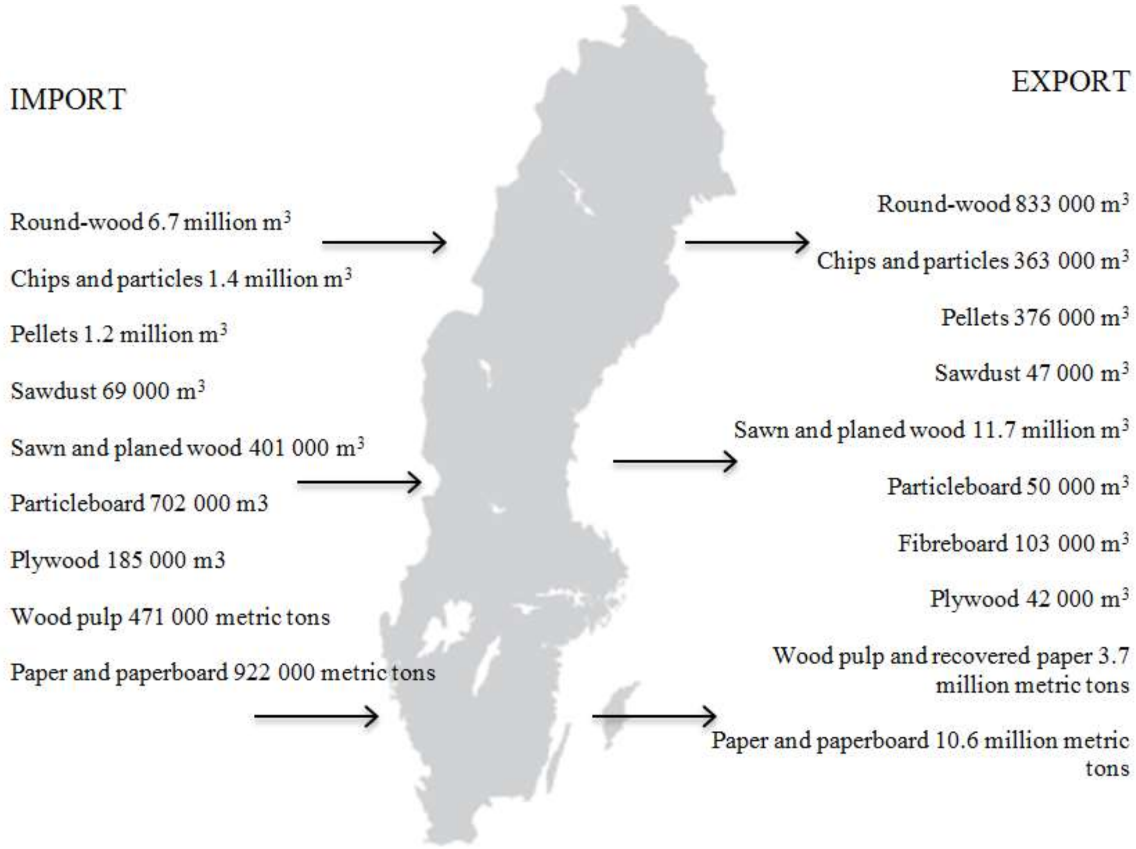

Figure 4. Import and export of forest products in Sweden 2011 (Swedish Forest Agency, 2013). Data for round-wood, chips and particles, pellets, and sawdust is given in m^3 solid volume excluding bark.

2.2 FOREST MANAGEMENT

Sweden has a modern forestry in the sense that there is legislation regulating many issues, including: replantation; amounts of dead wood that must be left after harvesting in order to provide biotopes for insects; birds and other animals; the use of insecticides and fertilizers; the relative area which must be set aside for environmental preservation ensuring biodiversity, preventing deforestation and securing forest viability. But at the same time, the legislation leaves many decisions open to the owner. The legislation text can be found on the home page of the Swedish Forest Agency (The Swedish Forest Agency, 2013).

Forest management in Sweden is mainly performed on a compartment basis, which means that whole compartments are managed as unities. Alternatives include selection forestry or uneven aged forestry, where single trees are selected for different management actions, but as these management practices are applied on only small areas in Sweden, they will not be described here.

When the trees on a compartment reach the height of 2-4 m, the forest is pruned, i.e. trees that are inferior are cut so that the remaining trees will have better conditions and grow faster. The cut trees are left in the forest as fertilizers. When the trees reach the height of 12-22 m, it is time to perform thinning. Thinning results in more space for the remaining tree crowns and therefore promotes growth for the trees selected as the best. The thinned trees are used for pulp production and sawing.

Approximately 25-30% of the wood that reaches the industry comes from thinning. By performing correct thinning, the total yield in SEK will be significantly higher than without such management. A compartment can be thinned up to three times during one growth cycle. Regulations require thinning to be done so that the remaining forest is evenly distributed on the compartment and is healthy enough to ensure the production potential of the forest.

At final harvesting, which is approximately 60-70 years after plantation in southern Sweden and 90-120 years in northern Sweden, the compartment is cut down. However, clear cutting is no longer applied and there are rules on how much wood must be left to provide biotopes for insects and other fauna. Furthermore, certain percentages of the forest has to be set aside for environmental preservation, and there are also so called key biotopes, which are considered especially valuable for the biodiversity and therefore recommended to be exempt from harvesting.

The stem wood is used mainly for production of sawn wood products and pulp. The bark is used as fuel in pulp and saw mills and can also be sold as solid biofuel to heat producers. At saw and pulp mills, side streams such as saw dust and fines are produced and used as fuel. With today’s prices, the forest owners generally aim at producing as much timber as possible, i.e. trees that are suitable for sawing. There is almost no forest harvested for the purpose of making fuel – neither solid, liquid nor gas.

2.3 FOREST BIOMASS

2.3.1 Macro composition of the tree

A tree consists of a root system, a stump, stem and so called GROT, i.e. branches and tops (GRenar Och Toppar, in Swedish). Today, approximately 50-60% of a tree’s total biomass is extracted from the forest at a typical harvest, see Figure 5.

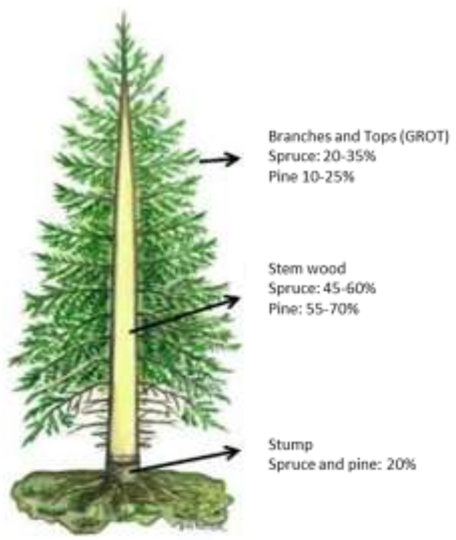

Figure 5. Partition of a tree’s biomass. (The Forest Research Institute of Sweden, 2013)

GROT is a solid biofuel suitable for burning in central furnaces adapted to high ash content and equipped with flue gas cleaning systems. GROT is also expected to be a significant feedstock for other bioenergy applications such as liquid and gaseous biofuels. It is widely accepted that there is a potential for increased harvest of GROT without risking the balance of nutrients in the soil, but the actual size of this potential is under debate. However, harvest of GROT can be costly in remote areas since transportation costs are high. Estimations of GROT potentials can be found on home-pages of, e.g. the Swedish Energy Agency and Skogforsk. This will be further discussed under the case study paragraphs later in the report.

Stumps are harvested in Sweden only on a very limited amount. The risk of nutrient withdrawal associated with stump harvest is lower than for GROT harvest, but there are other risks with stump harvesting, such as reduced biodiversity and disturbed carbon circulation – topics that are subject to research (Hellsten, Axelsson, Olsson 2008). Trials with stump harvesting have been set up several times, but it has been difficult to achieve any economic profit (however, in Finland, stump harvesting has been in practice since the 1990's, mainly as a means to prevent root rot). The stumps have to dry for approximately one year before they can be used as fuel. They contain earth, dust, stones etc. and their fibers are of inferior quality and cannot be used for pulp production. The high content of ash and earth make them unsuitable for boilers in private houses.

2.3.2 Forestry and forestry residues

Forestry biomass is subdivided into woody biomass (harvested products) and residues from forestry. Table 1 gives an overview of all subcategories and included types of biomass.

Table 1. Woody biomass and residues from forestry and trees outside forests: Biomass subcategories, origin and included types of biomass. Adapted from BEE (2010).

Biomass subcategory	Origin	Type of biomass
Woody biomass		
From forestry	Forests and other wooded land incl. tree plantations	Harvests from forests and other wooded land incl. tree plantations, i.e. stemwood
From trees outside forests (landscape)	Trees outside forests incl. orchards and vineyards, public green spaces and private residential gardens	Harvests from trees outside forests incl. orchards and vineyards, excl. residues
Woody residues		
Primary residues	Cultivation and harvesting / logging activities in all of the above incl. landscape management	Cultivation and harvesting / logging residues (twigs, branches, thinning material and stumps), pruning from fruit trees and grapevines etc.
Secondary residues	Wood processing, e.g. industrial production	Wood processing by-products, i.e. sawdust, bark, black liquor, tall oil etc.

Woody biomass from forestry includes all biomass from forests (or other wooded land), tree plantations, and trees outside forests.

Woody forestry residues include both primary residues, i.e. leftovers from cultivation and harvesting/logging activities (twigs, branches and tops, thinning material, stumps etc.), secondary residues, i.e. those resulting from further industrial processing (sawdust, bark, black liquor). Tertiary residues, i.e. used wood (wood in household waste, end-of-life wood from industrial and trade uses, waste paper, discarded furniture, demolition wood etc.) are considered organic waste and are not treated in this report.

2.4 BIOMASS AT DIFFERENT LEVELS

The type of biomass potential is an important parameter in biomass resource assessments because it affects to a large extend the fact that there is a limitation in biomass availability and that the utilization thereof needs to be prioritized. Four types of biomass potentials are commonly distinguished:

- Theoretical potential
- Technical potential
- Economic potential
- Implementation potential

Moreover, the concept of a fifth type of potential, *the sustainable implementation potential*, is introduced. See Figure 6 for an overview of the different biomass potential types.

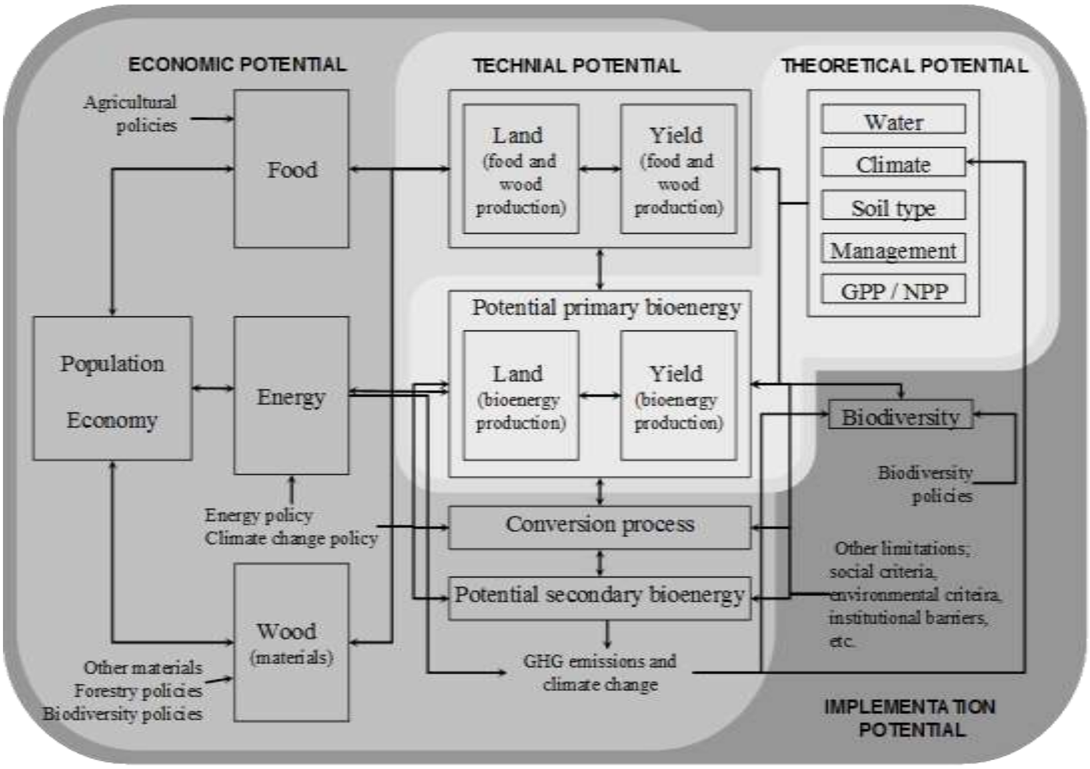

Figure 6. Illustration of the different biomass potentials (Smeets et al., 2010).

Theoretical potential

The theoretical potential is the overall maximum amount of terrestrial biomass, which can be considered theoretically available for bioenergy production within fundamental bio-physical limits. The theoretical potential is usually expressed in joule primary energy, i.e. the energy contained in the raw, unprocessed biomass. Primary energy is converted into secondary energy, such as electricity and liquid and gaseous fuels. In the case of biomass from forests, the theoretical potential represents the maximum productivity under theoretically optimal management taking into account limitations that result from soil, temperature, solar radiation and rainfall. In the case of residues, the theoretical potentials equal the total amount that is produced.

Technical potential

The technical potential is the fraction of the theoretical potential which is available under the regarded techno-structural framework conditions with the current technological possibilities (such as harvesting techniques, infrastructure and accessibility, processing techniques). It also takes into account spatial confinements due to other land uses (recreation, fibre production etc.) as well as ecological (e.g. nature reserves) and possibly other non-technical constraints. The technical potential is usually expressed in joule primary energy, but sometimes also in secondary energy carriers.

Economic potential

The economic potential is the share of the technical potential which meets criteria of economic profitability within the given framework conditions. The economic potential generally refers to secondary bioenergy carriers, although sometimes also primary biomass is considered.

Implementation potential

The implementation potential is the fraction of the economic potential that can be implemented within a certain time frame and under concrete socio-political framework conditions, including economic, institutional and social constraints and policy incentives. Studies that focus on the feasibility or the economic, environmental or social impacts of bioenergy policies are also included in this type.

The classification in types of biomass potentials helps the reader to categorise what information is presented in biomass potential estimates. For instance, some biomass types show high technical potentials while their economic potential is rather limited due to the high costs of extraction and transport. In existing resource assessments, it is often difficult to distinguish between theoretical and technical potential and between economic and implementation potential. The technical and theoretical potentials, and the economic and implementation potentials, form two pairs of potential types. However, even more important than making this distinction between four types is the provision of insight into explicit conditions and assumptions made in the assessment.

Sustainable implementation potential

Also, a fifth type of potential can be distinguished, which is the sustainable implementation potential. It is not a potential on its own but rather the result of integrating environmental, economic and social sustainability criteria in biomass resource assessments. This means that sustainability criteria act like a filter on the theoretical, technical, economic and implementation potentials leading in the end to a sustainable implementation potential. Depending on the type of potential, sustainability criteria can be applied to different extents. For example, for deriving the technical potential, mainly environmental constraints and criteria are integrated that either limit the area available and/or the yield that can be achieved. Applying economic constraints and criteria leads to the economic potential and for the sustainable implementation potential, additional environmental, economic and social criteria may be integrated, see Figure 7.

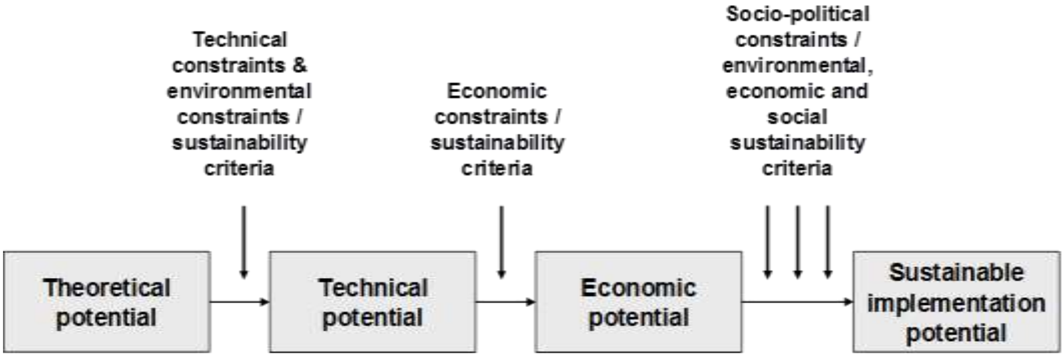

Figure 7. The integration of sustainability criteria in biomass potential assessments.

There is a strong demand for inclusion of sustainability aspects in bioenergy potential. As bioenergy in general and biofuels in particular have lost some of their good reputation due to the food versus fuel debate and due to an increased awareness of land use changes, both industry and politics strive for more sustainable practices. The concept of sustainable biomass potential contains multiple environmental, economic and social aspects, though integrating these aspects may be complex.

The share of the potential that is ultimately realized is dependent on the multitude of factors mentioned above. It is however useful to bear in mind the different levels of potentials; i.e. theoretical potential, technical potential, economic potential and sustainable implementation potential, and their internal hierarchy and determining factors when discussing the future availability of biomass.

2.5 FORESTS FOR ECO SYSTEM SERVICES AND ENVIRONMENTAL OBJECTIVES

The forests serve many purposes besides being a source for valuable biomass: They help preserve a biodiversity of flora and fauna, they bind carbon when growing, and also contribute to soil carbon and water capture. They are also important for hunting, fishing, tourism and recreation etc. Some of these so-called ecosystem services are fairly easily quantified and associated with an economic value, whereas others are more difficult to quantify and price. Nevertheless, all these ecosystem services need to be taken into account when discussing harvest of biomass and forestry and be considered as products from forest biomass. An increased harvest of forest biomass can negatively affect many of these services, and in worst case, the changes might be irreversible.

Research is being done on ecosystem services and how to value ecosystem services and the Swedish government is planning to include impacts on them as a part of the sector investments, starting from 2017.

There are several Swedish environmental quality objectives affecting (or being affected by) the management of Swedish forests. Most prominently, the Swedish environmental quality objectives: *Reduced Climate Impact; Natural Acidification Only; Sustainable forests;* and *A rich diversity of Plant and animal life*, can be considered as most relevant.

Sweden, as a member state of the European Union, must comply with the EU environmental objectives but has also, to a certain extent, the possibility to set stricter goals and policies. The latest high-importance EU agreement on GHG emission reductions is the EU Climate & Energy Package (20/20/20) (Official Journal of the European Union, 2009a). According to this EU-legislation, by the year 2020, 20 % of the EU energy must come from renewable sources, the energy efficiency should increase by 20 %, and emissions of GHG will be 20 % lower than 2005. For Sweden, this implies that the share of renewable energy will increase from 39.8 % in 2005 to 49 % in 2020 (Official Journal of the European Union, 2009b). Also, of special consideration for the transport sector is that the share of energy from renewable sources used for transportation (incl. electricity) must be at least 10 % by 2020.

However, following the need for an even more stringent climate policy and longer term planning, the Swedish government has commissioned a vision “Sweden – a country without GHG emissions by 2050”, in which a climate neutral Sweden is desired by 2050. In order to set out a plan to achieve this, the Swedish Environmental Protection Agency, has published a report setting out the “roadmap” for Sweden to reach a zero-net emission of greenhouse gases in 2050. This roadmap specifies a number of ways in which emissions can be reduced, but also highlights the importance of increased carbon sequestration in Swedish forests and land areas, inter alia by natural reserves (Swedish Environmental Protection Agency, 2012). For the transport sector, the Swedish Transport Administration was in charge of the vision support material.

2.6 APPROACHES AND METHODOLOGIES FOR FOREST BIOMASS ASSESSMENTS

Assessing future biomass potentials is complex. There are four traditional approaches, which are used to quantify biomass resources and to make future projections:

- A *resource-focused approach* is applied in ‘assessments that focus on the total bioenergy resource base and the competition between different uses of the resources (supply side).
- A *demand-driven approach* is applied by studies which analyse the competitiveness of biomass-based electricity and biofuels, or estimate the amount of biomass required to meet exogenous targets on climate-neutral energy supply (demand side), see Figure 8.
- An *integrated assessment approach*, whereby a combined demand-driven and resource-focused approach is used.
- A fourth type is referred to as *feasibility and impact approach*, whereby the technical, economic or environmental feasibility or impacts of a certain bioenergy policy target or scenario are investigated.

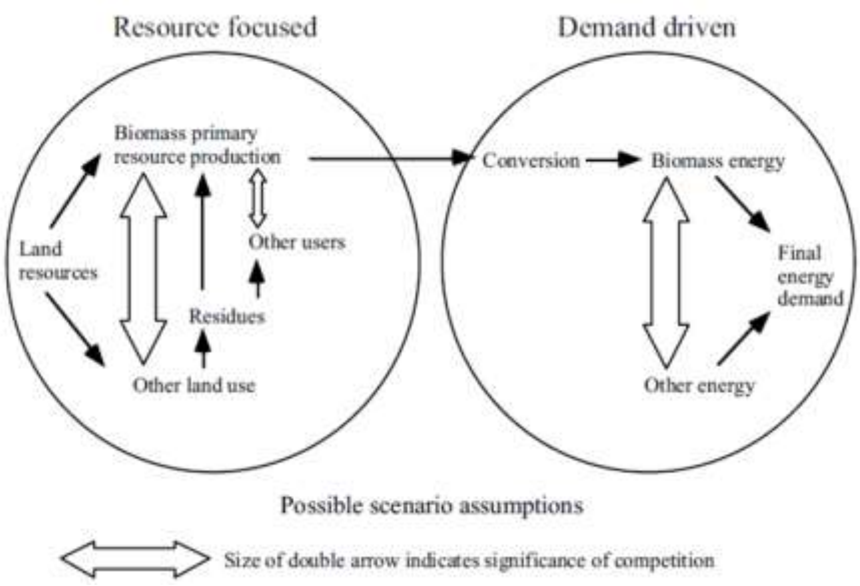

Figure 8. The classification 'demand-driven' and 'resource-focused' (Berndes et al., 2003)

In addition to the above, an approach focusing on forestry biomass called *wood resource balance* has been developed (Mantau, 2005) which is 'based on available production and trade statistics and a consumption analysis which can be based on available statistics and is strongly supplemented with field research'. This approach 'facilitates assessing inter-sectorial trade flows and cascaded uses and estimates demand for wood and possible supply of wood simultaneously taking into account multiple use of wood' (Mantau et al., 2008).

The following methodologies for biomass resource assessments are identified:

- Statistical analysis. The least complicated studies estimate the energy potential based on assumptions concerning the yield per hectare, which is based on expert judgment, field studies and literature review, in combination with assumptions concerning the fraction of forest biomass available for energy production, which accounts for the use of land and biomass for other purposes and environmental or social barriers. Frequently, results from other studies are used, but some studies also use scenario analysis. The potential of residues is generally calculated based on projections of the production of wood, multiplied by residue generation coefficients and multiplied by a factor that accounts for the fact that many residues cannot be collected in practice. Some studies also assess the use of residues for other purposes.

- Spatially explicit analysis. The most advanced resource-focused assessments include spatially explicit data on the availability of forests in combination with calculations of the yields of forests. The scenario analysis takes into account forestry policies, technological development, population growth, income growth etc.

- Cost-supply analysis. The cost-supply analysis begins with a bottom up analysis of the potential, based on assumptions on the availability of forest and forest residues. The demand of land and biomass for other purposes and environmental and other (social, technical) limitations are included, ideally by scenario analysis. The resulting bioenergy cost-supply curves are then combined with estimates of the costs of other energy systems or policy alternatives, often with specific attention for policy incentives (e.g. tax exemptions, carbon credits, and mandatory blending targets).

- Energy-economics/energy-system model analysis. Energy-economics and energy-system models mimic the dynamics of the demand and supply of energy, including bioenergy, by means of investigating economic and non-economic correlations. Most energy-economics and energy system models use scenarios, whereby typical scenario variables include the fundamental drivers of energy demand and supply, such as population growth and income growth as well as technological developments and policy incentives. These variables are often integrated into a coherent set of scenario assumptions. Some models also include greenhouse gas and energy balances for different energy systems, which allows for the optimisation of costs towards greenhouse gas reduction or an energy security target. The ideal study is able to deal with the competing claims of food, feed and fuel on production factors in order to estimate a real economic feasible production of biomass for fuel.

- Integrated assessment model analysis. Integrated modeling assessments use integrated assessment models (IAMs), which are designed to assess policy options for climate change. IAMs include mathematical correlations between the socio-economic drivers of economic activity and energy use that leads to emissions and other pressure on the environment. IAMs are unique because they combine information about economic, energy and climate variables across various scientific disciplines, time, and spatial scales. IAMs are particularly useful for the purpose of addressing policy questions, mostly by means of scenario analysis.

Each approach and methodology has specific (dis)advantages, which are summarised in Table 2. Statistical analyses offer only very limited possibilities to account for environmental or social needs as these only can be included as a general reduction factor. This factor usually refers to an average and thus cannot reflect specific local conditions. Static spatially explicit analyses are more adequate to reflect a biomass potential that is adapted to local or regional circumstances which makes it much easier to take into account environmental or social aspects. Here, different layers containing relevant and local soil, water and climate information can be combined. Static spatially explicit analyses, as statistical analyses, do not offer any possibility to include feedback mechanisms, trade-offs and synergies between the three sustainability dimensions. Furthermore, it is not possible to adequately account for the economic dimension, which is especially important when evaluating the feasibility of changes in technology and thus the availability of forest biomass now used for fiber purposes.

Table 2. The advantages and disadvantages of different methodologies used in existing biomass resource assessments.

Methodology	Disadvantages	Advantages
Statistical analysis	No economic mechanisms, no spatially explicit information, no integration, based on crude assumptions, sometimes inaccurate	Simple, transparent, cheap, data are easily available
Spatially explicit analysis	No economic mechanisms, no integration, complex tool	Spatially explicit, transparent, based on data on land use and climate, soil characteristics
Cost-supply analysis	No economic mechanisms, no integration	Cheap, transparent
Energy-economics /energy-system model analysis	No integration with other markets, not spatially explicit, no integration, no validation based on bottom-up data on land use and climate, soil characteristics, non-transparent	Economics mechanisms are included
Integrated assessment model analysis	Complex, non-transparent, expensive, results are difficult to interpret, model is user un-friendly, level of details is limited	Integrated/consistent, spatially explicit

2.7 INDIRECT EFFECTS OF ALTERATIONS IN THE UTILIZATION OF FOREST BIOMASS

The topic of this pre-study is the effects of an alteration in the use of Swedish forest biomass. An alteration in a system causes effects. The direct effects are often obvious and rather straight forward and easily related to the change in question. However, there are also so called indirect effects, which are more complex to both measure and analyse. As the main starting point of this study is that the amount of available forest biomass is limited, it is important to analyse the indirect effects of an alteration in the use of this raw material.

Growing populations and affluence levels increases the demands for energy and food, which in turn increases the pressure on productive land areas globally (Nonhebel 2005; Tilman 2002). In addition, the need for climate change abatement has increased the interest in biomass-based energy sources. Particularly, non-food biomass, such as forest biomass, and technologies for converting it into low-carbon biofuels are being studied widely (Hämäläinen et al, 2011). The European Union and the Nordic countries promote biomass-based energy production. For example, EU targets aim to increase its proportion of final energy consumption from renewable sources to 20% and 10% of all transport fuels sold must be biofuels by 2020 (EC, 2008). The International Energy Agency (2008) estimates in their Blue Map scenario with 50% GHG reductions to 2050 that the use of biomass will increase four times (quadruple) on a global scale.

Apart from the direct positive effects of the actual replacement of fossil fuels and potential negative environmental effects of the production of the biomass-based biofuel, such a large increase and transition is bound to have side effects also in other parts of the energy system and in other sectors of society that have demand for the forest biomass. Such effects are discussed in the literature as indirect effects, or more frequently, as rebound effects. Economic rebound stems originally from microeconomic literature and the term was confined to direct increases in demand for an energy service whose supply had increased as a result of improvements in technical efficiency in the use of energy (e.g. Khazzoom 1987). Hence the efficiency improvements reduce the cost of a service for the consumer and can lead to increased consumption of that service (Druckman et al, 2011). This is called a direct rebound effect. The broader term “indirect rebound effects” mean that the money saved from reduced costs due to energy efficiency can lead to more consumption of other goods and services that also need energy to produce. Although indirect rebound effects is a broader term, it is not adequately applicable to the case of what happens when there is competition for forest biomass as this resource may have to be replaced due to price effects. Another term is indirect effects that also encompass the more narrow rebound effect. Jonsson and Johansson (2006, p 153), in a paper on indirect effects on transport infrastructure investments, define indirect effects as effects that result from “changes in the use of infrastructure and the structuring influence that infrastructure has on society”. Their example is that the effects of infrastructure can have effect on settlement structure, which can lead to effects in future transport volumes (ibid.) When indirect effects are included in e.g. environmental assessments, it will have a cumulative effect on the outcome (ibid.). Börjeson and Berglund (2007) have analysed indirect environmental effects of conversion to biofuel systems. They define indirect environmental effects as those that are “caused by emissions that are not directly related to the energy conversion in the systems, for example, changed emissions of ammonia and nitrous oxide from arable land and leakage of nitrate due to changed farming practice, or emissions of methane, ammonia and nitrous oxide from the storage of manure” (ibid. p 327). Effects considered in this respect are still related to the *main* production system that is in focus, while we in this report look at the effects of *other* production systems that may be affected by changes in the primary production system. Such effects are more closely related to the “world-wide rebound” and “transformational rebound effects”. World-wide rebound is described in the energy economic literature and occurs when more efficient production (and use) fuels more growth and energy consumption at a macroeconomic scale (e.g. Sorrel, 2009). Transformational rebound effect is when consumers’ preferences are changed and has impacts on the structural organization of production (Greening et al., 2000). Transformational rebound effects refer to changes in consumer preferences, rather than price mechanisms, but those changes in preferences will in turn lead to market changes. However, the competition for raw material and the potential consequential increase in prices and changes in the market are not discussed as economic rebound/indirect effect context to our knowledge. The connection between alternative forest biomass uses and the economic rebound/indirect effects that the different uses may lead to is important to explore. Particularly in view of increasingly scarce resources and increased competition for raw materials, so that unexpected indirect effects can be anticipated and mitigated.

3 FOREST INDUSTRY PRODUCTS

An understanding of the current use of Swedish forest biomass is necessary for anyone who has an interest in Swedish bioenergy and biomass supply and demand. Therefore, an overview is given in this chapter.

Wood consists of 40% lignin, 40% cellulose and 20% hemicellulose. The latter two are hydrocarbon chains whereas the lignin consists of a complex carbon-based structure and serves as the “skeleton” of the tree. The cellulose is the main constituent in chemical pulp, whereas mechanical paper contains all three above-mentioned constituents.

The production of pulp and paper generates several side streams relevant for this study and will therefore be described here. Saw mills generate byproducts such as solid biofuels in the forms of bark, chips and saw dust. Additionally, the heat from the drying chambers can be used for district heating.

3.1 PULP AND PAPER

Approximately 35 million m^3 wood is processed in Swedish pulp and paper mills and 35 million m^3 in saw mills (of which approximately 10 consist of chips that are send to pulping, which need to be added to the 35 million m^3 to pulp production). This means that if wood is to be used for production of other purposes, e.g. biofuels, the volumes used for pulping and sawing will have to decrease (unless Sweden intensifies its forestry, increases it import or the demand for pulp and sawn wood products decrease, but as mentioned, that issue is not within the frame of this study).

There are several types of pulp, and below are short descriptions of the most common ones.

3.1.1 Mechanical pulp

Mechanical pulp is produced by wet grinding wood in order to separate the fibers. The lignin is not separated from the cellulose, so the yield is high, which means that there are few biomass by-products suitable for fuel from a mechanical pulp mill. However, bark is commonly used internally as fuel. Mechanical pulp is used in paper products with a short life time, such as magazines and fluting (middle layer in cardboard). The production of mechanical pulp in Sweden has decreased, as reported by Swedish Forest Industry Federation (Wiberg & Forslund, 2012).

3.1.2 Chemical pulp

In the production of chemical pulp, the wood is debarked, chipped, boiled, washed, often (but not always) bleached and finally dried. Figure 10 illustrates the pulping process. In the pulping process, lignin and hemicellulose are separated from the cellulose, which is the main constituent of the pulp. There are two main processes for chemical pulp: sulphite and sulphate (Kraft). The latter is a newer process and the dominating process in Sweden and illustrated in Figure 9. The two processes result in somewhat different pulp and byproduct qualities and also have different prerequisites for recovery of the cooking chemicals as well as purification of effluents and potential of adding value to side streams. In this project we will not describe the differences in detail and focus on Kraft pulp since this is the dominating process in Sweden.

The difference between a market pulp and an integrated paper mill is that the former does not produce paper from the pulp. Papermaking consists of dissolving the fibres and mixing them with sizers and fillers (mineral constituents). Depending on the type of paper, up to 40% of the final product consists of fillers/sizers. Papermaking is an energy demanding process, so the energy balances differ between pulp and paper mills. Paper mills can be integrated, i.e. they first produce pulp and then paper, or only paper mills, i.e. they buy pulp for production of paper.

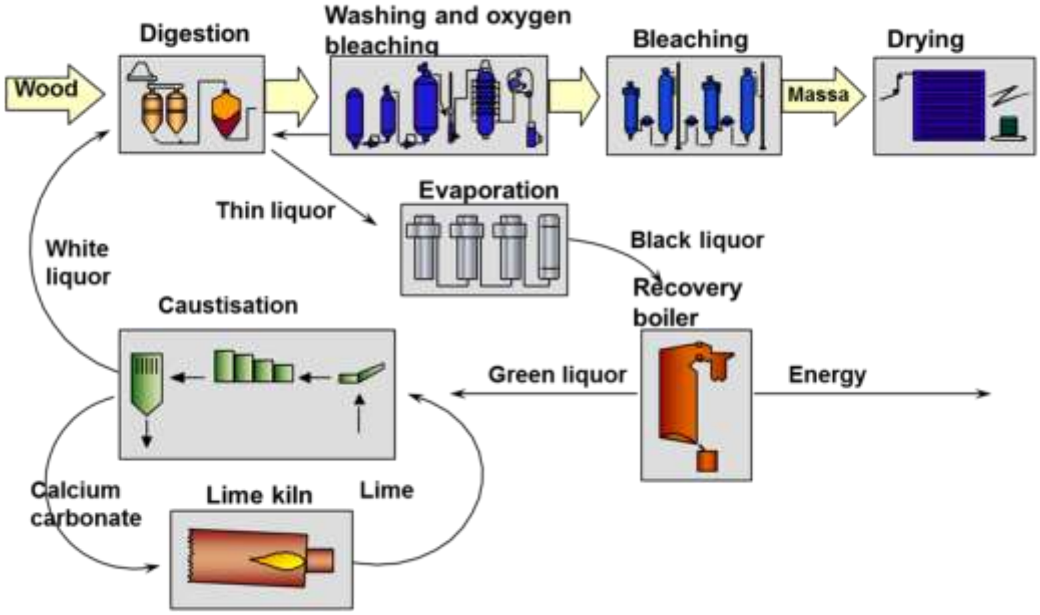

Figure 9. Overview of the Kraft pulping process. Source: Södra Skogsägarna ekonomisk förening, personal communication.

During cooking of the chips, the lignin is dissolved in the cooking liquor. This liquor is called black liquor and is evaporated in several evaporation steps from a dry matter content of a few to approximately 85%. The thick black liquor is burned in the recovery boiler, which has two main purposes: separating the cooking chemicals for regeneration and providing steam and heat for the pulping process. For a modern market pulp mill, the energy from burning the black liquor covers the energy need of the mill and generates a surplus of both hot water and steam that can be sold externally. Excess heat can be used for district heating, and there are numerous examples of Swedish mills selling heat to the neighboring communities, such as Södra Cell's mills, SCA Östrand and Domsjö. Steam can be used for production of electricity that can be distributed through the external grid.

3.1.3 Pulp and paper mills in Sweden

There are approximately 50 pulp and paper mills in Sweden with production capacities ranging from 150 000 – 750 000 tonnes/year. They process 35 million m^3 of wood (from domestic production and imported raw material) and 10 million m^3 chips from saw mills (see Figure 3), and production of 1 ton of chemical pulp requires 5 m^3 round wood. As mentioned, Sweden is today a net importer of wood as feedstock for pulp production, and a net exporter of pulp and paper products (see Figure 3 and 4). Swedish pulp and paper mills have improved their energy and resource efficiencies significantly over recent decades. They have also reduced the emissions to both air and water of substances such as phosphorous, nitrogen, and organic substances (www.scb.se). As mentioned above, some mills are net producers of energy and sell solid biofuels, heat through district heating pipelines and electric power to the external grid.

3.2 BY-PRODUCTS FROM FOREST INDUSTRY

The aim of this chapter is to give an overview of side-streams from Swedish forestry, relevant to energy and fuel. The quantities of all the side-streams and by-products from the forest are naturally dependent on each other: the amounts of each depend on how much forest is harvested and managed. Today, forest is managed and harvested with the aim of maximizing timber production and energy biomass is today a by-product.

The by-products described in this chapter are solid biofuels/residues and liquid streams such as tall oil, black liquor, turpentine, etc. A summary of the described side streams is given in Table 3.

3.2.1 Solid by-products

As discussed in Section 2.3.1, major solid by-products from forest are bark, stumps, GROT (i.e. branches and tops), chips and saw dust. The main use of these is fuel for boilers in such as CHP and private boilers. These fractions can be used directly or first converted to pellets.

Bark constitutes approximately 10% of a tree and is separated from the stem-wood at the pulp mills and saw mills. A large part of the bark is used as fuel on site, but there are also significant amounts sold to facilities such as CHP plants and district heating boilers.

Stumps constitute a source for biomass fuel. However, as described earlier, there are challenges associated with handling and burning the stumps and there is no large scale stump harvest in Sweden even though trials for this have been conducted several times during the last 50-60 years.

GROT is a large source for solid biofuel. It is also considered to be a future feedstock for production of both liquid and gaseous fuels. As shown in Figure 5, GROT constitutes 10-35% of the total biomass of a tree, depending on species and forest management. Approximately 7.5 TWh (=1.5 Mtonnes DS) of GROT is harvested yearly in Sweden.

Traditionally, the pulp and paper sector has been offering higher prices than the energy market for suitable biomass, but the situation has changed. The price gap between solid forest biomass for energy and pulp wood (wood chips) has decreased since the year 2000, approximately, and between 2006 and 2009, the price for solid by-products was higher than wood chips, see Figure 10. This might affect the flow of biomass to the pulp and paper and energy industries, respectively.

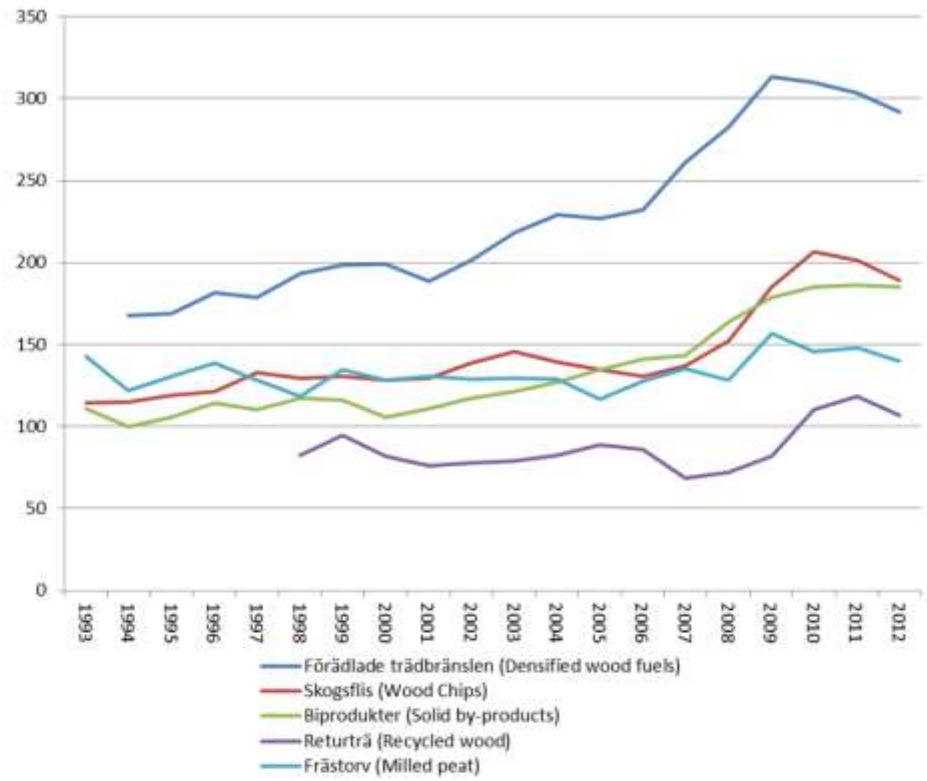

Figure 10. Price curve for wood fuels and peat at district heating plants, SEK/MWh, 2012. Source: Swedish Energy Agency.

The availability of GROT is a complex issue, relating to the description of potentials in chapter 2.4. However, it is generally accepted that there is a potential to increase the harvesting of GROT and this is discussed further in Section 10.2. One example of such forecasts is made by The Swedish University of Agricultural Science (SLU) and the Swedish Forest Agency (Skogsstyrelsen) from 2008, where they calculated that the ecologically sustainable potential of GROT harvesting in Sweden is 85 TWh, but, taking into account technical challenges associated with the harvesting, the potential amounts to 53 TWh (Swedish University of Agriculture & Swedish Forest Agency, 2008). Other estimations mention GROT potentials to be between 15 and 36 TWh (3.2-7.4 Mtonnes) (Swedish University of Agriculture & Swedish Forest Agency, 2008) depending on technical and economical restrictions. The available amount of GROT is also dependent locality: in Götaland, i.e. southern part of Sweden, the amounts of GROT are 2-3 times higher than those in Norrland, i.e. northern part of Sweden. Transporting GROT from northern to southern parts of Sweden is of course technically possible, but today, the market for solid biofuel, including GROT is regional, and we assume in this report (for the case studies) that this will not change within the near future and thus that GROT and other solid biofuels will, for economic reasons, not be transported longer distances than 200 km.

3.2.2 Black liquor

As described in 3.1.2, the black liquor contains lignin and cooking chemicals. Approximately 1.7 ton dry matter black liquor is generated per ton pulp. The energy content of black liquor is 3.3 kWh/kg (Ekbom, Berglin, & Lögdberg, 2005), which means that a medium sized pulp mill that produces 300 000 ton pulp/year generates 1.7 TWh/year in its black liquor. The major part of this energy is required for the process as steam, electric power and heat. In a modern market pulp mill, however, there is a surplus of energy from the black liquor that can be sold on the external market.

3.2.3 Tall oil

Extractives and fatty acids are mainly derived from pine, but also from spruce and to some extent birch wood. These substances are released during cooking of the wood chips and collected in a soap fraction. The soap is acidified to produce crude tall oil, which constitutes a valuable side stream. The extractives are used as a feedstock for the production of resins and other valuable substances, whilst the fatty acid fraction is used for the production of bio-diesel. For example, Arizona Chemical uses tall oil for production of resins, polymers, rubber products, etc. and SunPine uses the fatty acid fraction of tall oil to produce a diesel that is blendable with ordinary diesel. Another example is the margarine Benecol, that contains cholesterol lowering phytosterols originally produced from tall oil. The amount and composition of tall oil produced in a pulp mill varies according to the composition of wood processed and other process parameters, but a modern mill produces approximately 35 kg of tall oil/tonne pulp. Of this, 35-55% are fatty acids, 20-35% rosin acids and 5-25% neutrals (Lee, Hubbe & Saka, 2006).

3.2.4 Turpentine

Turpentine consists of volatile terpenes and is collected from the cooking step. The average yield is 5-10 g/tonne pulp but depends on wood handling, wood species etc. The turpentine fraction can be used as base for perfumes or be used as a fuel – mostly internally at the mill.

3.2.5 Methanol condensate

The methanol condensate contains methanol and various sulphur compounds such as methyl sulphates and mercaptanes resulting in a very malodorant liquid. The yield is approximately 10 kg/tonne pulp and the condensate is extremely difficult to handle due to the odor. Today, it is mainly used as fuel internally at the mills.

Table 3. Overview of by-products from the Kraft process.

Substance	Approximate yield per m3 wood (under bark)	Approximate yield per tonne pulp	Energy content
Bark	36 kg/m3 wood	180 kg/tonne pulp	19 MJ/kg DS
Black liquor	0.3 tonne/m3 wood	1.7 tonne/tonne pulp	12 MJ/kg DS
Tall oil	7 kg/m3 wood	35 kg/tonne pulp	40 MJ/kg DS
Turpentine	0.6 – 1 kg/m3 wood	3-5 kg/tonne pulp	20 MJ/kg DS
Methanol condensate	2 kg/m3 wood	10 kg/tonne pulp	20 MJ/kg

4 THE SWEDISH TRANSPORT SECTOR

As mentioned above, Sweden has set several goals for the share of renewable transportation fuel. It is therefore relevant to present a short overview of both the current situation and the forecasts of fuel use in Sweden.

Table 4 shows the, the total fuel consumption during 2011for land transportation in Sweden, according to the Swedish Energy Agency. The figures include rail transport.

Table 4. Energy use in the Swedish transport sector 2011. Source: Swedish Energy Agency.

Fuel	Energy (TWh)
Gasoline	36.9
Diesel	44.49
Ethanol	2.48
Natural gas + biogas	1.23
Biodiesel	2.72
Electricity	3.03
Total	**292**

The Swedish Transport Administration constructed a baseline scenario to support the Roadmap 2050 (Swedish Environmental Protection Agency, 2012), mentioned in previous chapter, which contained an analysis of progress under current climate policies (Swedish Transport Administration, 2012). This is discussed below.

The baseline scenario

In the baseline scenario, the main drivers to reduce the energy need of Swedish transport are the current fuel efficiency standards and the shift to diesel engines. Figure 11 shows the expected change in the energy split of transport in Sweden and includes all modes of transport. Of particular interest for the current study is that bio fuels are not expected to grow to more than ~7 TWh by 2030 and remains the same to 2050.

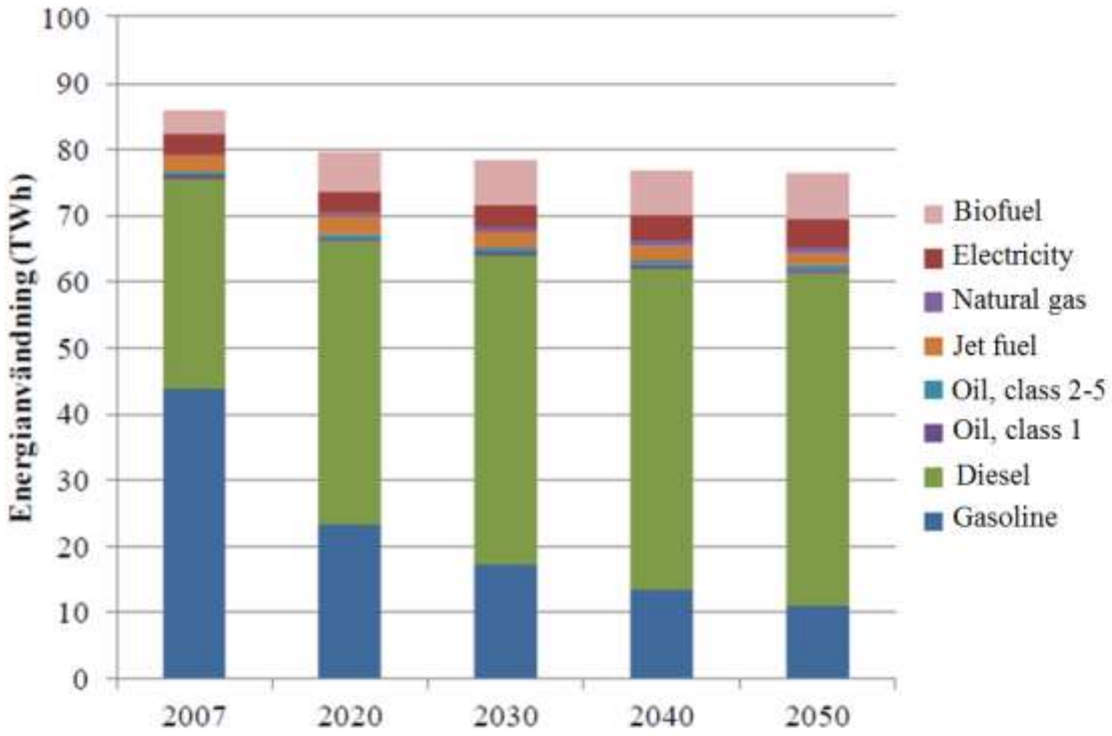

Figure 11. Expected development of fuel use according to the baseline scenario of the Swedish Transport Agency.

Figure 12 illustrates the forecast for shares of different renewable fuels in Swedish transportation.

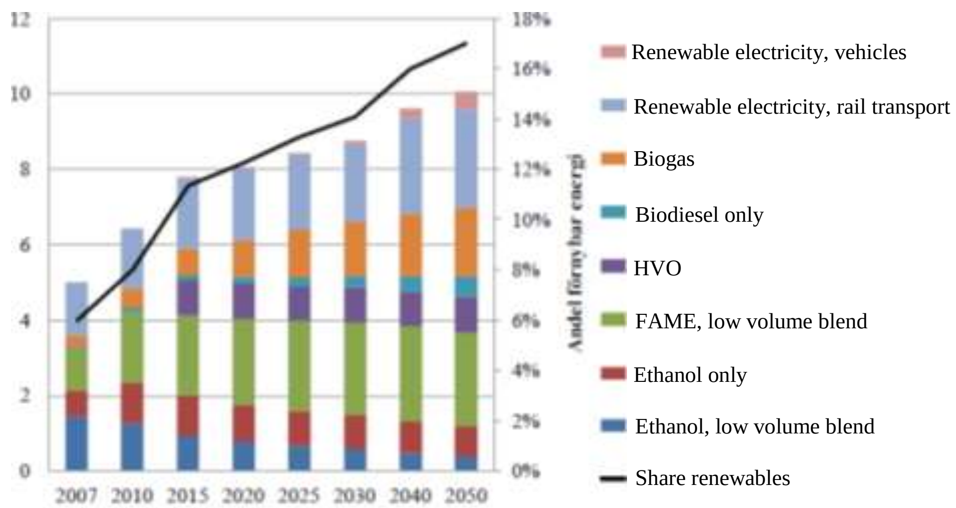

Figure 12. Expected development of use of biofuels and electricity in transport, according to the baseline scenario established by the Swedish Transport Agency.

Figure 12 shows that the use of ethanol fuels is expected to drop from just over 2 TWh in 2010, to 1 TWh by 2050. Sweden will also reach the target for a renewable share of 10% by 2020 with a margin (12%), which suggests that there will be little further incentives from governmental agencies regarding this target.

Data is only available up until 2030 for the analysis of vehicle categories. According to the latest official Swedish emission projections (Gustafsson et al., 2012), the development of fuel use in light duty vehicles for road transport will see a heavy shift towards diesel use.

Table 5 Forecast of the fuel type shift from 2005 to 2030. Source: (Gustafsson et al., 2012), Gustafsson, 2012, personal communication

TWh fuel use (excl. electricity)	2005	2020	2025	2030
Heavy duty trucks (diesel)	18	21	22	23
Heavy duty bus (diesel)	3	3	3	3
Light duty trucks (diesel)	4	6	6	5
Light duty vehicles (diesel)	5	21	21	21
Diesel total	**30**	**50**	**52**	**53**
Light duty trucks (gasoline incl. renewables)	1	0	0	0
Light duty vehicles (gasoline incl. renewables)	46	20	18	16
Gasoline (incl. renewables) total	**47**	**20**	**18**	**16**

The shift in fuel demand from mainly gasoline to diesel is predicted to be primarily driven by future fuel efficiency standards.

The Ambition scenario (S1)

The S1 scenario raises the ambition to reach a climate neutral Sweden by 2050, and projects an increase from ~7 TWh biofuel use in road transport to 14 TWh by 2030- This is split into 8 TWh for heavy duty vehicles (diesel engines), and 6 TWh for light duty vehicles (mainly diesel). This increase is not huge, but the scenario leaves room for interpretation when it pictures Sweden as a big exporter of biofuels (for transport use). Conflicts are also avoided through appropriate legislation such as the protection of some land areas for other uses. The major biofuel energy carriers in the S1 scenario are anticipated to be biodiesel and biogas.

Table 6. S1 scenario, Forecast of energy demand in Swedish domestic road traffic per fuel category. Swedish Transport Agency.

Road traffic (TWh)	2004	2008	2020	2030	2050
Gasoline (excl ethanol)	46.6	40.8	14.7	4.4	0.0
Ethanol in low-blend	1.3	1.3	1,1	0.5	0.0
Ethanol (E85, ED95)	0.2	1,1	1,1	1.0	0.5
Diesel (excl. Biodesel)	28.2	33.1	32.6	10.4	0.0
Biodiesel (FAME, HVO, FT)	0.1	1.1	1.7	5.5	7.0
DME	0.0	0.0	1.0	2.0	2.0
CNG	0.2	0.3	0.0	0.0	0.0
Biogas	0.1	0.3	1.2	5.0	6.2
Electricity	0.0	0.0	0.3	4.0	10.3

It is anticipated that further renewable biofuels will not be needed since the main reductions in fossil fuels will derive from the development of a low-transport society and major energy efficiency improvements, as is shown in Figure 13 below (Swedish Transport Administration, 2012).

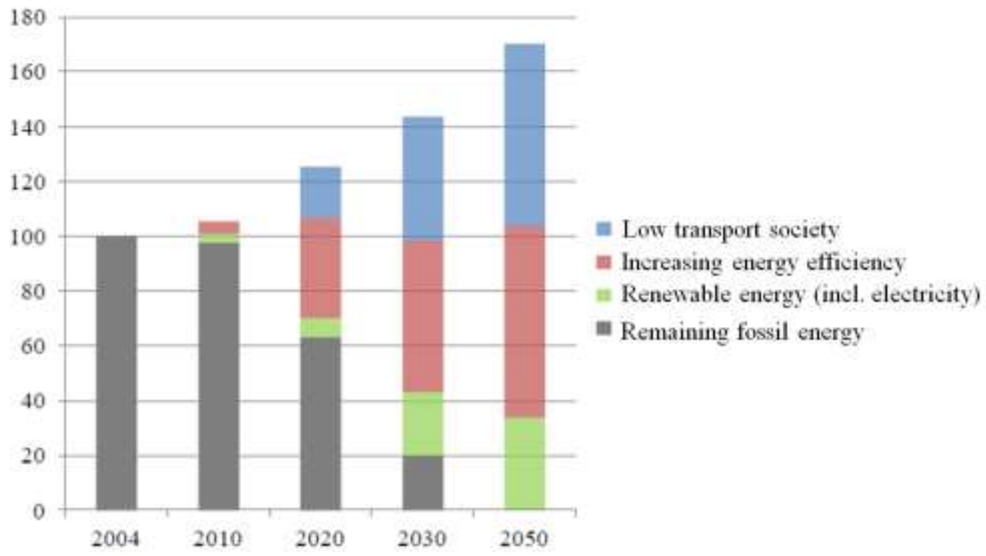

Figure 13. Scenario 1 road transport fossil energy savings. Index 2004=100. The combined height of the bars corresponds to the development of fossil energy use without climate policy instruments. The grey parts represent the development of fossil energy use after introduction of such instruments. The contributions of each of the three classes of instruments to the general decrease in the use of fossil fuel are indicated with colours.

5 WORKSHOP ON ALTERNATIVE SOURCES FOR PRODUCTS COMPETING WITH FOREST BIOMASS

5.1 CURRENT AND ALTERNATIVE USE OF BIOMASS

One important pillar in the pre-study is the workshop, to which stakeholders and other expertise were invited to discuss the issue of alternative feedstock for products competing for forest biomass. The aim of the workshop was to hear the participators view on the issue and what they foresee can be the consequences of different utilizations of forest biomass.

The discussion groups (see participant list in Appendix A) were provided with a figure of current uses of forest biomass to use as a basis for discussion and then complement with more information. Discussions covered both current uses, such as construction material, biofuel, paper, and anticipated future ones such as special chemicals, aeroplane fuel (included in biofuel) and healthcare (e.g. pharmaceuticals). The participants also indicated which uses they expected to increase or decrease a lot, which is indicated in the figure with red arrows in Figure 14. Conflicting perspectives between the participants, such as was the case for paper, or expressed uncertainty are also indicated in the figure. The input from the workshop participants provided a valuable overview of forest biomass uses (Figure 14).

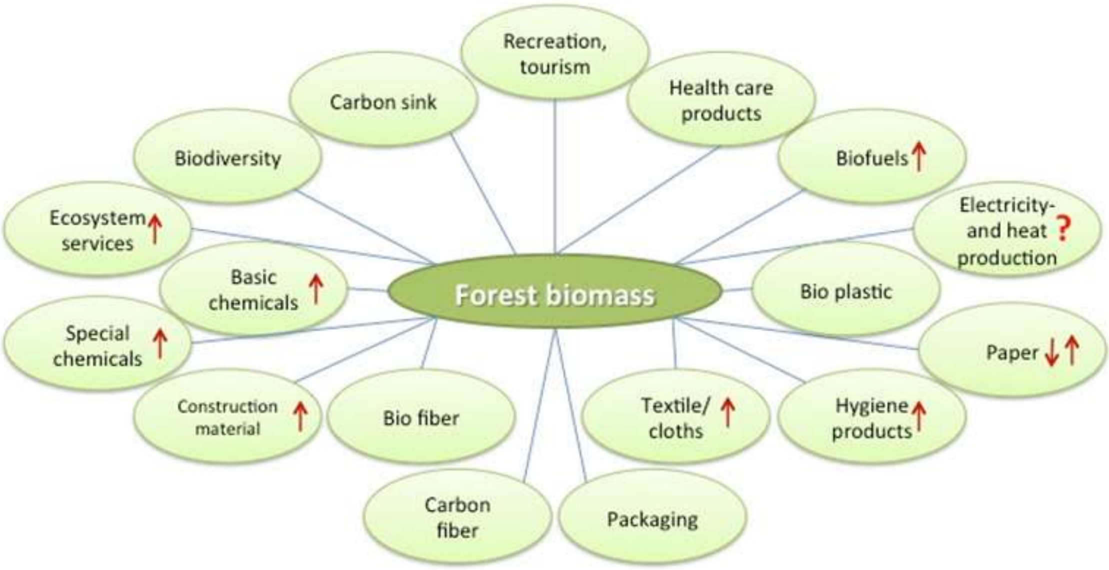

Figure 14. Overview of the system.

The participants then discussed which alternative material/service sources that might be used instead of forest biomass, i.e. alternative sources. The result of this input is shown in Figure 15.

The discussions showed that some materials/services are very difficult to find substitutes for. This is particularly so for services. For ecosystem services and biodiversity it is difficult to substitute forest with something else. Forest recreation and tourism can also not be replaced, but can of course be redirected towards other types of natural environments. Other suggestions for replacements demand an increase in other kinds of land-use, such as growing crops for fibre and biofuel. For other materials and services, the potential substitutes for forest biomass are fossil resources.

This illustrates the importance of assessing the indirect effects of increased forest biomass for biofuel. If the net effect is an increased use of oil in another sector, then the situation is worse than before.

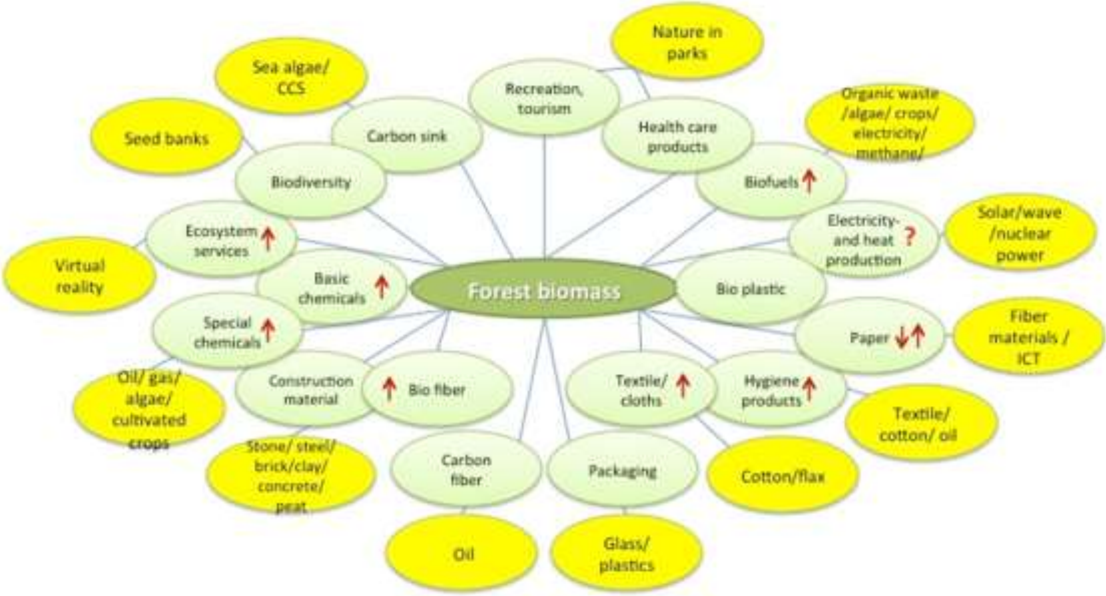

Figure 15. Alternative material/service sources for products derived from forest biomass.

5.2 IMPORTANT ENVIRONMENTAL ASPECTS

In the second part of the workshop, the participants discussed the potential environmental impact of an increased use in alternative sources/services. They indicated this in a prepared table with the Swedish Environmental Quality Objectives on one axis. Positive impact (helping to reach targets) was indicated by a plus sign, and negative impact (increased environmental load) with a minus sign. Each of the four groups picked one to three alternatives and discussed the impacts. The groups discussed an increase the use of:

- Concrete for construction
- Steel for construction
- Aluminium for construction
- Cotton for textile
- Oil for basic chemicals
- Annual crops for paper
- Waste for biogas
- Crops are used to produce biofuels
- Micro Algae is used to produce biofuels
- Macro algae is used to produce biofuels

When all the results of the discussion had been noted on a whiteboard, each participant voted for the impact they considered to be the most important (Table 13, Appendix B).

The impacts considered most important by the participants were:

- When cultivated crops that could be used for food are used instead as biofuel. This can have a negative impact on climate change, be positive for forests, and both positive and negative on biodiversity.
- When more concrete is used in construction, which can have a negative impact on climate change.
- When more cotton is used for textile, which can have negative impacts on the ground water and increase emission of toxic substances.
- When more oil is used to produce basic chemicals, which has a negative impact on climate change and perhaps a positive for forests.
- When waste is used to produce biogas, which can contribute to mitigation of climate change.

Important issues raised

At the end of the workshop the participants also reflected on the content and the discussions. In general the feedback was that the workshop was valuable and the workshop design was good. One comment was that some competencies, such as politicians and forest owners, were missing. Additional input to the project and proposed research areas are discussed in section 12.

6 METHODS USED IN CASE STUDIES

For assessments of environmental impact, the LCA method is one of the most accepted methods, see below in section 8.1. However, aspects like ecosystem services and biodiversity are not covered by traditional LCA, which demands for new methods that include these factors. This report uses established and conventional methods of evaluation, which are described in this chapter.

The methods used in the workshop and the case studies vary according to what are most suitable and are described in this chapter. LCA will be used where applicable for both ethanol and black liquor gasification as it is a well-known and transparent analysis.

6.1 THE ETHANOL CASE

For the ethanol case, life cycle assessment, LCA, a method to evaluate the environmental performance of products or processes, has been used. The methodology for LCA is described in the international standard known as ISO 14044 (ISO, 2006) and is described further in section 8.1. In the standard, the method is described as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). According to the ISO-standard an LCA consist of four phases. These are the goal and scope definition, the inventory analysis, the impact assessment and the interpretation, see Figure 16.

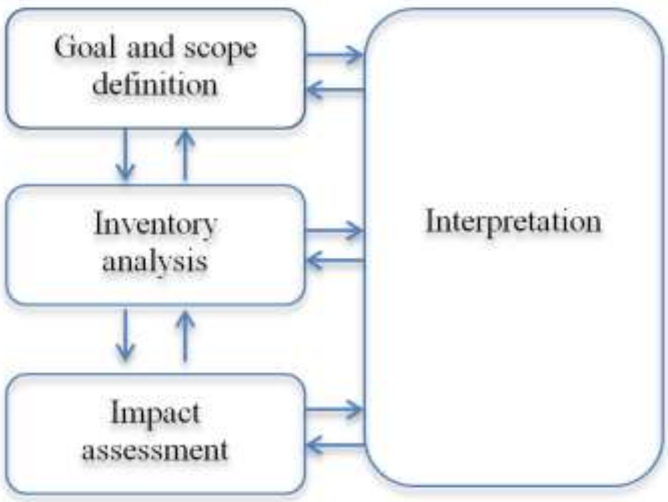

Figure 16. The different phases in an LCA according to the ISO-standard (ISO, 2006).

6.2 BLACK LIQOUR GASIFICATION

The technique of black liquor gasification (BLG) is neither commercial nor has been demonstrated at full scale. Therefore it is not as well analysed in terms of LCA as is the production of first generation bioethanol. Therefore the approach in this study for the BLG case is to use approximations of energy yields, feedstock utilizations and emission factors.

7 EFFECTS OF SYSTEM BOUNDARIES

7.1 SYSTEM BOUNDARIES

As described in section 2.7, there can be indirect effects outside of a given system. Biomass is a limited resource and traditional methods of analyzing environmental impacts do not consider resource availability. It is therefore important to expand system boundaries in order to include indirect effects of changes in the utilization of biomass. In this chapter, such specific system expansion for this particular context is discussed.

7.2 SYSTEM EXPANSION FOR FOREST BIOMASS UTILIZATION

If the production of biofuels increases to a level where the production volume is higher than the estimated available potential (regardless of the actual size of the potential – see sections 2.4 and 2.7), it will affect the environmental performance of the produced biofuel, due to changes in the overall forest systems. However, projections and evaluations of such changes or effects are very difficult.

In Tufvesson et al. (2013) the environmental performance of biogas systems using industrial residues as substrates was analysed using a life-cycle perspective. The substrates were considered interesting since they do not compete directly with agricultural land for food production. The contribution to GWP was calculated using both according to the method described in the ISO-standard and following the method presented in the EU RED. By applying system expansion it was shown how the environmental performance of the produced biogas changed if the residues were currently used as animal feed. The results showed that biogas from all residues investigated leads to a reduction of GHG-emissions compared to fossil fuels. However, when system expansion was applied, the benefit was significantly smaller since the alternative utilisation of the substrates as animal feed was considered and included in the system. This would also lead to an indirect land-use competition since additional feed crops would have to be cultivated. This type of calculations, with enlarged systems, is important to consider when estimating the environmental performance of also other biofuel systems. Calculating the environmental performance of a system as long as the production volume is within the estimated production potential is rather straightforward. Therefore it is very important to specify up to which potential production volume the result are valid. As described in chapter 8, the GHG-performance of ethanol produced from forest biomass is beneficial as long as the production is within the estimated potential. This potential might also increase in the future, due to climate change effects and higher growth rates. The future potential is further discussed in section 10.2. The difficulties in evaluating the environmental impacts are when the production volumes exceed the available potential. Then investigations of the changes that will occur in the systems are required. In this section different possible scenarios are described and discussed:

- Using forest biomass as raw material is considered as using a renewable source, but it is important to remember that the amount available is not unlimited. If more forest is harvested than regrows, the system is not sustainable in the long term. Such a scenario will not only lead to increased contribution of GHG-emissions, but also other effects such as loss of diversity and whole ecosystems.

- An increased availability of forest biomass can be made possible by fertilisation of forestland. In Sweden forest growth is often limited by the availability of nutrients, in most cases nitrogen, together with the rather short growth season (Skogsstyrelsen, 2013). Therefore fertilisation of forestland is often seen as an option to increase the forest growth within a rather short period in time. In Sweden the fertilised areas have decreased in recent years. One reason for this might be the increased awareness of possible negative effects on the environment that can occur. Another reason might be the deposition of nitrogen by air pollution and the fear that nitrogen saturation can occur in the forest and the related nitrogen leaching that then can occur. Of course also other options to increase the production volumes by intensification in the Swedish forestry are available, for example introduction of new species, improved silviculture and forest management.

- An increased demand for forest biomass can result in increased import of forest biomass from other countries or a decreased export from Sweden to other countries. This can have many indirect effects, such as less control of forestry and the environmental effects of production at other locations. Predicting changes in the trade system due to such change in demand requires further, in depth, studies.

- A decreased demand for different paper products has been seen in some regions during recent years. For example, there is a decrease in the demand for newsprint in Europe. This means that more raw materials might become available for biofuel production. On a global level, a general decreased demand in mature economies and an increased demand in developing countries can be seen. For example the production in China is increasing (Skogsindustrierna, 2012). Furthermore, also other products than biofuel might compete for the biomass in the future: clothing, textiles and new packaging materials from biomass are areas where an increased demand for forest biomass is foreseen. More research is needed in order to understand the future demand for forest biomass, taking into account all new possible products derived from this feedstock.

- An increased demand can lead to an increased import of forest industry products from other parts of the world. These products can then be produced in less energy efficient processes using energy sources less environmentally benign than in Sweden. This means that the environmental burden of one system is transferred to another.

The above mentioned possible consequences illustrate the need to investigate how the raw material is used today. The consequences can happen directly or in the future – either suddenly or gradually due to changes in availability and demand, which contributes to the complexity of the system and the changes within it. The changes can happen in several steps and most likely a combination of the described scenarios might occur at the same time. Another aspect that makes these changes even harder to investigate is that when the biofuel is produced, several by-products are also affected, such as electricity and/or heat. As an illustration, if 1 tonne of Swedish wood that was previously used for paper production is instead used to produce biofuels, then 1 tonne of wood somewhere else needs to be used for paper production (if the demand is unchanged). That paper production might take place somewhere where the energy efficiency is lower and/or where less environmentally benign energy sources are used for process energy, i.e. the environmental burden is moved from one system to another. This can take place directly – 1 tonne of wood for biofuel production leads to production of paper from 1 tonne of wood somewhere else or partly. But, most likely, a combination of the consequences described above will occur, maybe in several steps. This means that the entire system needs to be considered – something which is indeed not easily done but is an important area for future research.

8 CASE STUDY – ETHANOL

Bioethanol is the most widely produced biofuel today. The production takes place mainly in the US and in Brazil, where, in 2007, 23 billion litres and 21 billion litres were produced respectively (Morschbacker, 2009). Today, ethanol is produced primarily from sugarcane in Brazil and from corn in the US. The market price of ethanol varies in the range of 0.45-0.65€/L (EOF – Ethanol, 2011) and fluctuates mainly due to variations in raw material prices and supply vs. demand. The production in 2007 represented about 4% of the gasoline consumed globally (Balat & Balat, 2009).

The available feedstocks for ethanol production can be divided into three groups: sucrose containing feedstock, starch materials and lignocellulosic feedstock. The drawback in producing ethanol from the two first is that the feedstock tends to be expensive and attractive in other applications as well. Conventionally the ethanol is produced through the fermentation of sugars. As a means to avoid competition for this feedstock, extensive research and development is carried out focusing on the use of cellulosic raw material, known as second-generation bioethanol. Pilot-scale projects have shown promising results and several second-generation facilities are under construction. One example is a factory, *Beta Renewables*, which is under construction in Crescentino, Italy. Wheat straw and Arundo donax (a non-food cellulosic crop) will be used as feedstock (Beta Renewables, 2012). Another large-scale facility is under construction in Kinross, Michigan, US, and is estimated to start production by the end of 2013. The factory is a joint venture by the companies *Mascoma* and *Valero*. *Mascoma* develops a process in which the substrate is both hydrolysed and fermented. With this technology it is possible to use lignocellulosic material as feedstock, in this case hardwood pulpwood (Mascoma, 2011).

In recent years several life cycle assessments have been conducted on various systems for the production of bioethanol. However, most of these studies focus on ethanol produced from first generation feedstocks. The aim of this study is, instead, to evaluate the environmental performance of second-generation ethanol produced from lignocellulosic feedstock, namely from forest biomass. The environmental performance of the produced ethanol is largely dependent on the studied system. Therefore a review of studies undertaken evaluating the environmental performance of ethanol systems based on lignocellulosic feedstocks will be presented. However, these results are only valid when there is available feedstock that can be used in the production system without affecting any other production system causing changes in the feedstock supply there or when the outtake from forestry is on a level that can be seen as sustainable.

In the first section of this chapter the use of LCA as a tool to evaluate the environmental performance of ethanol will be discussed. When evaluating different biofuel systems several methodological concerns have been identified and these are important to recognise when evaluating LCAs of biofuel systems. In the second part, available LCAs of ethanol systems using lignocellulosic feedstocks will be presented and identified hot-spots will be described. Finally, the importance of identifying the available potential will be discussed and different scenarios or examples of what can happen if “too much” biofuel is being produced at the cost of too intensive forestry or at the cost of affecting the production systems for other products.

8.1 LCA AS A TOOL; METHODOLOGICAL ASPECTS OF IMPORTANCE

When conducting an LCA, the guidelines found in the ISO-standard (ISO, 2006) are to be followed but it is, nevertheless, up to the author to decide various features, which may influence the result.

Direct comparisons of LCAs to assess the environmental performance of different products can therefore be problematic. Uncertainty regarding input data, choices and relations within the system as well as variability in choice of system boundaries, both geographical, technical and in time must be acknowledged (Mattila et al., 2011). When the review of LCAs of biofuels (ethanol) was carried out, this was indeed observed. In some cases the results in an LCA vary significantly even when similar production systems are analysed. Therefore the most important methodological aspects that influence the result of an LCA are discussed in this chapter.

8.1.1 Goal and scope definition

In the first phase of the LCA, the goal and scope definition, the product or process to be studied and the purpose of the study are described (ISO, 2006). The ISO-standard stresses that the goal and scope of a study must be clearly defined and also consistent with the intended application of the LCA. In the goal and scope definition also the context of the study is defined. Also the specifications of the modelling, for example, the functional unit, must be determined. In this phase of the LCA several assumptions are being made, affecting the outcome of the LCA. The most important methodological aspects recognised in this phase of an LCA include the functional unit, the boundaries of the studied system, and the input data used.

Functional unit

The functional unit is the definition of the functional outputs of the product system and in an LCA the functional unit is the reference to which the inputs and outputs are related (ISO, 2006). It is important that the functional unit is defined correctly: quantitatively, qualitatively and in time. This is crucial, especially when comparing two products, as the functional unit is then used as the basis of comparison (Baumann & Tillman, 2004).

In the context of renewable products and especially for system including the use of raw materials from cultivation, some methodological concerns not found in products based on fossil systems, are recognised. For example, renewable systems often require the use of land, and the reference system might consider alternative land uses. Especially when developing production systems for biofuels it is important to evaluate factors such as area efficiency. This can easily be included by a complementary or additional functional unit and thereby indirectly evaluate the differences in land use between different production systems.

System boundaries

The system boundaries are used to define which processes that are included in the analysed system. The choice of system boundaries must, according to the ISO-standard, be consistent with the goal of the study (ISO, 2006). System boundaries are needed between the technical system and the environment, and between the studied system and other product systems. Also geographical boundaries and time horizons must be determined and described.

The choice of system boundaries is, as long as it is in compliance with the recommendations in the ISO-standard, the author's choice. Several LCA-studies of biofuels have shown that the environmental impact of biofuels depends largely on how the system boundaries are set for the production system (Börjesson & Tufvesson, 2011, Börjesson 2009, Singh et al. 2012, Sathre & Gustavsson 2011), which connects to the discussions in this pre-study.

Technical boundaries

In LCAs, the manufacturing and maintenance of field machinery are often not included in the assessment; neither the environmental impact of capital goods (i.e. machines, vehicles, etc.). The contribution from construction, maintenance and demolition of the production plants are considered to be low, especially considering the large biomass and energy flows handled in these facilities during their lifetime. Therefore also these aspects are often excluded in environmental assessments.

Boundaries in time

The time horizon applied in a study can greatly affect the result. For this reason it is very important to choose a functional unit defining the performance of the product or process studied also over time. The time aspect is also important when looking at the long-term effects on aspects of land-use, such as changes in organic matter in the soil. When forest or agricultural material is used as feedstock in biofuel or energy production, carbon will be released much faster during combustion than during natural decomposition. Also carbon storage in litter and soils is affected.

In Lindholm et al. (2011) the GHG-balances for using stumps and logging residues as energy sources in Sweden was tested using different time horizons. The result clearly showed that the contribution to global warming for the use of forest biomass for energy purposes is time dependent. The authors tested three different time periods: One short time horizon using a 20 year perspective, one middle term perspective corresponding to one rotation (77 years in south of Sweden and 120 years in north of Sweden), and finally, a long time perspective corresponding to two and three rotations respectively (231 and 240 years). The result showed large GHG-savings in a long time perspective, but in a short time perspective (20 years) no GHG-savings was seen when natural gas or coal was substituted with biomass in a CHP plant. The results also indicated a geographical variation: The savings are smaller in the north of Sweden due to the cooler climate leading to slower decomposition rates in a short time perspective. The stumps were also decomposed slower than the logging residues since it takes longer time for the decomposing organisms to invade the stumps.

Geographical boundaries

The geographical boundaries set in the LCA have a great influence on the outcome of a study. Issues of importance include yields per hectare, type of biomass available and nitrogen leaching. Other parameters affecting the comparability, which often also have a considerable impact on the outcome of the LCA, that differs for different locations are the electricity mix, and the energy sources used for process energy.

In Eliasson et al. (2012) the carbon balance for forest was estimated using two different system boundaries, the single-stand and the landscape. This clearly illustrates the importance of using accurate assumptions regarding both time horizon and geographical boundaries.

Input data

According to ISO 14044 (ISO, 2006) the requirements on the quality of the data must be specified in order to attain the goal and scope. The quality of the data should be such that the time-related, the geographical and the technical coverage, and also issues such as representativeness, consistency, reproducibility and uncertainty, are addressed (ISO, 2006).

Average or marginal data

The question of when to use marginal or average data has been discussed widely within the LCA community in recent years. For biofuel production, this includes the use of average or marginal electricity and to some extent also the use of average or marginal land for the production of biofuels (Börjesson & Tufvesson, 2011).

An argument for not using marginal data for the electricity use in biofuel systems has been that in most of the cases an existing technology is assumed to be replaced by a new one, which does not increase the total energy demand. In Börjesson and Tufvesson (2011) different sources of primary energy in the conversion processes, which can be seen as marginal energy sources, were tested in the sensitivity analysis. This showed how the result of an LCA would differ depending on the primary energy source chosen, which can be seen as one example to solve the problem regarding the choice of average or marginal data.

The issue of marginal or average data on land is important for the production of biofuels and produced, especially from crops. Assumptions regarding the choice of land are of great importance for the overall result of an LCA. If for example land where rainforest was previously grown is used for cultivation the contribution to climate change will be much higher than when average land is assumed. However, assuming marginal land to be used for all cultivation of crops for biofuels is not a realistic scenario. Here the availability of different types of land for producing biofuels needs to be assessed so that estimations on what kind of land is most appropriate to assume in the LCA can be made. When performing system expansion on biofuels a decision whether the by-products are to replace an average or a marginal product must also be made.

8.1.2 Inventory analysis

When life cycle inventory (LCI) data for all activities included in the system are collected, the amount of resources used and emissions are calculated in relation to the functional unit. Collecting life cycle inventory data is often straight forward, but there is one methodological aspect that can largely influence the environmental performance of the system: many processes result in more than one product. The environmental load of such a process must then be divided, i.e. allocated, between the different products. One example when allocation might be needed is when by-products from the raw material production can be used for the internal energy demand. This might be the case for lignocellulosic ethanol, where the by-products can be used for steam production. Surplus steam produced can, moreover, be used for electricity production, which makes the production system a net producer of electricity.

Allocation

According to the ISO-standard, whenever possible, allocation should be avoided by dividing the process into sub-processes and input and output data from the sub-processes should be collected separately. If this is not possible, the product system should be expanded to include additional functions related to the co-products, called system expansion. If such an approach is not applicable, the inputs and outputs of the system should be divided between them in a way that reflects their physical properties, for example mass or energy content (physical allocation). If also this is not possible, then the inputs and outputs should be divided in a way that reflects other relationships, for example, economical allocation (ISO, 2006).

System expansion

System expansion can be adapted to make two different systems comparable and to ensure that the systems include similar bases for comparison. System expansion can be important when two usable outputs are provided in a system, for example, the desired product and excess energy. A problem with using system expansion is that it requires additional inventory data and thus becomes more complex and time-consuming. The increased uncertainty when involving more inventory data must also be taken into account. In several biofuel systems by-products are generated. However, limitations using system expansions as calculation method has also been recognised (Tillman, 2000; Finnveden & Ekvall, 1998). One example is when no reliable inventory data exist for the alternative product, realistically replaced by the by-product. Another example is when several potential replacements exist and it is not possible to define the most realistic alternative.

Physical and economic allocation

For physical allocation the basis of the allocation is independent of time but no consideration is given to the quality of the different products. In biofuel processes, by-products, considered more or less as waste, should then share the environmental burden of the process equally with the desired product. This is especially important to consider for low yield processes where large amounts of by-products are created. One concern regarding economic allocation is that prices vary over time. However, the price of all raw materials is often closely connected and higher prices for one raw material often affect also other materials (Börjesson & Tufvesson, 2011).

One way to overcome the problem with different allocation procedures leading to diverging result is to undertake a sensitivity analysis to illustrate how the choice of allocation method will affect the results. For multi-input multi-output systems, such as biorefineries, LCA, as used today, has its limitations and a discussion on how to handle allocation issues for biorefineries are needed (see e.g. Luo et al., 2009).

8.1.3 Impact assessment

The life cycle impact assessment (LCIA) aims to describe the impacts of the environmental loads quantified in the inventory analysis. First the inventory data are classified into different impact categories, e.g., global warming potential (GWP), acidification potential (AP) or eutrophication potential (EP). The next step is the characterisation, where the relative contributions of the emissions to each type of environmental impact are calculated, for example, all emissions affecting global warming are calculated into CO_2-equivalents, based on natural science.

8.1.4 Interpretation of the results

The fourth, and last, phase is the interpretation of the results. The study and the results are evaluated concerning completeness, sensitivity and consistency, and then conclusions are drawn (ISO, 2006). In a sensitivity analysis the parameters identified as important, the so-called *hotspots*, are systematically altered. Sensitivity analyses can also be done for aspects such as time perspective, choice of primary energy source, allocation method and alternative land use, etc.

8.1.5 Other environmental impact

Many LCAs of renewable products, such as biofuels from forest-based raw materials, focus only on a limited number of impact categories. The most frequently used environmental impact categories include energy use, GWP and EP, although some studies only include the contribution to climate change (measured as GHG-emissions). However, an increased use of biofuels may lead to other impacts related to the more intense use of land and more intensive forestry. Issues such as loss of biodiversity, excessive water use and emissions from soil can also be of importance. These issues can be ‘lost’ if not sufficient studies of the systems are undertaken and were discussed in section 7.2.

8.2 REVIEW OF AVAILABLE LIFE CYCLE ASSESSMENTS

Already in 1991, the production of second-generation ethanol using residues was advocated with hopes for commercial production in ten years’ time (Lynd et al., 1991). Currently, it is instead estimated that the production will develop over the coming 10-15 years and increase significantly after this (Cherubini and Strømman, 2010).

As bioethanol is the most developed and most widely used biofuel, comprehensive reviews of LCAs have already been made. Many of these focus, however, on first-generation production from agricultural crops or on second-generation production where agricultural residues are used as substrates. So far, only a limited number of LCAs have been published which investigate the environmental impact of bioethanol produced from lingo-cellulosic feedstock. In the literature review, the environmental performance of different ethanol systems was analysed. Direct comparison of LCAs is often problematic as the scope of the studies varies in a multitude of ways. The LCAs reviewed in this study are no exceptions from this and aspects such as system boundaries; functional unit; feedstock type, and electricity mix vary significantly in the investigated reports. Life cycle assessment is, nevertheless, one of the currently most reliable and developed method of calculating environmental performance. When the authors of the LCAs show where system boundaries are set, how calculations are made and make comprehensive sensitivity analyses, interesting notes on the environmental performance of products can often be made.

In von Blottnitz and Curran (2007), 47 environmental assessments were reviewed and it is suggested that sugarcane-based ethanol produced in tropical countries has an acceptable environmental impact but that the same is not clear for ethanol from lignocellulosic feedstock, which is suggested to be be investigated further (Von Blottnitz & Curran, 2007).

In Börjesson et al. (2012) the GHG-emissions of future ethanol production from lignocellulosic feedstock were estimated. An integrated production of both ethanol and pellets was assumed to give a conversion efficiency of about 70%. Studies show that production plants where ethanol is produced from wood are expected to have an overall efficiency of 50-90% of which ethanol is 35-45%. High conversion efficiencies involve large amounts of low value energy such as excess heat that requires heat sinks, such as district-heating systems, to be useful and thereby contribute to the overall conversion efficiency. The GHG-emissions for future production of ethanol from by-products from forest industry are estimated to be below 20 g CO_2 equivalents/MJ when system expansion is applied (Börjesson et al., 2012).

In Mu et al. (2010) biochemical and thermochemical production of lignocellulosic ethanol are compared. The investigation is based on life cycle assessments of the two routes, where the investigated stages include cultivation and transport of feedstock and ethanol production. For the biochemical route, co-current dilute acid pre-hydrolysis with simultaneous enzymatic saccharification and co-fermentation is employed. The separated lignin fraction is combusted for internal energy demand, and excess electricity produced is sold on the grid and allocated as credits for the avoided use of electricity. Natural gas is used for the production of required process steam. In the thermochemical production, atmospheric-pressure indirectly-heated dual fluidised bed gasification is applied, followed by a Fischer-Tropsch process to generate ethanol. Co-products include mixed alcohols, which are assumed to replace heating oil. It is concluded that, depending on circumstances and how the system boundaries are set, both alternatives can be the better performing alternative. Both technologies, however, show very favourable GWP performances compared to petrol and diesel (Mu et al., 2010). The results from the study are illustrated in Figure 17 below. With a heating value for ethanol at 21,3 MJ/litre (Börjesson et al. 2010, rapport 70) the corresponding contribution to GWP is between 8-15 g CO_2 equivalents/MJ ethanol for the studied cases.

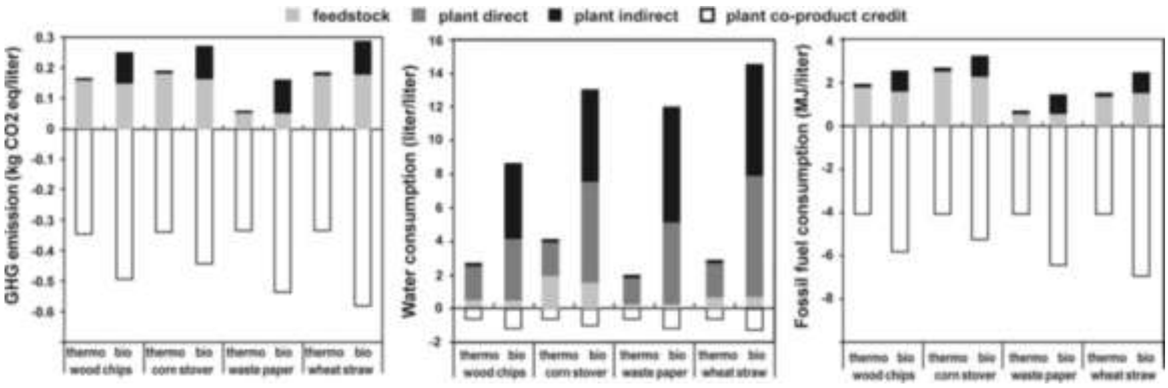

Figure 17. Results from the base case scenario (Mu et al., 2010).

In a study by Kemppainen and Shonnard (2005) virgin timber from Michigan's Upper Peninsula was assumed as raw material for the production of bioethanol. The analysed system is a production plant that is developed to produce $227*10^6$ litres (60 million gallons) of ethanol per year. The raw material is assumed to be pre-treated using sulphuric acid hydrolysis and steam. The cellulose enzymes are produced on-site by fungus and then use in a simultaneous saccharification and fermentation process. The solid fraction is used for steam and electricity production. The process generated about 19,200 MJ/h of excess electricity. The hot spot of the system was found to be the heating, which was very energy intensive. The contribution to global warming for ethanol from virgin timber was estimated to 196 g CO_2eq/L of ethanol, which corresponds to about 10 g CO_2 equivalent/MJ of ethanol.

In Zhi Fu et al. (2003) the Iogen plant located in Ottawa, Canada, was analysed in an LCA. The functional unit in the study was 1 km driven. Different raw materials were included in the study, amongst other, forest wood residues. The by-products generated in the process, lignin and pentoses, were assumed to be used for internal process energy and animal feed respectively. However, in the environmental assessment the by-products were not included and instead the entire environmental burden was allocated to the ethanol, which can be seen as a very conservative assumption. The result of the study indicates that the manufacturing of enzymes and the steam production are the main contributors to the overall environmental impact. For GHG-emissions the primary energy source was identified as critical. The results are presented for E10 (90% gasoline and 10% ethanol) and it is therefore difficult to estimate the GHG-emissions from only the ethanol produced. The total GHG-emissions are estimated to 0.256 kg CO_2eq / km driven when assumed that one can drive 11.9 km per litre of E10.

In Norway, unlike Sweden and Finland, the forest resources are relatively underutilized as bio-energy and provide less than 1% of Norwegian net primary energy demand. In Bright and Strømman (2009), two different pathways to produce ethanol from woody biomass routs are examined; one biochemical route and one thermochemical route. The biomass is assumed to be productive natural forests. The biochemical route includes a high-temperature dilute and hydrolysis pre-treatment, followed by simultaneous saccharification and fermentation of sugar monomers. The thermochemical process involves gasification of wood chips into synthesis gas, followed by a catalytic synthesis into ethanol and other mixed alcohols. Both processes are self-sufficient in process energy. The results are presented per kilometre driven in a flexi-fuel vehicle and are compared to a gasoline reference (158 g CO_2 equivalents/km). The contribution to GWP for the two systems are between 60.3-62.1 g CO_{2eq}/km for thermochemical route, and between 74.6-88.1 g CO_{2eq} /km for the biochemical route including vehicle production, fuel production and vehicle operation. These results are based on no competition with the current use of round wood in Norway. The authors also state that although ethanol was the focus in the study, other wood-biofuel systems, such as Fischer-Tropsch diesel, methanol or dimethyl ether, with biomass conversion efficiencies similar to those of the study, will have similar results since the conversion efficiency was a key variable in the system (Bright & Strømman, 2009).

In the review two studies also focusing only on forestry in the Nordic countries are included: Valente et al. (2011) and Seppälä et al. (1998).

In Valente et al. (2011) a life cycle assessment on the Norwegian woody biomass supply-chain was performed. The study focused on two regions located in the Middle of Norway, Hedmark and Oppland where the forest areas are classified as Norwegian mountain forests. The rotation time is about 150 years and the forest areas are located about 1000 metres above sea level. The dominant species are spruce and pine. The study is a cradle-to-gate analysis until the wood is delivered to the terminal and the functional unit is 1 m^3 of woody biomass. The result shows a great potential that today is unused in the area, of both stem wood as well as logging residues. The GHG emissions were estimated to 17600g CO_{2eq}/m^3 solid cubic metre over bark (which is equal to the Swedish measure “skogskubikmeter”, m^3sk). The main contributor to the environmental performance was the transportation to the terminal.

In Seppälä et al. (1998) the Finnish forest industry was studied from a life-cycle perspective. The whole Finnish production system was analysed, both the mechanical and the chemical forest industry, including 170 sawmills, 21 panel mills and 50 impregnation plants. The pulp and paper, i.e. chemical forest industry, includes 47 mills. The result showed that the forestry and the production phases were the hot spots of the system and accounted for approximately 80% of the total environmental impact.

The environmental performance of bioethanol has been hotly debated during the last couple of years (see e.g. Ahlgren & Börjesson (2011) for a comprehensive review of the differing results, or the discussions in Searchinger et al. (2008) and Mathews and Tan (2009)). The issue is complex, and results vary significantly depending on what type of system is studied. In Börjesson (2009), the complexity is illustrated through the example of bioethanol produced from wheat in Sweden, showing that the current Swedish wheat ethanol production and use give an 80% reduction of GWP compared to petrol. As comparison, the Brazilian sugarcane ethanol gives a 85% reduction of GWP and the US corn ethanol gives a 25% reduction of GWP. However, a comprehensive sensitivity analysis shows that the environmental performance varies significantly depending on various factors. Four main such factors are identified: the efficiency of the cultivation and the emissions of nitrous oxide connected to this stage; direct land use change (dLUC) – the type of land replaced by the cultivation (organic soil carbon changes); the chosen method for allocation; and the type of energy source used in the ethanol plant (Börjesson, 2009).

Also in Kim and Dale (2009), the difference in environmental performance of bioethanol production is investigated. The result varies depending on the location of the production and the farming practice employed. The 40 biorefineries included are all located in the USA and the feedstock used is corn. The functional unit is one kg of bio-based product. System boundaries include the cultivation of feedstock, the biorefinery production and the upstream processes and products used. Direct land use changes are included and indirect land use changes are simulated and discussed in a sensitivity analysis. System expansion is used to deal with the displacement effect of the by-product DDGS (Distillers' Dried Grain with Solubles). The result of the study shows that the environmental performance of the bioethanol production varies significantly depending on location and farming practice, the GWP varying between 1.1-2.0 kg CO_2-eq./kg bioethanol. The two sources contributing the most are N_2O emissions from soil and use of natural gas in the bioethanol production (Kim and Dale, 2009). In an older paper by Kim and Dale (2005) the production of bioethanol using corn grain and corn stover as feedstock are investigated. The production takes place in Iowa, USA, and the functional unit is "1 ha of arable land for a 40-year period". The focus is thus rather on the cultivation system than on the bioethanol production process. In the fermentation of corn stover, a lignin-rich residue is obtained which is used for electricity production. In terms of GWP, all simulated cropping systems give negative values, i.e. carbon credits (Kim and Dale, 2005).

8.3 RESULTS FROM THE REVIEW

8.3.1 Hot spots from LCAs of ethanol

Type of biomass

The type of biomass used as raw material significantly affects the environmental performance of biofuels, mainly due to differences in biomass yields, but also due to differences in fertilising rates and effects of changes in soil carbon content. The second-generation biomass types often perform better than first-generation systems in LCAs of biofuels (Jungbluth et al., 2007). The second-generation biofuels are those produced from cellulose, hemicellulose and/or lignin, for example, cellulosic ethanol, dimethyl ether (DME) and Fischer-Tropsch fuels. The benefit of using second-generation biofuels is that they do not require agricultural land for the biomass production, and therefore lead to less competition between food and fuels (Börjesson et al., 2008; Börjesson et al., 2010). This advantage was seen also in the literature review presented here.

Carbon dioxide emissions due to land use change

Similar to most sectors where land is used for production of feedstock, biofuel production using crops can give rise to land use changes. All productive land contains large amounts of carbon, fixed both in the vegetation and in the soil. These carbon stocks are affected when the land is used for cultivation and carbon dioxide is released to the atmosphere, which will reduce the climate benefit of biofuels produced from cultivated crops. A distinction is generally made between direct land use changes, *dLUC*, and indirect land use changes, *iLUC*, and both effects give climate impacts by releasing or binding carbon to the soil. Direct land use change can be both positive and negative. When perennial vegetation (in the worst case tropical forests or peat land) is converted into agricultural land a loss of carbon stock will take place, but if land previously set-aside is taken back into the production system the carbon stock may increase (Cherubini et al., 2009). Also indirect effects of land use change (iLUC) may occur: When an increased production of biomass feedstock on agricultural land leads to new land for food production being taken into the agricultural system somewhere else in the world, for example tropical forests, changes in the carbon stock will occur there. In contrast to the effects of direct land use change that occurs where the biofuel is actually produced, indirect land use change occurs elsewhere in the world. This makes the calculation of iLUC very complex, as it is very difficult to estimate where the land use change will occur. These displacement effects and their effect on the environmental performance of biofuels have been widely discussed in recent years. In 2008, two articles by Searchinger et al. and Fargione et al. were published in which the authors argued that the GHG emissions due to land-use changes could potentially affect the environmental performance of biofuels considerably (Searchinger et al., 2008; Fargione et al., 2008). The inclusion of an iLUC factor in LCAs has been criticised, see for instance Kim and Dale (2009), who argue the current iLUC discussion has fundamental flaws since biofuel production is the only land use activity that is required to take iLUC into consideration. Moreover, a consensus on how to handle iLUC is needed. The importance of national land-use restrictions and regulations to minimise the risk of iLUC has also been recognised (Börjesson et al., 2008). The conclusion here is that it is important to recognise the potential risk of iLUC, especially for first generation biofuels, but more research is needed within this issue.

Process Yield

One hot spot that is recognised is the conversion efficiency. A high product yield in a process will give the system a favourable overall environmental and economic feasibility. Especially for biofuels a high yield can significantly improve the overall environmental performance, since the biomass demand is decreased (Tufvesson, 2010). Achieving a higher yield can also give indirect environmental benefits by lowering the up-stream transportation of raw material.

Process energy demand and primary energy source

Another recognised hot spot with a large impact on the overall environmental performance is the process energy need. Furthermore, the source of the primary energy chosen in the process is seen to be very important. Several studies have shown that the choice of energy source can shift the result for biofuels from giving a GHG benefit compared to fossil fuels, to the opposite. The type of energy source used in the process largely influences the environmental performance of the production system. In Börjesson (2009) bioethanol produced with coal as process energy (instead of bioenergy as in the base case) gives a GWP larger than that of petrol. Also in Kim and Dale (2009), the natural gas used in the bioethanol process was recognized as a hot spot. In conclusion, the energy demand and the source of the primary energy in the processes are important and must be included in the environmental assessments. Inventory data for different primary energy sources are also readily available in the literature. The choice of primary energy source and the energy efficiency can also be tested in the sensitivity analysis.

In Jungmeier et al. (2003) guidelines for the treatment of energy aspects in life cycle assessments of forest products are treated and recommendations on how to handle this issue are given. According to the authors the following aspects need to be considered in LCAs of products from forest biomass: wood characteristics, energy balance and primary energy input, the carbon balance, CO_2 uptake via photosynthesis, CO_2 emissions from combustion, and carbon storage in carbon pools.

The biorefinery, an integrated approach

Producing biomass-based products in a biorefinery is a way to efficiently make use of the available biomass feedstock. A biorefinery is a production facility that can produce a number of different products (e.g. food, feed, fuels, chemicals, and energy) from a range of different feedstock. When using cellulose and lignin-rich substrates the biorefinery is often called a second-generation biorefinery. LCA studies on biorefinery systems using forest biomass as feedstock are still scarce and only a limited number of studies are available.

In a future bio-based economy, a combination of the biochemical and the thermochemical route could be possible in a biorefinery to optimise the biomass utilisation. For example, Van Dam et al. suggest that the C5 and C6 residues from the biochemical route can be used for thermochemical production of syngas (2005). A similar approach is given in Cherubini and Strømman (2010). Here, the C6 part of the feedstock is used to produce bioethanol, the C5 to produce furfural and the lignin part is used for production of FT-diesel (Cherubini & Strømman, 2010).

Traditionally the pulp industry has been considered as a source of pollution and an intensive energy user. One option to decrease the environmental impacts can be to use the biomass also to produce value-added products in a biorefinery. In Gonzalez-Garcia et al. (2011) an LCA is undertaken to quantify the environmental impacts of a Swedish softwood-based biorefinery where total chlorine-free (TCF) dissolving cellulose is produced together with ethanol and lignosulfonates. The functional unit in the study was 1 tonne of air-dried (10% moisture content) high-quality dissolving cellulose from a blend of spruce and pine. Together with pulp also 59.52 kg of ethanol and 23.81 kg of lignosulfonates are produced. Seventy five percent of the wood was assumed to come from Swedish plantations and 25% from the Baltic countries. In the process 100% of the steam demand and 28% of the electricity demand is generated internally. The rest of the electricity is bought from the Swedish national grid. The total inputs in the form of energy were then 1325 kWh of electricity (956 kWh purchased from the grid) and 4962 kWh of steam. The result shows that the forest activities play only a minor role (about 5%) in the different environmental impact categories studied. Instead the production of chemicals consumed in the cooking and bleaching stages, and the on-site energy production system was identified as hot spots for the impact categories studied.

In Yu and Chen (2008), a biorefinery is simulated where bioethanol is produced from corn stover and PHA (polyhydroxy alkanoates) is produced from the black liquor that remains from the bioethanol fermentation. The system is thus producing three products: corn for food and feed purposes, bioethanol and bioplastics (Yu & Chen, 2008). These types of solutions would simplify many problems related to competition for raw material and the study confirms the fact that one means of utilisation of a feedstock not necessarily has to exclude another. Also Börjesson et al. (2012) suggests a biorefinery approach. Apart from the direct improvements in GHG performance through higher raw material efficiency, the multi-output systems can also indirectly improve the GHG performance by replacing several fossil-based products. However, from a LCA-perspective, the biorefinery concepts include methodological challenges as the system boundaries often need to be enlarged to include infrastructure for energy, forest and chemical industries and several functional units may be needed.

8.4 CONCLUSIONS FROM THE ETHANOL CASE

Today no commercial large-scale ethanol production from forest biomass exists in Sweden. The reviewed life cycle assessments are instead evaluation of pilot-scale facilities or potential large-scale facilities to be built in the future. The result shows that if no limit exists in the available potential of biomass the contribution to global warming potential is often below 20 g of CO_2 equivalents per MJ of ethanol. This result is also similar to other studies on biofuels from lignocellulosic biomass. However, these results depend on the conversion efficiency in the production process. In some of the studies the use of the excess heat, for example in a district heating system, is pointed out as important for the overall energy balance. One option can also be to use the biorefinery approach to optimise the use of the biomass.

With availability of forest biomass or residues the production of ethanol is promising from a GHG-emission point-of-view. However, other environmental aspects, for example biodiversity, also need to be considered when evaluating the environmental performance. Since the availability of forest biomass is limited it is important to also include the available potential in the assessment of the environmental performance. In addition, the aspect of time and the time scale when addressing future alternatives for the use of forest biomass is important to take into consideration. These issues are discussed further in chapter 12.

9 CASE STUDY – BLACK LIQUOR GASIFICATION WITH SYNTHESIS OF DME

9.1 ROLE OF BLACK LIQUOR IN A MODERN MILL

The black liquor (BL) is formed during the cooking of the wood chips in a Kraft mill and contains spent cooking chemicals and lignin, as described in section 3.2.2. After the cooking, it has a concentration of approximately 15% dry substance and is subjected to a multistep evaporation until it has a concentration of approximately 85% DS, at which it is burned in the recovery boiler. The BL is burned to generate heat and steam for the process (heat for e.g. the cooking step and steam for drying the pulp). In a KAM pulp mill (see section 9.3 below), there will be a surplus of energy generated, as shown in Table 8 and both heat, as e.g., district heating, and electric power can be delivered to external pipelines and grids while still providing enough energy to the process, as described in section 3.1.2.

As the purpose of this case study is to discuss the competition between alternative uses of forest biomass, exact calculations are not the focus. Figures on emissions, energies etc. are calculated from data found in the literature and no detailed analysis of, e.g., energy balances or yields have been performed. The results from the calculations performed serve as the basis of discussions in the report and the authors do not present them as being exact figures.

9.2 BLACK LIQUOR GASIFICATION, TECHNIQUE AND YIELD

There are alternative technologies for upgrading of BL. A technology that has attracted much attention and development work is gasification to syngas with subsequent production of transportation fuel such as methanol, di-methyl ether (DME) or Fisher-Tropsch diesel (FT diesel) - processes that can be integrated in a pulp and paper mill (Consonni, Katofsky, & Larson, 2009; Naqvi, Yan, & Dahlquist, 2010; Berntsson, 2008). All of these fuels can replace diesel and are therefore attractive alternatives to fossil fuel. In this study, the focus will be on the DME, which is a particularly attractive fuel for heavy transport due to its energy density. In addition, although it is a gas fuel it can be liquefied at room temperature under moderate pressure and therefore be distributed in its liquid form, and maintained as such in pressurized tanks in the vehicles. Volvo has a project demonstrating the feasibility of using DME in trucks (Volvo Group, 2013).

One of the most advanced techniques for BLG has been developed by Chemrec (Chemrec, 2013). Extensive research and development work has been conducted from mid-1980’s until 2013, when the rights to the process were transferred to Luleå Technical University, who will continue the research work and the development work at the pilot plant located at Smurfit Kappa mill in Piteå, Sweden.

In the Chemrec process, the BL is gasified with oxygen in a pressurised reactor and the green liquor is separated and recovered. The raw gas is then transferred to a cooler and subsequently compressed to syngas. The composition of the syngas varies according to process parameters, but a typical composition is approximately 25% CO, 17% CO_2, 27.5% H_2O and 32.5% H_2 (Berglin & Berntsson, 1998). From the syngas, either electric power or a variety of fuels can be produced.

According to Naqvi, Yan and Fröling (2010), a pulp mill producing 1000 ADt pulp/day can produce 131.9 MW DME, i.e. 3 166 MWh DME per day if all its black liquor is gasified with subsequent production of DME. As described in Table 3, 1.7 tonnes of black liquor solids (BLS) are produced per tonne pulp, with an energy density of 12 MJ/kg = 3.4 kWh/kg BLS. A mill producing 1000 ADt pulp per day thus produces 1700 ton BLS per day, with a total energy content of 5780 MWh. The energy yield of BLS to DME can thus be calculated to 55%.

There is no full scale, commercial black liquor gasification with subsequent production of fuel which makes the process less well characterized than production of bioethanol. There is one pilot plant in Piteå with a capacity of 20 tonnes BLS per day, and one plant in New Bern, U.S.A, with a capacity of 330 tonnes BLS per day, but it is not a high pressure, high temperature gasifier.

9.3 LCA AND OTHER EVALUATION METHODS OF BLACK LIQUOR GASIFICATION

Black liquor gasification is a starting point for various products for energy and/or fuel. The syngas produced in the gasification step can be used in a gas turbine for generation of power, for production of Fischer-Tropsch diesel (FT diesel), production of di-methyl ether (DME), methanol, etc. These processes have different impact on the energy balance of the pulp or paper mill and LCA is therefore not an as straight forward analysis as for example the production of bioethanol.

The two main approaches to evaluate BLG and associated subsequent processes have instead been to either:

- calculate CO_2 and energy balances for a mill with or without BLG with different productions of fuel or energy and to assess the economic performance of the process (Berglin & Berntsson, 1998; Consonni et al., 2009; Joelsson & Gustavsson, 2008; Larson, Consonni, Anand, & Realff, 2006; Pettersson & Harvey, 2010; Berntsson, 2008; Wetterlund, Pettersson, & Harvey, 2011), or to
- include only the production and use of biofuel and compare it to the production and use of fossil fuels in the system considered.

As mills differ in process setups, comparisons between technologies and estimations of effects of new technologies are difficult and there has been a need for a reference mill. A research program called The Eco-Cyclic pulp mill was launched in 1996 by Innventia (former STFI Packforsk) with the aim of designing a completely eco-cyclic pulp mill with an increased closure of energy, chemicals and other resources compared to existing mills (Axegård, Backlund & Warnqvist, 2002). The developed theoretical mill is called a KAM mill, where KAM stands for KretsloppsAnpassat Massabruk, i.e. Eco-cyclic pulp mill. This theoretical mill is a green-field mill built with only the best known (present and within foreseeable future) technologies. The KAM mill fulfills the requirements of a reference mill and has therefore often been used as such when effects of introducing new techniques need to be predicted, or when calculating energy and mass balances in the pulp sector. Also in this pre-study, the KAM market pulp mill will be used as a model when describing the consequences of replacing the traditional recovery boiler with a BLG process.

Some key properties of a KAM mill, reported in the literature, are presented in Table 7 below.

Table 7. KAM market mill characteristics. *)(Berntsson, 2008) **) (Axegård, 2005) *) (Pettersson & Harvey, 2010)**

Wood for pulp	**4148***	**tonnes DS/day**
Energy in pulp wood	45**	GJ/tonne pulp
Pulp production	2000*	ADt/d
Amount of black liquor solids	3400*	tonnes/day
Bark excess (= debarking minus need in lime kiln)	32***	MW
Electrical power surplus	45***	MW

Analyses of CO_2 balances for a pulp mill, with and without BLG and with subsequent production of fuel or electricity installed, show diverging results depending on whether the mill analysed is a market pulp or integrated mill, what the end product is and what system boundaries have been assumed. Naqvi (2010) reports an improved energy efficiency for a market pulp mill with production of CH_4 or DME compared to a mill with a conventional recovery boiler. Pettersson (2010) analysed the CO_2 emission balance of a kraftliner pulp mill with production of either DME, CH_4, FT-diesel and electricity. The system boundaries were varied in the study and found to have significant impact on the results, showing net CO_2 emission changes between 250 and -220 kg CO_2/MWh biomass compared to a conventional Kraft liner mill. Joelsson and Gustavsson (2008) also performed an analysis of CO_2 emission, oil reduction and energy efficiency in different pulp mills with varying products based on installed BLG. Also in that study, results vary depending on mill type and end product of the BLG.

Pettersson and Harvey (2012) have made a comparison of BLG with other, recovery boiler-based, biorefinery concepts such as lignin separation and electricity production. The analysis includes calculations of CO_2 emissions and economic performance of 15 cases with and without carbon capture and storage (CCS) techniques. The results depend on energy prices both for external energy to the mill to cover the deficit caused by BLG and for electrical power.

Other studies on BLG and its consequences for pulp and paper mills include studies on hydrogen production from a pulp mill integrated BLG plant compared to a stand-alone gasifier (Andersson & Harvey, 2007) and consequences of BLG on industry and society (Eriksson & Harvey, 2004). Most of the studies are performed for Swedish conditions, but similar analyses have been performed also for a US case (Consonni et al., 2009).

As stated above, results on the energy balance and CO_2 emissions net effects vary depending on assumptions made regarding mill type and end product. However, there are a few common results: market pulp mills have better prerequisites for successful BLG than integrated mills and there is a clear energy deficit caused by BLG, which has to be compensated with external energy.

To our knowledge, no study has yet analyzed the practical consequences in the forest and on biomass availability regarding how this energy deficit is covered and included that within the system boundaries of the analysis. Therefore, in this study, we will discuss these consequences but without performing a detailed LCA or energy balance study. All data used regarding in- and outputs (energy and feedstock), yields etc. are taken from the literature and based on a Swedish KAM mill producing 2000 ADt bleached Kraft pulp/day. The data take into account that biomass is a limited resource and that in Sweden already most of the biomass is used in the production of either materials or energy and that there are thus alternative uses for this extra biomass needed in a mill with BLG.

In subsequent discussions regarding biomass availability and GROT potentials, the focus is on energy content in feedstocks and products and CO2 emissions. No economic or technical feasibility aspects regarding harvesting of the GROT are taken into consideration. Neither is a discussion on the quality of the GROT available. However, a geographical limitation has been made: The region considered is Götaland as that is where the majority of Swedish market pulp is produced and it is assumed that it will not be economically feasible to transport GROT from Svealand or Norrland to Götaland (see section 3.2.1). The authors are aware that these limitations and assumptions constitute a simplification but at the same time do not affect the general conclusions being made.

9.4 CONSEQUENCES OF BLG TO A KRAFT MARKET PULP MILL

If the black liquor is gasified, the energy that is normally recovered from the recovery boiler and used in the pulping process will have to be replaced by other energy sources. The BLG itself generates both heat and steam, but not enough to cover the internal needs of the mill. In the discussions and calculations, we assume that all black liquor is gasified. There is the option of gasifying only a part of it, but that alternative is not considered here.

As seen in the Table 7, describing the KAM mill, there is a surplus of bark that can be sold externally as solid fuel for use in, e.g. a CHP. If a BLG is installed, the surplus bark can be either gasified or burned to generate energy, but that will not cover all the energy needs. Further discussions and calculations in this report are based on the assumption that a mill with BLG burns the bark in a conventional boiler for generation of both steam and electrical power for process needs. In Table 8 below, the direct energy deficit of a KAM2 (i.e. an updated KAM) mill with installed BLG with subsequent production of DME is shown. Data are calculated from installed effects reported by Pettersson and Harvey (2010), and 8400 operating hours per year has been assumed.

A KAM mill that produces 2000 ADt/day and operates 8400 h/year will have a production of 700 000 ADt/year, and thus a wood consumption of 330 000 m^3 solid under bark, i.e. 1 380 000 tonnes, with an energy content of 6970 GWh (assuming 5.28 kWh/kg dry wood).

Table 8. Energy balance per year for a KAM pulp mill producing 2000 tonnes AD pulp/day with a conventional recovery boiler and a BLG with DME production. Energies calculated from efficiencies reported by Pettersson 2010.

Black liquor processing	Mill with recovery boiler (GWh/year)	Mill with DME production (GWh/year)
Black liquor	3896	3896
Motor fuel	-	2200
Power production	832	344
Power consumption	472	792
Surplus/deficit power	**368**	**-448**
Bark excess	256	144
Consumption in CHP plant	0	1144
Surplus/deficit biomass	**256**	**-1000**
Total surplus/deficit	**624**	**-1448**

The energy deficit of a KAM 2 mill with installed BLG thus has an energy deficit of 448 GWh electric power and 1000 GWh biomass for steam production, which corresponds to 21% of the energy in the wood raw material. In addition to this deficit, the surplus biomass and power that a mill with a recovery boiler can export need to be replaced on the market by other energy forms. These numbers are in the same order of magnitude as reported by Ekbom et al. (2005), Naqvi et al. (2010) and by Pettersson and Harvey (2012). Thus, a total of 368+448 = 816 GWh electric power and 256+1000 = 1256 GWh biomass need to be “replaced”, corresponding to 27% of the energy in the wood (solid under bark) raw material of the mill.

According to the literature a KAM mill, which gasifies 3896 GWh of BLS will generate 2200 GWh DME fuel (Ekbom et al., 2005; Pettersson & Harvey, 2010). Assuming the same engine combustion efficiency in diesel and DME, this is equivalent to 210 400 m^3 diesel (à 10 MWh/m^3), corresponding to approximately 5.5% of Sweden’s diesel consumption.

In order to compare CO_2 emissions of the fuels and the different consequences resulting from the replacement of black liquor with other forms of biomass to a mill with BLG, emission factors are a useful tool. Different fuels are associated with different emission factors (Pettersson & Axelsson, 2012), taking into account all combustions and emissions from the production of the energy carrier. The combustion of bio-DME saves 122 g CO_2 eqvivalents per kWh of fuel compared to fossil fuel (ibid.), which means that combustion of 2200 GWh DME saves 122*2200/1000 = 268 ton CO_2-eqvivalents when fossil diesel is replaced by bioDME.

This figure does not, however, take into account the consequences caused by the energy deficit in the pulp mill equipped with BLG, which will be discussed in chapter 9.5.

9.5 INDIRECT CONSEQUENCES OF BLG IN A KRAFT MARKET PULP MILL

With the challenge of limited availability of forest biomass in mind, the indirect consequences of a BLG installation in a Kraft mill have to be discussed, taking into account alternative uses of the biomass required to compensate for the deficits at the mill. The purpose of this chapter is not to give any exact data on CO_2 emissions or LCA results but rather highlight the need of expanded system boundaries when analyzing the environmental impact of BLG with subsequent production of DME. As discussed earlier in this report, such a system expansion in order to include indirect effects on raw material availability is highly relevant for assessment of environmental performance of biofuels.

As seen in the previous chapter, a KAM market pulp mill with BLG instead of a recovery boiler requires extra energy equivalent to 21 % of the energy in its feedstock. In addition to this, 368 GWh electricity and 256 GWh biomass that were sold externally are withdrawn from the market and need to be replaced by other energy carriers. There are several alternatives to how the direct energy deficit can be covered at the mill:

- Incineration of solid forest fuels (i.e. bark, GROT etc)
- Incineration of wood
- Oil or other fossil fuels
- Partly with renewable forms such as wind power, but no specific calculations of such case has not been made. This can be a topic for further studies.

Subsequent discussion on the consequences of covering the energy deficits caused by BLG, include both the mill's internal deficits, i.e. 448 GWh electricity/year and 1000 MWh biomass/year for a mill that produces 2000 ADt pulp/day and the surplus energy and biomass that is generated at a mill with a recovery boiler and sold externally, i.e. totally 816 GWh electricity and 1256 GWh biomass.

9.5.1 Replacement with GROT

Many estimations of GROT potential in Sweden have been made, as discussed in sections 2.3.2 and 10.2. Table 9 below shows the average amounts of GROT harvested during the recent three year period in Sweden and a middle scenario GROT potential for four main regions of Sweden, as estimated by the Swedish Energy Agency. (For further discussion on future biomass potentials, please see section 10.2.)

Table 9. GROT harvests and potentials in Sweden. *) from The Swedish Forest Agency (Skogsstyrelsen) **) from The Swedish Energy Agency (Energimyndigheten).

Region	Harvest* (GWh)	Total potential** (GWh)	Surplus (GWh)
Götaland	2590	8100	5510
Svealand	990	6310	5320
Southern Norrland	490	6100	5610
Northern Norrland	390	450	4110

To cover the total biomass deficit caused by installation of BLG to a KAM mill producing 2000 ADt pulp per day requires 1256 GWh.

In addition to the internal biomass deficiency of a market pulp mill with BLG with DME production, there is the electricity deficiency caused by the DME production and the removal of green electric power sold externally by the original recovery boiler mill that has to be included in the analysis. If this electricity is to be replaced by electricity from biomass-fired CHPs with an electricity efficiency of 30%, an additional 816/0.3 = 2720 GWh solid biofuel need to be harvested in the forest (the heat from the burning of this additional biomass, i.e. 1904 GWh will contribute to the energy system but is not included in the calculations here). It might be argued that when compensating only the electricity production, it is better to consider a condensing power production rather than a CHP. In that case, an electricity output of 40% can be assumed, meaning that the externally produced power of 816 GWh require 2040 GWh of solid biofuel, on which yield the calculation below is based.

This means that, per mill of 2000 ADt/day capacity, a total of 1256+2040 = 3296 GWh solid biofuel is required to the mill and external biomass-based electricity generation if zero net bioenergy output is to be achieved. This energy corresponds to 60% of estimated GROT potential in Götaland (Swedish University of Agriculture & Swedish Forest Agency, 2008) and to approximately 47% of the energy in the pulp wood of the mill. The production of market pulp today in the Götaland region is approximately 1.7 million tonnes per year (Skogsindustrierna, 2013), i.e. 2.4 KAM mills of the discussed capacity. If mills in Götaland install BLG with production of DME fuel, there would not be enough GROT available within reasonable distance and furthermore, there will be no room for increase of other activities requiring GROT such as production of pellets, gasification of forest biomass and/or increased capacity for CHPs fired with forest biomass without compromising on existing use of forest biomass.

The production of 2200 GWh of bioDME with black liquor gasification thus requires 3976 GWh extra inflow of solid biofuels to the mill and to biomass-fired CHPs to compensate for both the direct energy deficits at the mill and the withdrawal of solid biofuel and green electric power from the external market.

What alternative uses is there for this amount of GROT? As the amounts of GROT available are limited, these alternatives have to be taken into account when assessing the impact of BLG with subsequent production of DME.

The GROT could instead be used in a CHP to generate heat and power. 3976 GWh solid biofuel can generate approximately 1193 GWh power, with an assumed efficiency of 30%.

It was calculated above that using 2200 GWH bioDME instead of 2200 GWh fossil diesel saves 268 kton CO_2, which is used in the below calculations.

If marginal power production is assumed to be coal condensation, which has a CO_2 emission factor of 856 g CO_2/kWh, these 1193 GWh electric power would cause emission of 1193*856 = 1021 kton CO_2. This means that replacing 2200 GWh diesel with bioDME through BLG causes a net increase in CO_2 emission with 1021-268= 753 kton CO_2.

If the production of marginal electric power is instead assumed to be produced with NGCC (Natural gas combined cycle), having a CO_2 emission factor of 376 g CO_2/kWh, the CO_2 emission from production of 1193 GWh is 1193*376 = 448 kton CO_2. The net increase of CO_2 emissions would thus be 448-268 = 180 kton CO_2.

With similar calculations as above, but referring to European electricity mix, having a CO_2 emission factor of 462 g CO_2/kWh (Itten, Frischknecht, Stucki, Scherrer, & Psi, 2012), the result is a net emission of 283 ktonnes of CO_2 for a KAM market pulp mill of 2000 ADt/day capacity.

World electricity mix has an emission factor of 721 g CO_2/kWh (ibid.), resulting in a net emission increase of 592 ktonnes CO_2 equivalents. Applying the same calculation using Nordic power mix as reference results in a net decrease of 118 ktonnes.

The resulting net effect on CO_2 equivalents emissions depends on what kind of electricity is chosen as marginal, as summarized in Table 10 below. It could be argued that Nordic power mix should be the method of choice, but most common in LCA calculations today is either coal condensation or NGCC.

Table 10. Summary of net effects on CO_2 emissions for a KAM mill of 2000 ADt/day with BLG with DME production depending on choice of marginal electricity production method.

Reference power production method	CO_2-eqv. emission factor (g CO_2eq/kWh)	CO_2eq emission per year corresponding to 1193 GWh (ktonnes)	Net increase of CO_2 eq with BLGDME at a KAM market pulp mill of 2000 ADt/year (ktonnes)
Coal condensation	856	1021	753
NGCC	376	448	180
European power mix	462	551	283
World power mix	721	860	592
Nordic power mix	126	150	-118

It can be argued that the biomass needed in the BLG mill and thus withdrawn from the external market can be replaced by other forms of biomass, such as agricultural or marine biomass. This is true, but the reasoning behind alternative uses of feedstocks still remains. Agricultural feedstock for energy purposes compete with other energy purposes and of course with food production. Whilst marine biomass, such as algae, is today an unexploited resource and the potential quantities available are based on estimates. Technologies for large scale production of macro or micro algae are still lacking.

9.5.2 Replacement with wood

Another possibility to cover the biomass deficit is to utilise wood. But as all wood harvested today is used in production of some sort, there would either have to be a competition for that wood or an increased harvesting and/or import. According to the Swedish Forest Industries Federation, net growth of forest in Sweden is 3% and The Swedish Forestry Agency reports that 33 million m^3 solid including bark was harvested in Götaland 2011, corresponding to 27 million m^3 solid under bark. An extra 3% of this volume, i.e. 0.8 million m^3 solid under bark, is theoretically possible if a zero net growth rate would be acceptable. This volume corresponds to an energy of 1690 GWh, i.e. not enough for a 2000 ADT/day KAM market pulp mill with BLG.

Covering the biomass deficit in a BLGMF mill by utilising wood will thus have many parallel and/or alternative consequences, including increased importation of wood, decreased production of wood pulp in Sweden. These scenarios in turn cause indirect effects on biomass competition that are difficult to overlook.

9.5.3 Oil or other fossil fuels

It would also be possible to compensate for the energy deficiency of the DME-producing mill with oil or other fossil fuels, but then no net gain regarding use of fossil fuels and environmental impact will be achieved. Biomass would, though, be available for other purposes, such as combustion in CHP plants, pellets production and other applications.

9.6 CONCLUSIONS REGARDING BLG WITH DME PRODUCTION

Black liquor gasification with subsequent production of DME fuel is, although not commercial today, a way to produce a renewable liquid fuel suitable for heavy transport vehicles. Whether this production decreases the overall environmental impact compared to using conventional diesel has been investigated, as described above, but not with alternative uses of the biomass taken into consideration, which inevitably is a relevant issue when there is a competition for the feedstock.

System boundaries have, as shown, a significant impact of the environmental impact of BLG with subsequent DME production.

Although the primary focus of this study is biomass as a limited resource, prices of biomass need to be taken into consideration in order to provide a more complex picture of the situation.

10 COMPETITION FOR BIOMASS

10.1 FUTURE PRODUCTS: NEW DEVELOPMENTS AND FUTURE DEMANDS

Apart from the classic utilization of forest biomass, i.e. solid fuel, building material (sawn wood products) and paper-based products (paper, board, packaging, etc.), numerous new possibilities beside liquid or gaseous fuels for transport are arising: textile, barrier materials, bioplastics, smart packaging etc. These applications are in various stages of development but constitute potential competitors for forest biomass. At the same time, the global demand for paper is forecasted to rise during the next decades as a result of increased standard of living in emerging markets (Jonsson, 2009 and 2011). The competition for biomass is thus likely to increase rather than decrease in the future. It is therefore important to discuss future availability of biomass and if that will be less than the need for it, each utilization of this resource will have impacts on the economy, society and environment caused by the production of potentially forest biomass-derived products that instead will be produced from alternative sources. The issue of increased biomass potential is discussed in this chapter to give an overview of the complexity of the issue.

An important aspect, which links to the issue of Sweden becoming a large exporter of biofuels, is the potential international demand of Swedish biofuel for co-firing in coal power plants. Such an international demand could put strong pressure on the Swedish biomass market and prices. It has however recently been shown that the potential international demand should be possible to be met by sources other than from Sweden (Hansson, Berndes, Johnsson, & Kjärstad, 2009). However, it remains to be seen how the demand for Swedish biomass from other countries e.g., for co-firing in coal power will develop.

10.2 FUTURE POTENTIAL

Forest and agricultural land, and its bio-resources are scarce both from a Swedish and an international perspective. At the same time, demand for what that land offers us such as ecosystem services, feedstock for materials, food and energy is steadily growing. The bio-resource system encompasses a multitude of actors, from the single farmer to large industries such as energy companies and pulp and paper manufacturers and the chemical industry. The very nature of the bio-resource system is complex and its development is closely linked to many different policy areas, business logics and technical and societal systems. Some of the interlinkages in the bio-resource systems are explored in this chapter, looking into definitions of biomass, approaches and methods for estimating the potential of biomass resources for energetic purposes. Furthermore a detailed qualitative and quantitative review of biomass resources assessments, focusing on forestry resources, for Sweden is presented.

10.2.1 Increased forest yield

One way to meet a higher demand for forest biomass for both material and energy purposes is to intensify forestry. This can be achieved with either selected actions such as fertilization, ditch cleaning, introduction of new species, increased thinning and pruning, forestation of old farmlands, etc. Such actions are heavily debated and there is a concern among some experts that an intensive forest management will have further negative impacts for biodiversity and other eco-system services that they consider already today neglected in the modern forestry. A discussion on the consequences and possibilities of intensified forestry is not within the frame of this study, but in order to provide a notion on potentials discussed among experts, Larsson, Lundmark and Ståhl estimated in a report that up to additional 36 $*10^6$ m^3 could be harvested if all actions were taken and no consideration of environmental issues would be made (2008). This estimate does, however, not include modern techniques with somatic embryogenesis (Lelu-Walter, 2013) which enables optimization of tree clones to use for each specific area. With this technique, another 30% increase in biomass volume would be possible where implemented (Larsson et al., 2008).

One solution could be to allow for certain forest areas to be managed with intensive forestry while others would be saved for environmental purposes. This poses, however, challenges as 50% of the Swedish forests are privately owned and the owners have a certain freedom of how to manage their properties.

10.3 REVIEW OF FORESTRY BIOMASS POTENTIAL ESTIMATES FOR SWEDEN

10.3.1 Selection of studies for analysis

Studies for further analysis was selected from a broad field of scientific and grey literature on biomass potentials estimates. The criteria for selection are divided into two groups. The first group determines which types of biomass resources have to be assessed by a study. Selected studies have to cover but not be limited to all sorts of woody biomass derived from forest and forest plantations during wood harvesting – stem wood and harvest residues (twigs, branches, stumps, thinning materials etc.), as well as residues of wood processing industry, i.e. sawdust, bark, black liquor etc. The second group of criteria sets spatial levels to be included in the review. The selected biomass resource assessments have to cover Sweden in its entirety. Additional criteria of the selection were clearly presented results as well as wide recognition of the authors by a scientific and policy making community.

Based on these criteria, 24 biomass resource assessments were selected and quantitatively reviewed in this report (Table 11). In addition to those, four studies were qualitatively assessed (Ericsson & Nilsson (2006),, Grahn & Hansson (2010), Lundmark (2004) and the Swedish renewable energy action plan (Prime Minister’s Office, 2010).

Table 11. Biomass potential assessments reviewed in this study. Time frame is approximate.

Study	**Biomass categories**	**Coverage**	
		Geographical	Time frame
Asiakainen et al. (2008)	Primary forest residues, stumps	EU27 with results for Sweden	2008
Börjesson et al. (1996)	Primary forest residues	Sweden	2010
Elforsk (2008)	Primary forest residues, fuelwood, secondary forest residues	Sweden	2010, 2020
EEA (2007)	Primary forest residues, stemwood	EU27 with results for Sweden	2000, 2010, 2020, 2030
Ganko et al. (2008)	Total primary forest residues (aggregated)	EU27 with results for Sweden	2000, 2020
Hagström (2006)	Primary forest residues, fuelwood, stemwood, secondary forest residues	Sweden	2000
Hektor et al. (1995)	Primary forest residues, stemwood, secondary forest residues	Sweden	2000, 2020
Jacobsson (2005)	Primary forest residues, stumps, fuelwood, stemwood,	Sweden	2000
Kommissionen mot Oljeberoende (2006)	Primary forest residues, secondary forest residues, black liquor	Sweden	2000, 2020, 2050
Förnybart.nu (2009)	Total forestry biomass potential (aggregated)	Sweden	2000, 2020
Mantau et al. (2010)	Primary forest residues, secondary forest residues, black liquor	EU27 with results for Sweden	2010, 2020, 2030
Panoutsou et al. (2009)	Primary forest residues, secondary forest residues	EU27 with results for Sweden	2000, 2010, 2020
Profu (2012)	Primary forest residues, secondary forest residues, black liquor	Sweden	2015, 2025
Skogsindustrierna (1995)	Primary forest residues, secondary forest residues	Sweden	2000
Skogsstyrelsen & SLU (2008)	Primary forest residues, stumps	Sweden	2010
SOU 2000:23 (2000)	Primary forest residues, fuelwood, secondary forest residues	Sweden	2000
SOU 1992:90 (1992)	Primary forest residues, fuelwood, secondary forest residues	Sweden	2000
STEM (2013)	Primary forest residues, fuelwood, secondary forest residues, black liquor		2020, 2030
STEM (2009)	Primary forest residues, stumps, fuelwood, secondary forest residues	Sweden	
Svebio (2004)	Primary forest residues, stumps, fuelwood, stemwood, secondary forest residues	Sweden	2010
Svebio (2008)	Primary forest residues, fuelwood, stemwood, secondary forest residues	Sweden	2000
Swedish EPA (2012)	Primary forest residues	Sweden	2010, 2020, 2030, 2050
Thrän et al. (2006)	Stemwood, secondary forest residues, black liquor	EU27 with results for Sweden	2000, 2010, 2020
Thuresson (2010)	Primary forest residues, stumps, fuelwood, stemwood	Sweden	2000, 2020

10.3.2 Terminology and units

Different terminology was used in the selected assessments and clear definitions of the terms were not always given. Reviewing the studies and their results, the terminology of the studies was used to gain insights into methods and assumptions used.

The wood biomass potentials were reported in the selected assessments using different unites: cubic meters (m^3), Joules (J), Watts-hours (Wh), tonnes of oil equivalent (toe), cubic meters of round wood equivalent, bone-dry tonnes (bdt) etc. All these units were converted to Wh to facilitate comparison.

10.3.3 Biomass energy potentials

Compiled potential estimates based on the extensive review are presented in Appendix C. This section provides a synopsis of the results.

Figure 18 shows a summary of the reported biomass potentials in Sweden for the different biomass categories assessed. The maximum and minimum values are presented as to give a span of the biomass potentials reported in the literature.

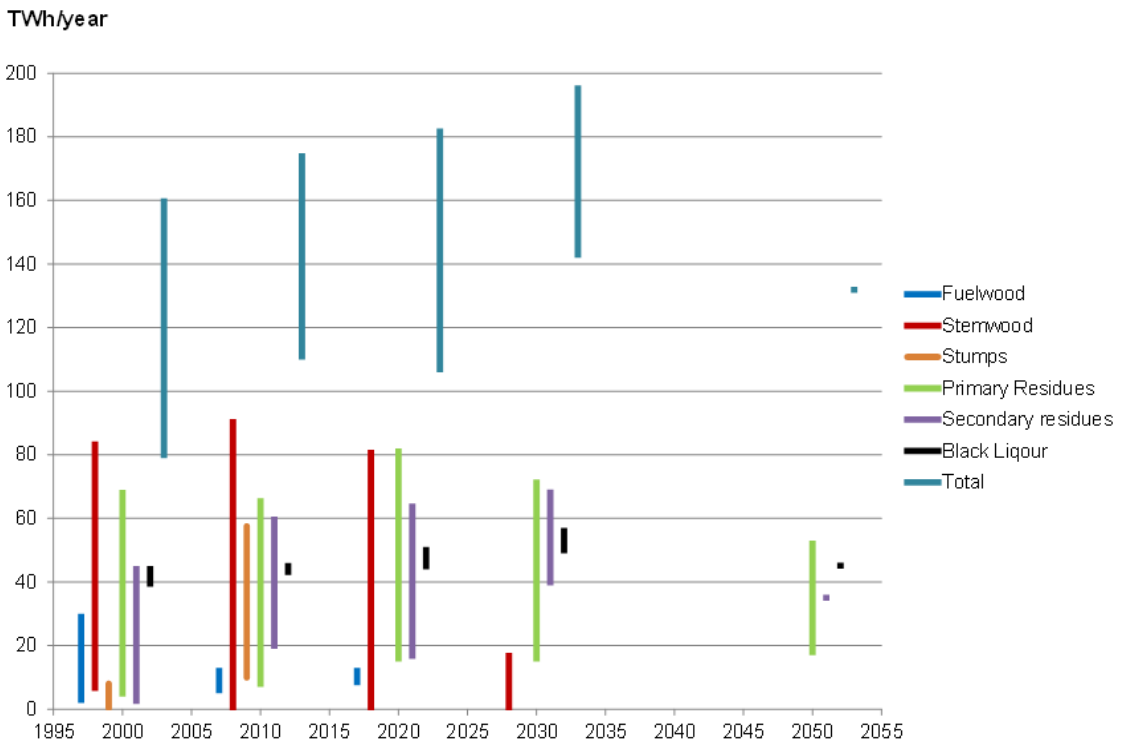

Figure 18. Summary of biomass energy potentials in Sweden. Lines span form the minimum to the maximum potential reported in the literature.

Note that for some biomass categories and timescales only very few, or indeed only one, potential estimate is reported, for instance secondary residues and black liquor in 2050. Whereas for other timescales and categories there exists a plethora of biomass potential assessments, there are for instance 20 estimates of primary forest residues for the period 2000-2009.

One may also note that the potential of some biomass categories may seem well defined, showing a small span between the minimum and maximum reported potential. However, underlying variables in the potential estimates may strongly impact the resulting potential; this is for instance true for black liquor where the development and competitiveness of the Swedish pulp & paper industry strongly affects availability in coming decades.

For reference it can be mentioned that 60% of the surface area in Sweden is covered by forest, corresponding to 23 million hectares of productive forestland. Of this, about 40% is owned by the forest companies or the government, and about 50% by small private owners. Pine and spruce are the most common species (39% and 42% respectively). Products centre on papers and cardboard, and to a lesser extent, wood production and bioenergy (Keskitalo et al. 2011).

10.4 DISCUSSION ON BIOMASS POTENTIALS

Biomass potential definitions are, in general, not as free from ambiguous influence on the results as one might assume. For all commonly used definitions – except perhaps the “theoretical” potential – a major shortcoming is that their meaning is far from unequivocal. For instance, in the cases of the “technical” and “economic” potentials, their actual values can vary substantially depending on the underlying assumptions. This means that different assessments might arrive to higher values on the “economic” potentials than the “technical” ones, which of course is inconsistent with the definitions. Hence, the definitions as such do not convey precise information about the factors behind the potentials. Therefore, they do not ensure consistency regarding the conditions underlying the potential.

In addition to the aforementioned influences the analysis has shown that different terminology and systematisation of categories as well as insufficient documentation of approaches and scenario assumptions makes comparison of results quite difficult.

Table 12. Issues impacting the comparison and usefulness of bioenergy assessments, and their relative importance for this analysis.

Issue	Relevance
Ambiguous biomass categories and sector/system boundaries	Minor – Medium
Inconsistent and/or ambiguous time scales	Minor – Medium
Inconsistent and/or ambiguous definitions of concepts of potentials	Medium – High
Inconsistent and/or ambiguous assumptions on development of key characteristics in the wood fibre systems (e.g. production, competition, land use)	High
Inconsistencies in near-time feasibility of accomplishing potentials	High

The last point in Table 12 refers to the considerable differences there may be between biomass categories to what extent an estimated potential can be exploited, taking into account the inertia there exist in realising the potentials. This inertia in expanding supply capacity and exploiting the potentials varies between biomass categories, and depends on the presence of actors, markets, machinery, infrastructure, etc. If those things already are in place to a large extent, potentials can of course be exploited faster.

It takes time to increase the forest growth and potential harvest levels in the northern temperate to boreal climate with long-rotation forestry. This means that in a short-term (0-30 years), to a large extent have to rely on current growing stock. A more sustainable short-term option is to supply the energy industry with forest biomass that is not traditionally used by the forest industry or with low-price forest biomass that the energy industry can compete with on the market. For example, bark, saw dust, shavings etc. To fulfill biomass supply gap, focus today on forest biomass traditionally left in the forest, for example, logging residues and stumps and small diameter trees.

In cases with very large disparities between assessments, it is mainly the latter of the aspects presented in Table 12 (i.e. system-external factors) that explains the differences, since, for instance, assumptions on the development of key characteristics of the traditional uses for forestry resources, i.e. timber and pulp and paper, have a most substantial influence on biomass potentials. Both influencing mobilisation of primary and secondary residues, but also affecting the competitiveness of dedicated supplementary felling's of stemwood for energy purposes.

At present, almost all residues from the Swedish forest industry (i.e., sawdust, shavings, bark, black liquor etc.) are used for bioenergy purposes (Egnell et al. 2011). The residues from logging operations (i.e., primary residues and stumps) therefore have to meet the new demands from the Swedish bioenergy market in the short term (0-30 years). This market is already growing by approximately 3 TWh annually, corresponding to 1.5 million m^3 of solid wood. In addition, a new market for bioenergy is emerging in Europe and globally. One needs to have realistic expectations on future market potential of biomass for energy from forestry. A number of limitations will make the amount of market available biomass considerably less than the theoretically available biomass. Limitations of different kinds: social, ecological, technical, economical and then finally gives a market potential. Moreover, secure feedstock is an important issue for investors within the bioenergy sector. In most cases not the global supply, but rather the supply on local and regional markets (Egnell & Börjesson 2012).

11 ECONOMIC ASPECTS ON DRIVERS AND BARRIERS FOR USE OF BIOMASS

From an economic perspective, it must first be reminded that several analysis show that an increase use of forest biofuels is likely to cause spillover effects into other forest products through the impact on relative prices and substitution of production materials (Bisaillon et al., 2008; Lundmark & Söderholm, 2003; Lundmark, 2007). And it is valid to consider that local impacts from an increased demand might be larger than regional impacts, due to the importance of transport costs for biofuels.

Given the outlook presented in the Swedish Färdplan 2050 (Swedish Environmental Protection Agency, 2012; Swedish Transport Administration, 2012), it is reasonable to consider one of the economic barriers to bio-based fuels in Sweden to be the relative low domestic demand. On an international market, this demand might be met by import rather than domestic production of biofuel.

Another very important economic barrier is the risk of investing in the 'wrong' technology. Currently, as is presented in this paper, there are numerous options available for producing renewable fuels, where high hopes currently are given to electric vehicles (Swedish Transport Administration, 2012). So investing in biofuel production is now a risky option, which is discouraging for investors.

One of the economic opportunities is on the other hand the relatively high private consumer willingness to pay for vehicle fuel. This gives these products a chance to be profitable even at high prices.

Another economic opportunity is the possibility that prices of fossil fuels will increase faster than prices for biofuels (due to scarcity), making biofuels more competitive in the future.

Finally, an uncertainty that can be considered both a barrier and an opportunity, is the direction of future climate policy. One example of this is the recent proposal from the European Commission to limit global land conversion for biofuel production. According to the proposal the use of biofuels produced from raw materials suitable for food would be limited to 5 of the 10% renewable fuels in road transport (European Commission, 2012a).

12 DISCUSSION AND CONCLUSION

There are many simplifications made in this study, which have impacts on the results that can be drawn from the discussions presented. For example, almost no economic or feasibility aspects have been taken into account, both of major importance to the availability of biomass for different purposes. The impact of future forest management methods, resulting in increased production of forest management has also not been taken into account even though such increased availability will have impact on the potential to increase the amounts of products derived from forest biomass. However, these simplifications do not change the fact that if forest biomass will be a limited resource also in the future, the proposed system expansions and considerations of alternative sources for forest derived products must be included in the decisions of how to prioritize the use of this resource.

12.1 CONCLUSIONS FROM WORKSHOP

At the workshop, several issues were identified that are important for the biofuel/renewable energy field in general, and also for the project to focus on in the future:

- The time scale needs to be defined. When addressing future alternatives for use of forest biomass, what time scale is to be considered?
- The system boundaries need to be defined carefully if LCA case studies are to be made. For example which kind of forest, which quality of forest biomass, biomass from forest on agricultural land?
- It is vital to consider the risk that fossil fuel based products replace forest biomass when forest biomass is used as biofuel. In such a scenario the potential benefit for reduced climate change of using biofuel is actually offset. This potential risk should be identified.
- Policy instruments that influence decisions to use alternative sources that have negative impacts on the environment should be analysed, and is an area for further research. For example in construction.
- The idea that ecosystem services is one use for forest biomass, is new in this context according to the participants. This should be explored further, particularly because ecosystem services cannot easily be replaced by other products/services. One example is recreation in forest. If ecosystem services are affected negatively, it may have severe consequences.
- Life cycle assessments should be done to explore the indirect environmental consequences of increased forest biomass use.
- Biodiversity was indicated, in the discussions on conflicts/synergies with environmental targets (see Appendix B), as both a potential synergy and potential conflict for several alternative sources. Hence this may be an important issue to explore further.
- The production aspects are important. The research should not only focus on the demand, but also at what is supplied.
- It is extremely important to focus on those alternative sources that are identified as having only negative impact in Table 13 in Appendix B. One such example is the use of cotton for textile, which is a big problem.

- These issues cannot be isolated but are in a global context, e.g. the enormous fossil resources in the worlds influence the discussion.
- Similarly it may be important to also focus on the alternative sources that the participants identified as having positive impact on the environmental objectives. These may be part of the solution, e.g. use of algae to produce biofuel.

Most participants reflected that the issue of indirect effects and chain reactions in the system when the use of one kind of material, i.e. forest biomass, is increased – is very complex and difficult to get a grasp of. The participants highlighted that it is important to get an overview of the system and the possible indirect effects. The workshop was a step in that direction and a contribution in this sense. The complexity should be taken in to account, and explored further. Furthermore, since the composition of the participants should ideally have been more diverse, for example no politicians or representatives from forest owners or forest industry were present, in further research the perspectives of these and other stakeholders should also be looked into. Such stakeholders may bring important perspectives on future developments and potential indirect effects that were not brought up during this workshop.

Stakeholder expectations of these issues can, in future research projects, be used as input in setting up LCA study assumptions and modeling different potential scenarios for forest biomass use.

12.2 CONCLUSIONS FROM THE STUDY

Regarding the time aspect, several questions need to be considered in the assessment. For what time frame is the result of an LCA valid? What time horizon has been used in the assessment? The time aspect is especially important when evaluating biomass with a rather long rotation time, such as forest.

The current use of the forest biomass is also important to consider. If it is already used for something else than biofuel production, this needs to be included in the LCA by expanding the system boundaries. If this is not taken into consideration there is a risk that the environmental burden will be moved from one system to another. For further discussion see e.g. Tufvesson et al. (2013).

Also the potential biomass supply must be investigated and described in the assessment. For ethanol the environmental performance of second-generation ethanol produced from forest, the environmental performance is good; the contribution to global warming is often below 20 g CO_2-equivalents/MJ for the different studies investigated in the review. But this result is only valid within the available potential. What will happen after this limit in potential is passed?

The future is inherently uncertain, but it is indicative that the Swedish Transport Administration does actually project a decrease in ethanol use from 2010 onwards to 2020, 2030, and 2050 (Swedish Transport Administration, 2012). It appears as if from a Swedish perspective, the risk of a large increase in the competition for biomass from Swedish forests might be exaggerated.

However, parts of this picture relate to the importance of some key technologies delivering what they promise. Most prominently, the Carbon Capture and Storage (CCS) technology is a key technology in the Swedish as well as the EU road map 2050 projects (European Climate Foundation, 2010; European Commission, 2011; Swedish Environmental Protection Agency, 2012). Also, the use of electric vehicles and/or hybrids is in the ambition scenario (S1) a prerequisite for the transport sector to meet the renewable targets. For Sweden in the baseline scenario, some 3.5% of total transport demand is estimated to be met by electric and/or hybrid vehicles in 2050. In the ambition scenario (S1), the corresponding number is 60% (Swedish Transport Administration, 2012). If these technologies don't deliver what they promise, other solutions might be needed and a demand for biofuels might very well be much higher.

A similar reasoning can be applied also for BLG with subsequent production of energy and fuel, such as DME. The energy content in black liquor has to be replaced by other forms of energy carriers in order for the pulp mill to have heat and steam for its process, which in first hand is forest biomass in forms of GROT and other residues or wood. The assessment of environmental impact of DME from black liquor will have to include the effects of using this additional biomass for the pulp mill instead of for other purposes. This has, to our knowledge, so far not been done satisfactorily for the aims of this study.

It is equally important to discuss not only alternative uses for the limited biomass, but also include a discussion on how these alternative products can be produced if they are not produced from biomass and include these effects in the assessment of the environmental impact of a certain product based on forest biomass.

In future studies of the environmental burden from different biofuel production systems the available potential must be estimated and it is also important to use a broad systems perspective, including both time aspects as well as current and alternative uses of the biomass. LCA as a tool is today somewhat limited to only cover those environmental aspects that can be quantified rather easy, for example global warming potential and acidification potential. In future assessments also other environmental aspects need to be considered, for example biodiversity. Also possible conflicts between different environmental goals need to be addressed.

The authors are aware of that a system expansion of the proposed kind is complex and maybe not even feasible, but nevertheless is such a discussion necessary as we have seen that forest biomass is a limited resource and that the use of it can have both decreased and increased environmental impact compared to current uses, depending on what applications are prioritized. More efforts are needed to develop either LCA methods or equivalents that take at least some of these considerations into account as well as dealing with the consequences of forest biomass utilization elsewhere in the world. This is particularly important when establishing environmental objectives and designing financial instruments, sustainability criteria, etc. There is a risk that when an environmental objective is established and stimulated with financial systems, such as renewable energy certificates or green fuel premiums, too much biomass is directed towards such applications and withdrawn from other applications, resulting in an increased environmental burden due to alternative sources for these products.

It might be right, both in the long time perspective and/or in a small system, such as one country, or EU, to promote certain uses of biomass even though this is not the optimal way in a global system for, e.g. political, economic or other reasons, but it is important that policy makers and experts are aware of the broader consequences of directing biomass towards certain applications, thereby withdrawing it from others.

It is clear that more research in how to deal with these system expansions and the consequences is needed.

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14 APPENDIX A.

Participants at the workshop. Apart from the workshop leaders Yevgeniya Arushanyan and Åsa Svenfelt, KTH, the following people participated:

1. Alvfors Per, KTH
2. Attebo Bengt, Göteborg energi
3. Berglin Niklas, Innventia
4. Björkman Max, LTH
5. Börjesson Pål, LTH
6. Fredriksson Möller Björn, E.ON
7. Johannesson Thomas, ordf. f3
8. Nyström Ingrid, f3
9. Pettersson Karin, Chalmers
10. Staffas Louise, IVL (project participant)
11. Svensson Jan-Anders, E.ON
12. Torén Johan, SP (project participant)
13. Tufvesson Linda, LTH (project participant)
14. von Schenck Anna, Innventia
15. Voogand Emmi, f3
16. Zinn Erik, Göteborg Energi

15 APPENDIX B

Table 13. Table of environmental consequences on impacts of shifted use of forest biomass, compiled during the workshop.

Environmental objective / Alternative source	Reduced Climate Impact	Clean Air	Natural Acidification Only	A Non-Toxic Environment	Protective Ozone Layer	Safe Radiation Environment	Zero Eutrophication	Flourishing Lakes and Streams	Good-Quality Groundwater	Marine Environment	Thriving Wetlands	Sustainable Forests	Varied Agricultural Landscape	Magnificent Mountain Landscape	Good Built Environment	Rich Diversity of Plant and Animal Life
Cultured crops is used to produce biofuels	- *****		-	- *			-	-		-	+/-	+ ****	+			+/- **
Macro algae is used to produce biofuels	+? **		+													+/-
Micro Algae is used to produce biofuels			+	+			+	+							+/-	+/-
Concrete for construction	- **** **	-										+?				+?
Steel for construction	-	-		-			-?	-?	?			+?				+?
Aluminium for construction	-	-		- *				-?	?			+?				+?
Cotton for textile				- **			-	-	- *******				-			-
Oil for basic chemicals	- **	+?	-							-		+? ***				+? **
Annual crops for paper	-			-			-	-			-	-				-
Waste for biogas	+ ********	+	+	+			+					+				+/-

Legend: + = positive impact, - = negative impact, ?? = uncertainty, * = vote for most important

16 APPENDIX C

In this Appendix the detailed estimates from the review of potential biomass are given.

16.1 POTENTIAL FOR PRIMARY FOREST RESIDUES

The studies listed in Table A- 1 present the potential for primary forests residues, also referred to branches and tops. See also Figure A- 1.

Table A- 1. Potential for primary forest residues in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
Asikainen et al 2008	Total	102.5					
Asikainen et al 2008	Available	64.2					
Börjesson et al 2010	High	21.9	65.3				
Börjesson et al 2010	Low	20.0	52.8				
Elforsk 2008			36.0	54.0			
EEA 2007	Max	24.8	28.5	29.8	30.6		
EEA 2007	Protected area	24.8	33.3	31.3	34.8		
	Protected area & Biodiversity	24.8	25.8	27.7	27.9		
Hagstrom 2006		57.1					
Hektor et al 1995	High	68.0		81.0			
	Low	63.0		65.5			
Jacobssen 2005		15.0					
Kommissionen mot Oljeberoende 2006		20.0		40.0			52.0
Mantau et al 2010			63.5	68.1	71.2		
Panoutsou et al 2009		46.7	51.5	56.9			
Profu 2012			34.0	42.0			
Skogsindustrierna 1995		14.0					
Skogsstyrelsen & SLU 2008	Nivå 1		36.3				
	Nivå 2		25.0				
	Nivå 3		15.5				
SOU 2000:23	High	55.0					
	Low	50.0					
SOU 1992:90	High	40.0					
	Low	36.0					
STEM 2013				34.0	42.0		
STEM 2009	Ekonomisk, 110 SEK/MWh	5.0					
Svebio 2004			64.0				
Svebio 2008		68.0					
Swedish EPA 2012	Miljöscenario		8.0	16.0	16.0		18.0
	Produktionsscenario		8.0	16.0	16.0		18.0
Thuresson 2010		7.6		16.5			
Number of assessments		20	15	14	7		3
Minimum		5.0	8.0	16.0	16.0		18.0
Maximum		68.0	65.3	81.0	71.2		52.0

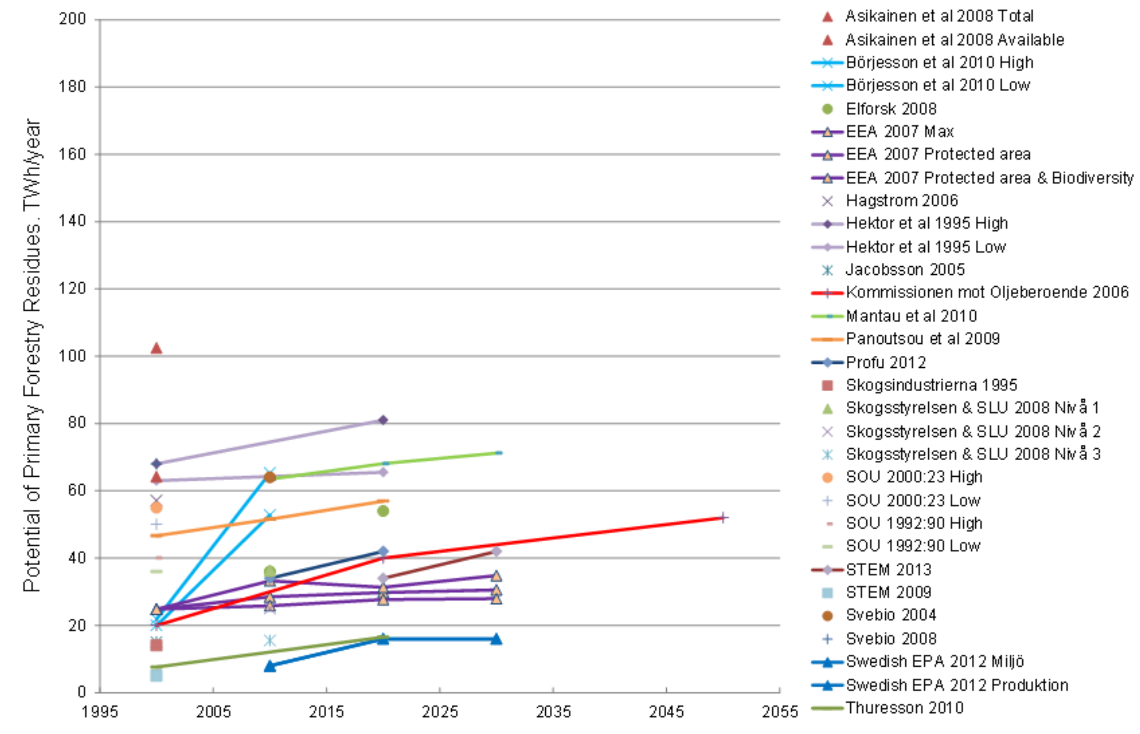

Figure A- 1. Potential for primary forest residues in Sweden [TWh/year].

16.2 POTENTIAL FOR STUMPS

The studies listed in Figure 2 present the potential for stumps. See also Figure A- 2. Stumps are by definition included in primary forest residues but as they are yet to be commercially harvested on any larger scale they are reported separately in this review.

According to Egnell and Börjesson (2012) the theoretical potential for stumps is reduces by several technical limitations (for example suitable ground conditions and only final cuts etc.). Further limitations that may reduce the number of suitable sites and thereby the market potential further due to economic, social and environmental reasons include: Economics: small sites, sites with low standing stock, sites distant to market, sites with long terrain transport distances. Social: Sites with the reindeer herding area, sites owned by forest owners that are reluctant to harvest stumps. Environmental: sites with high nature protection values, sites with a high density of ancient remnants, sites close to urban areas. Further: some stumps are needed to stabilise the soil along strip roads, some stumps are left close to living and dead trees do avoid damage and stumps are left close to buffer zones along surface waters to counteract wind damage.

Table A- 2. Potential for stumps in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
Asikainen et al 2008	Total	56.8					
	Available	6.7					
Jacobssen 2005		5.1					
Skogsstyrelsen & SLU 2008	Nivå 1		57.5				
	Nivå 2		33.7				
	Nivå 3		20.7				
STEM 2009	Ekonomisk, vid 110 SEK/MWh	8.0					
Svebio 2004			10.0				
Thuresson 2010		0.3		10.0			
Number of assessments		5	4	1			
Minimum		0.3	10.0	10.0			
Maximum		8.0	57.5	10.0			

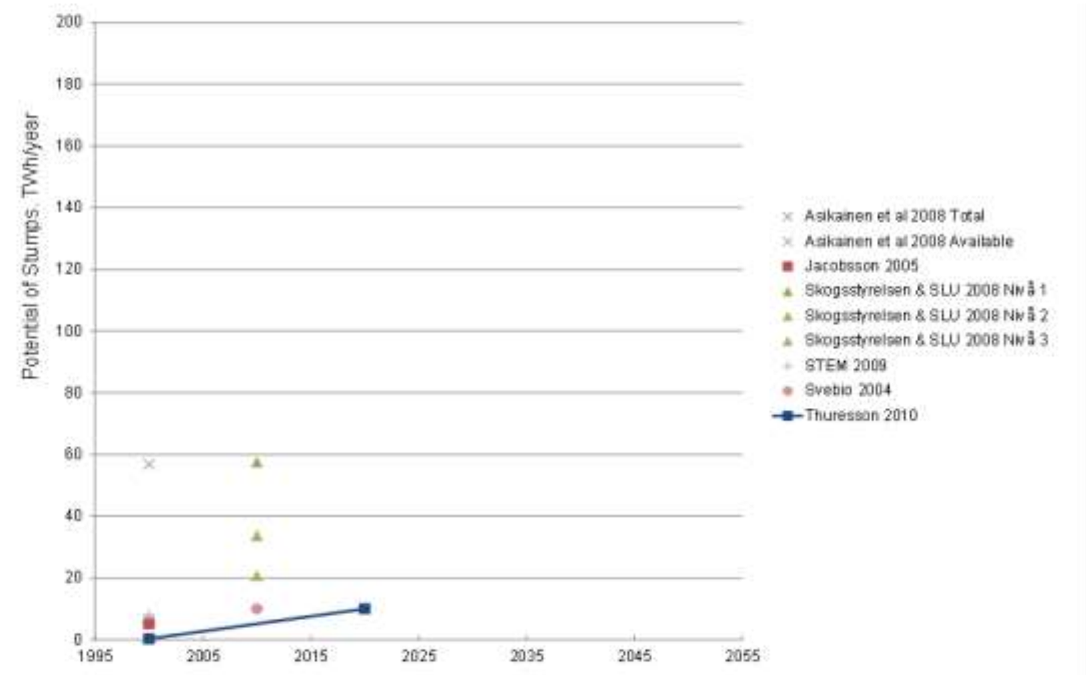

Figure A- 2. Potential for stumps in Sweden [TWh/year].

16.3 POTENTIAL FOR FUELWOOD

In Table A- 3 the potential for fuelwood is listed, see also Figure A- 3. Fuelwood is traditionally used for small scale heating of single family houses.

Table A- 3. Potential for fuelwood in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
Elforsk 2008			12	12			
Hagstrom 2006		17.9					
Jacobsson 2005		9					
Skogsindustrierna 1995		12					
SOU 2000:2	High	11					
	Low	11					
SOU 1992:90	High	29					
	Low	24					
STEM 2013				11	11		
STEM 2009	Ekonomisk, vid 110 SEK/MWh	3					
Svebio 2004			6				
Svebio 2008		7.5					
Thuresson 2010		8.5		8.5			
Number of assessments		10	2	3	1		
Minimum		3.0	6.0	8.5	11.0		
Maximum		29.0	12.0	12.0	11.0		

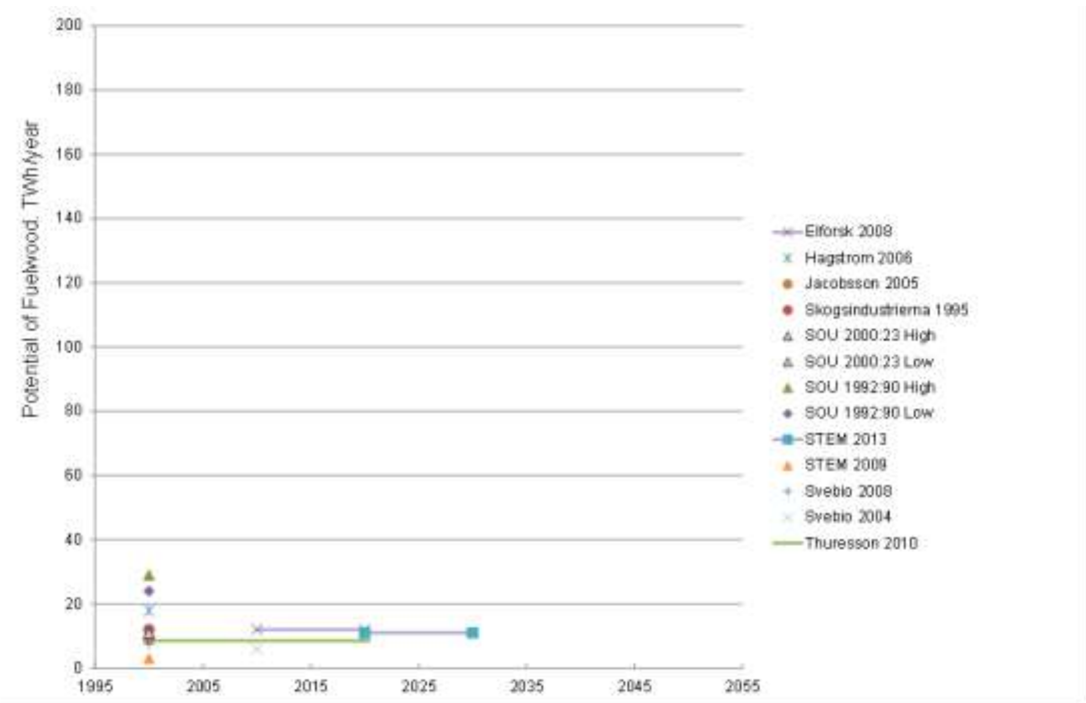

Figure A- 3. Potential for fuelwood in Sweden [TWh/year].

16.4 POTENTIAL FOR STEMWOOD FOR ENERGY

Additional fellings of stemwood for energy is assessed in some forestry biomass potential estimates. Levels of stemwood fellings are presented in Table A- 4 and corresponding Figure A- 4.

Table A- 4. Potential for stemwood for energy in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
EEA 2007 Max	Max		16.6	13.2	16.7		
	Protected area		1.2	0.6	1.1		
	Protected area & Biodiversity		0.0	0.0	0.0		
Hagstrom 2006		12.4					
Hektor et al 1995	High	45.5		45.0			
	Low	33.0		26.0			
Jacobsson 2005		6.8					
Svebio 2004			31.0				
Svebio 2008		15.2					
Thrän et al 2006		83.2	90.3	80.6			
Thuresson 2010		7.8		13.8			
Number of assessments		7	5	7	3		
Minimum		6.8	0.0	0.0	0.0		
Maximum		83.2	90.3	80.6	16.7		

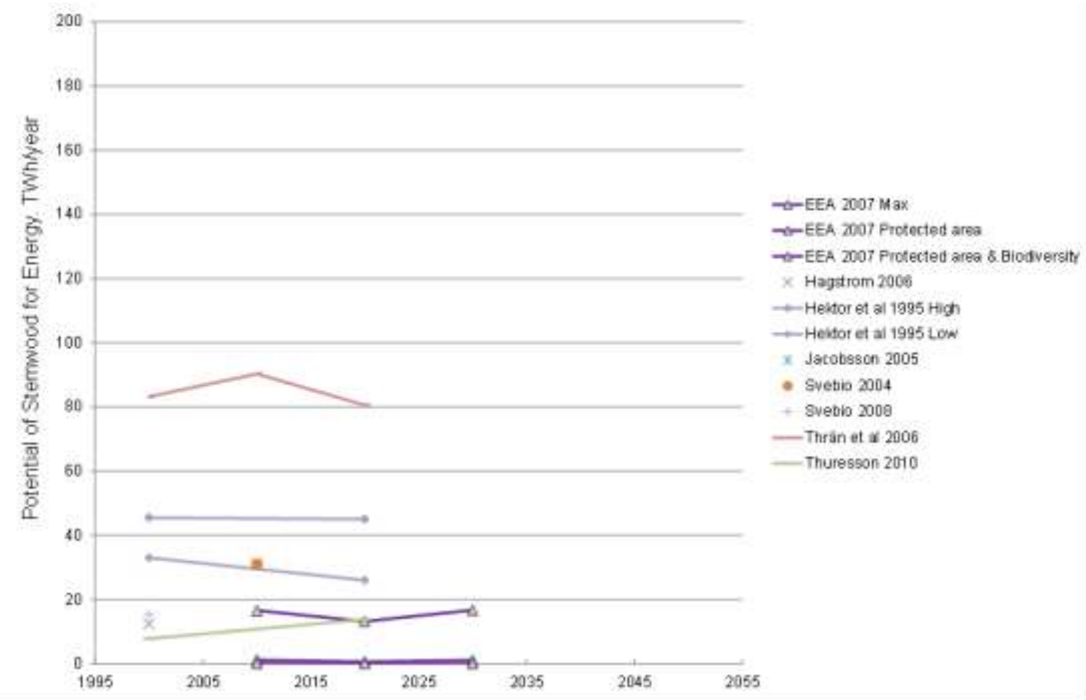

Figure A- 4. Potential for stemwood for energy in Sweden [TWh/year].

16.5 POTENTIAL FOR TOTAL PRIMARY FOREST BIOMASS

The total primary forest potential consists of previous 4 forestry biomass categories combined, i.e. primary forest residues, stumps, fuelwood and stemwood, see Table A- 5 and Figure A- 5. Note that not all biomass potential estimates assess all biomass categories.

Table A- 5. Potential for total primary forest biomass in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
Asikainen et al 2008	Total	102.5					
	Available	64.2					
Börjesson et al 2010	High	21.9	65.3				
	Low	20.0	52.8				
Elforsk 2008			36.0	54.0			
EEA 2007	Max	24.8	28.5	29.8	30.6		
	Protected area	24.8	33.3	31.3	34.8		
	Protected area & Biodiversity	24.8	25.8	27.7	27.9		
Hagström 2006		57.1					
Hektor et al 1995	High	68.0		81.0			
	Low	63.0		65.5			
Jacobsson 2005		15.0					
Kommissionen mot Oljeberoende 2006		20.0		40.0			52.0
Mantau et al 2010			63.5	68.1	71.2		
Panoutsou et al 2009		46.7	51.5	56.9			
Profu 2012			34.0	42.0			
Skogsindustrierna 1995		14.0					
Skogsstyrelsen & SLU 2008	Nivå 1		36.3				
	Nivå 2		25.0				
	Nivå 3		15.5				
SOU 2000:23	High	55.0					
	Low	50.0					
SOU 1992:90	High	40.0					
	Low	36.0					
STEM 2013				34.0	42.0		
STEM 2009	Ekonomisk, vid 110 SEK/MWh	5.0					
Svebio 2004			64.0				
Svebio 2008		68.0					
Swedish EPA 2012	Miljöscenario		8.0	16.0	16.0		18.0
	Produktionsscenario		8.0	16.0	16.0		18.0
Thuresson 2010		7.6		16.5			
Number of assessments		23	14	16	7		3
Minimum		16.0	25.8	16.0	16.0		18
Maximum		113.5	111.0	126.0	71.2		52

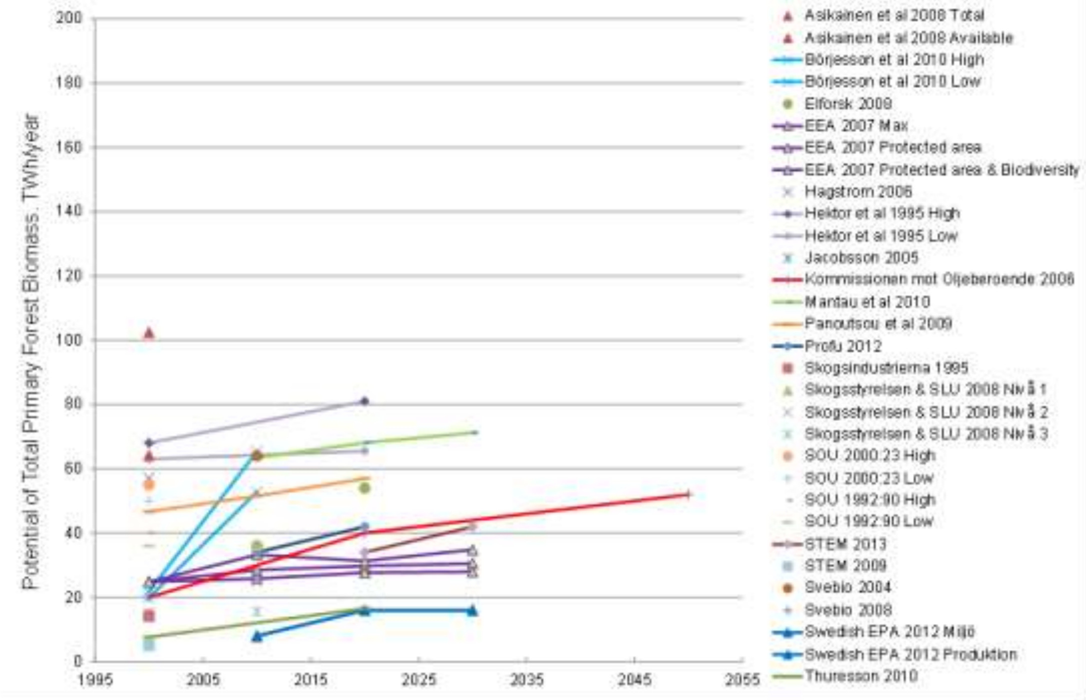

Figure A- 5. Potential for Total Primary Forest Biomass in Sweden [TWh/year].

16.6 POTENTIAL FOR SECONDARY FOREST RESIDUES

The studies listed in Table A- 6 presents the potential for secondary forests residues, see also Figure A- 6. Black liquor is not included in these figures but presented separately in the next section.

Table A- 6. Potential for secondary forest residues in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
Elforsk 2008			20	20			
Hagstrom 2006		27					
Hektor et al 1995	High	17		19			
	Low	16		17			
Kommissionen mot Oljeberoende 2006		16		22			35
Mantau et al 2010			60	64	68		
Panoutsou et al 2009		20	22	24			
Profu 2012			32	40			
Skogsindustrierna 1995		17					
SOU 2000:23	High	24					
	Low	24					
SOU 1992:90	High	13					
	Low	12					
STEM 2013				32	40		
STEM 2009		44					
Svebio 2004			20				
Svebio 2008		20					
Thrän et al 2006		37	40	43			
Number of assessments		13	6	9	2		1
Minimum		12.0	20.0	16.8	40.0		35.0
Maximum		44.0	59.6	63.7	68.1		35.0

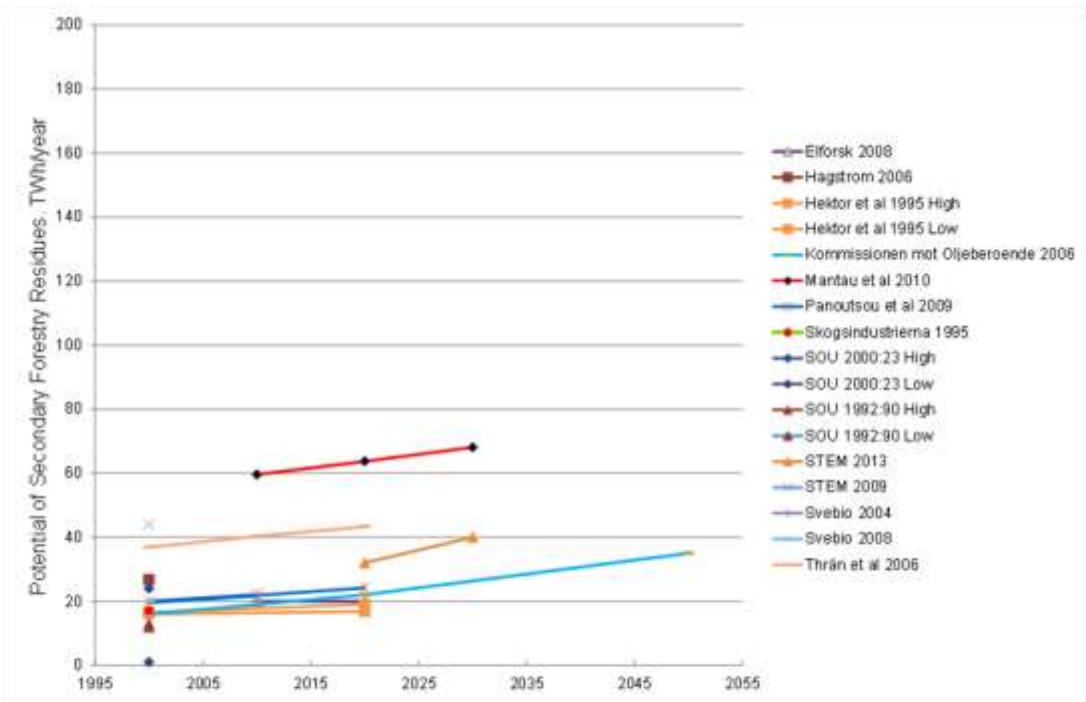

Figure A- 6. Potential for secondary forest residues in Sweden [TWh/year].

16.7 POTENTIAL FOR BLACK LIQUOR

Black liquor is by definition a secondary forest residue but is presented separately because of its special characteristics in relation to the biofuel system. Potentials of black liquor is listed in Table A- 7 and visualised in Figure A- 7.

Table A- 7. Potential for black liquor in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
Kommissionen mot Oljeberoende 2006		44		45			45
Mantau et al 2010			44	50	56		
Profu 2012			45	50			
STEM 2013				45	50		
Thrän et al 2006		40	43	46			
Number of assessments		2	3	5	2		1
Minimum		39.6	43.2	45.0	50.0		45.0
Maximum		44.0	45.0	50.0	55.9		45.0

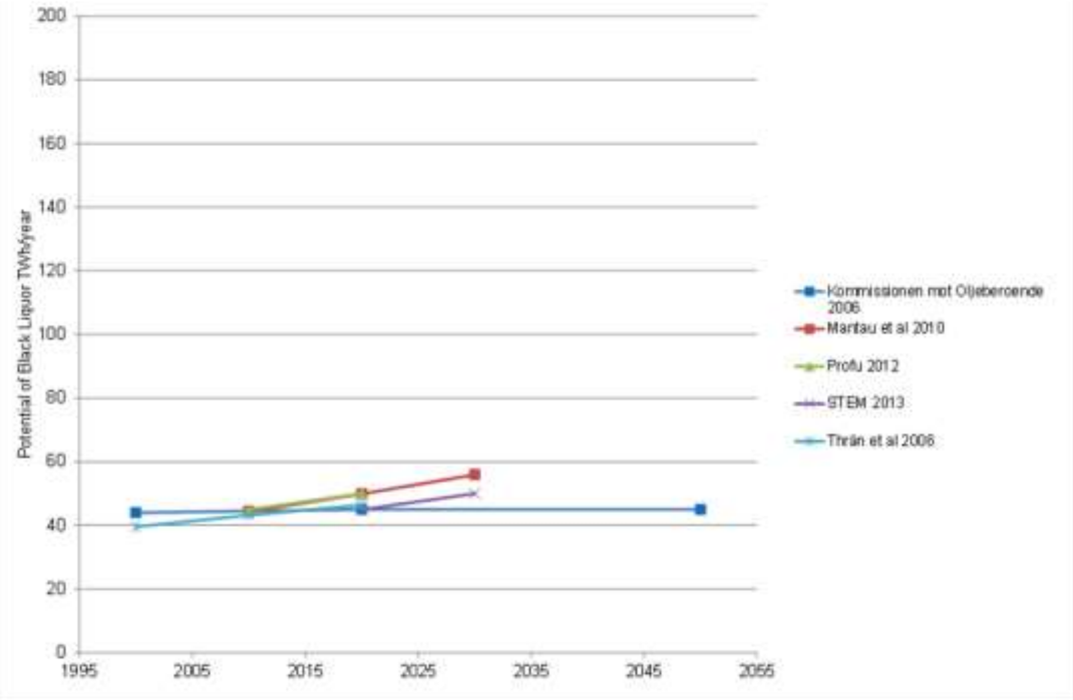

Figure A- 7. Potential for black liquor in Sweden [TWh/year].

16.8 POTENTIAL FOR TOTAL FOREST BIOMASS

Only a limited number of biomass potentials estimates cover what can be defined as the total forest biomass available for energetic uses, also note that all does not cover all biomass categories but are sufficiently complete to be included none the less. The potential estimates are presented in Table A- 8 and Figure A- 8.

Table A- 8. Potential for total forest biomass in Sweden [TWh/year].

Study	Scenarios	Time frame					
		2000	2010	2020	2030	2040	2050
Kommissionen mot Oljeberoende 2006		80.0		107.0			132.0
LRF, SNF, Tällberg Foundation 2009		112.6		140.6			
Mantau et al 2010			167.4	181.7	195.2		
Profu 2012			111.0	132.0			
STEM 2013				122.0	143.0		
Thrän et al 2006		159.6	173.8	170.3			
Number of assessments		3	3	6	2		1
Minimum		80.0	111.0	107.0	143.0		132
Maximum		159.6	173.8	181.7	195.2		132

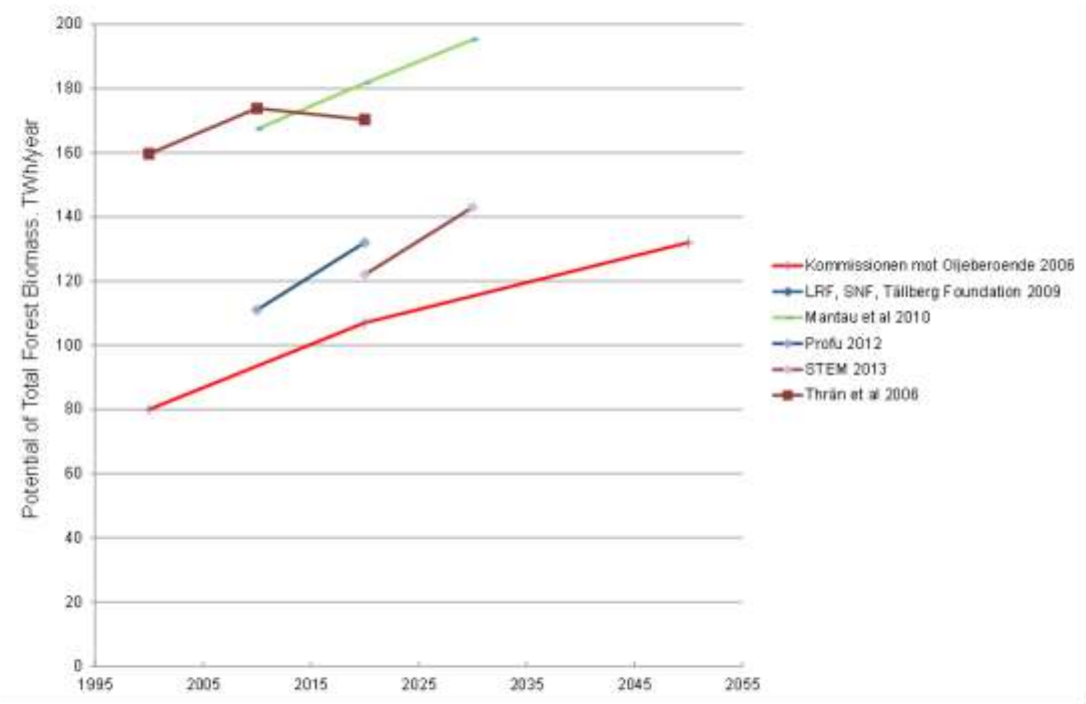

Figure A- 8. Potential for total forest biomass in Sweden [TWh/year].