CHAPTER 3:

Cost and CO_2-emission reduction of biomass cascading – Methodological aspects and case study of SRF poplar[*]

Abstract

This study presents and applies a coherent methodological framework to compare biomass cascading chains, i.e. the subsequent use of biomass for materials, recycling and energy recovery, considering land use, CO_2 emission reduction and economic performance. Example cascading chains of short rotation poplar wood are compared to each other on basis of literature data. Results for these chains vary strongly, namely, from CO_2 mitigation benefits of 200 €/Mg CO_2 to CO_2 mitigation costs of 2200 €/Mg CO_2, and from net CO_2 emission reductions per hectare of biomass production of 28 Mg CO_2/(ha*yr) to net CO_2 emissions of 8 Mg CO_2/(ha*yr). Using a present-value approach to determine CO_2 emissions and costs affects the performance of long-term cascading chains significantly, i.e. cost and CO_2 emission reduction are decreased. In general, cascading has the potential to improve both CO_2 emission reductions per ha and CO_2 mitigation costs of biomass usage. However, this strongly depends on the biomass applications combined in the cascading chain. Parameters that significantly influence the results are market prices and gross energy requirements of substituted materials and energy carriers, and the efficiency of biomass production. The method presented in this study is suitable to quantify land use, CO_2 emission reduction and economic performance of biomass cascading systems, and highlights the possible impact of time on the attractiveness of specific cascading chains.

---

[*] To be published in *Climatic Change*; Co-author: A.P.C. Faaij.

1 Introduction

According to many studies, the use of biomass for energy and material purposes may contribute significantly to the reduction of global carbon dioxide emissions if produced in a sustainable way (IPCC, 2001b; Turkenburg et al., 2000). Biomass can replace fossil fuels not only for the supply of heat, electricity and transportation fuel, but also as a feedstock for material production. Nevertheless, the use of biomass for material and energy applications can have two main disadvantages. Firstly, the costs involved are often higher than the costs of alternatives based on fossil fuel. Secondly, biomass production needs large quantities of often-scarce land resources if it is to contribute substantially to the world's energy consumption. Accordingly, an efficient use of biomass with regard to costs and land use is desirable in order to reduce CO_2 emissions. Such an efficient use of biomass can be realised by biomass cascading. In this context, cascading means that biomass is first used for a material application; next, it may be recycled for several further material applications; and finally, energy is recovered from the biomass. By means of cascading, reference materials and fossil fuels can be saved more than once during the lifetime of the biomass.

While cascading has been proposed for improving the GHG reduction efficiency of biomass systems—see e.g. Fraanje (1997) and Goverse et al. (2001)—few integrated analyses of biomass material and energy systems analysing their efficiency with respect to CO_2 emissions reduction, costs and land use have been carried out. Several studies have investigated carbon balances and land use of biomass materials, in particular from long-rotation forestry wood; see e.g. Schlamadinger et al. (1997) and Börjesson and Gustavsson (2000). In addition, several studies have analysed carbon balances of the utilisation of biomass for energy (Lettens et al., 2003; Ney and Schnoor, 2002). However, none of these studies compared the subsequent use of biomass for materials and energy with the use of biomass for either material or energy. Hence, the effects of biomass cascading on final CO_2 emission reduction and costs with regard to the area of land used for biomass production are not well understood from a bottom-up perspective.

Methodological aspects play an important role in quantifying these effects. For example, the choice of a reference system to determine CO_2 emission reductions of a biomass cascading chain can be very important, as shown by life cycle analyses of bio-material systems (Patel et al., 2003; Finnveden and Ekvall, 1998). Another aspect is the evaluation of CO_2 emission reductions at different moments in time. This becomes particularly important if long-life products are considered and CO_2 emissions can be distributed over a time span up to some hundred years. While for biomass material and energy systems this problem has not been studied extensively, several approaches have been developed to evaluate the sequestration of carbon in forests as function of time (IPCC, 1999; OECD and IEA, 2001; Marland et al., 2001). In conclusion, to enable a quantitative analysis of land use, CO_2 emission reduction and costs of complex biomass cascading chains, a coherent methodological framework is needed but not available.

A wide variety of biomass material applications and possible cascading chains exist, and it is unclear yet, which biomass chain is optimal with regard to costs, CO_2 emission reduction and land demand. This is due to the large number of parameters (e.g. material production process, crop yield, reference energy system) affecting the overall performance of biomass cascading chains. Preliminary analyses have shown that CO_2 emission reduction per hectare of biomass production and the CO_2 mitigation costs differ significantly for different biomass cascading systems (Dornburg and Faaij, 2001a).

Therefore, the methodological framework defined in this study is used to investigate and compare different biomass cascading chains. In order to analyse the effect of combining different material and energy applications in a biomass chain, we demonstrate the methodology with a single biomass crop. For that purpose, we select short rotation (SR) poplar wood. Key criteria for this selection are that the crop should be suitable for a broad variety of material applications, can be cultivated on different land qualities and has a relative high yield in Northern Europe, which is the geographical area considered in this study.

Summarizing, the aim of this study is twofold: *(1) to select and develop a coherent methodological framework for the comparison of different biomass cascading chains in terms of costs, land demand and* CO_2 *emission reductions and (2) to identify key parameters and issues that influence the efficiency of biomass cascading chains.*

The remainder of this chapter is organised as follows: In Section 2, the methodological framework is defined, while special attention is paid to the inventory and evaluation of different approaches for such a framework. Important aspects of this framework are (1) the boundaries of the biomass cascading system and the respective reference system, (2) inclusion of land use, (3) dealing with the time dimension and (4) definition of reference applications. Section 3 gives an overview of the biomass chains of SR poplar wood that are selected for this study, and presents the reference applications for the material and energy carriers produced from biomass. In the second part of this section, the background of input data for the calculation of costs, land demand and CO_2 emission reductions of the biomass systems is discussed. Results of applying the methodology to the SR poplar chains, together with sensitivity analyses are presented in Section 4. Finally, Section 5 discusses the results and draws general conclusions.

2 Methodology

2.1 System boundaries of biomass and reference system

To determine the CO_2 emission reduction that can be achieved by using biomass, a reference system needs to be defined (IPCC, 2001b). Usually it is assumed that materials and energy carriers from biomass substitute materials and energy carriers that fulfil the same functions; see e.g. van den Broek et al. (2001).

If more than one function is fulfilled in the biomass system—in our case through the production of several materials and energy carriers—two main approaches to define a reference system exist (CML, 2001). First, within a 'mono-functional' approach one 'main function' of the biomass system is compared to a reference function. Impacts related to this 'main function' are determined by allocation. Second, within a 'multi-functional' approach, all functions of the biomass system are compared to functions of the reference system. As an example, combined heat and power production using biomass can be compared to heat and power production from fossil fuels ('multi-functional'). On the other hand, part of the impacts of combined heat and power production using biomass can be allocated to biomass power generation. Subsequently, these allocated impacts of power generation from biomass can be compared to power production using fossil fuels ('mono-functional'). A main objective of this study is to compare different biomass cascading chains that fulfil several functions. Therefore, a *multi-functional approach* is applied.

Some studies that compare different biomass systems use a product-basket approach; see e.g. (van den Broek et al., 2001). This implies that the system boundaries of each biomass cascading system are extended in such a way that all systems fulfil the same functions. For example, to compare a biomass power plant (system A) to particleboard production and electricity recovery by incineration of the board at the end of its life cycle (system B), board production would be added to system A. However, when analysing a number of biomass cascading chains, each one producing a different suite of materials, the resulting product basket would become very complex. Therefore, in this study *every single biomass cascading chain is compared to a single reference system.* This enables a fair comparison between various biomass chains, which is what we want to demonstrate here.

Because a final waste-to-energy step of the biomass is included in the analysis for a fair comparison, the reference materials are assumed to be converted to energy after use too. The amount of energy carriers produced in both systems is evened out by assuming that surplus energy carriers in either the biomass or the reference system would be produced from an average mix of fossil fuels in the respective other system.[1]

Transportation of biomass and materials, as well as collection of waste materials, is not considered in this study, because a detailed analysis of all transportation steps is beyond the scope of this study and in general, the impact of transport on overall energy balances tends to be minor (Biewinga and van der Bijl, 1996; Dornburg and Faaij, 2001b). Therefore, we simply assume that logistics in the biomass and the reference cascading chain are comparable.

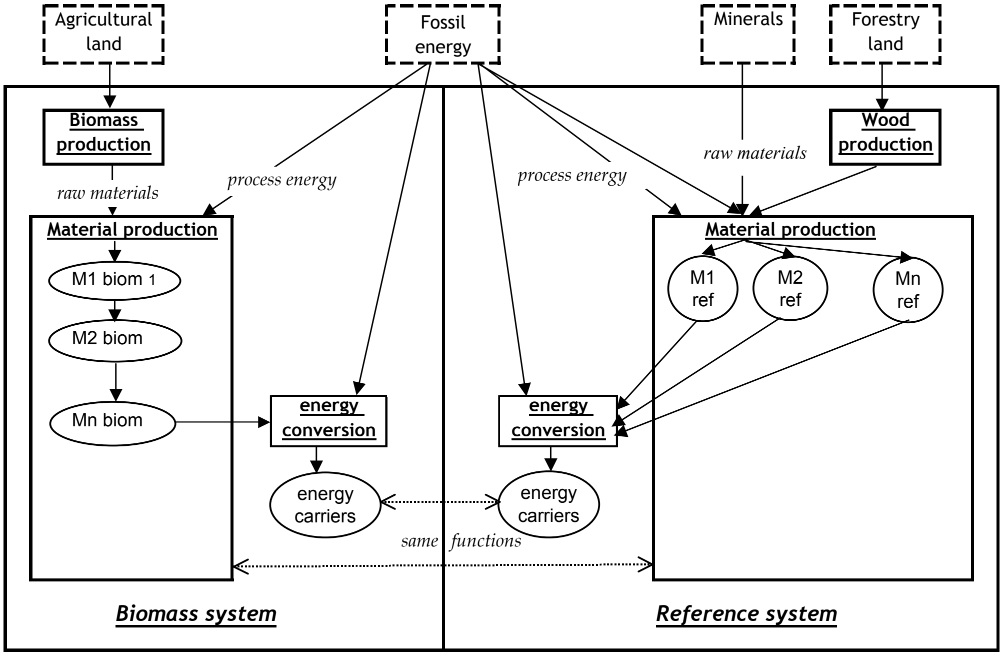


Figure 3.1: Schematic representation of biomass cascading system with according reference system

Figure 3.1 gives an overview of the biomass reference system as investigated here. Within the rest of this study, the biomass system refers to cascading chains of SR poplar. Note that biomass may be used for material production in the reference systems as well, because in

---

[1] Thus, we assume that biomass energy would most likely replace fossil energy.

some cases products from SR poplar substitute wood products from conventional forestry. The implications of reference products from conventional forestry for the inclusion of land demand into the analysis are discussed in Section 2.2.

2.2 Land use

Land use, i.e. the area of land occupied by biomass production, is a crucial parameter in the analysis and comparison of biomass systems (Schlamadinger et al., 1997). While the inclusion of land use in comparative analyses of biomass energy and material systems is not common practice yet, this issue has been gaining importance in recent discussions; see e.g. Green (2000) and chapter 4 of this thesis. Approaches to include land use in the analysis of biomass systems vary. In a study of van den Broek et al. (2001), the area of land used is a function in the biomass system. Other functions in this biomass system are food and energy carriers produced. Consequently, in the biomass and the reference system, the same area of land is used and the same amounts of food and energy are produced. Other authors limit the use of land to the biomass system. CO_2 emissions and other environmental impacts are then calculated per ha of land used in the biomass system, see e.g. Gärtner et al. (2002).

Roughly, the geographical context considered in this study is Northwest-Europe (i.e. North-France, The Netherlands, Belgium and Germany). These countries have quite comparable conditions for biomass production and, moreover, comparable material markets. It is assumed that short rotation poplar is cultivated on medium quality agricultural land. Thus, in this study 1 ha of *land use in the biomass system* refers to the occupation of 1 ha of *medium quality agricultural land in NW-Europe* for one year.

At any rate, the production of biomass in the biomass system requires land. Moreover, for the production of reference materials, land may be used too. This is clearly the case if SR poplar products in the biomass system substitute wood products from conventional forestry in the reference system. On the other hand, if short rotation poplar products substitute only fossil fuel based or mineral materials, no land is needed in the reference system. In this study, both situations are considered.

If land is used to produce wood products from conventional forestry in the reference system, it has to be accounted for. The area to produce wood products is typically larger than the area to produce short rotation poplar products with equivalent functions. This is due to lower yields in conventional long-rotation forestry (Kaltschmitt and Reinhardt, 1997). Therefore, defining land use in the biomass system as the land use for biomass production minus the land use for conventional wood production may lead to negative net land uses.

As a negative net land use is not a useful unit for comparison, another method is applied to account for the land use in the reference system.

The *land use of conventional forestry* can be *converted to CO_2 emission reductions and cost reductions*, which are the main objectives of biomass systems in this study. In order to do so, the amount of energy crops that could be produced on this forestry land if it would not be used for wood production, is calculated. If these energy crops replace fossil fuels, CO_2 emissions are reduced. (CO_2 emission reductions are the CO_2 emissions due to the use of fossil fuels minus the CO_2 emission due to the production of energy crops.) Similar to the reduction of CO_2 emissions, these energy crops can also reduce costs, i.e. the costs of fossil fuel use minus the costs of energy crop production. By using this approach, specific CO_2 emission reduction and cost reduction per area of reference land demand can be determined.[2]

However, yields of energy crops on forestry land are in most cases lower than yields of energy crops on agricultural land. Therefore, the yields of energy crops on forestry land are corrected by a dimensionless quality factor. For example, with a quality factor of 0.5, yields of energy crops expected on conventional forestry land are half of those expected on medium quality agricultural land.

2.3 Time dimension

(Avoided) CO2 emissions over time

The use of biomass, when derived from well-managed plantations, is considered to be close to having no net impacts on the carbon in the atmosphere, because all carbon sequestered during plant growth is released during energy conversion and vice versa. However, if cascading systems of biomass are considered, the release of sequestered carbon can take place significantly later in time than the moment biomass is harvested. Depending on the applications in the cascading chains this period can vary from several weeks (e.g. paper) to a century or more (e.g. construction wood). Furthermore, CO_2 is emitted at different moments in time in the biomass as well as in the reference system.

---

[2] Another obvious possibility to convert the use of conventional forestry land in the reference system to CO_2 emission reductions exists. Here, one would assume that alternatively the forest would not be harvested and consequently, carbon would be sequestered in the standing trees. This carbon sequestration could be expressed as carbon emission reduction. However, the hypothetical conversion of sequestered carbon to permanent carbon emission reduction is a disputed topic and several approaches exist; compare OECD and IEA (2001). Furthermore, sequestered carbon is never fully equivalent to avoided fossil fuel based carbon emissions. In order to circumvent this issue, we assume that in case the wood is not used for products, energy crop production instead of carbon sequestration takes place on the forestry land.

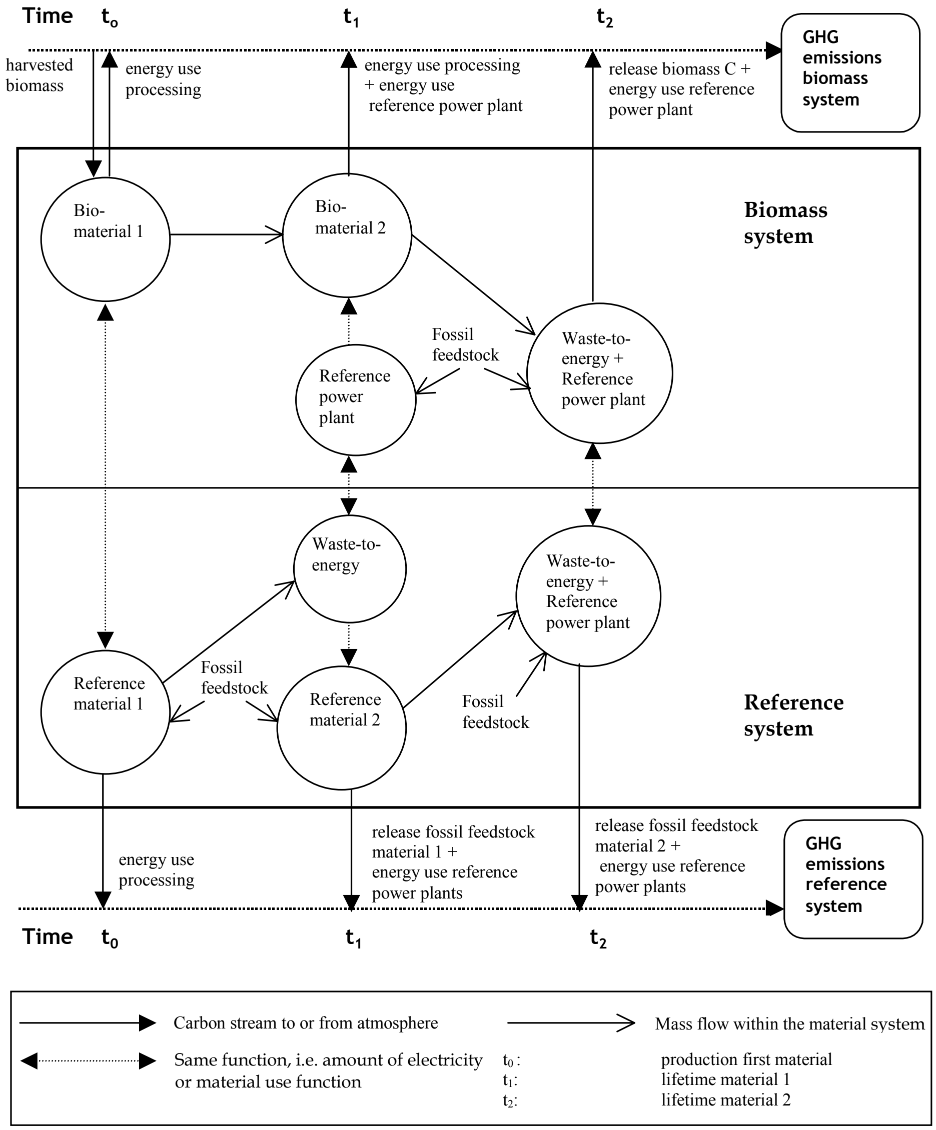


Figure 3.2: Carbon streams in time for a biomass cascading system with two material application steps

Figure 3.2 illustrates schematically CO_2 emissions for a cascading chain with two different material production steps and a waste-to-energy conversion step. The analysis starts with the input of carbon sequestered in the biomass at time t_o, when the first material in the cascading chain is produced, i.e. the biomass is harvested. After the lifetime of this first material, at time t_1, CO_2 emissions occur due to recycling and the production of the second material. At time t_2, after the lifetime of the second material, the biomass is converted to energy and the sequestered carbon is released. At the same moments in time reference materials and energy carriers are produced.

It is obvious that the later CO_2 is emitted to the atmosphere, the later the greenhouse effect due to this emission takes place. To account for CO_2 emissions at different moments in time, an indicator predicting climate change due to a certain emission at a certain moment would be desirable. However, this climate change depends on many external factors such as the concentration of greenhouse gases in the atmosphere and, thus, cannot be determined. (IPCC, 2001a) Alternatively, carbon emissions in time could be evaluated by an economic approach. Marland et al. (1997) evaluated CO_2 emissions by a carbon discount rate representing the potential economic damage of a certain emission. However, this damage also depends on many external and unpredictable factors.

Van den Broek et al. (2001) discussed that physical units that represent monetary values can be converted to present values. They applied this concept to the yields of a eucalyptus plantation. The concept may also be used for CO_2 emissions, since these are tradable and, thus, represent a monetary value, which may vary in time.

In this study, lacking a better instrument, we evaluate CO_2 emissions at different moments in time by assuming that these *CO_2 emissions represent a constant monetary value that can be converted to a present value taking into account an interest rate*. Besides CO_2 emissions, all other *cost items are converted into present values*, too. The interest rate assumed is a crucial parameter. Here, a low discount rate representing annual capital costs in public projects is assumed, because mitigating carbon emissions is considered a public responsibility.[3] To highlight the impact of time on the evaluation of CO_2 emission reductions in biomass cascading chains, the performance of CO_2 emission reduction is also analysed *without* present-value approach.

Technology developments

Because some biomass material applications last for quite a long time, it should be noted that during such a time period technological developments occur. Consequently, the economics and energy balances of processes to produce material and energy carriers out of both biomass and reference raw materials are affected. In such a way technological developments influence the performance of long-term cascading chains. However, data on expected developments of all relevant technologies are not readily available and the analysis of mechanisms behind these developments is beyond the scope of this study. Nevertheless, the potential impact of *possible developments of some technologies* is evaluated *in the sensitivity analysis*.

---

[3] For a discussion on the choice of interest rate in long-term problems as climate change; see (Portney and Weyant, 1999).

2.4 Definition of functional units

The biomass and the reference system are compared by means of equivalent functions, where functions are services that are embodied in material objects. (CML, 2001) The function of a certain material can be defined in several ways, because materials can have various (desirable) properties, such as the structural and indoor climate functions of a construction element. Typically, wood products have different secondary functions and characteristics than products from fossil fuels or minerals. In general, however, a main function can be identified, e.g. the structural function in construction. Only this *main function of an application* is considered in this study. The *functional unit* is the *function fulfilled by the biomass material produced from one hectare and one year of SR poplar production.* Based on this functional unit, the kind and amount of reference material can be determined. For a more detailed discussion of the reference materials, see Section 3.

2.5 Calculation method

Starting from one hectare and one year of biomass production, costs and CO_2 emissions of the biomass cascading chain in comparison to a reference system are determined. The following three key parameters are calculated for a comparison of biomass cascading chains:
- Annual CO_2 emission reduction per area of biomass production [kg CO_2/(ha*yr)]
- Net annual costs per hectare of biomass production [€/(ha*yr)]
- CO_2 mitigation costs [€/kg CO_2]

CO_2 emission reduction
The CO_2 emission reduction of a biomass cascading chain is the difference between the emissions in the reference system and those in the biomass system. These CO_2 emissions comprise emissions associated with biomass production, reference land use, material production, and the production of energy carriers. CO_2 emissions during biomass production result from the direct energy inputs and the indirect energy inputs of materials (e.g. machines, fertilisers). Moreover, we include N_2O emissions from fertiliser application using its CO_2 equivalent value. Other greenhouse gas emissions (such as CH_4 emissions from decay of roots) play only a small role in overall greenhouse gas emissions of biomass production systems (IPCC, 2001b) and are not taken into account.

Net annual costs
Analogous to the CO_2 emission reduction, the net annual costs (or benefits) of the biomass cascading chain are the difference between the annual costs in the biomass and the reference system. These cost items are biomass production costs and the costs of material and energy production. In general, no taxes or subsidies are taken into account. Net costs of

biomass applications (i.e. materials and energy carriers) are defined as the production costs of the biomass application minus the market price of the reference application. However, using market prices introduces uncertainty into the analysis due to possible fluctuations of such prices. This uncertainty is addressed by using ranges of market prices that are derived from relevant statistics.

3 Cascading chains of short rotation poplar

3.1 Applications

For a case study, biomass cascading chains of short rotation poplar have been selected on the basis of a review of possible applications and recycling options, which can be found in Appendix 1. For the selection of applications the following criteria were applied:

- The suitability of SR poplar wood for the investigated application
- A potentially large market volume of the material
- The possibility of cascading
- The likeliness of high CO_2 emission reduction and low CO_2 mitigation costs
- Inclusion of at least one application in key industrial sectors that are suitable for poplar wood (construction, packaging, pulp & paper, chemicals and energy)

Finally, eight application of SR poplar wood are considered in this analysis, i.e. particle lumber (LU), medium density fibre board (MDF), transportation pallets (PA), chemical pulp (PUL), ethylene (ET), methanol (ME), viscose (VI) and electricity (EL), and for each of these applications also a reference application is defined:

- *MDF board* generally substitutes other wood products. Main substitute is structural plywood from softwood that is the reference material in this study. Functional unit for comparison is the volume of board material.
- *Particle lumber* substitutes concrete. Respective amounts needed in equivalent houses with concrete or wooden frames substitute each other in the analysis.
- *Pallets* are not commonly produced from alternative materials, e.g. from HDPE or corrugated fibreboard, and, therefore, wooden pallets from softwood are assumed as a reference material.
- *Chemical pulp* from short rotation poplar replaces chemical pulp made from other fibre sources, i.e. softwood.
- *Ethylene* from SR poplar wood substitutes ethylene from fossil sources, i.e. naphtha, gas oils, liquefied petroleum gas and ethane. Because in Western Europe about 73% of ethylene production was based on naphtha in 1997, ethylene production via steam cracking of naphtha is regarded as the reference process (CEFIC, 2000).

- *Viscose* replaces mainly synthetic staple fibres. The most important staple fibres in terms of production volume are polyester (PES) fibres (CIRFS, 2002). Viscose can be used for most technical applications for which PES can be used. As a consequence, PES fibre is assumed as reference material for viscose. Functional unit for the comparison of PES and viscose fibres is the volume of fibres.
- *Electricity* from biomass is assumed to substitute the average Western European electricity mix in the reference system.
- *Methanol* replaces gasoline, which serves as a reference material. Functional units for the comparison are lower heating values.

Selected applications and reference applications for further analysis are summarised in Table 3.1.

Table 3.1: Applications of SR poplar wood and reference applications included in this study

Abbreviation	**SR poplar application**	**Reference material**	**Substitution**
LU	Particle lumber	Concrete	Fossil, mineral
MDF	MDF board	Plywood softwood	Wood
PA	Pallets	Pallets softwood	Wood
PUL	Chemical pulp	Chemical pulp from softwood	Wood
ET	Ethylene	Ethylene from naphtha	Fossil
ME	Methanol	Gasoline	Fossil
VI	Viscose	PES fibre	Fossil
EL	Electricity, IG/CC	Electricity mix, Western Europe	Fossil

3.2 Cascading chains

In this section, cascading chains of SR poplar are selected for a case study. Here, a 'cascading chain' is the production of one of the selected applications from SR poplar, zero or more recycling steps to subsequently produce other material applications of SR poplar, and finally an energy recovery step. Most chains comprise two or four applications, including energy recovery.

In line with the feasibility of recycling (see Appendix 1), a number of possible cascading chains result. Assuming that a waste-to-energy recovery step of poplar material always takes place, 12 representative chains presented in Table 3.2 are selected for further analysis from all 28 theoretically possible chains. Many of the theoretically possible cascading chains only differ with regard to the last waste-to-energy recovery step, i.e. either methanol or electricity production. Because both direct production of methanol and of electricity are included, it can be concluded whether a final conversion to methanol or electricity is more favourable without studying all these different cascading chains. Therefore, all selected cascading chains comprise electricity production as last cascading step. Moreover, of all possible cascading chains with four successive applications, chains that only differ with regard to one application are represented by a single chain. In only one case, i.e. PA-LU-LU-EL and PA-LU-MDF-EL, it is analysed what difference of results the change of one step causes.

Table 3.2: Cascading chains of short rotation poplar regarded in this study

Abbreviation	Raw material		Primary material		Secondary material		Tertiary material		Energy
EL	SR poplar	⇒							Elec. IG/CC
ME	SR poplar	⇒							Methanol
LU-EL	SR poplar	⇒	Lumber					⇒	Elec. IG/CC
MDF-EL	SR poplar	⇒	MDF					⇒	Elec. IG/CC
PA-EL	SR poplar	⇒	Pallets					⇒	Elec. IG/CC
PUL-EL	SR poplar	⇒	Pulp					⇒	Elec. IG/CC
ET-EL	SR poplar	⇒	Ethylene					⇒	Elec. IG/CC
VI-EL	SR poplar	⇒	Viscose					⇒	Elec. IG/CC
LU-LU-ET-EL	SR poplar	⇒	Lumber	⇒	Lumber	⇒	Ethylene	⇒	Elec. IG/CC
PA-LU-LU- EL	SR poplar	⇒	Pallets	⇒	Lumber	⇒	Lumber	⇒	Elec. IG/CC
PA-LU- MDF-EL	SR poplar	⇒	Pallets	⇒	Lumber	⇒	MDF	⇒	Elec. IG/CC
PA-MDF-ET-EL	SR poplar	⇒	Pallets	⇒	MDF	⇒	Ethylene	⇒	Elec. IG/CC

3.3 Input data

Detailed input data for the analysis of the selected SR poplar cascading chains are presented in Appendix 2. Mainly, data have been derived from comparative studies of material production efficiencies and agricultural and forestry studies on biomass and wood production. If necessary, these data are adapted through our own calculations.

Data on the SR poplar applications and their reference materials are presented in Table A3.1. The substitution between these materials is deduced from the functional units described above and lifetimes of materials are based on lifetimes of the main applications Wood inputs for the production of materials implicitly determine the land use and the impact for agricultural and forestry production of the materials.

On the basis of (environmental) studies on several material production processes, energy inputs for material production are defined. Energy inputs related to the cultivation of wood are not included here, but are accounted for separately; see below. The energy requirements of material production are converted to CO_2 emissions using carbon emission factors that are derived from average European energy mixes.

Energy inputs of material production consist of direct and indirect energy uses. Direct energy uses are electricity, steam and other primary energy carries used in the production process. (The utilisation of wood residues and by-products from various production steps is accounted for either as energy input of the process or by allocation, see Appendix 2.) Indirect energy use is the energy use for raw material production, i.e. feedstock and process energy for the production of these raw materials and their subsequent raw materials.

Production costs of biomass materials are also taken from studies on material production processes, while market prices of reference materials are derived from mainly economic studies. As market prices are subject to changes over time, ranges reflecting those changes in recent years and average prices are given.

Data on costs and efficiency of electricity generation by IG/CC (either from SR poplar wood directly or from used materials) are presented in Table A3.2. Data on wood production within the biomass chain (SR poplar) and the reference system (softwood) are presented in Table A3.3.

Yields, costs and energy inputs of wood production vary depending on production methods and location. Data used in this study refer to NW Europe, i.e. in this case to Germany and the Netherlands. Conventional forestry production of spruce is the reference for softwood production. For the production of SR poplar average values of a four-year rotation cycle are used. Information in literature differs in whether yields and production costs decrease or increase with longer rotation times of 10 to 15 years (REU and FAL, 1996; Teeuwissen, 1999)[4] Therefore, the production data of SR poplar of a four-year rotation cycle is assumed in the case of pallet production too, even though a longer rotation time is necessary for that application.

To convert land use of softwood production into CO_2 emission and cost reductions, it is assumed that otherwise energy crops, i.e. SR poplar would be produced on that land. Potential yields of energy crops are likely to be considerably lower on former forestry land, compared to agricultural land; this is expressed by the quality factor of forestry land. Nevertheless, this factor depends on circumstances like soil composition, climate, location, etc. and can have a broad range; see also Section 5.2. [5]

---

[4] Teeuwissen (1999) compared data from several sources for different rotation times.

[5] Also during conversion of forestry land to short rotation coppice, a change of soil carbon takes place. However, no studies estimating soil carbon changes in temperate climate of conversion of forestry plantations to short rotation forestry have been carried out. Hansen (1993) starts from the conversion of cropland to SRF and estimates an increase if

4 Results

Using the input data described in Appendix 2, a bottom-up analysis leading to CO_2 emission reduction and cost estimates of single cascading chains has been carried out. Results of this analysis are annual CO_2 emission reductions per hectare, CO_2 mitigation costs, net annual costs per hectare and the respective present values for each cascading chain[6]. The results for all base assumptions are discussed in Section 4.1. In Section 4.2, a sensitivity analyses is presented.

4.1 Base case results

In Figure 3.3, *the annual CO_2 emission reduction per hectare* for the selected chains (see Table 3.2) is presented. (Recall, that the CO_2 emission reduction is based on the comparison of all applications in the SR poplar chain to a reference application. Compare Table 3.1 for reference applications and abbreviations.) Two chains that include the production of particle lumber show net CO_2 emissions, but most cascading chains of short rotation poplar lead to net CO_2 emission reductions. In total, the results range from net emissions of 8 Mg CO_2/ (ha*yr) to net reductions of 28 Mg CO_2/(ha*yr).

Because of relatively low energy requirements of the respective reference materials, the production of particle lumber, ethylene, methanol and electricity have the lowest CO_2 emission reduction potentials. With the given assumptions on the reference energy systems and on the production processes from biomass, electricity production has a higher CO_2 emission reduction per ha and year than methanol production. Therefore, electricity production is the best waste-to-energy conversion step investigated. It is remarkable that the applications that substitute for products from softwood, i.e. MDF board, pallets and pulp, have a higher CO_2 reduction potential than those substituting for non-renewable materials. This is valid under the assumptions made for the utilisation of forestry land for energy cropping.

To add an additional reuse step to a cascading chain can lead to both higher and lower annual CO_2 emission reductions per ha. This depends on the additional application. For example, including particle lumber production in an existing cascading chain (e.g. PA-EL)

10-25 Mg C/ha over a period of 10 to 15 year, while Guo and Gifford (2000) state a change of 18% of soil carbon between cropland and plantations. Assuming an average soil carbon content of temperate forests of 105.5 Mg C/ha (Paustian et. al., 1998) and a duration of 100 years of the land use change to short rotation forestry, the emission of CO_2 from soil can be estimated to be about 0.5 Mg CO_2/(ha*yr).

[6] Results are expressed in relation to Mg CO_2. 1 Mg CO_2 is equivalent to 12/44 Mg C.

lowers the CO_2 emission reduction per ha per year, while including MDF production increases it.

As discussed in Section 2, the annual CO_2 emission reduction per ha and year is presented (1) without discounting CO_2 emission in time and (2) with a present-value approach of these emissions (assuming an interest rate of 5%). Applying a present-value approach to CO_2 emissions lowers the CO_2 emission reductions for a given cascading chain. This applies especially to chains that have a long lifetime, i.e. chains including particle lumber production. The maximal difference between the non-discounted CO_2 emission reduction and the present value of CO_2 emission reduction is about 12 Mg CO_2/(ha*yr) for the chain of PA-LU-MDF-EL. Applying present values also changes the order of best applications with regard to CO_2 emission reductions, i.e. ET-EL becomes better with present value approach than LU-EL.

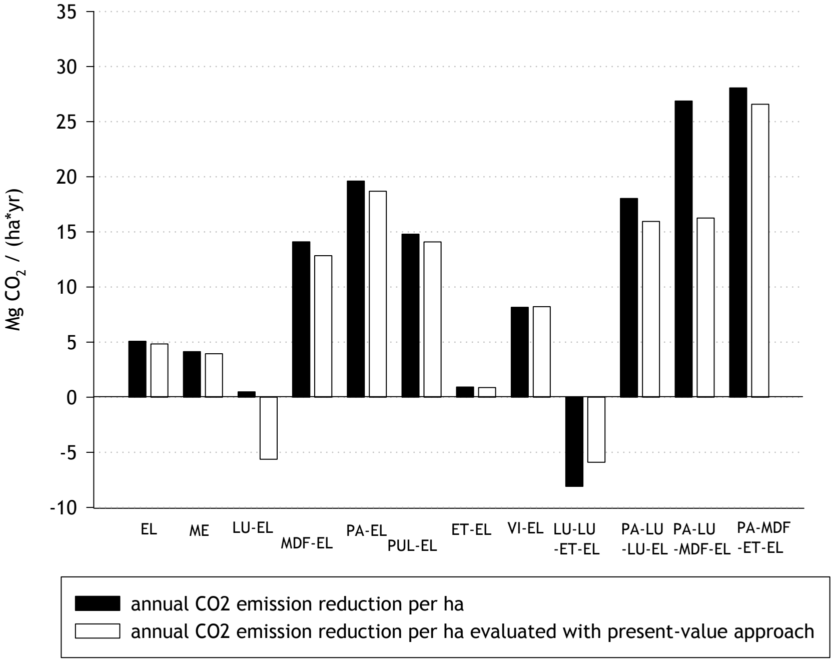


Figure 3.3: Net annual CO_2 emission reduction per ha (+) or net annual CO_2 emissions (-) of the different cascading chains with and without applying a present-value approach

In Figure 3.4, *CO_2 mitigation costs* are shown. (For cascading chains with net CO_2 emissions, no value for mitigation costs is presented.) While some cascading chains lead to net benefits, CO_2 mitigation by means of other chains is found to be very expensive. CO_2 mitigation costs of the different chains vary between net benefits of 200 €/Mg CO_2 and net costs of 2200 €/Mg CO_2.

Market price ranges of reference materials result in large uncertainties in these figures, as indicated by the error bars. These uncertainties can change the ranking of the different chains. For example, electricity production can become more expensive with regard to mitigation costs than pallet production with electricity recovery.

In the base case, the production of MDF board, transportation pallets and pulp, and most chains including a larger number of re-use steps, i.e. PA-LU-LU-EL, PA-LU-MDF-EL and PA-MDF-ET-EL, have the lowest CO_2 mitigation costs. In absolute terms, MDF board production replacing plywood scores best. Hence, also with regard to CO_2 mitigation costs, poplar wood applications substituting softwood products perform well. This depends, of course, on the potential yields of energy crops on the conventional forestry land; see Section 4.2. Electricity production is more favourable than methanol production as waste-to-energy step with respect to CO_2 mitigation costs. Compared to undiscounted mitigation costs, the present value approach does not change the results significantly. This is because both monetary values and CO_2 emission reductions are discounted and the effects partly offset each other.

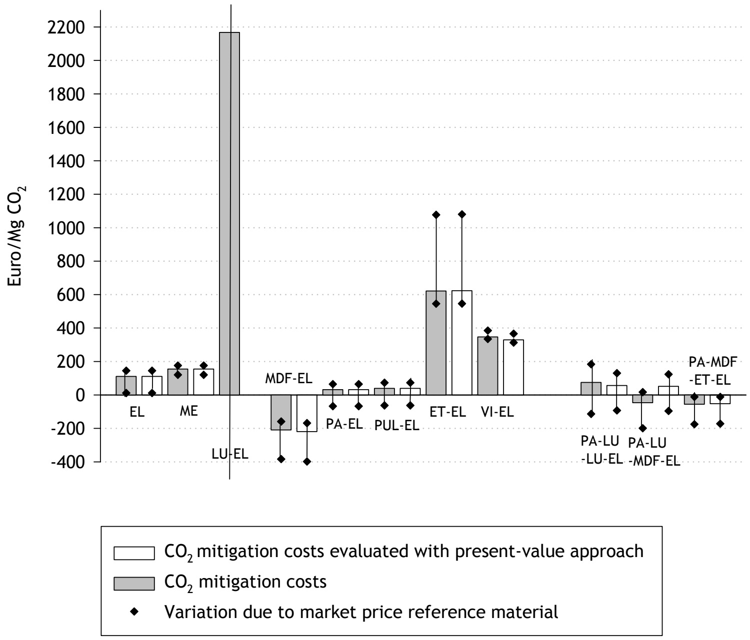


Figure 3.4: CO_2 mitigation costs (+) or benefits (-) of the different cascading chains with and without applying a present-value approach to costs, incomes and CO_2 emission reduction

Finally, the net annual *costs or benefits per ha* of the biomass cascading chains are shown in Figure 3.5. In total, they range from benefits of 3000 €/(ha*yr) to costs of 2900 €/(ha*yr) for the different cascading chains. For comparison, net margins of farmers in Ireland and the Netherlands are about 400 €/(ha*yr) and 1300 €/(ha*yr), respectively (van den Broek et al., 2002).

Also with regard to costs or benefits per ha and year, market prices of reference materials result in large uncertainties. Comparing the present value of costs and benefits to the undiscounted costs and benefits, the preferred order of cascading chains changes, i.e. PA-LU-MDF-EL becomes less attractive than ME, PA-EL, PUL-EL, ET-EL and EL in the present value approach. Highest incomes per ha and year (with and without present value) are achieved by MDF board production, followed by the cascading chain of PA-MDF-ET-EL. Highest costs per ha and year emerge from viscose production.

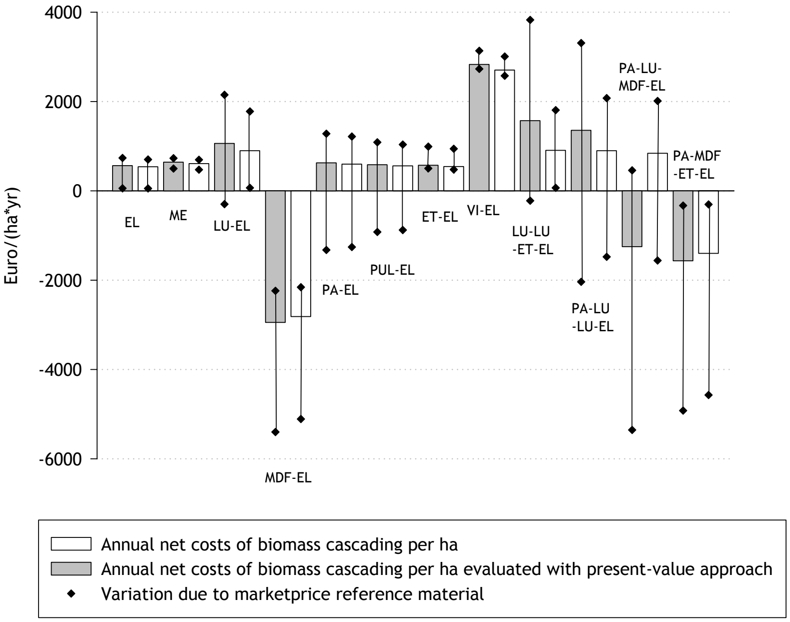


Figure 3.5: Net annual costs (+) or benefits (-) of the different cascading chains per ha with and without applying a present-value approach to costs and benefits

4.2 Sensitivity analysis

In this section, sensitivity to the main parameters is investigated. These main parameters are poplar yield, carbon emission factor of electricity, land price, rent and the quality factor for the conversion of forestry to agricultural land. Apart from that, the influence of technology developments is analysed. The sensitivity analysis focuses on present values of annual CO_2 emission reductions per ha and on present values of CO_2 mitigation costs.

Table 3.3 shows ranges of the main parameters that are varied. Concerning long-term technology improvements, many technologies of material production are well developed and no significant cost or efficiency improvements are foreseen. However, the production of methanol, ethylene and electricity from biomass with IG/CC technology are in a quite early stage of development. Therefore, potential developments of these technologies within a time frame of about 20-30 years are incorporated in the sensitivity analysis and input data are summarised in Table 3.4.

Table 3.3: Ranges of parameters for sensitivity analysis

Parameter	**Base**	**Min**	**Max**
Poplar yield[a] [Mg/(ha*yr)]	8.6	6.4 (74%)	19.3 (224%)
Land prices[b] [€/ha]	220	128 (58%)	338 (154%)
Carbon factor electricity[c] [kg CO_2 /GJ_e]	109	0 (0%)	270.3 (248%)
Interest rate[d] [%]	5	3 (60%)	18 (360%)
Quality factor land [$ha_{agriculture}$/$ha_{forestry}$][e]	0.66	0.2 (30%)	1 (152%)

[a] Depending on location factors (Lewandowski, 2001).
[b] Low and high average prices in NW-European countries (Eurostat, 2000).
[c] 100% renewable/nuclear power plants or 100% coal power plants (η_e = 45 %).
[d] Inflation rate compared to commercial amortisation rates.
[e] The lower limit is representative for conventional forest yields.

Table 3.4: Long term technological developments considered in the sensitivity analysis

Parameter	**Base**	**Min**	**Max**
Ethylene production[a] [$kg_{bio\text{-}mat}$ /kg_{wood}]	0.076	-	0.089 (117%)
Ethylene production costs[a] [$€_{2002}$ /$Mg_{bio\text{-}mat}$]	1400	1062 (73%)	-
Methanol production[b] [$kg_{bio\text{-}mat}$ /kg_{wood}]	0.447	-	0.525 (117%)
Methanol production costs[b] [$€_{2002}$ /$Mg_{bio\text{-}mat}$]	227	171 (75%)	-
Electric efficiency IG/CC[c] [%]	43.5	-	53 (122%)
Production costs electricity [$€_{2002}$/GJ_e]	10.4	4.5 (42%)	-

[a] Improvements of methanol production process, see below.
[b] Fuel production only 430 $MW_{th\text{-}input}$ plant as modelled in Hamelinck and Faaij (2002).
[c] Advanced IG/CC plant of 215 MW_e (Faaij et al., 1998).

Figure 3.6 presents the *sensitivity of present values of the annual CO_2 emission reduction per ha* to changes of the main parameters and to long-term technological developments. Overall, the variation of the parameters does not change the ranking of the cascading chains with respect to CO_2 emission reductions.

The maximum SR poplar yield considered in the sensitivity analysis leads to the highest possible CO_2 emission reduction per ha and year. SR poplar yields have the largest influence on applications substituting wooden reference materials, i.e. MDF boards, pallets and pulp. This is due to the fact, that poplar yields also influence CO_2 emissions that are calculated on basis of energy crop production on land used in the reference system; see Section 2. However, the sensitivity analysis shows that MDF boards, pallets and pulp are still better than ethylene and particle lumber production, and are comparable to methanol and electricity production if a low potential yield of energy crops on former forestry land is assumed. These low yields are about equivalent to wood yields in conventional forestry.

The influence of the carbon emission factor of electricity on the CO_2 emission reduction varies with the amount of electricity used during material production. Because electricity is used and produced in both the biomass and reference system, lowering the carbon factor of electricity can lead to either an increased or a decreased CO_2 emission reduction depending on the chain. In the chains LU-EL, VI-EL and LU-LU-ET-EL the annual CO_2 emission reduction per ha decreases if the intensity of carbon per unit of electricity increases. Finally, long-term technology developments lead to a slight increase of annual CO_2 emission reductions per ha.

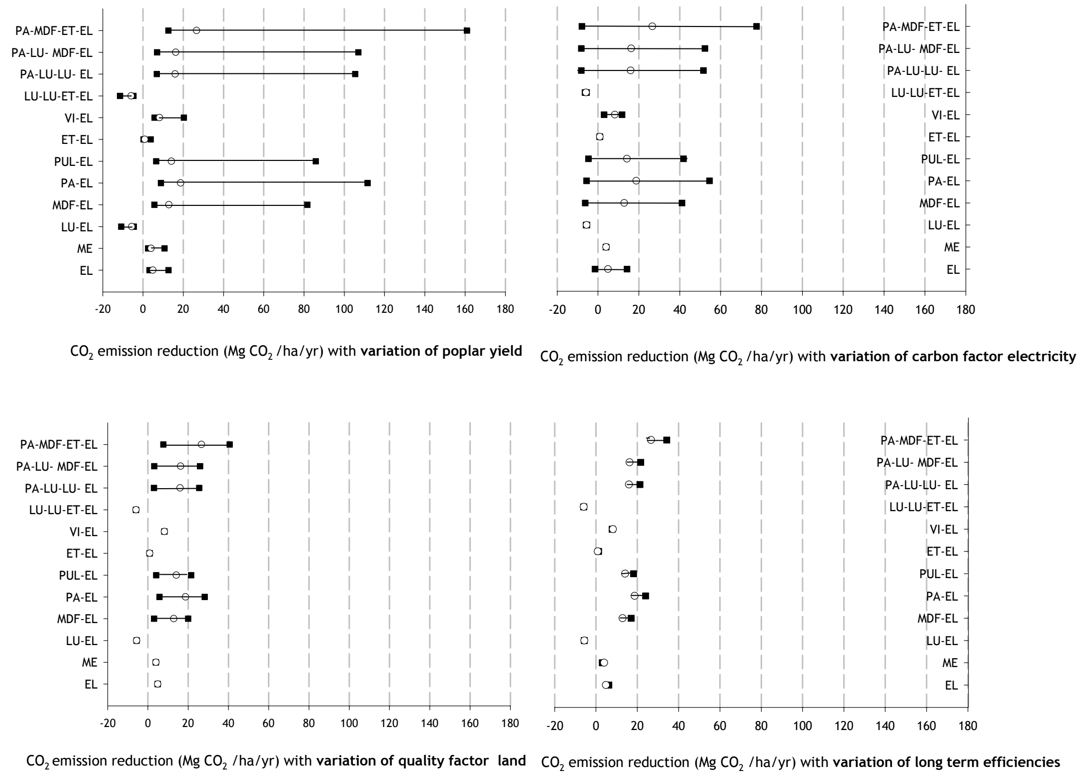
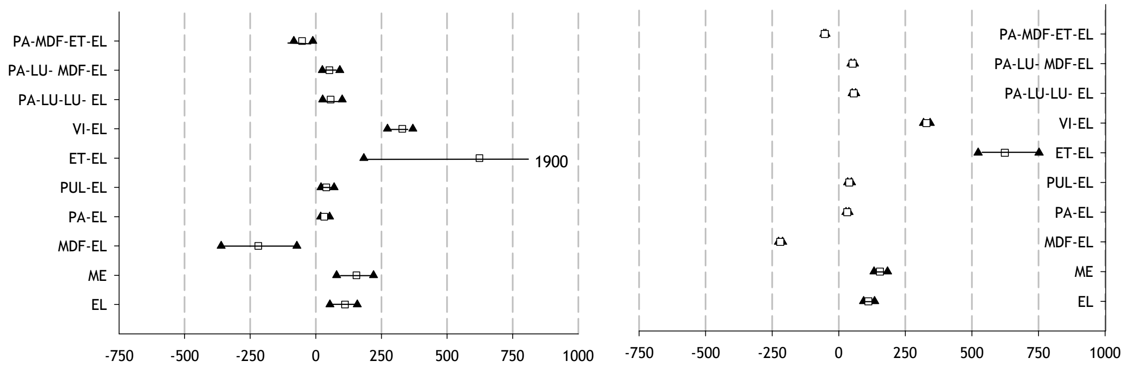
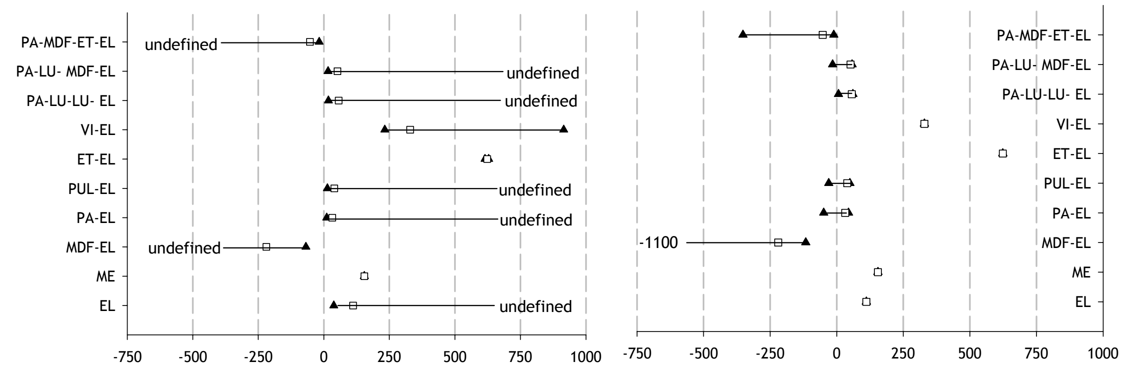


Figure 3.6: Sensitivity analysis with regard to annual CO_2 emission reduction per ha based on a present value approach

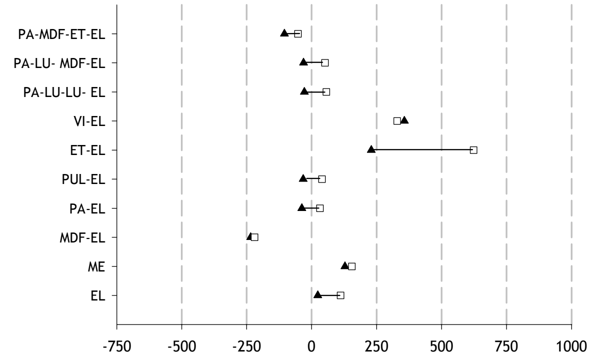


CO$_2$ mitigation costs (€/Mg CO$_2$) with **variation of poplar yield** CO$_2$ mitigation costs (€/Mg CO$_2$) with **variation of land price**



CO$_2$ mitigation costs (€/Mg CO$_2$) with **variation of carbon factor electricity** CO$_2$ mitigation costs (€/Mg CO$_2$) with **variation of quality factor land**

(a low carbon factor electricity results in net CO2 emissions and mitigation costs are undefined)



CO$_2$ mitigation costs (€/Mg CO$_2$) with **variation of long term efficiencies**

Figure 3.7: Sensitivity analysis of CO$_2$ mitigation costs to the variation of different parameters assuming a present-value approach

In Figure 3.7, the *sensitivities of present values of CO_2 mitigation costs* are presented. Several parameters show a strong effect on CO_2 mitigation costs. By far the highest CO_2 mitigation costs result from ethylene production assuming a low yield of poplar. This is due to the fact that only a small amount of ethylene is produced per unit of biomass. Consequently, biomass production costs per unit of ethylene produced are very high, if poplar yields are low. On the other hand, a potential low yield of energy crops on forestry land, i.e. a low quality factor of forestry land, increases CO_2 mitigation costs of applications substitution wood products only slightly. In many cases, CO_2 mitigation costs could not be defined for the variations of the carbon emission factor of electricity, because net CO_2 emissions result for the respective cascading chain and the respective value of the carbon emission factor.

If technology improvements are assumed, CO_2 mitigation costs decrease slightly for electricity and methanol production. For the production of ethylene, CO_2 mitigation costs decrease strongly, so that ethylene production becomes more attractive with regard to CO_2 mitigation costs than viscose production on the long term. This can be explained by the fact that the technology performance of ethylene production is assumed to improve significantly in the long term. These fluctuations in CO_2 mitigation costs are directly linked to the data used for the technologies and more thorough analysis is desired on this point. Finally, the variation of the interest rate (from 3 to 18%) had only a minor influence on the results and is, therefore, not presented in Figures 3.6 and 3.7.

5 Discussion and conclusions

In this study, we developed a methodology to evaluate biomass cascading chains with regard to CO_2 emission reduction, land use and costs. In a case study, a wide variety of cascading chains of short rotation poplar have been compared in order to identify key parameters that influence the performance of biomass cascading chains and to quantify costs, land use and CO_2 emissions of the cascading chains.

Key methodological aspects of this study were the definition of system boundaries, the inclusion of (indirect) land use and the inclusion of a time dimension. The method of inclusion of land use allows comparing different utilisation strategies of biomass produced from one hectare of land. Other environmental impacts—apart from CO_2 emissions—that can be important in biomass production and material systems were beyond the scope of this study. Nevertheless, for a complete evaluation of different biomass cascading chains, a complete LCA approach would be appropriate.

5.1 Potential benefits of cascading

In general, cascading of biomass has the potential to improve annual CO_2 emission reductions per ha and to reduce CO_2 mitigation costs. This is the case if every biomass application in the cascading chain is advantageous compared to the reference application, because the advantages add up when several materials are produced in sequence from a biomass resource. Parameters that strongly influence the CO_2 mitigation costs and/or annual CO_2 emission reduction per ha of biomass production are market prices of materials, gross energy requirements of reference materials, performance of material production, characteristics of reference energy systems and yields of biomass cultivation.

Whether adding an additional application to a cascading chain increases or decreases net CO_2 emissions per ha of biomass production depends on the net CO_2 emissions of the respective application. These net CO_2 emissions depend on themselves on the carbon intensity of the reference system and may change in the future. A short cascading chain with high CO_2 emission reduction per hectare of the single application, e.g. pallet and electricity production, can be favourable compared to long cascading chains.

Some poplar applications result in economic benefits of CO_2 mitigation, while others result in costs. Therefore, the effect of prolonging cascading chains by additional applications on the CO_2 mitigation costs can also be both positive and negative.

Fraanje (1997) concludes from a qualitative study of cascading pinewood, that more cascading increases the efficiency of resource use in general. On the contrary, the results of this study show that, depending on the depreciation of CO_2 emission reductions in time and the kind of biomass applications, a shorter cascading chain can be more favourable in terms of CO_2 emission reduction per hectare and CO_2 mitigation costs than a long cascading chain.

5.2 Quantitative results of the case study

The performance of the different cascading chains considered in this study varies strongly. CO_2 mitigation costs range from benefits of 200 €/Mg CO_2 (MDF-EL) to costs of 2200 €/Mg CO_2 (LU-EL). Net CO_2 emissions per unit of land used for biomass production varies from reductions of 28 Mg CO_2/(ha*yr) (PA-MDF-ET-EL) to net emissions of 8 Mg CO_2/(ha*yr) (LU-LU-ET-EL).

Substituting wood products from conventional forestry by short rotation poplar materials, i.e. MDF board, pallets and pulp, is very attractive from a cost and CO_2 emission reduction point of view. MDF board, pallet and pulp production in combination with electricity production and the cascading chains of PA-LU-MDF-EL and PA-LU-LU-EL result in both net annual benefits and net annual CO_2 emission reductions per hectare (assuming that market prices of reference products are offset against production costs of poplar materials). Some cascading chains have net benefits in terms of CO_2 mitigation costs. On the other end of the spectrum are cascading chains (e.g. VI-EL and LU-LU-ET-EL) that result in CO_2 mitigation costs of more than 100 €/Mg CO_2 and that are not likely to be applied in the near future, according to IPCC (2001b).

The utilisation of SR poplar for materials before conversion to energy is mostly favourable compared to pure energy utilisation with regard to annual CO_2 emission reduction per ha of biomass production. Only for ethylene production this is not the case. On the other hand, with respect to CO_2 mitigation costs, pure energy utilisation can be favourable compared to cascading of SR poplar, depending on the applications.

Main uncertainties affecting the results are related to data on market prices of reference materials and production costs of SR poplar materials. First, market prices can vary significantly over time and between regions. Effects of these variations are among others large ranges of possible CO_2 mitigation costs and a change in ranking between the cascading chains; see Section 4.1. Second, production costs of biomass materials are often not publicly available. Consequently, these costs had to be estimated. As a result, CO_2 mitigation costs as calculated in this study are not exact, but represent an order of magnitude. Also, data on biomass production and the reference energy system influence the results strongly, as shown in the sensitivity analysis. The value of these parameters is very site-specific and varies between countries and regarding biomass production even between different locations within a single country.

5.3 Bottom-up analysis

In this analysis, CO_2 emissions and costs are calculated bottom-up. That means that the results are valid for a small-scale application of a cascading chain. If one of these cascading strategies, however, would be implemented on a large scale, then the resulting CO_2 mitigation costs would be different. Several mechanisms play a role in such large-scale implementations, i.e. economies of scale and dynamic markets. On the one hand, production costs decrease with larger scales and on the other hand, market prices of biomass materials decrease, while at the same time market prices of agricultural land increase.

Furthermore, we assumed for the materials that substitute wood products from conventional forestry that the alternative use for conventional forestry land would be short rotation forestry. While this gives a bottom-up estimate of the CO_2 emission reduction potential of a cascading chain, transaction costs of such a land use change would occur during implementation.[7] In summary, this study defines CO_2 mitigation costs on a bottom-up level assuming 'ideal' substitution without transaction costs. A next step would be to calculate the costs of large-scale implementation of cascading chains that have been identified as promising in our study.

5.4 Methodological framework

The method presented in this study is suitable to quantify the CO_2 emission reductions, costs and land use of biomass cascading systems, while such quantification has not been carried out before. As demonstrated, using a present value approach to evaluate costs and CO_2 emission reduction of different strategies over time highlights the possible impact of time on the attractiveness of specific cascading chains. This impact can be significant. For example, present values of CO_2 emission reduction differ up to 12 Mg CO_2/(ha*yr) from the undiscounted results. However, present values are not directly related to the impact of a unit of carbon dioxide emitted at a certain time on global warming. Nor are present values directly related to the rather uncertain developments of future market prices of CO_2 emissions. Thus, a widely accepted methodology to evaluate time aspects in CO_2 reduction by biomass material use still has to emerge from scientific as well as political discussion.

5.5 Further research

To gain further insight in the CO_2 emission reduction potentials of biomass cascading several aspects deserve further research:

- Possible effects of technological learning for long term cascading chains, in particular for material production systems
- Alternative crops and applications other than the applications of short rotation poplar regarded
- More complex cascading chains, including material utilisation of rest products from production processes and including logistics for the different cascading chains

---

[7] Apart from the transaction costs, there are other aspects (e.g. ecological) that need to be considered in order to evaluate possible land use changes from conventional forestry to short rotation forestry.

- Material and land prices, including elasticity on the market in order to determine CO_2 mitigation costs if biomass materials and non-food crops are introduced on a larger scale
- Costs and effects of land use changes from conventional forestry to short rotation forestry

APPENDIX 1: Application of short rotation poplar

A 1.1 Overview and selection

Short rotation poplar

Short rotation (SR) poplar is typically cultivated with rotation times of 3-4 years (Dix et al., 1993), while rotation times of up to 20 years are possible. Main characteristics of poplar wood from short rotations of 3-4 years are a relatively low wood density, relatively low strength properties, low lignin content, and relatively short fibres (Balatinecz et al., 2001). Typical medium yields in Germany range from 7-9 oven-dry Mg/(ha*yr) (Lewandowski, 2001).

Bulk materials

Bulk materials that can be substituted by short rotation poplar products are mainly round wood, paper & board, cement and plastics. These materials together represent two thirds of total current bulk material production (Phylipsen et al., 2002; UN/ECE and FAO, 2001). The total production of wood products in the EU amounted to 84 thousand Mg in 1999[1]. Particleboard, fibreboard and engineered wood products together have a market share of 44 % of all wood products. These products can be produced from short rotation poplar and are expected to gain a larger market share in the future (UN/ECE and FAO, 2001).

Construction applications

Sawn wood is mainly used as construction material. However, short rotation poplar wood is not suitable for most sawn wood applications due to its relatively low strength characteristics (Balatinecz et al., 2001).

Fibreboard consists of a small amount of bonding resins and pressed wood fibres gained in pulping processes. Main categories of fibreboard (in order of decreasing density) are hardboard, MDF (medium density fibreboard) and insulation board. In principle, these materials can be produced from SR poplar wood (Stolp et al., 1996). MDF is the most important fibreboard on the market, even though it is a relatively new product. Worldwide production capacity in 2001 was about $30*10^6$ m^3/year (UN/ECE and FAO, 2002). Main uses of MDF are furniture panels and non load-bearing construction applications. Because of its market importance and the good suitability of juvenile poplar as a raw material for its production (see Roffael et al., 1992; Dix et al., 1993) MDF is included in this study.

---

[1] i.e. $161*10^6$ m^3; converted by means of average densities of different wood products

The term *particleboard* comprises a broad variety of materials composed of wood particles and bonding agents that serve different purposes—e.g. material for furniture and interior walls—while *particle lumber* is employed for load-bearing construction applications. SR poplar wood is suitable for all these particle-based applications, even though because of swelling characteristics and reaction wood content[2], other wood species are added (see Balatinecz et al., 2001; Stolp et al., 1996; Samson et al., 1999). Particle lumber is selected for further study, because (1) particleboard including particle lumber is the most important wood product besides sawn wood and (2) particle lumber, as opposed to particleboard, can substitute concrete, which is a relative energy-intensive product (van Heijningen et al., 1992).

Plywood is a panel product made from wood veneers, i.e. thin wood sheets. It has either structural or decorative applications. However, as juvenile poplar tends to discolour (Balatinecz et al., 2001) and has low strength characteristics, it is not very suitable for this purpose. Consequently, plywood is not considered in this study.

Engineered wood products are load-carrying elements that are glued from veneer or smaller timber pieces. Their structural qualities are equal or superior to those of sawn wood. However, due to low strength characteristics, SR poplar is not very suitable for these applications. Thus, engineered wood products are not considered in this study.

Packaging

Wood is mainly used for transport packaging applications, i.e. crates and pallets, while few products are primary packed in wood products. Most wooden transport packages are *pallets* for either single or multiple uses. About $5 * 10^6$ Mg wood, mainly from poplar, spruce and pine, were used for pallet production in Europe in 1994 (Hekkert et al., 2000). Because of this large production volume, pallets are selected as packaging application for this study. However, because wood from a very short rotation is not suitable for pallet production, a rotation time of 10 years would be more appropriate for this application. (Implications of this longer rotation time on poplar production are discussed in Section 3.2)

Pulp and paper

A broad variety of paper and board products can be produced from pulp. Main pulping processes are mechanical, semi-chemical and chemical. Generally, SR poplar wood is suit-

---

[2] Wood with different properties that develops as a reaction to a tree being tipped from vertical.

able for all pulping processes. Of all chemical pulping processes, sulphate pulping is the most suitable process for poplar wood. Poplar pulps are often mixed with softwood pulps before papermaking, because poplar white chips have both advantages (e.g. lower lignin-content) and disadvantages (e.g. shorter fibres) compared to softwood (Balatinecz et al., 2001). In 1996, European pulp production for paper was $12.8*10^9$ m^3 mechanical, $21.5*10^9$ m^3 chemical and $1.5*10^9$ m^3 semi-chemical (UN, 2002). Because of the high market volumes and the good suitability of juvenile poplar wood, chemical sulphate pulping is regarded in this study.

Chemicals

Most chemical products with a large production volume are so-called intermediates. In terms of production volume *ethylene* is the largest organic petrochemical intermediate. In Europe $17*10^9$ m^3 were produced in 1997 (UN, 2002). Ethylene can be produced from SR poplar wood via ethanol fermentation, via methanol production from synthesis gas and a methanol-to-olefin (MTO) conversion, or via flash pyrolysis (Patel, 2000). None of these processes are currently commercially developed and applied. However, considerable efforts are undertaken to develop the technology to produce ethanol from wood via fermentation, while dehydration of ethanol to ethylene has been applied on an industrial scale for a long time. Moreover, the production of methanol from wood is quite well developed and experience with the MTO process on a demonstration scale is available (Patel, 2000). Flash pyrolysis has only been tested on a pilot scale.

Other main organic intermediates in terms of production volume are *propylene* and *benzene*. About $10*10^9$ m^3 of propylene and $4*10^9$ m^3 of benzene were produced in 1997 in Europe (UN, 2002). These chemicals can be produced by thermo-chemical conversion of wood, e.g. by pyrolysis (Klass, 1998), but this is not commercially developed (DCO, 1999).

Because of the high market volume and the better technological development stage than that of the production of other chemical main intermediates from biomass, *ethylene* production is selected for this case study, even though this process is not applied commercially. The MTO route is analysed, because (1) flash pyrolysis at the current state of the art is not a realistic option and (2) gasification allows using waste wood—which offers cascading possibilities—while fermentation does not. However, if wood fermentation follows the predicted developments, the fermentation route may become very attractive in terms of costs and efficiency (Lynd et al., 1996; Nossin et al., 2002).

Chemicals that, unlike the intermediates discussed above, are derived from existing chemical structures in wood can be produced from SR poplar as well. Most important in terms of production volume are *chemicals derived from cellulose,* of which production is well commercialised since many decades. The largest product category within this group is fibre with 6.0 $*10^5$ Mg production volume in Western Europe in 1999 (CIRFS, 2002), mainly viscose (i.e. cellulose fibre).[3] To include one of these more traditional chemical products from wood, viscose is selected for the analysis, too.

Energy

The main energy carriers that can be produced from wood are heat, electricity and transportation fuels. The attractiveness of producing *heat* is very dependent on local circumstances, i.e. heat demand, existing heat sources, etc. Therefore, this option is not regarded in this study.

Electricity can be generated using a broad range of conversion technologies like combustion, gasification and pyrolysis. Integrated gasification combined cycle systems (IG/CC) are expected to reach high electric conversion efficiencies and to become commercially available at relatively low costs (Faaij et al., 1998). Currently, this technology is in a demonstration stage. Because of the potential attractiveness, IG/CC is considered as energy conversion technology in this study.

Main *transportation fuels* that can be produced from wood are ethanol, methanol, hydrogen and Fischer-Tropsch gasoline. However, the production of ethanol from wood is still in a pilot stage and requires relatively clean source material. Fischer-Tropsch gasoline, methanol and hydrogen can be produced from synthesis gas from wood gasification and allow for the utilisation of waste materials. Methanol production has higher efficiencies and lower costs than the production of Fischer-Tropsch gasoline, while the use of hydrogen requires a special infrastructure (Faaij et al., 2000; Hamelinck and Faaij, 2002). Therefore, *methanol* is regarded in this study, although none of these gasification-based routes is applied commercially at present.

A 1.2 Recycling

Every one of the above selected wood products requires certain raw material properties. Consequently, not every application can be produced from any waste material. In this section, for every selected application of SR poplar wood, raw material requirements and possible cascading steps are described. For particleboard production, particles with a size

---

[3] Production of viscose is decreasing, while the production of synthetic yarns is growing.

of 5-15 cm are required. Even though some producers are critical about the use of waste wood, waste wood with little contamination, e.g. old board materials, is actually utilised for particleboard production (Boogardt, 2000). It is assumed that these specifications are valid for *particle lumber* production, too. Therefore, waste materials from which slightly contaminated waste wood with required size specifications can be derived, are assumed to be suitable for particle lumber production, i.e. pallets and particle lumber in this case.

The raw material for the production of *MDF boards* is wood fibres produced from particles with a size of 5-15 cm. Non-wood components in the raw material can influence the binding between resin and wood fibres, hence, wood without contamination of sand, preservatives, varnish etc. is required. Possibly, waste wood can be refined for MDF production (Boogardt, 2000). Therefore, it is assumed that waste pallets as well as particle lumber can be utilised for MDF board production.

The production of *pallets* requires large pieces of sawn wood that cannot be derived from waste materials of applications regarded in this study.

Pulp is mainly produced from wood chips or waste paper. Because only non-contaminated fresh wood is a suitable raw material for pulp production, the use of waste wood from other applications is not considered (Boogardt, 2000). The production of pulp from waste paper is also not taken into account, because the material from SR poplar and the reference material are assumed to be identical, namely, chemical pulp. If we would assume that pulp from poplar is processed into paper and then recycled, it would be consistent to assume that the pulp produced from softwood is used in a similar way. Both the poplar and the reference systems would then gain the same benefits with regard to CO_2 reduction and costs from the recycling steps. Consequently, including pulp production from waste paper would not change the result of the cascading chains investigated in this study.

For *viscose* production, the raw material is chemical pulp (Patel, 1994). As chemical pulp cannot be produced from waste wood, it is assumed that viscose cannot be produced from waste materials either.

The production of *ethylene* starts with the production of methanol; see Section 3.1. Thus, ethylene can be produced from the same waste materials as methanol. *Methanol* and electricity from IG/CC are derived from synthesis gas from gasification. Waste products from the applications regarded in this study are suitable raw materials for these processes.

Appendix 2: Input data

Table A 3.1: Input data on SR poplar and reference applications. (In cases where the biomass material and the reference material are identical, differences between these materials can be zero. Respective input data are marked as 'N/a')

	LU:	**Reference LU:**	**MDF:**	**Reference MDF:**	**PA:**	**Reference PA:**	**PUL:**
	Particle lumber	*Concrete*	*MDF board*	*Plywood*	*Pallets*	*Softwood pallets*	*Pulp*
Substitution factors and wood inputs							
Substitution [kg][a]	0.45[b]	1	1.40	1	1	1	1
Lifetime [years]	75[b]	75	10[c]	10	1[f]	1	1[e]
Wood input [kg_{wood}/kg][i]	-	-	-	2.2[j]	-	2.7[k]	-
SR poplar input [kg_{wood}/kg][i]	1.0[j]	-	1.4[m]	-	1.5[h]	-	2.0
Energy inputs and CO_2 emissions of material production							
Electricity input [MJ/kg]	0.34	-	0.63[q]	0.4	N/a	N/a	N/a
Steam input [MJ/kg]	1.95	-	0[q]	3.45[q]	N/a	N/a	N/a
Primary energy input [MJ/kg][t]	-	-	0.84	-	N/a	N/a	N/a
Energy raw materials [MJ/kg][u]	7.2	1.41	5.2	1.6	N/a	N/a	N/a
CO_2 emission [kg CO_2/kg]	0.75[w]	0.51[x]	0.51[y]	0.16[z]	N/a	N/a	N/a
Lower heating value for energy recovery							
Lower heating value [MJ/kg]	16.1	0	15.0[af]	13.5	N/a	N/a	N/a
Production costs and market prices							
Production costs [$€_{2002}$/kg][ah]	0.31[j]	-	0.11[ai]	-	N/a	N/a	N/a
Average market price [$€_{2002}$/kg]	-	0.11	-	0.93	N/a	N/a	N/a
Range of market price [$€_{2002}$/kg]	-	0.06-0.16[am]	-	0.89-1.12[an]	N/a	N/a	N/a

	Reference PUL:	**ET:**	**Reference ET:**	**ME:**	**Reference ME:**	**VI:**	**Reference VI:**
	Softwood pulp	*Ethylene*	*Ethylene*	*Methanol*	*Gasoline*	*Viscose*	*PES fibre*
Substitution factors and wood inputs							
Substitution [kg][a]	1	1	1	2.15	1	1.10	1
Lifetime [years]	1	2[f]	2	0[g]	0	5[h]	5
Wood input [kg_{wood}/kg][i]	2.7[k]	-	-	-	-	-	-
SR poplar input [kg_{wood}/kg][i]	-	14.3[n]	-	2.2[o]	-	2.9[p]	-
Energy inputs and CO_2 emissions of material production							
Electricity input [MJ/kg]	N/a	0[r]	0.12	-	-	8.63	2.3
Steam input [MJ/kg]	N/a	0[r]	- 0.36[s]	-	-	12.0	0
Primary energy input [MJ/kg][t]	N/a	1.16[r]	53.4	-	43.3	3.06	5
Energy raw materials [MJ/kg][u]	N/a	-	-	-	-	-	78.6
CO_2 emission [kg CO_2/kg]	N/a	0.09[m]	3.89[aa]	0[ab]	0.68[ac]	2.31[ad]	5.80[ae]
Lower heating value [MJ/kg]	N/a	N/a	N/a	43.3	19.9	36.5	17.4[ag]
Production costs and market prices							
Production costs [$€_{2002}$/kg][ah]	N/a	1.40[aj]	-	0.23[ak]	-	1.04[al]	-
Average market price [$€_{2002}$/kg]	N/a	-	1.20	-	0.38	-	0.23
Range of market price [$€_{2002}$/kg]	N/a	-	0.56-1.38[ao]	-	0.33-0.46[ap]	-	0.09-0.33[aq]

[a] The amount of biomass in kg that is needed to replace 1 kg of reference material.

[b] Goverse et al. (2001).

[c] Estimation for applications such as furniture, door panels etc.

[d] Estimation. Average use of a returnable pallet is 20 trips. (Hekkert et al., 2000)

[e] Estimation; paper from chemical pulp is often used for packaging.

[f] Estimation; plastic products.

[g] Use as transportation fuel.

[h] Estimation for applications such as clothing.

[i] Wood inputs are stated in kg of wood fresh matter. This is equivalent to 7% moisture content for SR poplar wood and 50% moisture content for softwood.

[j] Efficiency of sawn wood production.

[k] Haygreen and Bowyer (1996).

[l] Balatinecz et al. (2001).

[m] Own calculation based on hardboard production figures of Richter et al. (1995).

[n] Joosten (2001). The amount of ethylene produced per kg of wood is quite low, because during the catalytic conversion of methanol to ethylene large amount of by-products are produced. These by-products are mainly propylene and a C_4 fraction (butenes, butadiene, BTX).

[o] Equivalent to net efficiency of *methanol* of 55% (HHV) (Faaij et al., 2000). Analyses by Katofsky (1993) and Williams et al. (1995) concluded a net HHV efficiency of 54 to 58%. If methanol is produced from waste resources, higher costs and a lower efficiency are to be expected due to additional gas cleaning. However, these losses have not been quantified yet and could, therefore, not be included in the analysis.

[p] Data from NMMO (dissolution in N-methylmorpholine N-methyl oxides) process (Eibl et al., 1996).

[q] Part of the energy demand is supplied by wood residues.

[r] Data include allocation of energy inputs to different outputs on basis of their energy contents, see footnote n.

[s] Steam output due to combustion of by-products.

[t] These are primary energy inputs of fuels, e.g. gasoline, that are not converted to electricity or steam or are embodied in the raw materials.

[u] These are the gross energy requirement (GER) in MJ primary energy per kg of main material that are embodied in the raw materials of the application. Gross energy requirements are feedstock and process energy for the production of these raw materials and their subsequent raw material. (GER of short rotation poplar wood and softwood are not included, but are calculated separately.)

[v] CO_2 emissions are calculated from the energy inputs given above in this table, i.e. electricity, steam, primary energy and gross energy requirements of raw materials. Carbon emission factors used for these conversions are: electricity - 109 kg CO_2 /GJ (average OECD European electricity mix in 1999 (IEA, 2002a)); steam – 95 kg CO_2 /GJ (average energy mix of heat production (IEA, 2002a)); primary – 73.3 kg CO_2 /GJ (factor of crude oil, which is in between the factor of natural gas 56 kg CO_2 /GJ, and coal 95 kg CO_2 /GJ).

[w] CO_2 emission due to process energy use (181 kg CO_2/Mg referring to particleboard (Frühwald et al., 1997) and gross energy requirement of average glue consumption. However, weight percentage of glue per Mg can vary between 6-12%. (equivalent to 353 - 707 kg CO_2/Mg) (Haygreen and Bowyer, 1996) .

[x] Amount of cement (Portland), gravel, sand and iron replaced by the substitution of piles (Goverse et al., 2001) combined with GER values (Heijningen et al., 1992).

[y] Inclusive gross energy requirements of a resin content of 6,5% (Haygreen and Bowyer, 1996) and credits from black liquor utilisation for heat and electricity production in a traditional recovery boiler (Hekkert and Worrell, 1998).

[z] Forintek (1993). This value includes gross energy requirements of 2% resin content (Hekkert and Worrell, 1998). Heat production from wood rests from the production process is accounted for.

[aa] Fuels that result as by-product are accounted for as process energy. The remaining emissions are allocated to the different products of the process, i.e. ethylene, propylene, C_4, BTX, by means of energy content (Joosten, 2001).

[ab] It is assumed that energy needs for the production of methanol are supplied from the biomass raw material.

[ac] IEA (2002c).

[ad] Data from NMMO (dissolution in N-methylmorpholine N-methyl oxides) process (Eibl et al., 1996). It includes the utilisation of the by-product lignin as fuel (Heijningen et al., 1992). In comparison, traditional viscose production emits about 2376 kg CO_2 /Mg (Patel, 1994).

[ae] Gross energy requirement of PET (Heijningen et al., 1992) and the energy use for spinning (Patel, 1994). However, estimates of gross energy requirements of PET vary from 59.4 (Patel, 1999) to 78.6 GJ/Mg (Heijningen et al., 1992) and 88.5 GJ/Mg (APME, 1999).

[af] Refers to hardboard.

[ag] Wiley (1985).

[ah] Production costs are only given for SR poplar materials and do not include the costs of SR poplar production. Production costs are compared to the market prices of reference materials.

[ai] Calculated from wood input prices and MDF board export prices in Europe (FAO, 2004).

[aj] MTO process costs (Joosten, 2001) and methanol production costs (Hamelinck and Faaij, 2002).

[ak] Production costs, excluding biomass costs, are 10-13 $US\$_{2001}$/GJ (Katofsky, 1993).

[al] Own calculation from investment cost of 16.000 DM_{1993}/(Mg*yr) (Patel, 1994), a lifetime of 25 years and an interest rate of 5%.

[am] Average price for pre-cast concrete in the Netherlands between 1994 and 2000, while prices varied about 20% (CBS, 2002). In 1994 the Dutch price was in the middle range of European prices, which is given as range (Eurostat, 1997).

[an] European export prices decreased between 1990 and 1998 and then recovered slightly in 1999 and 2000 (FAO, 2004). Assumed is the market price of 2000, while the full range of the last 10 years is indicated (using an average density of 500 kg/m^3 for conversion).

[ao] Total market price of all cracker products varied between 1100 and 1400 €/Mg$_{\text{ethylene}}$ from 1997 until begin 2001 (CEFIC, 2002). Price of 2001 is assumed.

[ap] Equivalent to 0.28 €/l. European gasoline prices excl. taxes were 0.243 to 0.313 €/l in spring 2002 and 0.26 to 0.32 US\$$_{2000}$/l between 1998 and 2000 (IEA, 2002b).

[aq] Average EU price for man-made fibres in 2000 (Eurostat, 2000; CIRFS, 2002). No (historical) price data for PET fibres were available. Ranges are estimated by prices of non-spun PET, i.e. 93-103 €/Mg in 1998 and 1999 (CBS, 2002), and production costs of polyester yarns, i.e. 330 €/Mg (own calculation by investment costs and crude oil prices (Solantausta et al., 1997; Eurostat, 2000)).

Table A 3.2: Input data related to electricity production in an IG/CC

	Unit	**Value**
Electric efficiency[a]	%	43.5
Production cost[b]	€$_{2002}$/GJ$_e$	10.4[b]
Market price	€$_{2002}$/GJ$_e$	8.33, range: 5.55-16.67
CO$_2$ emission reduction[c]	kg CO$_2$ /GJ$_e$	109

[a] Based on large state-of-the-art IG/CC plant (about 150 MW$_e$) (Faaij et al., 1998).

[b] Own calculation from 1.97 million €/MW$_e$ investment costs (Faaij et al., 1998) - a lifetime of 25 years, an interest rate of 5% rent and a load factor of 80%. According to Solantausta et al. (1997) and DOE (1997), investment cost for even smaller state-of-the-art plants of 62 and 75 MW$_e$ are about the same.

[c] Average OECD European electricity mix in 1999 (IEA, 2002a).

Table A 3.3: Input data related to wood production of SR poplar and softwood

Parameter	**Unit**	**SR poplar**	**Softwood**
Yield	Mg$_{\text{wet}}$/ha*yr	8.6 (MC 7%) [a]	2.6 (MC 50%) [b]
CO$_2$ emission	kg CO$_2$/(ha*yr)	1570 [c]	296 [d]
Production costs	€$_{2002}$/(ha*yr)	441 [e]	343 [f]
Quality factor land	ha$_{\text{agriculture}}$/ha$_{\text{forestry}}$	N/a	0.66 [g]

[a] Lewandowski (2001).

[b] Moisture content (Hekkert and Worrell, 1998) and yield (Kaltschmitt and Reinhardt, 1997).

[c] Includes equivalents of N$_2$O emission from fertiliser use (Biewinga and van der Bijl, 1996).

[d] Kaltschmitt and Reinhardt (1997).

[e] Production cost data (Stolp et al., 1996). Costs include arable land rents. In 1998 arable land rents in France, the Netherlands, Belgium and Germany were between 128 and 338 €/ha, a non-weighted average of 220 €/ha is assumed here (Eurostat, 2000).

[f] Estimated on basis of average round wood prices in Europe of 48 €$_{2002}$/m^3 (FAO, 2004) and including a land rent that is derived from average rents and the quality factor comparing forestry land to arable land.

[g] Personal communication, I. Lewandowski (2002). Assumptions are (1) that poplar is cultivated, because short rotation coppice is most suitable for former forestry land and (2) that no extreme (with regard to water availability, slopes, etc.) forest areas are used. If forest areas would be converted to agricultural land, establishment costs and energy uses occur for stump clearing and soil amelioration, which can be significant. However, as these are one-off costs that do not represent the situation of a permanent land use chance, they are not taken into account.