Long distance bioenergy logistics

An assessment of costs and energy consumption for various biomass energy transport chains

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Preface

Last spring, I started working on this graduation thesis, within the framework of my study, Science and Policy. With the help of Carlo Hamelinck and André Faaij a research project was defined, focussing on long distance biomass energy logistics. This project gave me the opportunity to spend some time living abroad and at the same time engage in the challenging task of conducting a research that is both socially and environmentally sensible. After a short and hectic period of making arrangements for a three-months stay in Sweden, I went to Lund and started gathering contacts and information. My research was characterised by innumerable phone calls and e-mails with people into biomass energy research, shipping management and forestry operations. I soon found out, that knowledge with respect to my subject is scarcely available and that finding the right contacts can be a full-time job. Back in Utrecht, the only real task left was to combine and interpret all data, in order to create a clear and credible report. This was a serious challenge, since a large share of my work consisted of coping with uncertainties. With the help of many people, I nevertheless succeeded in the completion of this work.

I want to thank Carlo and André for their enthusiasm and valuable support, and of course all other colleagues and students at the department in Utrecht. A significant part of my work has been performed in Sweden at the University Department of Environmental and Energy Systems Studies in Lund. I have been supported there with great expertise and enthusiasm by Pål Börjesson and Lars Nilsson, for which I am very grateful. I want to express my gratitude to all other colleagues and particular to Joakim, Maria and Suse for their extraordinary friendliness and hospitality. Tack så mycket!

No research project ever evolves without its moments of adversity or disarray. Perhaps mostly, because usually a period of study is frequently interrupted by this thing called life. I want to express my love and gratitude to those people who supported me, and will (maybe) continue to do so, with the latter: My parents and Anouk, for always being there and for giving me unconditional support. Walter, for preserving me from many a floating-point-overflow and for being a friend. Jochem, for the 'het is gelukt, gewoon doorlopen' doctrine. The Vink™ for nicely repairing my bike whenever it was necessary. Martijn, for preparing me for doom-soon. Jessica, for the 'kan je denken' doctrine. Ingrid, for showing true intelligence, occasionally. Lex, for his invaluable spiritual contribution. Claudia, for existing, and teaching me how not to pull analogies out of context. Ianthe, for running through the corn with me and being 'licht en luchtig'.

Best regards / Ha det bra,
Roald Suurs

Abstract

This study gives an analysis of costs and energy consumption, associated with long distance bioenergy transport systems. In order to create the possibility of obtaining an insight in the system's key factors, a model has been developed, taking into account different production systems, pretreatment operations and transport options. Various transport chains were constructed, which were subjected to a sensitivity analysis with respect to factors like transport distance, fuel prices and equipment operation times.
Scenarios analysed are Latin-America and Europe for which the distinguishing parameters were assumed to be the transport distances and biomass prices. For both regions, an analysis is made for a situation where ship transports are applied for both, a coastal and an inland biomass supply. In case of European biomass, a train transport was considered as well. In order to explore possibilities for improvement, the effects of these variables on costs and energy consumption within a chain, were assessed.

Delivered biomass can be converted to power or methanol. Model results are as follows: Total costs for European bioenergy range from 11.2-21.2 €/GJ_{MeOH} for methanol and 17.4-28.0 €/GJ_e for electricity. For Latin-America, costs ranges are 11.3-21.8 €/GJ_{MeOH} for methanol and 17.4-28.7 €/GJ_e for electricity. The lower end of these ranges is represented by transport chains that are characterised by the use of high density energy carriers such as logs, pellets or liquid fuels.

Transport chains, based on the transport of high density energy carriers, such as logs and pellets, are the most attractive for all scenarios considered. The transport of chips should be avoided categorically due to their low density and high production costs. Transport chains based on the early production of liquid energy carriers such as methanol or pyrolysis oil seem to be promising alternatives as well.
With respect to energy consumption, the transport of chips is highly unfavourable for the same reasons as stated above. The use of pelleting operations implies a high energy input, however due to energy savings as a result of more efficient transport operations, this energy loss is compensated. Energy consumption figures for the drying step can possibly be reduced to a large extent by utilising waste heat.
By far the most influential parameters are the operation window of the system and the harvest window. Other factors of importance are the interest rate and the international transport distance. Pretreatment operations do contribute an important share to the total costs and energy use, however energy costs and load factor figures, determining the application of pretreatment equipment exert a relatively weak influence.

Weak spots within this study are the shortage of data with respect to storage and transport of liquid fuels.

Contents

Abbreviations and symbols

dwt	Dead-weight: the total weight of cargo, cargo equipment, bunkers, provisions, water, stores and spare parts which a vessel can lift when loaded to her maximum draught as applicable under the circumstances. The dead-weight is expressed in metric tonnes.
GCW	Gross Combination Weight: the sum total of truck weight and its load.
GJ_{bio}	GJ biomass energy based on biomass energy content, excluding possible conversion losses
GJ_{e}	GJ electric energy
GJ_{prim}	GJ primary energy equivalent
GJ_{th}	GJ thermic energy
grt	Gross tonnage: The measure of the overall size of a vessel determined in accordance with the provisions of the international convention on measurement of vessels usually expressed in register ton; 1 register ton = 2.83 m^3.
HHV	Higher heating value: the thermal energy released during the combustion of a substance, including heat associated with the condensation of water. The HHV value is independent of the moisture content of the substance.
knots	Nautical miles/hour; 1 knot = 1.852 km/h.
LHV	Lower heating value: the thermal energy released during the combustion of a substance. Heat associated with the condensation of water is not included. The LHV value depends on the moisture content of the substance.
MC	Moisture content (% weight basis).
t	tonne
t_{dm}	tonne dry matter.
t_{fw}	tonne fresh weight.

1 Introduction

1.1 Biomass energy as a sustainable source of energy

One of the main issues of global concern is the degradation of the world's energy supply. Global power consumption is growing rapidly and the exploitation of fossil carbon reserves will someday in the future reach its limits. Furthermore, combustion of fossil fuels causes numeral environmental problems, such as atmospheric pollution, acidification and the emission of greenhouse gases. Another concern in this matter is the dependency of the world's energy consumers on a small group of fossil energy suppliers, most notably the OPEC member states. A possible way to deal with these problems, is the development of cleaner and renewable energy sources. Biomass is a promising source of renewable energy with regard to a variety of criteria such as availability, conversion efficiency and usability (i.e. power, as well as fuel can be produced). Due to plant uptake of CO_2 from the atmosphere, in the long term biomass energy can be produced and consumed on a practically CO_2-neutral basis. Disadvantages are the current high(er) costs of biomass energy compared to energy from fossil fuels and the land areas which are required for substantial amounts of energy (Faaij, 2000).

1.2 Background and rationale

Bioenergy has the potential to become one of the world's most important sources of energy. At the moment bioenergy is mainly derived from waste material and forestry residues, while biomass from energy crops is only marginally utilized. The potential supply of forestry residues on a global scale could amount to 14-110 EJ (Lysen, 2000). However, the increase of forestry operations is limited and to match the growing demand for bioenergy (estimated to become 20-50 EJ in 2050 (Lysen, 2000)), in the long term dedicated energy plantations are essential. In theory, energy farming on current agricultural land could contribute over 800 EJ, without jeopardising the world's food supply (Lysen, 2000). An estimation of the world's potential energy supply from different biomass categories is presented in Table 1.1. As can be seen the total contribution of bioenergy to the future world's energy supply could be as high as 1100 EJ. This figure exceeds the current global energy use of 400 EJ (Lysen, 2000).

Table 1.1: Estimated potential global annual energy supply in 2050 i).

Biomass category	Potential annual energy supply 2050 (EJ)
Energy crops current agricultural ground	0 – 870
Energy crops degraded ground	60 – 150
Food production residues	15
Forestry residues	14 – 110
Manure	5 – 55
Organic waste	5 – 50
Biomaterials (increased demand)	minus 0 – 150
Total	99 – 1100

i) Lysen (2000).

The key drivers behind large-scale production and export of biofuels are the climate policies of various Western European countries. In the Netherlands, energy producers have already shown interest in the possibility of importing biomass in order to produce 'green' energy (Faaij, 2001b) and various studies have given indications that intercontinental trade of biofuels or even bulk transport of wood could be economically feasible and does certainly not lead to dramatic energy losses (Agterberg et al., 1998).

Current insights suggest that some world regions (like for example Latin America and Eastern Europe) have a much larger bioenergy production potential than others. The basis for these potentials is a combination of large land areas with good crop production potential, low population density and often extensive agricultural practices. Consequently various countries may become net suppliers of renewable bioenergy to countries that are net importers of energy (Faaij, 2001b). In order for bioenergy to be available to importing regions a distribution of biofuels over relatively long distances is necessary. This implies extra costs, complex logistics and energy losses, hence a transportation problem exists. When transporting biofuels, a variety of alternative chains can be constructed.

International bioenergy trade can include direct transport of biomass materials (chips, logs, bales), intermediate energy carriers (such as bio-oil or charcoal) or high quality energy carriers such as ethanol, methanol, Fischer-Tropsch liquids and hydrogen or even electricity (Faaij, 2001b). Besides, factors like the production method of biomass, the transport type and the order and choice of pretreatment operations are of importance. The chain composition is expected to largely influence costs and energy expenditure and therefore this study will compare a variety of supposedly realistic transport chains. On a lower level, an individual chain's performance is influenced by a large number of variables, such as transport distance, fuel prices and equipment performance. In order to explore possibilities for improvement, it is important to gain insight in the effects of these variables on costs and energy consumption within a chain.

Earlier projects have been done on biomass transport systems, the most important of them are those conducted by Wasser (1995) and Agterberg (1998). Wasser (1995) explores the possibilities of supplying foreign wood fuels for power generation in the Netherlands. Two regions are analysed with regard to their potential for biomass export, Estonia and Uruguay. Little attention is given to overland transport and logistics and biomass pretreatment isn't discussed either. A costs overview is presented but energy balances are left out of account. Agterberg (1998) has produced an extensive research on possible bioenergy trade routes. An import chain analysis is presented for three countries, Sweden, Estonia and Ecuador. Costs as well as energy balances are taken into account and even employment effects have been considered. However, the report is explorative in nature and lacks detail with regard to timing and organisation of transport and logistics. Storage, pretreatment and transfer aren't studied thoroughly either.
Within this study a more detailed analysis of costs and energy consumption of transport chains is given than has been done in earlier studies. The most important improvement is the use of a parameterised model structure. This creates the possibility of constructing a variety of chains, while the influence of different factors can easily be adjusted and analysed. Other novelties are the application of flash pyrolysis to produce a high density energy carrier, the use of train transport and the modelling of chain mass balances, taking into account dry-matter losses and moisture content.

1.3 Research objective

The main objective of this study is to obtain an insight in the impact of different key factors, on chain performance. In order to obtain this information a number of realistic chain structures will be chosen, thereby taking into account a variety of transport options, pretreatment technologies and conversion options. In order to embed this analysis in a practical context, a number of import scenarios are defined for both, Europe and for Latin-America. For each scenario the different transport chains are analysed and compared in order to answer the following question:

- What pretreatment, transport and conversion technologies should be applied and at what point in the chain, in order to minimise total costs and energy expenditure?

The next step is to perform a sensitivity analysis with regard to the most important system parameters that determine a chain's performance. Factors like transport distances and equipment load factors are to be taken into account. The following research question can then be answered:

- What factors have the biggest influence on costs and energy consumption of a bioenergy transport chain?

With these questions answered it will be possible to indicate a most efficient chain structure with regard to costs and energy use and most important, performance ranges can be given, depending on recognised key factors, which creates the possibility to identify aspects for potential improvement.

As will be discussed in the Section 2, some choices have been made with regard to the different bioenergy carriers considered. This research considers both, forestry residues and dedicated energy crops. For the latter, Salix and Eucalyptus are considered, since these crops are widely available within the regions considered. With regard to the transport of liquid energy carriers, methanol and pyrolysis oil are considered, since these are assumed to be representatives for liquid fuels in general, such as ethanol or biodiesel (Faaij, 2000).

The next section will explain the general methodology. In Section 3 different system components will be presented and validated. All input data will be discussed and costs and energy expenditures of the individual components will be presented. The next step will be to project a number of scenarios, differing with respect to biomass production costs, distances and transport means (Section 4). Model parameters will be adjusted to fit the specific situation for the respective areas. These adjustments are geographical, agricultural, but also organisational in nature. Section 5 will give the calculated costs and energy use for all scenarios, accompanied by a parameter discussion. Finally Section 6 will deal with the overall conclusion and recommendations for further study.

2 Methodology

In order to analyse different transport chains a model study has been performed. This has resulted in a spreadsheet with a modular structure, giving detailed calculations of costs and energy use for different pretreatment technologies, truck, train and ship transport and the cultivation and energy conversion of biomass. The model input has been derived from interviews and literature. A major part of this background research has been done in Sweden, which is one of the leading countries on the subject of biomass handling (See Appendix I: Biomass energy practice in Sweden).
The next section will deal with the outline of this model. It presents the general approach and discusses the most fundamental assumptions.

2.1 System outline

In this section a description of the model structure will be presented. To start with, all system components will be discussed and subsequently the most important system variables are presented. The system components will be embedded within a logistic model, which will be discussed as well. Finally the outline of the computer model which has been constructed in order to integrate and analyse these chain components will be described.

2.1.1 System components and variables

Within this study four different system components are distinguished: biomass production, pretreatment, transport and energy conversion. Each system component represents a number of choices in determining the structure of a system’s chain. In Table 2.1 the components are presented, together with the options considered within this research.

Table 2.1: System components and the options considered.

System components		Options
Biomass production	Resource	forestry residues, energy crops
	Harvest method	felling, chipping, baling
Pretreatment		storage, chipping, drying, pelleting
Transport		truck, train, ship
Energy conversion		power, methanol, pyrolysis oil

For each component a separate costs and energy analysis can be made, based on a wide set of variables. A more elaborate description of the system components will be given in the next section but in order to obtain an insight in the system, the key variables are presented in Table 2.2.

Table 2.2: System variables.

System component	Variables
Biomass production	Harvesting window
Pretreatment	Equipment capacity
	Capital and maintenance costs
	Power, Fuel, Heat consumption
	Operation time
	Dry matter loss
Transport	Transport distance
	Cargo capacity
	Cargo weight and volume
	Capital and maintenance costs
	Fuel consumption
	Operation time
Energy conversion	Conversion efficiency
	Capital and maintenance costs
	Operation time

Chain components can be ordered and arranged in many ways but they are interdependent so there is a limited degree of freedom in choosing alternatives (for example pelleting is only possible with chipped biomass). Besides, some arrangements are unrealistic because of obvious disadvantages (for example pelleting of already transported biofuels isn't advisable because the advantages of a higher energy density are only to be gained during transport). In order to be able to define realistic transport chains the system components have been subjected to a geographical framework, representing the spatial context of the system. Section 2.1.2 describes this concept.

2.1.2 Geographical system outline

The system's spatial context offers a structural basis for the arrangement of the various system components. A situation with five possible transfer points is assumed: the production site, a central gathering point (CGP), two transport terminals (export and import) and the energy plant. Figure 2.1 gives a graphical view of the situation. The system consists of a maximum of four transport sections:

- Production site – Central gathering point
- Central gathering point – Export terminal
- Long distance transport
- Import terminal – Energy plant

The long distance transport step is assumed to take place by train or ship. For the other sections a truck transport is considered the most realistic. Biomass is collected locally at small scale production sites. After an optional conversion the material can be transported to a CGP. The CGP offers facilities for a number of smaller sites so it can operate at a higher processing scale, making the use of costs intensive pretreatment and conversion technologies economically feasible. Subsequently two possibilities are taken into account concerning long distance transport, ship transport and train transport. For the first option, biofuels have to be transported to a harbour from where they will be shipped to the destination country's import terminal. For the second option it is assumed that the biofuels are directly transferred on a freight train. In the destination country the biofuels have to be delivered to an energy plant or other end-user. This last transport from the harbour to the end-user is assumed to be only necessary when ship transport is applied.

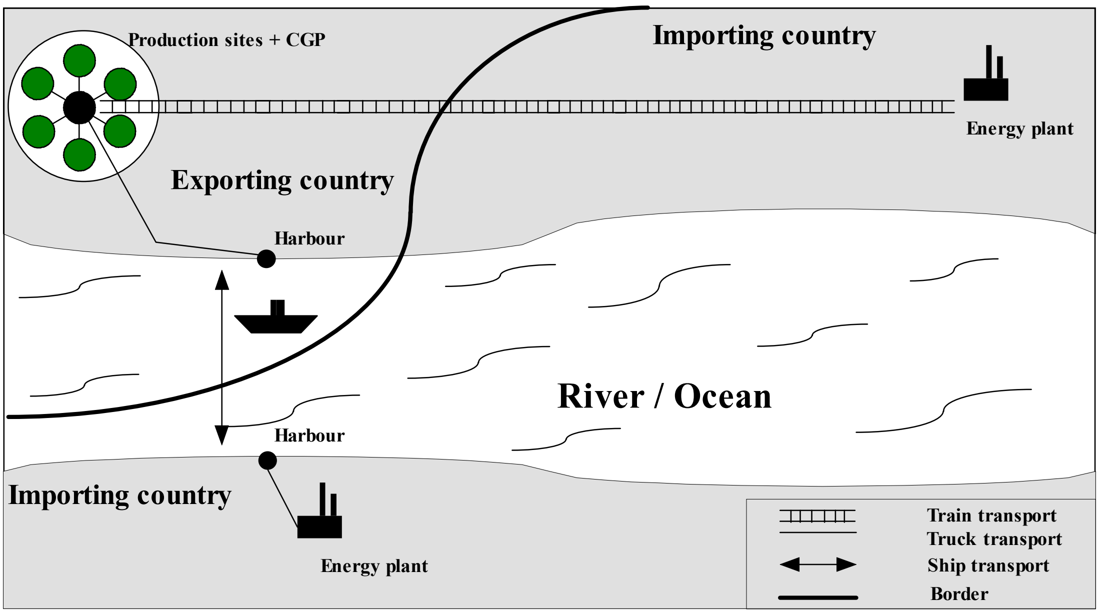


Figure 2.1: Geographical system outline.

The various transport distances are kept variable to create the possibility of assessing different situations. The distance for international transport for example, is strongly depending on the case considered. It can range from 500 km, for France or Germany to 10,000 km for Brazil or Canada. The distance between production site and CGP can be set to zero in case of a large scale production and the distance from CGP to export terminal (harbour) can be set to zero in case of a situation with a coastal CGP.

At three points within the chain, the biofuels can be subjected to pretreatment and conversion operations, in order to improve or preserve the quality of the material. These points include the production site, the CGP and the energy plant. Operations involve sizing, drying and densification but also the conversion of woody biomass to liquid fuels like methanol or pyrolysis oil. Depending on the complexity of the technology involved, some of these treatments can only be applied at certain locations within the chain. The possibilities at each processing point are discussed below:

Local production site

Besides harvest integrated baling or chipping, the biomass can be converted to pyrolysis oil right away. According to some sources this can be done on a small scale with minimal scale disadvantages. Other techniques for energy densification like drying, methanol synthesis or pelleting, are only efficient on a large scale so this will only be considered for conversion at the central gathering point. However, in case of possible high-intensity production sites, the local production site might be considered a CGP itself. This creates interesting options when considering advanced pretreatment technologies. Storage is possible as well.

Central Gathering Point

At the CGP, logs and bales can be converted to pellets or chips if desired. Furthermore a conversion to liquid energy carriers is possible. Conversions to be taken into account are methanol synthesis and pyrolysis. Drying and storage are also possible at this site with possible costs and energy advantages due to positive scale effects but also due to the possibility of using process heat for drying purposes. The latter is of course only relevant when a fuel conversion, pelleting operation or another heat producing step is included within the chain.

Demanding country

The final step in the chain will be the conversion of woody biomass to electricity or a liquid energy carrier like methanol or pyrolysis oil. Chipping and drying operations are available as well.

2.2 General model assumptions

This section presents some fundamental methodology, concerning the model calculations.

2.2.1 Economic calculations

All monetary values are corrected for devaluation at an assumed annual GDP deflation of 3.0% for the EU and 2.5% for the United States (OECD, 1996) and presented in 2001-Euros[1]. Capital investments are calculated by annuitising the total investment costs, taking into account a yearly paid interest of 10%. Operation and maintenance (O&M) costs are determined by taking a specific percentage over the total investment costs of the equipment involved. Variable costs associated with fuel and energy consumption are calculated by consumption parameters and fuel or energy prices. Heat prices strongly depend on the situation considered. In this study heat prices are assumed to be 2.4 €/GJ, except at points where waste heat can be utilised free of charge. Electricity prices are assumed to be 3.5 €ct/kWh (Halen, 2000).

2.2.2 Energy balance calculations

In order to calculate the total fossil energy consumption from the use of different secondary energy carriers, the efficiency factors applied, are presented in Table 2.3.

Table 2.3: Energy conversion efficiencies for secondary energy carriers.

Energy Carrier	Efficiency (LHV basis)	Source
Electricity:	0.43	Dornburg (1999)
Diesel:	0.89	Hendriks (2000); Jager (1998)
Heat:	0.90	Dornburg (1999)
Crude oil (HFO):	0.99	Hendriks (2000)

Some of these efficiencies can possibly be improved on the long term. Especially with regard to electricity production, where the efficiency could increase to 0.54 if in the future fuel and electricity production are combined (Hendriks, 2000). It must be noted that production efficiencies for electricity could be lower as well (for example in technologically underdeveloped countries). Heat can be obtained at a higher efficiency when CHP-installations are possible.

2.2.3 Mass balance calculations

All calculations in this study are based on a demand driven system. To be able to meet up to a certain need for bioenergy at the end of a transport chain, it is necessary to compensate the scale at the supply-end of the chain for the inevitable dry matter losses during storage, transport and handling. A consequence of this feature is that at different points within a chain, the system's logistic capacity, expressed by the number of tonnes of material to be processed each year, must differ. Near the end of the transport chain, the logistic capacity of the system is nearly equal to the demand, whereas at the top, logistic capacities need to be higher. Another important factor to be taken into account, concerning this issue, is the moisture content of the material. When considering a supply of biomass with a 50% moisture content, the facilities at the top of the chain need to process nearly twice as many tonnes as the facilities at the bottom (assuming the biomass is practically dry at the bottom of the chain). Obviously when most processing capacities are volume limited, rather than mass limited, the influence of moisture contents on the logistic capacity is of minor importance with respect to chain performance. Ideally, the difference between the logistic capacity at the top and the bottom of the chain are as low as possible. In order to calculate the logistic capacity on different points within a chain, a mass balance approach has been used. Table 2.4 gives a typical example of such a mass balance.

[1] **Currency exchange rates august 2001.**

EUR	DM	NLG	USD	SEK	FFR	SFR	CAD	BPD	FIM
1,00	1,96	2,20	0,94	9,45	6,56	1,52	1,41	0,63	5,95

All calculated costs and energy data are normalised with respect to the amount of biomass dry tonnes before the energy conversion. This quantity determines the end scale of the system (for the given example the end scale amounts 2 Mt_{dm}). This means that for chains based on an early conversion of biomass to liquid fuel, the chemical dry matter losses during conversion are not taken into account with respect to the normalisation of costs and energy figures. Hence a comparison is possible for all chains.

Table 2.4: A typical chain mass balance with an annual conversion scale of 2 Mt_{dm}.

Chain structure	Dry matter left	Dry matter loss	Moisture content	Moisture content loss	Logistic capacity Mt_{dm}	Mt_{fw}
Production	100 %		50 %		2.53	5.07
Harvesting and forwarding	100 %	17 %	50 %		2.53	5.07
Storage in pile	83 %		50 %	10%	2.10	3.83
Baling	83 %	2 %	45 %		2.10	3.83
Storage at roadside	81 %		45 %		2.06	3.75
Local transport	81 %		45 %		2.06	3.75
Central storage	81 %	3 %	45 %	3%	2.06	3.75
Central chipping	79 %		44 %		2.00	3.54
Central drying	79 %		44 %	77%	2.00	3.54
Train transport	79 %		10 %		2.00	2.22
Storage at conversion unit	79 %		10 %		2.00	2.22
Conversion	79 %		10 %		2.00	2.22

The moisture content and dry matter losses depend on the technology used, as well as the organisation within a chain. Mass balance values are derived from Forsberg (1999) and presented in Table 2.5. Dry matter losses during covered storage are taken from Feenstra (1995) and amount up to 3.0 % each month. In this study it is assumed that dry matter losses only occur as a result of decomposition when biomass is chipped and has a moisture content above 20% (Van den Heuvel, 1995; Feenstra, 1995). Mass losses also occur during energy conversion operations such as pyrolysis or methanol synthesis. With regard to the costs and energy calculations made in this study, it is assumed that mass losses until the first moment of transport, are included in biomass production costs.

Table 2.5: Dry matter losses and mass efficiencies (ii and iii) within a biomass transport system.

Operation	Dry matter loss
Harvesting and forwarding	2 %
Storing in pile	15 %
Baling residues	2 %
Forwarding bales	0 %
Storage at roadside	2 %
Truck transfer and transport	0 %
Ship transfer and transport	0 %
Train transfer and transport	0 %
Covered storage [i)]	3 % / month for chips with MC>20%
Chipping residues or bales	0 %
Drying chips	0 %
Pelleting chips	0 %
Pyrolysis [ii)]	37%
Methanol [iii)]	44%

Forsberg (1999) except i) Feenstra (1995), ii) Schenkeveld (2001) and iii) Hamelinck (2001).

The material's moisture content is expressed in weight percentages. The moisture content decreases only marginally during storage. Feenstra (1995) uses 1.5%point each month for covered storage, however chips increase in moisture content during uncovered storage, by the same amount. The volume of the material is regarded to be independent of its moisture content. Moisture characteristics of chips, bales and pellets will be discussed in Section 3.2 on biomass pretreatment technologies but for completeness' sake their values are already presented in Table 2.6.

Table 2.6: Moisture content changes during operations.

Operation	Moisture content
Storage in pile and/or at roadside	results in 35-45 % (assuming an original value of 50 %)
Covered storage	decrease of 1.5 %point / month (wet chips only)
Forced drying	results in 10 %
Pelleting	results in 8 %

2.2.4 Effective Use of Equipment (EUE)

When considering high value investments, an important aspect to take into account besides the economical lifetime of the equipment involved, is the actual effective operation time. A piece of equipment won't be effectively utilised for the full 100% of its lifetime. Two factors are considered to be of importance to determine the equipment's EUE-factor:

Practical load factor (PLF)

During the operation of a machine, a piece of equipment can be working a maximum number of 8766 hours each year. Obviously, for many cases this figure will be rather somewhere around 1800 (45 weeks a year and one 8 hour working shift) due to the limited allocation of labour units. The PLF is also reduced by micro scale feedstock limitations. For example when truck loads are available only part of a day. Or when equipment has to be transferred from one harvesting site to an other, this will reduce the practical load factor.

Operation window (OW)

When considering biofuel transport, the effective use of certain equipment units can possibly be reduced by a limited feedstock supply due to seasonal effects. The operation window is defined by the number of months of uninterrupted functioning during one year. Theoretically a year can have multiple operation windows. It is of high importance to keep the system's operation window as wide as possible, possibly by combining multiple biomass chains with the use of the same capital. A schematic of this concept is presented in Figure 2.2.

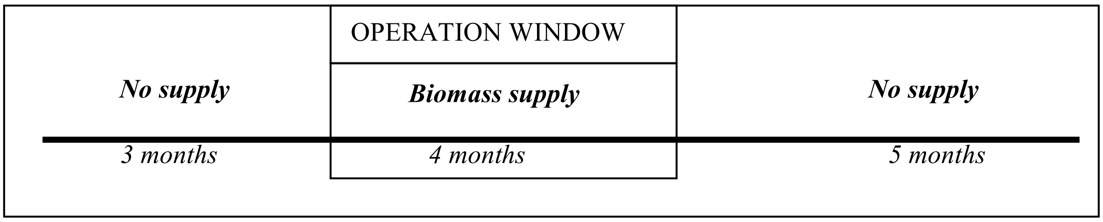


Figure 2.2: Schematic representation of a system's operation window.

Technical load factor (TLF)

Some installations need to be 'down' for a certain amount of time each year, in order to perform maintenance work. When this time is less than the amount of months left out of the operation window, this factor can be ignored. In the other case the amount of time exceeding the 'no supply' period must be subtracted from the operation window.

EUE-factor

The combined factor determining the amount of time of effective use for the capital can be calculated with Equation 2.1.

$$EUEF = PLF*OW - 8766*MAX\{ [(1-OW)-(1/8766)*(8766-TLF)], 0 \} \qquad \text{Equation 2.1}$$

with:

	EUEF	Effective use of equipment factor (h/y)
	PLF	Practical Load Factor (h/y)
	OW	Operation window (y/y)
	TLF	Technical Load Factor (h/y)

For this study maintenance is considered to take place during operation time so the TL-factor will be fixed at its maximum of 8766 h/y. The practical load factor and the operation window determine the effectiveness of capital use.

2.2.5 Model structure

A schematic of the model structure is presented in Figure 2.3. General parameters are entered as input data and a chain structure is defined. Subsequently costs and energy consumption values are determined for each system component, taking into account mass balances and dry matter losses. Finally the separate output values are summed up and presented.

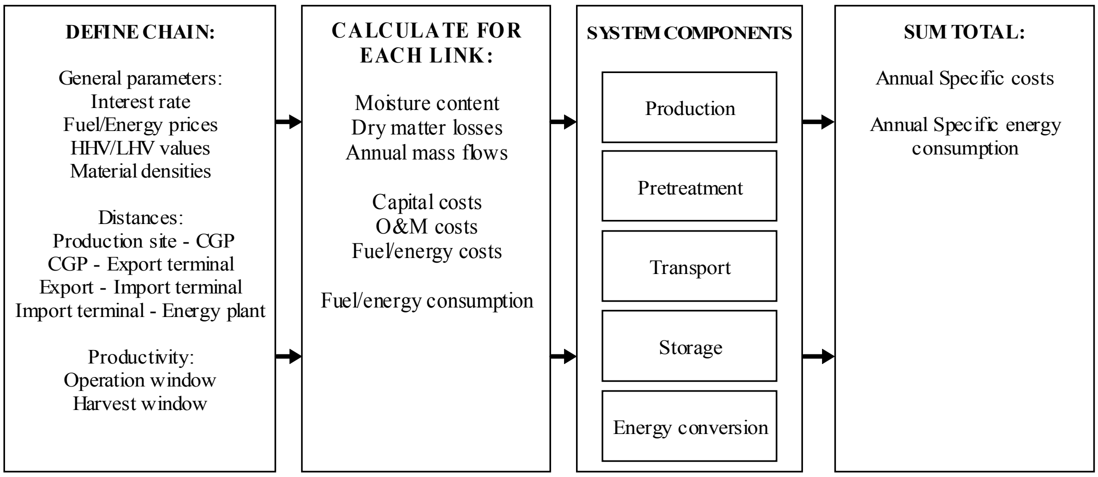


Figure 2.3: Schematic representation of the model.

3 System components

3.1 Biomass production

Two sources of biomass are considered in this study, forest residues and dedicated energy crops. Forest residues consist of the foliage of trees and tree tops (branches and crowns), unmarketable bolts and undergrowth trees. They form the most notable and also economically significant source of raw material in the production of wood fuels. Forest residues are currently available in large amounts in Sweden, as well as in the Baltic states. Sites with dedicated energy crops are also to be found in these areas but absolute production levels are still very low. In Sweden, mainly Salix is grown as energy crop. Agricultural plots of Salix can be found scattered all over the country (18000 ha in southern Sweden (Savolainen, 2000)), but cultivation and harvest are still rather inefficient due to the small scale of operation. This means prices are presently still relatively high. However, in the future production and efficiency could improve so prices for dedicated energy crops are expected to evolve to the same range as forest residue wood (Svenningsson, 2001). Latin America offers great potential for large scale Eucalyptus cultivation. In Brazil already an area of 6 Mha of plantations exist, which are used for pulpwood as well as energy production. For the north-east part alone a potential of 8-13 EJ for eucalyptus energy exists (Azar and Larson, 2000).

Harvest window

In Sweden and other European countries, forest residues are available during the whole year, since spruce trees, which make out the major part of the area concerned can be harvested anytime of the year. However it offers some advantages to harvest during the winter because the wood can dry over the summer. During that time it is also possible for the needles to dry and fall of, so valuable nutrients are preserved for the forest ecosystem. Salix is always harvested during winter time after leaf-fall and when the soil is frozen (Savolainen, 2000). Eucalyptus can be harvested during the whole year (Damen, 2001), however drying conditions are sub optimal during the rain season so differences in biomass quality can be expected (Lowe, 1994).

Forestry residues

Felling areas are typically 0.5-1 ha in size and spread throughout a large area of the country, typically of a magnitude of 100.000 ha. An annual production of 0.26-0.60 t_{dm}/ha.y is assumed (Börjesson, 1996). Different harvesting methods exist in the modern forestry sector. Sweden and Finland are two of the most advanced countries in the field of forestry and harvesting operations are fully mechanised in both countries. While cutting down the trees, the harvesters sort out the logs and the branches on different piles. These materials are recovered in different ways:

Residue logs

Logs are mainly used for valuable applications like timber and paper. The lower part of the tree stem is used for the timber industry whereas the next three meters are normally destined for the pulp industry, however when energy prices are close to paper prices, this part can be used for energy production as well. The top part of the tree stem and the branches will be available for energy production. Furthermore, logs from thinnings will be available for energy production. However it is important to realize that the supply of logs is strongly depending on the market mechanism of competing demanders. Since the energy production is one of the less valuable forms of utilisation, the possibility must be taken into account that even in the future, residue logs will not be available for energy production in sufficient amounts. In this study logs are assumed to be from spruce trees with a bulk density of approximately 0.3 t_{dm}/m^3 (Håkansson, 1994). At the time of harvest, residue logs have a moisture content of about 50%.

Residue chips

The branches are scooped up by machines and formed into huge storage piles, typically about 4x(25-50)x4 meters in size. These residues are left drying for the summer and after about 6 months the moisture content will decrease from 55% to 30-45% during outside storage (Forsberg, 1999; Savolainen, 2000). Gradually parts of the pile will be chipped locally and transported directly to the conversion plant. Chips are usually fired right away when they are still wet, however this is not an option to be considered when long distance transport is necessary. Chips have a relatively low bulk density of about 0.15 t_{dm}/m^3 (Savolainen, 2000). The chips possess a moisture content of 50% at the moment of harvest.

Composite Residue Bales

A new development in harvesting technology is the compression of forest residues into log-shaped compressed bales or compressed-residue-bales (CRL's). These CRL's have a diameter of about 0.75 m and are about 3 m in length. They have a bulk density of 0.15-0.23 t_{dm}/m^3 and normally an initial moisture content of 50% (Glöde, 2000b). CRL's can be handled like logs by conventional forestry equipment and therefore no special investments are needed. In Sweden 50 million tonnes of pulpwood and sawlogs are handled every year so an increase in the range of several millions will hardly be noticed (Glöde, 2000b; Glöde, 2000a; Andersson, 2000/2001; Andersson, 2000; Skogforsk, 2000). The CRL's moisture content depends on the humidity of the feedstock material. In case of fresh residues, the bales will have a moisture content of 45% but after in-field drying lower figures can be reached (30%).

Dedicated energy crops

Two types of dedicated energy crops are considered in this study, Salix and Eucalyptus. Both crops are short rotation coppices, meaning that plantations are coppiced 3 to 4 times, with 3 to 6 year intervals, after which the cycle ends and the plantation is renewed. The harvesting site area is typically of a relatively small scale (1,000-10,000 ha) but for the future large scale cultivation areas (>100,000 ha) are considered as well.

Salix

Salix is the most important crop type for biomass cultivation in Northern conditions. Salix can be harvested every 4 years with an average annual production of 9-17 t_{dm}/ha.y (Börjesson, 1996). A cultivation stand is usually utilised for 25 years. There are two possible ways of harvesting the plants. The first method is to directly chip the material during the harvesting operation. This direct chipping system presents a special problem where storage is concerned. The harvested 3-4 years old plant usually contains approximately 50% water and a lot of easily degradable rich nutrients. These properties together with a large surface area encourage fungal growth, resulting in dry matter losses and health hazards (toxic fumes). The alternative harvesting method for Salix is the whole stem harvester which cuts the stems on-board during harvesting and discharges a bundle on the ground. The bundles are collected by harvesters with large capacities. The bundles can be dried outside during summer; the moisture content will decrease to 30-45% before autumn (Savolainen, 2000). In this study Salix chips and bundles are assumed to be handled for transfer and transport, in the same way as respectively residue chips and CRL's.

Eucalyptus

In Latin America and southern Europe, Eucalyptus is one of the most important sustainable sources of biomass. Eucalyptus can be harvested as chips, or cut down with a chainsaw (Lowe, 1994). According to Damen (2001), yields of 22.4 t_{dm}/ha.y are to be expected. The bulk density of eucalyptus stems is 0.28 €/t_{dm} (Van den Broek, 2000). The moisture content of cut trees is reduced from 60% to 35% after 4 weeks of drying in the field (Lowe, 1994). It is possible to harvest throughout the year without seriously jeopardising coppice regrowth or increasing tree mortality rate, however the rate of moisture loss during in-field-drying depends highly on the weather conditions. In this study it is assumed that during the rain season, in-field-drying is not possible.

Costs

Figures on biomass cultivation costs are ubiquitous, however it is difficult to distinguish between cost figures and prices. Because the European wood market has been rather competitive during the last years profit margins are now very low in the wood fuel sector. Some Swedish forestry companies even decided to quit the business altogether (Svenningsson, 2001) so generally prices will not be much higher than costs figures. An overview is presented in Table 3.1.

Table 3.1: Costs ranges of different biomass forms excluding off-site transport [i].

Biomass form	Production costs (€/t_{dm})	Range (€/t_{dm})	Average (€/t_{dm})	Origin	Literature reference
Residue Logs	13.64-15.49	11.8-25.5	18.62	Finland	Savolainen (2000)
	11.78-17.29			Estonia / S. America	Wasser (1995)
	18.05-25.46			Estonia	Agterberg (1998)
Residue Chips	28.70-30.55	28.7-57.2	42.96	Finland	Savolainen (2000)
	48.68			Sweden, residues	Andersson (2001)
	29.79-38.51			Sweden, CRL's	Andersson (2001)
	37.13			Sweden	SNEA (2000)
	57.22 (45.38)			Sweden	Börjesson (1996)
Residue Bales	20.99-28.26	21.0-27.6	24.30	Finland	Savolainen (2000)
	22.52-27.61			Sweden CRL's	Andersson (2001)
Salix chips / bundles	58.71	53.3-125.0	89.14	Sweden	Agterberg (1998)
	80.90 (53.28)			Sweden	Börjesson (1996)
Eucalyptus chips	17.4-43.5	4.7-43.5	24.1	Brazil	Azar (2000)
	19.6-22.9			Brazil	Damen (2001)
	4.7-11.6			Nicaragua	van den Broek (2000)
Eucalyptus bundles	3.0-4.5	3.0-4.5	3.8	Nicaragua	van den Broek (2000)

i) All prices exclude costs for transport from roadside to a storage terminal (CGP).

Energy

Energy inputs are based on Börjesson (1996) and Forsberg (1999). Energy expenses due to transport of biomass have been deducted from the original figures where necessary. The results are presented in Table 3.2.

Table 3.2: Total energy input during production of different biomass forms excluding off-site transport, including motor fuels, seeds, fertilizers, ash, lime, pesticides, machinery and machine transport.

Biomass form		Energy input (GJ/t_{dm})	Source
Forestry residue chips	final fellings	0.3 – 0.5	Börjesson (1996)
	thinnings	0.9 - 1.9	Börjesson (1996)
CRL's		0.3 – 0.5	Forsberg (1999)
Salix	chips	0.4 – 1.0	Börjesson (1996)
	bundles [i]	0.2 – 0.8	Börjesson (1996)
Eucalyptus	chips [i]	0.36 – 0.4	Damen (2001)
	bundles	0.18 – 0.22	Damen (2001)

i) For chipping, 0.18 GJ/tdm is added for Eucalyptus and subtracted for Salix.

3.2 Pretreatment

In order to improve the efficiency of the transport chain, different pretreatment methods are available. Logistics, costs and energy aspects relevant to these techniques will be discussed in this section. These techniques are sizing, drying and densification of biomass.

3.2.1 Sizing

To make handling more easy, a shredder can be used to size the wood to chips of 5-50 mm length. As described in Section 3.1 it is common to chip forestry residues locally and transport them directly to an energy plant. For the case considered in this study this option isn't advisable, since because of their small size and high moisture content, chips are highly susceptible to fungal growth and tend to decompose when kept for longer periods of time. These features put serious limitations on chip handling. To avoid fungal growth and dry matter losses, the chips should be artificially dried or chipped as late as possible in the transport chain. A possible advantage to be gained from this principle is the increased efficiency of the chain due to positive scale effects. As local chipping is considered to be included in the harvesting operation, this chapter exclusively discusses central biomass chipping at large scale (i.e. CGP or energy plant).

The practical load factor for central chipping equipment is typically 1500 hours a year (Feenstra, 1995). This figure must be corrected for the width of the operation window. The processing capacities depend on the type of chipper. Some large scale chipping installations are presented in Table 3.3. Capacities range from 5 to 80 t_{fw}/h.

Table 3.3: Characteristics of different chipping installations.

Type	Roll crusher [i)]	Hammermill [i)]	MP Bolagen [ii)]
Capacity (t_{fw}/h)	1-10	25-50	80
Power. Consump. (kW_e)	65	240	1320
Capital costs (1000 €)	137.32	358.22	529.07
Maintenance (% invest.)	20	20	20
Lifetime (y)	15	15	15

i) Pierik (1995) ii) Malmborg (2001).

Costs

Chipping costs are based on annuitised capital costs, maintenance and energy costs. Because capacity figures in literature are based on fresh weight figures without specifying the moisture content of the material, it is impossible to determine the exact capital investments needed. In this study it is assumed that the feedstock material described in literature has a moisture content of 50%. All figures are corrected in order to make the operation speed independent of the material's moisture content. Table 3.4 gives the calculated results for the total chipping costs for three different chipping installations, including O&M as well as electricity costs.

Table 3.4: Total specific costs of chipping woody biomass for three chipping machines (€/t_{dm}) [i)].

Operation window	Roll crusher	Hammermil	MP Bolagen
12 months	6.5	3.5	2.0
9 months	8.7	4.7	2.7
6 months	13.0	7.0	4.1

i) Electricity prices are assumed to be 3.5 €ct/kWh (Halen, 2000).

A literature survey has been conducted to validate these calculations. The results show that the specific costs found in most literature sources are higher. Sikkema (1993) comes up with a figure of 20.1 €/t_{fw} (31.0 €/t_{dm}) and Feenstra (1995) even reports a figure of 23.8 €/t_{fw} (66.8 €/t_{dm}). Andersson (2000/2001) uses even 25.43 €/t_{dm} but Savolainen (2000) estimates the costs of central chipping at only a mere 4.2-6.7 €/t_{dm}. It must be noted that the scales involved are relatively low (about 10 t_{fw}/h for Feenstra compared to 80 t_{fw}/h for Malmborg) and this might explain the big differences.

Energy

The calculated specific energy consumption is calculated with the use of the power figures presented above. Total power consumption is assumed to be linearly dependent on the installed capacity and therefore the specific energy consumption is independent of the scale of operation. Table 3.5 gives the calculated total specific power consumption for the machines considered.

Table 3.5: Total specific primary energy consumption of chipping woody biomass for three chipping machines (GJ_{prim}/t_{dm}) i).

Type	Roll crusher	Hammermill	MP Bolagen
Primary energy consumption (GJ_{prim}/t_{dm})	0.18	0.13	0.23

i) A primary energy conversion efficiency of 0.43 is assumed for electricity (Dornburg, 1999).

Figures range from 0.1 to 0.2 GJ/t_{dm}. Again the literature values are significantly higher (Van den Heuvel, 1995; Feenstra, 1995). Most figures range from 400 to 3000 MJ/t_{dm}. However the reports show great variations and even a low figure of 29-64 MJ/t_{dm} is mentioned for forestry chippers (Van den Heuvel, 1995). Chipping technology is still in development, which might explain these big variations in energy consumption.

3.2.2 Forced drying

Three different reasons exists for the artificial drying of woody biomass. Just after felling, woody biomass has a moisture content of typically about 50%. Depending on the feedstock criteria of the plant used to convert the wood to power or liquid fuel, this might be too wet. A solution to this problem is to upgrade the biomass quality by drying it. A second reason for reducing the moisture content of the material is the decomposition risk associated with wet biomass. Biomass forms like chips will quickly start to decompose, resulting in high dry matter losses in only a matter of weeks. An accompanying effect is the fire and health hazards caused by the rotting material. The third reason for reducing the moisture content is of a logistic nature. Drying reduces the weight of the material and this could bring down the transport costs in the other parts of the chain. However drying doesn't seriously affect the volume of the material so it is important to know what factors are determining the transport costs, weight or volume. This matter will be further analysed in Section 3.3. All dryers demand the feedstock material to be sized to chips so a sizing step will always precede the drying operation.

Different types of dryers are available. The most simple and common technology for biomass drying is the rotary drum dryer (RDD). With this technology the biomass is dried by bringing it in direct contact with hot air or flue gas while rotating it around in a drum. A more recent technology is the fluidised bed dryer (FBD), which uses a continuous flow of gas, flowing through a bed, consisting of biomass particles and inert material like sand. The heated gas enters the bed at the bottom and leaves at the top. A third technology which is even more sophisticated is the recompressive dryer (RD). This machine utilises steam heat without the requirement of an external heat source (Pierik and Curvers, 1995).

All technologies have different characteristics but it is beyond the scope of this study to take these into account. Pierik (1995) has done an elaborate study on drying equipment in which costs and technical parameters of the different dryers are presented. Table 3.6 summarises some of the information which is considered relevant to this study.

Table 3.6: Characteristics of different drying installations.

Type[2]	RDD					FBD	RD
Brand[3]	VdB i)	VdB ii)	St ii)	Fl/A ii)	Gdk ii)	E W ii)	V,F ii)
Capacity (t_{fw}/h)	100	36	17.8	33.48	25-45	14.57	38,2
Heat consump. (MW_{th})	12.5	?	10	?	20.47	4.875	-
Electr. consump. (kW_e)	2000	750	120	180	50	294	3629
Moisture input (%)	70-80	50	50	50	60	50	?
Moisture output (%)	7-10	10	10	15	15	15	?
Capital costs (mln €)	5.0	4.1	1.6	6.5	0.61	1.4	5.1
Maintenance (% invest.)	3	3	3	3	3	3	?
Lifetime (y)	15	10-15	10-15	10-15	10-15	10-15	?

i) De Jonge (2001); ii) Pierik (1995).

The capacities of the equipment considered, range from about 15 to 100 t_{fw}/h. According to De Jonge (2001) a large scale drying installation is usually operative for 8500 h/y, being practically 24 hours a day. This makes the potential EUE-factor very high but effectively it might be reduced by the presiding supply restrictions.

Costs

Costs are calculated by adding up capital investment, maintenance, operation, power and heat costs. Lifetime is assumed to be 15 year for all systems and operation and maintenance is assumed to be 3% of the total investment costs. For operation a salary of 25 €/h and a crew of two persons is considered reasonable (De Jonge, 2001). Power is assumed to be available at 65 €ct/MWh and heat prices are 0.13 €ct/kWh (Halen, 2000), however it must be noted that both, heat and electricity prices are highly dependent on the local conditions (for example the availability of waste heat from CHP or the national energy supply structure) and can vary by a high amount. It must be noted that heat consumption figures are unknown for two of the RDD-type dryers. This slightly distorts the cost picture for those dryers.

Table 3.7: Total specific costs for drying chipped biomass from 40% to 10% moisture content (€/t_{dm}) i).

Operation window	RDD VdB	VdB ii)	St	Fl/A ii)	Gdk	FBD E W	RD V,F ii)
12 months	3.7	7.1	9.1	8.9	4.3	10.6	23.8
9 months	4.8	8.7	10.6	11.0	4.9	12.2	30.2
6 months	6.8	11.9	13.5	15.3	6.1	15.5	43.1

i) Power is assumed to be available at 0.035 €/kWh and heat prices are 65 €ct/MWh (Halen, 2000); All calculations are based on 40% MC figures; ii) Heat consumption figures are unknown for these dryers.

The prices for biomass drying, range from 3.8 to 23.8 €/t_{dm} for a 12 months operation window and from 6.1 to 43.1 €/t_{dm} for the smaller operation window of 6 months. If the more expensive alternatives are discarded, it can be seen that biomass can be dried for about 4-15 €/t_{dm}. Literature values aren't far of from this estimate. Van den Heuvel (1995) indicates a price range of 1.1-12.9 €/t_{dm} for respectively 20-50% MC so it seems that the calculations presented above are correct. However, Feenstra (1994) uses figures of 6.5-17.3 €/t_{dm} for respectively 25-50% MC which is actually very close to the results from the calculations in this study.

Energy

The specific energy consumption is calculated with the use of the power figures presented above. In a similar way to the calculations for the sizing operation the total power consumption is assumed to be linearly dependent on the installed capacity and therefore the specific energy consumption is independent of the scale of operation. Table 3.8 gives the calculated primary energy consumption.

Table 3.8: Total specific primary energy consumption for drying sized biomass (GJ_{prim}/t_{dm}) i).

[2] RDD: Rotary Drum Dryer; FBD: Fluidised Bed Dryer; RD: Recompressive Dryer
[3] Brand names as presented in Pierik (1995)

Type	RDD					FBD	RD
Brand	VdB	VdB [ii)]	St	Fl/A [ii)]	Gdk	E W	V,F [ii)]
Energy consumption (GJ_{prim}/t_{dm})	1.1	0.3	3.9	0.1	3.9	2.5	2.6

i) A primary energy conversion efficiency of 0.90 is assumed for heat and of 0.43 for power (Dornburg, 1999); ii) Heat consumption figures are unknown for these dryers. Calculations are based on 50% MC figures.

If the incomplete data are left out of the range, primary energy consumption varies between 1.1 and 3.9 GJ/t_{dm}. Literature values proof to be similar in magnitude as studies by Van den Heuvel (1995) and Feenstra (1994) indicate a range of 1.3-5.6 GJ_{prim}/t_{dm}.

3.2.3 Densification

One of the more sophisticated methods for upgrading woody biomass is to compress it into dry pellets. Pellets are a high-quality fuel. They consist of compressed wood and are typically 6-12 mm in diameter. Generally speaking, there are two reasons to make pellets. The first is that their transport is cheaper and safer than with wet or dried bulky biomass and the second is that they can be immediately substituted for coal (Colquitt, 2001). The allowed moisture content of the feedstock depends on the type of equipment used. The produced pellets have a bulk density of 0.5-0.7 t_{fw}/m^3 and a moisture content of 8% (Van den Heuvel, 1995; Brikettenergi, 2001a; Brikettenergi, 2001b). Refined wood fuels can be stored without risk of decomposition or self-ignition. The energy content does not change during storage so dry matter losses are of no concern during storage. However, the refined fuel must be protected against rain (Brikettenergi, 2001a). Table 3.9 summarises some key characteristics for different densification machines from Pierik (1995).

Table 3.9: Characteristics of different densification installations, excluding all pretreatment equipment [i)].

Type	Extruder						Roller Press
Brand	Valm SRL	ECO Briq	Fr. Hausm	Spaenex	Desmi	M. Wirth	A. Kahl
Capacity (t_{fw}/h)	0.2-3.2	0.8-1.0	0.1-2.0	0.15-3.0	1.1-2.0	0.25-0.46	0.5-5.0
Elect. cons. (kWh/t_{fw})	34-90	22-28	41-130	36-56	29	30-60	60-70
Capital costs (1000 €)	13.7-271	92.3-115	7.0-140	6.4-366	77.1-129	12.2-22.5	18.3-366

i) Pierik (1995).

It is assumed for all machine types that the feedstock material has to be chipped and dried to a moisture content of 10% before pelleting is possible (Forsberg, 1999) which means that a drying step will always precede the pelleting step. It must be noted that this assumption is uncertain, since equipment characteristics available are not clear on this. Specific investment costs are high so it is important to keep the machinery running continually. It is assumed that the pelleting machine operates at a practical load-factor of 7300 h/y (Feenstra, 1995).

Costs

Table 3.10 gives some cost ranges, calculated with the use of the characteristics mentioned above. It is assumed that only machinery with the highest capacities will be used. Therefore, in all calculations, the high end of the given costs and capacity ranges is taken to be the most reasonable. The capital lifetime is assumed to be 10 years for all systems and annual operation and maintenance costs areassumed to make up 40% of the total investment costs. The latter parameters are derived from Agterberg (1998).

Table 3.10: Specific costs of pelleting chipped wood in €/t_{dm}.

	Extruder						Roller Press
Operation window	**Valm SRL**	**ECOBriq**	**Fr. Hausm**	**Spaenex**	**Desmi**	**M Wirth**	**A. Kahl**
12 months	10.8	10.9	8.2	12.6	6.7	6.6	9.0
9 months	13.2	14.2	10.2	16.1	8.5	8.0	11.1
6 months	18.0	20.8	11.2	23.1	12.2	10.9	15.3

So it can be seen that costs range of 10-20 €/t_{dm} must be expected. Validation of these calculations is hard because financial information is scarcely available. According to Van den Heuvel (1995) costs will be around 24.4 €/t_{dm} but this is a crude estimate so the results from the calculations described above are probably more reliable. One possible explanation for this big difference is that drying and chipping costs are included in many literature figures. However Samson (2000) seems to contradict this for direct pelleting costs are about 43 €/t_{fw} according to a survey of wood pellet producers. Feenstra (1995) as well gives a figure of 57 €/t_{dm}. An estimate which comes closer to the results calculated is given by Agterberg (1998), who reveals a figure of 48 €/t_{dm}, but this figure includes chipping, drying and even storage; simple pelleting costs are quite similar to calculated figures.

Energy

The primary energy consumption during pelleting is based upon the power characteristics presented in Table 3.9. Energy expenditure is considered to be linearly dependent on production scales. The results are presented in Table 3.11.

Table 3.11: Specific primary energy costs of pelleting dried wood chips.

Type	**Extruder**						**Roller Press**
Brand	**Valm SRL**	**ECOBriq**	**Fr. Hausm**	**Spaenex**	**Desmi**	**M Wirth**	**A. Kahl**
Energy consumption (GJ_{prim}/t_{dm})	0.84	0.26	0.52	0.52	0.27	0.56	0.65

According to Savolainen (2000), the energy needed for the production of pellets is generally approximately 10% of their own energy content, which is consumed in drying the raw material. In case of dry raw material being used, the pellet consumption consumes only about 1 to 2% of their energy content. This implies an energy consumption of about 0.2-0.4 GJ/t_{dm} in magnitude, which is close to the calculated values. Van den Heuvel (1995) indicates a value of 0.4 GJ/$t_{dm.}$ and a study by Feenstra (1995) reveals a value of 0.2 GJ/t_{dm} for pelleting paper. So it seems that calculated energy consumption figures are not far of from most literature values.

3.3 Transportation

This section will deal with the different modalities of transport used to move biomass from its location of origin to a distant demander. In this study, truck transport, train transport and oceanic ship transport are considered. These forms of transport will be discussed separately.

3.3.1 Truck transport

On relatively short transport distances, trucks can be used for transport. In the situation considered, three links exist where transport most probably will take place by truck:

- Transport from the production site to the central gathering point
- Transport from the central gathering point to the export terminal
- Transport from the import terminal to the energy conversion plant

The first two transport links are considered to differ only with respect to the distance and the characteristics of the transported cargo. Between the first and the second link the biofuel might have been upgraded to a product of a higher quality (i.e. a higher energy density). The third link considered is different from the first two because it is likely to be located in another country (The Netherlands) so different rules might apply for road transport. According to Ehrning (2001) truck capacities are restricted to the allowed Gross Combination Weights in different countries, as given in Table 3.12.

Table 3.12: Allowed Gross Combination Weights [i].

Location	GCW (tonnes)	Load capacity (tonnes)
Sweden / Finland	60	40
Norway	50	30
Europe	40	25

i) Ehrning (2001).

Costs don't depend much on the type of transport but are more sensitive to the bulk density and moisture content of the cargo. In this study four different types of truck are considered. Table 3.13 depicts their most relevant characteristics.

Table 3.13: Characteristics of different truck types.

Truck type	Dutch bulk	Swedish bulk	Chemical tanker [i]	Pellets truck
Truck capacity max (ton)	25	40	25	35
Truck capacity max (m3)	120	130	33	80
Average speed (km/h)	65	65	65	65
Fuel use (L Diesel/100 km)	34	45	45	45
Km-costs (€/km)	1.24	0.85	1.24	1.1

i) km-costs and fuel use are assumed to be equal to solid bulk transports.

The first truck (NL) is a virtual Dutch truck with the maximum possible volume and weight capacity, of which the characteristics are based on Van den Heuvel (1995). The Swedish trucks (SV) have a maximum capacity of 40 ton and 130 m^3 according to Söderhielm (2001) and Malmborg (2001). When transporting methanol, a chemical tanker is needed, of which the capacities are in the order of 25 tonnes and 33 m^3 according to Walsum (2001). The other features are considered to be equal to solid bulk transport. For pyrolysis oil transport, it is assumed that the same tanker can be used. The last truck (PT) is solely used for transporting pellets. Information is provided by Mared (2001) of Brikettenergi, a pelleting company in Huskvarna. These trucks are specially equipped with spouts to quickly facilitate a large number of households with heating fuel and might therefore be unnecessary for the more crude transport operations, considered in this study. It is assumed that pellets can be transported by a bigger regular Swedish truck as well, which is cheaper.

In order to gain insight in the logistic aspect of truck transport, average speed and transfer time are of importance. All trucks are considered to travel at an average speed of 65 km/h. Transfer speeds are based on Malmborg (2001), who states that trucks can be loaded or unloaded at a rate of two truckloads

per hour. A value of 240 m^3/h is assumed for logs, bundles and bales and a value of 260 m^3/h for chips and pellets. The utilisation of pumps and spouts for the transfer of methanol and pyrolysis oil results in much higher transfer speeds. Values are estimated to be approximately 500 m^3/h. This kind of equipment could increase the transfer speed for chips and pellets as well, however so far no information was available for truck transfer.
Depending on the average speed and loading rate it takes a certain amount of time per truck to fulfil one transport cycle. Given the scale and operation window of the transport, the total number of trucks to be utilised can be calculated as formulated in Equation 3.1.

$$TN = \frac{LC/(OW \cdot 365)}{CC/TT}$$ **Equation 3.1**

with:
- TN Number of transport entities needed (--)
- LC Logistic capacity (m^3 or t)
- OW Operation window (y/y)
- CC Cargo capacity of the type of transport used (m^3 or t)
- TT Total transport time (days)

At a logistic capacity of 20 Mm^3 and a total transport time of 9 hours, including transfer, continuously about 160 trucks are required to fulfil all necessary transports within 12 months. The logistic pressure on the transfer facilities can be indicated by calculating the time interval between each incoming truck with the aid of Equation 3.2. A 24 hour work shift is assumed and all trips are spread out evenly over the day. For the situation considered above, about 3.5 minutes exist between two subsequent deliveries or pick-ups. This figure is independent on the transport distance.

$$TI = \frac{CC \cdot OW \cdot 365 \cdot 24 \cdot 60}{LC}$$ **Equation 3.2**

with:
- TI Time interval between two transports (minutes)
- LC Logistic capacity (m^3 or t)
- OW Operation window (y/y)
- CC Cargo capacity of the type of transport used (m^3 or t)

When transporting materials with a low energy density, the bulk density of the cargo might be lower than the mass-volume ratio of the truck used. In that case the number of necessary truck rides can be limited by applying special densification techniques to the material. In case of material with a high energy density, the maximum allowed tonnage is crucial. A lot of weight is caused by the water contained in the biomass so the number of necessary truck rides can possibly be reduced by drying the material before transport.

Costs

Costs are derived by calculating the costs corresponding with the amount of truck-kilometres necessary to transport the total amount of biofuel (Table 3.13 last row) and adding transfer costs (two-way trips). Loading and unloading costs are calculated on volume-basis and are about 0.87 €/m^3, according to Van den Heuvel (1995) including handling from storage to truck. A study by Lysen (1992) presents a range of 1,2-2,1 €/t corresponding with a range of 0.2-1.3 €/m^3 depending on the material's moisture content and density. A range of 0.29-0.56 €/t_{dm} is given by Feenstra (1995), which can be converted to approximately 0.03-0.3 €/m^3, depending on the density. So it seems that transfer costs are susceptible to strong variations. An average value of 0.5 €/m^3 will be assumed for now. This figure is generally applied to all different types of cargo. Although it is likely that specific costs for methanol and pyrolysis oil transport will be somewhat higher, a lack of data on this subject calls for a generic approach. Truck transport costs are independent on the system's scale. Some typical results are presented in Table 3.14.

Table 3.14: Specific costs of truck transport of woody biomass (€/t_{dm}) and liquid fuel (€/tonne) for different cargo types.

Distance	MC	Logs	Chips	Bales	Pellets	Pyrolysis oil	Methanol
50 km	45 %	7.9	12.3	9.9			
	<10 %		11.0		4.1	6.5	5.8
200 km	45 %	20.8	24.1	22.9			
	<10 %		24.1		11.1	23.0	20.7

The results show that the drying of chips has no effect on the total transport costs. The chips density is low, even when the material is wet. Hence the volume determines the amount of transports needed. Transfer costs are dependent on volume as well, so a weight reduction is of no use. The application of densification technologies might be of interest though. Transport costs for pellets are much lower than those for chips and transporting liquid fuels is cheaper as well. When these data would be normalised with regard to energy content, the costs for pyrolysis oil and methanol transport would be relatively lower.

Energy

The energy consumption during truck transport is determined by the total amount of diesel consumption during transport, taking into account a LHV of 35.7 MJ/l for diesel. Transfer operations cost about 5 MJ_{prim}/t_{dm} (Feenstra, 1995). Table 3.15 gives the results of calculations for a 50 km as well as a 200 km distance.

Table 3.15: Specific primary energy consumption during truck transport of woody biomass (GJ_{prim}/t_{dm}) and liquid fuel (GJ_{prim}/tonne) for different cargo types [i)].

Distance	Logs	Chips	Bales	Pellets	Pyrolysis oil	Methanol
50 km	0.10	0.11	0.10	0.07	0.09	0.09
200 km	0.38	0.43	0.38	0.23	0.33	0.33

i) A primary energy conversion efficiency of 0.89 is assumed for Diesel (Hendriks, 2000; Jager, 1998).

These results correspond with a range of 0.6-1.0 MJ/t.km, including the return trip. According to Börjesson (1996) a range of 1.3-1.7 MJ/t.km is plausible (the higher end of range is based on future bioenergy based transport system) and a value of 0.5 MJ/t.km is given by Van den Heuvel (1995) and Feenstra (1995). It seems that calculated results are well within range of literature values.

3.3.2 Train transport

A major advantage when transporting biofuels by train is the possibility to bypass two transfer points, the exporting harbour and the importing harbour. This seriously brings down the costs and the amount of time needed. Besides it is unnecessary to provide large storage facilities since a trainload is of a much smaller magnitude as a shipload (this feature will be discussed more elaborately in Section 3.4). Logistic conditions in Europe are far from ideal. At some borders the engine has to be changed or sometimes even the whole train because of a difference in track width. In the future some difficulties might be solved but certainly not all. These conditions are partly responsible for the fact that it is almost impossible to gain insight in the cost determining factors of rail transport.

The logistics involved in train transport are similar to those discussed in Section 3.3.1 on truck transport. Trains are considered to carry a volume of 2500 m^3 and 1000 t Feenstra (1995) with an average speed of 75 km/h. In a similar way as has been described in Section 3.3.1, the number of trains necessary and the amount of time between two transports can be determined. At a two-way distance of 3000 km and an annual scale of 20 Mm^3 about 37 trains are needed which travel with 65 minutes interval schedules. Note, that a load of little less than 2500 m^3 is expected each hour, which is about equal to the amount processed in the truck transport link (a truck load of 130 m^3, every 3.5 minutes). As long as the operation windows of the chain components are identical, the processing speed matches by definition.

Costs

The costs for rail transport are difficult to obtain but something can be said about prices. The prices are hard to generalise because they depend on the availability of return-freights, the total volume of transport in the same direction, the transfer terminal policies and the route. A container transport from Rotterdam to Paris costs four times as much as a transport from Rotterdam to Barcelona (Nolen, 2001). Intermodal container transport seems to be an attractive possibility for biofuel transport, since transfer is limited to containers, rather than bulk goods. However Nolen (2001) gives an estimate of about 70-100 €/t, for respectively Rotterdam-Malmö and Rotterdam-Stockholm, which is far too high for the type of cargo considered in this study. Another estimate is derived from a study by Börjesson (1996) and presented in Table 3.16.

Table 3.16: Train transport costs, including transfer, for different energy carriers in (€/t_{dm}) for woody biomass or (€/t) for liquid biofuels [i].

Biomass form	500 km	1000 km	1500 km	2000 km
Salix	25.5	36.3	47.2	58.0
Forest residues	28.6	40.8	53.1	65.3
Pellets	9.0	12.8	16.7	20.5
MeOH [ii]	31.7	45.2	58.7	72.2

i) Börjesson (1996) except pyrolysis oil: Salix: 860+1.4d (US$/TJ); Logging Residues: 740+1.1d (US$/TJ); Methanol: 430+0.67d (US$/TJ); it is assumed that the originally energy based values are based on LHV50%MC for Salix, LHV 25%MC for residues and LHV 19.91 GJ/tonne for MeOH; ii) based on tonnes of liquid fuel.

Börjesson's figures give an indication of train transport costs, depending on distance and cargo. A costs assumption for pyrolysis oil transport is hard to make since the costs associated with increased safety protocols are unknown. In this study it is assumed that transporting pyrolysis oil by train costs the same as transporting methanol. In a logistic survey Feenstra (1995) gives an indication for intermodal container transport costs, based on containers of 38 m^3 and 15 t which can be put on a train (three containers per wagon), of 4.7-11.7 €/t. No distance indication is given here, however the report focuses on domestic biomass sources so the value should be compared to the figures in the left part of Table 3.16. Transfer costs are not included either but these are about 1.0 €/t_{dm}, as presented in the same report. When assuming a 50% moisture content, the upper part of Feenstra's figure comes close to the lower end of Börjesson's forest residues data range (24.4 €/t_{dm} for Feenstra compared to 28.6 €/t_{dm} for Börjesson). In this study Börjesson's values will be used. This implies that train transport costs are assumed to be scale independent. All later calculations are based on values for forest residues (for all woody fuels except pellets). For pellets it is assumed that train transport costs are cheaper, because of their lower density. A factor of 0.3 is applied, representing the density ratio of the material.

Energy

Energy consumption is based on Börjesson (1996), who calculates a figure of 0.63-0.70 MJ_{prim}/t.km, based on trains of 800 t and 2400 m^3, including the energy embodied in the vehicle and infrastructure. For a distance of 1000-1500 km, this implies an energy expenditure of 630 to 1050 MJ_{prim}/t. For a life cycle study on biomass transport systems, Forsberg (1999) uses a figure of 0.29 MJ_e/t.km, assuming an electrical engine, 52 carriages and 40% degree of use, resulting in an energy consumption of 725-1090 MJ_{prim}/t.km. Feenstra (1995) gives a value of 0.50 MJ/t.km for a 2508 m^3 and 990 t train. Energy consumption as a result of transfer operations amounts to 10 MJ/t_{dm} (Feenstra, 1995).

3.3.3 Ship transport

The longest transport link within the chain will take place by ship or train. A train transport has the advantage of avoiding some cost increasing transfer points. Sea transport will be more expensive at this point, however it has the lowest variable costs possible. A logistic model has been created which tries to relate the costs and the energy use of sea transport to aspects like distance, ship capacity, cargo type, time scheduling and more. The shipping business is an opaque field where activities are optimised according to boundary restrictions valid within a specific location and time. So it is difficult to find real costs and prices and if found they are almost impossible to generalise or extrapolate. To gain insight in the costs determining aspects of sea transport it is necessary to make some assumptions, which will be explained below.

Ocean ships come in all sizes, ranging from less than one to hundreds of thousands tonnes dead weight (dwt). One generalisation that can be made is that the bigger the cargo capacity of a ship, the more efficient a transport can take place. Hence, at the large logistic scales considered in this study it is best to consider the larger vessels. Ships can be equipped to be self-(un)loading which could decrease the transfer costs in port. However according to Jansen (2001), director of the Baltscand Bioenergy

Company this will only increase the capital costs of the ship by the same amount. To keep the modelling simple it is assumed that all vessels have to be unloaded by port cranes.
Table 3.17 presents the characteristics of the ships that are taken into account. The first two vessels are conventional bulk carriers of different sizes CV-I and CV-II (Willekes, 2000). The Tornator type is a bulk vessel as well but of a smaller size (Ehlers, 2001). The fourth ship is a large capacity bulk vessel used by Citadel Shipping (Grandelius, 2001) for intercontinental pellets transport, however, it is not dedicated to this type of cargo only. The last ship to be considered is a chemical tanker, assumed to be suitable to transport methanol or pyrolysis oil (Roktrader, 2001).

Table 3.17: Characteristics of different ships.

Type	CV-I i)	CV-II i)	Tornator ii)	Pellets iii)	Tanker iv)
Capacity (t)	-	-	-	22000	-
Capacity (m3)	21300	42600	7000	30000	4927
Ship dwt t	15000	30000	5000	25000	4527
Vessel costs (mln €)	11.9	15.2	11	16	10.6
Life time	25	25	25	25	25
Fuel use HFO (t / km)	0,03	0,04	0,015	0,04	0,015

i) Wasser (1995); ii) Ehlers (2001); iii) Grandelius (2001); iv) Roktrader (2001).

Besides more or less predetermined parameters such as logistic capacity, distance and speed, two other factors determine the amount of ships needed to transport all cargo over a given distance. In the first place the size of the ships used; the larger the cargo capacity of a vessel, the smaller the total number of transports needed. In the second place the timeframe wherein all transport operations must be fulfilled. This operation window is mainly determined by supply restrictions but even if this is not the case it might be problematic to spread out this timeframe over the whole year because of logistic limitations in other parts of the transport chain. This time constraint affects the operation window of the whole transport system and is therefore an important cost determining factor. The bigger the operation window, the fewer ships are necessary to fulfil the annual shipment, thereby reducing the transport costs.
Ships can be specially dedicated to carrying biomass so they cannot be used effectively on their return trip. When ships are designed to carry out more general tasks, they can be used to take return freights. For the latter case, ships are assumed to be in use only one-way.
The cargo transfer rate is strongly dependent on the port facilities and the possibility to utilise them. Different figures have been found. A business manager of Malmö harbour indicates loading and unloading rates of 60, 90 and 100 t/h for logs, chips and pellets respectively and methanol can be transferred at speeds faster than 1000 t/h (Olsson, 2001). According to Malmborg (2001), director of a biomass importing terminal in Ystad, logs and chips can be loaded or unloaded at equal rates of 200-300 t/h. A figure of 125 t/h and 833 t/h is given by Wasser (1995) for respectively logs and chips. In an exploratory study by Willekes (2000) a figure of 420 t/h for chips is presented. Pellets can be loaded with spouts at speeds of about 500-1000 t/h but the unloading is much slower (Grandelius, 2001; Colquitt, 2001). Encountered ranges of loading and unloading speeds for different types of cargo are presented in Table 3.18.

Table 3.18: Transfer speed for different cargo types.

Cargo type	Speed for loading or unloading (t/h)
Logs	60-300
CRL's i)	40-200
Chips	90-835
Pellets	100-1000
MeOH	>1000
Pyro-oil ii)	>1000

i) treated as logs, corrected for their lower density; ii) assumed to be equal to MeOH.

Transfer rates can theoretically be improved by using additional cranes and adjusting the ship's design but an optimum would soon be reached because of spatial limitations. For further calculations it is assumed that transfer will take place at the highest rates presently found.
The minimum size of the fleet can be determined with the aid of Equation 3.1 and the time interval between two transports is calculated by using Equation 3.2 as presented in Section 3.3.1. Some typical

values are presented in Table 3.19. In case dedicated ships are utilised, the fleet would have to be twice as large but the time interval remains unaffected.

Table 3.19: Fleet size and time interval between two transports for different transport scales and distances. A non-dedicated shipment with a freight capacity of 42,600 m^3 is assumed.

	20 Mm^3/y		**80 Mm^3/y**	
OW (y/y)	**1,500 km**	**10,000 km**	**1,500 km**	**10,000 km**
0.5	10 ships (9 hours)	50 ships (9 hours)	38 ships (2 hours)	200 ships (2 hours)
1	5 ships (19 hours)	25 ships (19 hours)	19 ships (5 hours)	101 ships (5 hours)

Costs

The costs for sea transport consist of capital costs, operation and maintenance costs, fuel costs, transfer costs and port charges. An elaborate description of each of these cost factors is presented below.

Capital and O&M costs

Capital costs are calculated by annuitising the total ship costs with an optional correction for the possibility of dedicated ships being only in use part of their devaluation period. Annual operation and maintenance expenses are assumed to amount to 10% of these total ship capital costs.

Fuel

Fuel costs are based on specific fuel consumption for the ship considered and the total transport distance. For dedicated ships the return trip is assumed to add to the fuel costs as well, however because of the empty cargo holds, fuel consumption is down to 65% of the full load consumption level (Wasser, 1995). Large ships use mainly Heavy Fuel Oil (HFO) in amounts ranging from 0.01-0.03 t/km. HFO can be purchased at prices ranging from 139-290 €/t (Wasser, 1995). For port manoeuvring usually Marine Diesel Oil (MDO or gasoil) is used. This type of fuel is more expensive (Wasser, 1995) but the consumption rate is very low because these diesel engines are only used in port. In this study, MDO consumption is considered to be negligible compared to HFO consumption.

Transfer

Transfer costs are assumed to be solely dependent on the type of cargo considered. Figures are based on a report by Wiklund (1996) and a personal communication with the business manager of the port of Malmö (Olsson, 2001). In Wiklund's study the loading and unloading of chips and logs is estimated to cost about 2 €/t. Transferring pellets costs 2.6 €/t. Olsson's figures are considerably higher, with costs ranging from 4.3 €/t for pellets to 6.4 €/t for logs. Olsson also gives an indication for the costs of methanol transfer of about 1.6 €/t. An estimate of 7.4 and 4.4 €/t is given by Wasser (1995) for loading and unloading logs and chips respectively. In Table 3.20 ranges are given for different cargo types. Loading and unloading are assumed to be equally expensive in all cases. For bales or bundles it is assumed that transfer prices are equal to those of logs, on a volume basis. For pyro-oil, figures are assumed to be equal to methanol figures.

Table 3.20: Transfer costs for different types of cargo.

Cargo type	**Costs for loading or unloading (€/t)**
Logs	2.0-7.4
Bales [i)]	3.1-10.1
Chips	2.0-4.4
Pellets	2.6-4.3
MeOH	1.6
Pyro-oil [ii)]	1.6

i) treated as logs, corrected for their lower density; ii) assumed to be equal to methanol

Port charges

The port charges are assumed to represent the total costs involved in capital use at the shore. Because the monetary value of the cargo types considered in this study is relatively low, the port charges amount to a large share of the total costs for sea transport, namely about one third. The port charges are highly dependent on the type of service a port provides. Generally the rate is solely dependent on the

ship's dead-weight tonnage and therefore relates only marginally to the amount of ships used (smaller ships have proportionally smaller dead-weights). There are no set rules about who should cover the charges. It totally depends on the contract whether it is the ship owner, the transport company, the loading or the discharging customers who has to pay. In this study it is considered irrelevant who pays these costs for in the end they will add up to the total sum anyway. But it should be kept in mind that when deriving costs from prices, they may seem high because of these hidden expenses. The operations manager of the port of Norrköping, states the total port charges consist of 0.34 €/gross tonnage plus 0.39 €/ton cargo; the latter being fairway taxes (Söderhielm, 2001). The director of MP Bolagen, a Swedish biomass importing company in Ystad, states a figure of about 0.54 €/ton cargo (Malmborg, 2001). For the average Dutch situation a figure of about 0.68 €/ton is plausible (Willekes, 2000).
When adding up these costs, a costs figure can be calculated for different distances and cargo types. Table 3.21 shows some results. Transport costs are independent of the system's scale.

Table 3.21: Total specific costs of sea transport with a CV-II and an operation window of 0.5 to 1 y/y, expressed in €/t_{dm} (woody biomass) or €/t (liquid fuels).

Distance	Dedicated	Logs i)	Chips ii)	Bales iii)	Pellets iv)	Pyro oil v)	MeOH vi)
1500 km	no	25	22	39	12	8.4	11
	yes OW:1-0.5	27-34	26-34	42-52	13-16	11-16	15-22
10,000 km	no	42	55	66	21	30	42
	yes OW:1-0.5	51-74	77-119	80-117	27-39	45-77	64-112

i) at 44%MC; ii) at 10%MC; iii) at 42%MC; iv) at 8%MC; v and vi at 0%MC.

For dedicated transports, ranges are the result of a difference in capital utilisation. Dedicated carriers are more expensive, even when the system's operation window is 1 y/y. This is the result of additional fuel use during the return trip for dedicated ships.

Energy

The energy use for shipping biofuels is assumed to be equal to the primary energy content of the amount of fuel oil consumed during transport. The energy consumption during transfer operations is about 0.04 GJ_{prim}/t_{dm}, according to Feenstra (1995). Fuel consumption during return freights of non dedicated transports is assumed to be 65% of the full load consumption. Some calculated results are presented in Table 3.22.

Table 3.22: Total specific energy use during sea transport with a CV-II and an operation window of 1 y/y days in GJ_{prim}/t_{dm} (woody biomass) or GJ_{prim}/t (liquid fuels).

Distance	Dedicated	Logs i)	Chips ii)	Bales iii)	Pellets iv)	Pyro oil v)	MeOH vi)
1,500 km	no	0.26	0.46	0.37	0.18	0.24	0.32
	yes	0.38	0.71	0.55	0.25	0.34	0.47
10,000 km	no	1.30	2.63	2.00	0.77	1.14	1.65
	yes	2.09	4.30	3.24	1.23	1.82	2.67

i) at 44%MC; ii) at 10%MC; iii) at 42%MC; iv) at 8%MC; v and vi at 0%MC.

In a study by Börjesson (1996) a figure of 0.17-0.23 MJ_{prim}/t.km is used to estimate the energy input during ship transport. This range corresponds to 0.26-0.35 GJ_{prim}/t for 1,500 km and 1.7-2.3 GJ_{prim}/t for 10,000 km. Which is within acceptable range of the calculated values.

3.4 Storage

At a number of points in the transport chain it is necessary to create storage possibilities for biofuels. Particularly at points where cargo is transferred between transport modalities of different scales. A large ship can take more than a thousand times as much freight as a road truck. This implies logistic bottlenecks which can only be resolved by providing sufficient storage facilities. Another reason for the necessity of storage facilities is the possible seasonal dependency of biofuel supply. The supply of biomass is often limited to a part of the year, while demand is always up and high capital investment costs call for a continuing supply of feedstock. This asks for a peak production during part of the year, which could stress the logistic capacity of the storage facilities and potentially of the whole chain. In Table 3.23 some characteristics of different storage facilities are given.

Table 3.23: Characteristics of some storage facilities.

Biomass form	**Logs, bales and bundles**			**Chips and pellets**	
Type	**Open air** [i]	**Outdoor uncovered** [ii]	**Outdoor roofed** [ii]	**Bunker** [iii]	**Silo** [iii]
Size (m^3)	2	3000	3000	25000	5000
Surface area (m^2)	1	--	--	--	--
Capital costs (1000 €)	--	27	108	1630-2170	331
Maintenance (% invest.)	3	3	3	3	3
Lifetime (years)	N/A	25	25	25	25
Land costs (€/m^2.y)	2.3	--	--	--	--

i) Malmborg (2001); ii) Pierik (1995); iii) Feenstra (1995).

No information has been found about the storage of liquid fuels. However, as will be clarified later, significant costs are only associated with the storage of large supplies of woody biomass. So this problem is more or less resolved.

In order to determine the total needed storage capacity, two situations must be considered. When considering a constant supply of biofuels, it suffices to calculate the buffer capacity needed at each transfer point to process the biggest possible shipments. However, when supply limitations occur, a larger storage capacity is necessary. In that case large stocks of biofuels must be stored at some point in the chain. Both situations will be discussed.

For the situation with a constant biofuel supply, a base capacity is deemed satisfactory in order to be able to cope with transfer and handling. As a base capacity, a two-day buffer storage is considered reasonable. The size of this storage is determined by calculating the total amount of biomatter processed during two days. Since biomass flow is the same throughout the chain, as determined by the operation window of the logistic system, the storage buffer size will be the same for all transfer points, namely approximately 0.5% of the system's end scale.

For the alternative situation where a supply restriction presides, a way between two alternatives is possible. One possibility is a large scale storage of biofuels at the end of the chain. However this would ask for a drastic increase in chain performance, because all material has to be transported during a small part of the year. The lying idle of purchased capital during the rest of the year makes the situation even less attractive. The second alternative is to store all biofuels at some point at the top of the chain. For residues and chipped biomass forms the material needs to be upgraded in some way, however this restriction does not hold for logs, bales or Eucalyptus and Salix stems, so this option offers good prospects in case of seasonal dependency of supply.

For both ways, and every possible middle course, the additional storage capacity is calculated by multiplying the system's scale by the operation window required for the harvesting. In case of a six months harvesting window, a supply buffer storage capacity of half the total annual scale is considered necessary. Table 3.24 gives some examples.

Table 3.24: Some typical storage capacities, assuming an annual scale of 10 Mm^3 and a supply harvesting window of 0.5 y/y.

Chain	Ordinary storage (m^3)	Supply storage (m^3)
Harvesting site	50,000	0
CGP	50,000	5,000,000
Export terminal	50,000	0
Import terminal	50,000	0
Energy plant (Truck)	50,000	0
Total	250,000	5,000,000

It can be seen from these figures that a supply restriction, drastically increases the need for storage capacity. For this study it is assumed that if necessary, the total supply buffer storage will be situated at the top of the chain (CGP). This means, a large storage capacity for liquid fuels isn't necessary.

During storage, biomass tends to decompose when the material is wet and/or chipped. This results in dry matter losses. Material can dry during storage as well, depending on storage conditions, such as humidity and ventilation. Table 3.25 gives drying and decomposing characteristics for two types of storage.

Table 3.25: Dry matter losses and drying characteristics during storage.

Storage operation	Dry matter loss	Moisture content loss
Storage in pile and or at roadside	15 %	results in 35-45 % [i)]
Covered storage	3%/month (only for chips with MC>20%)	decrease of 1.5 %point/month (chips with MC>20%)

i) an original value of 50% MC is assumed

Costs

Costs are calculated with the use of the data presented above in Table 3.23 by annuitising capital investments and adding 3% maintenance. Land costs, which are only included in the open air alternative are assumed to be 2.3 €/m^2.y, based on Malmborg (2001). Power consumption is assumed to be negligible. In Table 3.26 an overview of the results is presented.

Table 3.26: Specific storage costs, depending on average storage time (€/m^3).

Biomass form	Logs, bales and bundles			Chips and pellets	
Type	Open air	Outdoor uncovered	Outdoor roofed	Bunker	Silo
Costs (€/m^3)	1.1	1.3	5.0	12.2	9.3

From these figures a mass based costs estimate for storage of different types of biomass can be deduced. Depending on the density of the biomass, specific costs per tonne range from 3 to 7 €/t_{dm} for uncovered outdoor storage and 16 to 81 €/t_{dm} for roofed or indoor storage. These estimates are given in Table 3.27.

Table 3.27: Range of specific storage costs for different types of biomass (€/t_{dm}).

	Logs	Bales or Bundles [i)]	Pellets	Chips
Costs (€/t_{dm})	4 (16)	3-7 (23-25)	16-20	62-81

i) Residue bales, Salix and Eucalyptus bundles are included within the given range. Values in brackets give the costs for covered storage.

For a comparison, a comprehensive study by Van den Heuvel (1995) indicates ranges of 3.3-19.0 €/t_{dm} and 8.1-27.1 €/t_{dm} for respectively indoor and outdoor storage. So it seems that the presented calculations are within range of known literature values.

Energy

Since artificial drying is not considered part of the storage operation, no energy expenses are associated with storing biomass. In case of storage of chemicals like methanol or pyrolysis oil, some additional technology might be necessary to safeguard security, however this aspect is left out of consideration due to a lack of data.

3.5 Energy Conversion

A variety of different biomass conversion techniques exist. The most important distinction to be made within this study is related to the choice of utilisation, the production of power or the production of liquid fuels. The production of heat energy is not considered useful because of its relatively low application value.
Energy conversion technologies are currently rapidly developing so efficiency figures as well as costs are difficult to predict, even on the short term. It lies beyond the scope of this study to give a thorough analysis of state-of-the-art conversion techniques so instead some key values will be used.

3.5.1 Power production: gasification

Power is one of the most valuable forms of energy and biomass electricity prices can easily be compared to prices for electricity from conventional sources. For this study one conversion technologies is considered, the gasification of biomass.

Gasification

Gasification means the thermal gasification of biomass or the thermochemical conversion of biomass into gaseous fuels by means of partial oxidation of the biomass at high temperatures. Many different types of biomass gasification processes are commercially applied. For this study the recent biomass integrated gasification/combined cycle (IGCC or BIG-CC) technology is considered (Faaij et al., 1998).
For all cases biofuels are considered to possess an energy content of 16-17 GJ_{LHV} per tonne at 8-10% moisture content or 19.5 GJ_{HHV}. The most relevant characteristics of both combustion, co-firing and gasification plants are presented in Table 3.29.

Table 3.28: Characteristics of some power conversion technologies, including pretreatment.

Type	BIG/CC [i)]
Capacity plant (MWth LHV)	316
Investment costs (mln €)	325
Efficiency power (% LHV)	48
O&M costs (% inv.)	4
Life time (y)	25

i) Faaij (1998).

3.5.2 Liquid fuel production: methanol synthesis and pyrolysis

The conversion of woody biomass to liquid fuels offers some efficiency advantages during transport and handling, however the utilisation form is completely different in nature so a comparison is difficult. A sensible analysis will have to be made on the account of domestic requirements and relative costs. Two liquid substances are assessed within this study, methanol and pyrolysis oil.

Methanol synthesis

Biomass-derived methanol is produced through gasification. The biomass is converted into a synthesis gas that is processed into methanol. Because of the high investment costs and the sophisticated technology involved, methanol synthesis is considered to be limited to large scale activities. Methanol has a density of 0.79 t/m^3, a HHV of 19.92 GJ/t and a LHV of 25.22 GJ/t (Jager, 1998). This could make storage and transport operations more efficient but safety measures must be taken into account due to the toxicity and flammability of the substance. Methanol can be used as a blend in transportation fuel and in the long term, possibly as a fuel in fuel cell vehicles.

Pyrolysis oil synthesis

During pyrolysis, biomass is heated in the absence of air, resulting in a breaking down into a complex mixture of liquids, gasses, and a residual char (usually charcoal). The composition of this mixture depends on the exact conditions during the process. Pyrolysis can be carried out under a variety of conditions to capture all the components, and to maximise the output of the desired product be it char, liquid or gas. Recent research activities have focused mainly on the fast production of the liquid oil (flash pyrolysis) and have pointed out that production could be cheap and economically profitable at

low scales (Faaij, 2001a; Van den Heuvel et al., 1994). For this reason this study focuses solely on the production of liquid oil with respect to pyrolysis. Dry pyrolysis oil has a density of about 1.175 t/m^3 and an energy content of 20-24 GJ/t, depending on the exact composition (Schenkeveld, 2001; Meeuwesen, 1997). The liquid oil is easier to store and transport than solid biomass material due to spatial characteristics, however because of its toxic and corrosive nature, security measures must be taken which are likely to be expensive. In Table 3.30 some basic characteristics of pyrolysis and methanol synthesis technologies are presented. Data for methanol synthesis are derived from Faaij (2000). For pyrolysis related technology, data is derived from Schenkeveld (2001).
For pyrolysis oil the utilisation is not obvious. Unlike methanol, it is as yet impossible to run combustion engines on pyrolysis oil. In the long term future, oil fired gas turbines and diesel engines might possibly be adjusted to make the application of pyrolysis oil as a transport fuel possible (Meeuwesen, 1997) but at present none of these options is in a developed state. In this study it is assumed that pyrolysis oil is gasified, in order to generate electricity or methanol. Performance figures for this type of technology are based on BIG/CC technology (Faaij et al., 1998) and methanol production technology (Hamelinck, 2001; Hamelinck et al., 2001).

Table 3.29: Characteristics of fuel conversion technologies, excluding pretreatment except for i).

	Methanol synthesis i)		**Pyrolysis ii)**	**Pyro-methanol iii)**	**Pyro-power iv)**
Type	**Small scale**	**Large scale**			
Capacity plant (MWth LHV)	375	830	34	405	316
Capital costs (mln €)	302	574	9.1	203	247
Efficiency fuel (% LHV)	52	51 v)	67	64	48
O&M costs (% inv.)	4	4	4	4	4
Life time (y)	25	25	25	25	25

i) Faaij (2000); ii) Schenkeveld (2001); iii) Hamelinck (2001): unit 6 was used, without pretreatment and tar cracker; iv) Faaij (1998): the largest available SOTA system was used, without pretreatment and tar cracker; v) an additional 13% of power is produced by this system, which is deducted from the total annual costs, taking into account an electricity price of 3.5 €ct/kWh.

Logistics

It is assumed that all conversion technologies operate with a practical load factor of 8000 hours per year. No operation window restrictions are applied because it is considered eminent that power and fuel production continue the whole year.

Costs

Costs are calculated by annuitising the total capital investments and adding a 4% operation and maintenance share. It is assumed that capital investments will be relatively cheaper for large scale installations so capital costs are scale dependent.

Table 3.30: Specific costs of different energy conversions in €/t_{dm} (woody fuels) or €/tonne (Pyro conversions); values in brackets represent costs in €/GJ.

Process scale	**BIG/CC i)**	**Methanol i)**	**Pyrolysis**	**Pyro-MeOH**	**Pyro-Power**
Large scale	84.4 (8.8)	38.2 (4.1)	--	--	--
Small scale	--	76.8 (8.1)	25.5 (2.1)	65.2	47.2

i) pretreatment included

It must be noted that pretreatment steps like sizing and drying are included within the capital costs of methanol and power conversion installations. It is hard to determine exactly what share of this price is made up by pretreatment installations and operations. For this study, all calculations will be corrected by subtracting the earlier calculated pretreatment costs from the values presented above.

4 Scenario outlines

In this section a number of scenarios will be presented. Based on geographical, agricultural and scale related factors, different situations are assessed, taking into account all possible chains considered to be of serious interest. The main scenarios considered are on one hand Europe, where Scandinavia and the Baltic countries are considered, and on the other hand Latin America, with Brazil and Nicaragua as two possible suppliers. Both continents offer promising potential to supply large amounts of biofuels in the future but at the same time these areas are different in many ways, which makes it possible to gain insight in the way a chain's organisation should be adjusted to account for these differences. The main factors of differentiation are:

- Biomass source: Yield figures, production densities and costs figures will differ
- Geographical situation: Depending on the availability of coastal or railroad connections, certain chains might offer more attractive transport conditions.
- Transport distances: Logistic costs might be a serious constraint and besides that this factor seriously influences the time, necessary to transport the biofuels.

A number of other factors might influence chain performance as well (interest rate, oil prices), but since they are not specifically related to the scenarios considered, they are discussed within the sensitivity analysis (Section 5.2). Scale effects are not taken into account, since all operations run at a large scale where efficiency figures are unaffected by variations.

4.1 The transport chains

A variety of chain structures is proposed for each scenario. The order and organisation within these chains are based upon the information presented in the first three sections. Table 4.1 gives an overview of all chain alternatives to be analysed. Each chain and its steps will be clarified individually.

Logs

The chain of logs is probably the most simple of all chains considered. The trees are considered to be harvested mechanically, as has been described in Section 3.1. After haulage to the roadside the logs can be stored to dry during the warm summer months. No pretreatment is intended so the next step is a truck transport directly to the harbour or railway terminal. At these export terminals a storage option is available. After ship transport, the biofuels are transferred to a truck and taken to the energy plant, again a storage facility is present. In case of an international train transport, no additional transfer is necessary and the fuels are taken directly to the energy plant. Finally the logs will be sized to chips, dried to 10% moisture content and converted to methanol or power. This chain is not applicable to Salix or Eucalyptus, since the stems of these crops are too thin. Heat used for drying is assumed to be freely available.

Chips

This chain is also relatively simple and widely applied, especially when transport distances are relatively small. This chain is applicable to residue wood, as well as Salix and Eucalyptus. Salix, Eucalyptus and forestry residue chips are considered to possess the same density and moisture content so they can be treated equally during transport and handling operations. As has been described in Section 3.1, trees and plants are considered to be dried in-field before being chipped in-field. After haulage to the roadside the chips can be transported to the CGP by truck. At the CGP, the chips will be force-dried to prevent high dry matter losses and health hazards during handling. The dry chips can be stored for some time and subsequently a truck transport will take them to the export terminal. In the import terminal, a storage facility is available so truck transport to the energy plant can be organised smoothly.

Note that the key difference between this chain and the logs chain, is the position of chipping and drying. Chipping logs centrally is a lot cheaper than chipping residues locally, however fresh residues cannot be transported easily because of their shape. An alternative possibility would be to chip the logs centrally before the international transport. However, chips have a low density and the decomposition is high. The next chain offers a possibly attractive alternative.

Bales / Bundles

This chain is based on a new system for compacting logging residues as has been described in Section 3.1. After in-field drying, residues are compacted and shaped into bales (CRL's), whereas Salix and Eucalyptus stems are tied in bundles of similar shape. As discussed earlier it is assumed, that bundles of Salix and Eucalyptus stems can be considered as CRL's during transport and handling operations. No central pretreatment steps are intended so there is no need for a CGP and transport is limited to a truck ride, directly to the harbour or railway terminal. At the export terminal, a storage facility is available. After the international transport the imported biofuels are either directly taken to the conversion plant (in case of a train transport or coastal plant) or they are first transferred and transported by truck and then taken to the conversion plant (in case of an inland conversion plant). Heat used for drying is assumed to be freely available.

Table 4.1: Selected transport chains.

Production system	**Logs**		**Chips**		**Bales/Bundles**							
CHAIN STRUCTURE	**Logs**		**Chips**		**Bales**		**Pellets**		**MeOH**		**Pyro**	
S = Internat. Sea transport L = Internat. Overland transport	S	L	S	L	S	L	S	L	S	L	S	L
Harvesting and forwarding	•	•	•	•	•	•	•	•	•	•	•	•
Storage in pile												
Baling					•	•	•	•	•	•	•	•
Chipping			•	•								
Storage in pile			•	•	•	•	•	•	•	•	•	•
Storage at roadside	•	•										
Pyrolysis oil synthesis											•	•
Local transport	•	•	•	•	•	•	•	•	•	•		
Central storage			•	•			•	•	•	•	•	•
Central chipping							•	•	•	•	•	•
Central drying			•	•			•	•	•	•	•	•
Central Pelleting							•	•				
Methanol synthesis									•	•		
Central transport	•		•		•		•		•		•	
Storage at export terminal	•	•	•	•	•	•	•	•	•	•	•	•
Train transport		•		•		•		•		•		•
Ship transport	•		•		•		•		•		•	
Transport to conversion unit	•		•		•		•		•		•	
Storage at conversion unit	•	•	•	•	•	•	•	•	•	•	•	•
Chipping	•	•			•	•						
Drying chips	•	•			•	•						
Power conversion	•	•	•	•	•	•	•	•			•	•

Pellets

The bales chain is assumed to form the basis for a pellets based transport chain. Since, as has been shown in Section 3.1, the bales production system is the cheapest, next to the system of logs, of which the future applicability is highly uncertain. Furthermore the bales system offers possibilities for utilisation of residues, as well as energy crops in a variety of regions. Besides, the material shape offers some advantages during transport and handling.

After the bales have been produced, a truck transport is arranged to take all material to a CGP where the chipping, drying and pelleting operations will be performed. A storage facility is available at this point. The pellets are subsequently transported, either by train to the conversion plant in the importing country or by truck to the harbour (the latter is unnecessary if the CGP is located at the harbour) where they are shipped, after optional storage for some time. As a last step, the pellets are taken from the harbour to the energy plant by truck.

Methanol

The bales chain is assumed to constitute the basis for a methanol based transport chain for the same reasons as stated in the pellets chain description. The sole difference, compared to the pellets chain is the early conversion of dried chips to methanol, in stead of pellets. This conversion takes place on a relatively small scale. Heat used for drying is assumed to be freely available.

Pyrolysis oil

The pyrolysis chain is based on the idea of local scale liquid fuel production since the conversion technology might proof relatively cheap. However, the feedstock material needs to be chipped and dried to 8% moisture content before the conversion (Meeuwesen, 1997). For that reason, a cost intensive drying step is also necessary so the scale of operation must still be high enough to justify the investments needed (units of 30 MWth are assumed, based on Schenkeveld (2001)). The basis for this alternative is the bales production system, with an in-field chipper, dryer and pyrolysis reactor. The local production site is considered to be equivalent to a CGP for this alternative. The oil can be stored locally, after which it is directly transported to the harbour or railway terminal. At the export terminal, again a storage facility is available. After international transport the imported biofuels are either directly taken to the conversion plant (in case of a train transport or coastal plant) or they are first transferred on a truck in the import terminal (in case of an inland conversion plant). Heat used for drying is assumed to be freely available.

Utilisation

At the bottom-end of each chain, the energy carriers delivered, will be utilised as either power or methanol. These conversions will take place by a large scale gasification (BIG/CC technology) or large scale methanol synthesis. Both options will be considered for all chains, except with respect to the methanol chain, since in that case, the energy carrier (methanol), already has a high application value, rendering subsequent conversions are pointless.

4.2 The Scenarios

It lies beyond the scope of this study to assess the nature and quantity of all possible sources and destinations so in order to simplify this assessment a number of general cases will be constructed that are suitable for the situation of large scale biofuel import to the Netherlands.
Some choices are made, concerning the equipment used. For drying and sizing equipment the cheapest alternatives have been chosen. Densification equipment was selected for the average price. With regard to ship transport the largest scale was selected, which is also the cheapest. An overview is presented in Table 4.2.

Table 4.2: Equipment used for scenario calculations.

Equipment	Type used
Chipper	MP Bolagen
Dryer	Van den Broek RDD (large)
Pelletiser	Fr Hausm. Extruder
Ship transport	CV II 30,000 dwt (woody fuels) and Chemical Tanker 4,527dwt (liquid fuels).

4.2.1 Europe

The European countries to take into account as biomass producers are Sweden and Finland in the north, and Poland and the Baltic countries in the east. Biomass sources to be utilised are forestry residues and Salix. No distinction is made between the two, since material characteristics are not too different and costs are assumed to be practically the same in the near future. The logs chain, however is not available for Salix or Eucalyptus.
Three different geographical situations are taken into account. International distances range from 1000 to 2000 km but an average of 1500 km will be used in this analysis. An overview of the considered situations and their characteristics is presented in Table 4.3. The distance, from production site to CGP (local transport) is assumed to be 50 km in average for all situations. The distance from CGP (central transport) to the export terminal is assumed to be 200 km. Materials can be transported by ship or overland by train. A train transport is assumed to run directly from CGP to the point of utilisation in the destination country. For the ocean transport alternative, two options are considered, one for a situation

with an inland CGP and one for a situation with a coastal CGP. For the latter, the central transport distance is set to zero.

Table 4.3: Assumed transport distances for four different situations in Europe.

		Inland CGP	Coastal CGP
Ocean	Local	50 km	50 km
	Central	200 km	0 km
	International	1500 km	1500 km
Overland	Local	50 km	
	Central	0 km	
	International	1500 km	

A harvest window of 0.5 y/y is defined, due to the seasonal dependency of biomass supply. The system's operation window is set at 1 y/y, since operations are not supply limited due to the application of long term storage facilities at the production site.

4.2.2 Latin America

The Latin-American countries to consider in this study, are Brazil and Nicaragua. The most important biomass source to be utilised in these regions is Eucalyptus. Distances range from 9,000 to 13,000 km but in this scenario analysis a value of 10,000 km is used. An overview of the characteristics of these situations is presented in Table 4.4.

Table 4.4: Assumed transport distances for four different situations in Latin America.

		Inland CGP	Coastal CGP
Ocean	Local	50 km	50 km
	Central	200 km	0 km
	International	10,000 km	10,000 km

A long distance train transport is obviously impossible within this scenario, so only ocean transport situations are considered. As in the previous case, two situations are considered, one with an inland CGP and one with a coastal CGP. For the latter the central transport distance is set to zero. A harvest window of 0.5 y/y is defined, as a result of seasonal dependency of biomass supply. The system's operation window is set to 1 y/y, since log term storage facilities safeguard a continuous supply.

5 Results and discussion

This section will deal with the results of the analysis of all transport chains, for the three presented scenarios. Chain components have been combined to form systems, including production, transport, transfer, pretreatment and energy conversion as was presented in Table 4.1. As has become clear from the preceding sections, the input data is often of an uncertain nature. As a consequence the calculated performance figures for the whole chain, for both costs and energy consumption, should be considered a rough estimate. The main purpose of this analysis is to make a comparison between different alternatives.
Section 5.1 presents the model outcome for the different scenarios. To gain a clear insight in chain performances and to make comparison more easy, costs and energy losses during the conversion step are excluded at first. An estimation of electricity and fuel costs based on different biomass chains and conversion technologies will be given separately. In order to acquire an insight in the influence of model parameters and the sturdiness of the presented outcome, a sensitivity analysis has been conducted, the results of which will be presented in Section 5.2. Finally a discussion with regard to the uncertainty of input data is given in Section 5.3.

5.1 Model outcome

5.1.1 Mass balance

An overview of dry matter losses for the different chains is presented in Table 5.1. During ship transport and during storage in transfer facilities, the materials are dry and/or compacted so the only significant losses of dry matter occur at or near the point of harvest. Since biomass prices are assumed to include dry matter losses during harvest and forwarding, losses are only taken into account from the moment of local truck transport to the moment of conversion. For the chips chain, dry matter losses are 10%, because of decomposition losses during long term storage. The other chains are unaffected by decomposition, due to the application of pretreatment operations.

Table 5.1: Total dry matter losses for different transport chains.

Chain	Biomass dry matter losses
Logs	0%
Chips	10%
Bales	0%
Pellets	0%
Pyrolysis oil	0%
Methanol	0%

5.1.2 Europe

Costs

In Figure 5.1 and Figure 5.2 the model outcome is presented for European conditions for an inland and coastal CGP respectively.

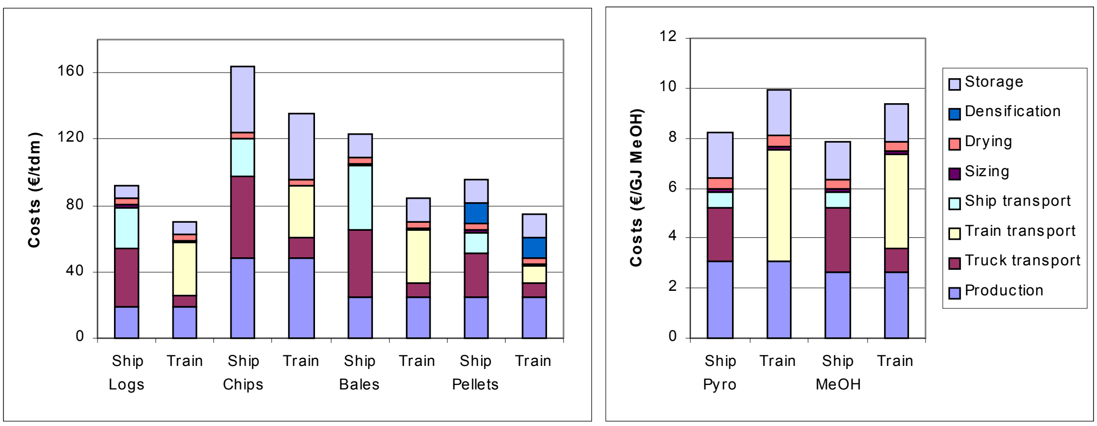


Figure 5.1: Chain costs for a European situation with an inland CGP in €/t_{dm} (woody biomass) or €/GJ_{fuel} (liquid fuels); international transport distance 1500 km; conversion costs are excluded.

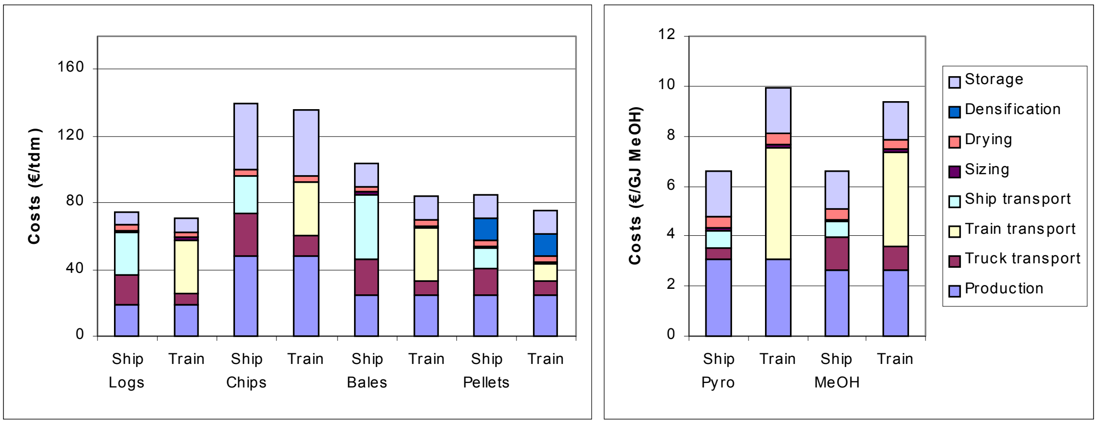


Figure 5.2: Chain costs for a European situation with a coastal CGP in €/t_{dm} (woody biomass) or €/GJ_{fuel} (liquid fuels); international transport distance 1500 km; conversion costs are excluded.

Performance

For the inland CGP alternative, costs for woody biomass, delivered and ready-to-burn at the energy conversion plant range from 71-135 €/t_{dm} or 92-164 €/t_{dm} for train and ship transport respectively. For liquid fuels a smaller range of respectively 9.4-9.9 €/GJ_{fuel} or 7.8-8.2 €/GJ_{MeOH} applies. In case of a coastal CGP, the ship transport chains become cheaper. Woody biomass, transported by ship can be acquired at prices ranging between 75-140 €/t_{dm}. Liquid fuels transported by ship are available at 6.6 €/GJ_{MeOH}.

Chain comparison

For woody biomass, a chain comparison makes clear that the pellets and logs chains are financially the most attractive. The bales chain is more expensive and the chips chain is the most costly of all. It seems that the densification of biomass, by baling but especially by pelleting, proofs worthwhile. With respect to liquid fuels, the pyrolysis oil based chain oil is slightly more expensive than the methanol chain. The logistic advantage during truck transport and the higher energy density of pyrolysis oil, compared to methanol seem to be compensated by the high conversion losses during methanol synthesis. With regard to the long distance transport alternative within the chain, a train transport seems to be a better option than a ship transport for all chains delivering woody biomass. For liquid fuels, a ship transport is cheaper.

Components contribution

Pretreatment costs are relatively low, even for the pellets chain. Sea transport is also relatively inexpensive, but due to the necessity of additional truck transfers and transports, ship transport chains still have to compete with the train transport chains. Truck transport and train transport contribute a major share to the total costs. Storage and biomass production can be expensive as well, depending highly on the type of biomass produced. Chips appear to be economically unattractive due to their high production costs and the necessity of expensive storage facilities.

Improvement potential

A significant reduction of costs, can be achieved by reducing transfer and transport costs, especially with regard to truck transport. An easy way to accomplish this, is to reduce the number of transfer points within the chains. This especially reduces the costs for ship transport chains, as is made clear by the results presented for a coastal CGP situation. Another possibility is to reduce costs of biomass production. A possible solution is to import biomass from developing countries in the tropics. Besides, the necessity of a long term storage of biomass could be reduced by exploiting multiple areas, covering a full-year supply.

Energy

Figure 5.3 and Figure 5.4 depict the energy balance for all chains within Europe for a situation with an inland and coastal CGP respectively.

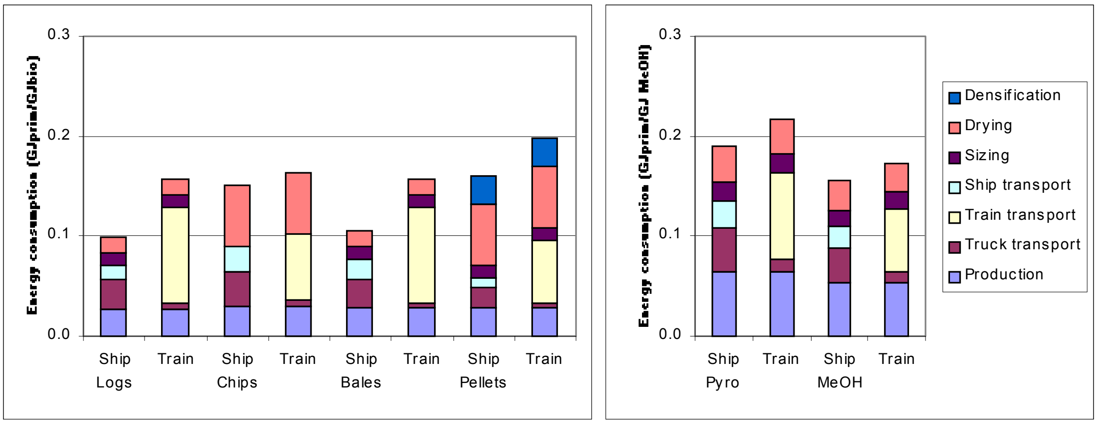


Figure 5.3: Chain energy consumption figures for a European situation with an inland CGP in GJ_{prim}/GJ_{bio} (woody biomass) or GJ/GJ_{fuel} (liquid fuels); international transport distance 1500 km.

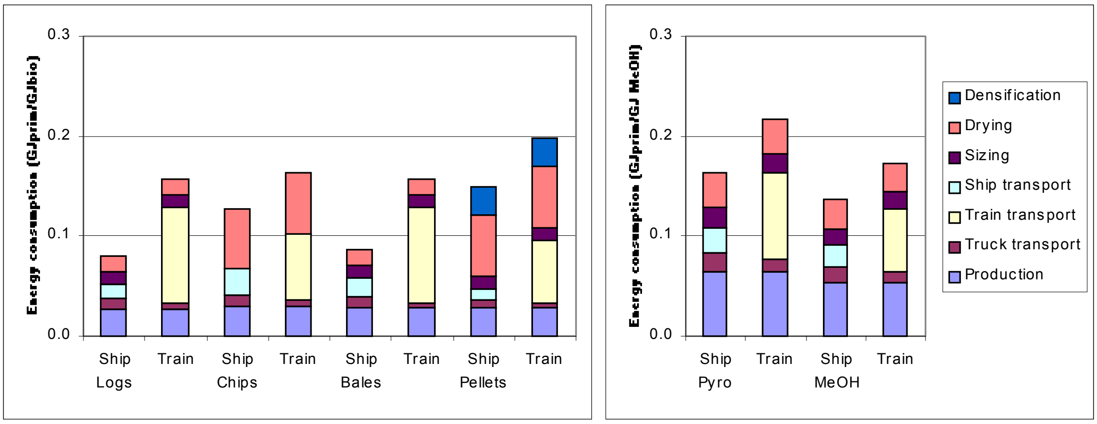


Figure 5.4: Chain energy consumption figures for a European situation with a coastal CGP in GJ_{prim}/GJ_{bio} (woody biomass) or GJ/GJ_{fuel} (liquid fuels); international transport distance 1500 km.

Performance

For a situation with an inland CGP the energy consumption ranges between 0.16-0.20 GJ_{prim}/GJ_{bio} for a train transport and 0.10-0.16 GJ_{prim}/GJ_{bio} for a ship transport regarding woody biomass. Liquid fuels are available at 0.17-0.22 GJ_{prim}/GJ_{MeOH} and 0.16-0.19 GJ_{prim}/GJ_{MeOH} for train and ship transport respectively. When a coastal CGP is utilised, the chains making use of a ship transport will become slightly more attractive. These energy consumption figures lie within a range of 0.08-0.16 GJ_{prim}/GJ_{bio} for woody biomass and 0.14-0.15 GJ_{prim}/GJ_{MeOH} for liquid fuels.

Chain comparison

The bales and logs chains are the most favourable among the woody biomass chains. The pellets chain has a much higher energy consumption than the other chains. The increased energy input as a result of pelleting, apparently doesn't pay off with respect to energy use during transport. With respect to the liquid fuel chains, methanol is favourable. This is the result of high conversion losses associated with the pyrolysis chain. The choice between international train and ship transport seems to be of a relatively high importance, since the differences between chain performance as a result of this choice are larger than the energy input differences between the different chains. Train transport is clearly much more energy consuming than ship transport.

Components contribution

Pretreatment operations like densification and especially drying contribute the largest share to the total energy consumption. Drying operations are especially unfavourable for the chips and pellets chain, due to the lack of waste heat. Truck transport and ship transport contribute only marginally to the total energy consumption. Train transport, however is a very important energy consumer. Biomass production is an important factor as well, however differences between chains are small. Chain energy consumption figures do not positively correlate with the chain costs. This is mainly due to the larger influence of pretreatment operations on energy expenditure in comparison to costs. Besides, the storage of biomass, which is a major factor in determining costs, doesn't influence energy expenditure at all.

Improvement potential

In general, drying is the most energy consuming step within the systems considered. Significant energy savings can be made by using waste heat from other operations. With regard to train transport, the potential for energy reductions is hard to estimate, because of the limited knowledge of the technology involved. Biomass production, might become less energy consuming in the future, due to scale advantages in the utilisation of forestry and agriculture equipment.

Application

In order to make a comparison of actual costs, based on the application of bioenergy, all chains are constructed to result in the production of a single bioenergy form. In Figure 5.5 an integral comparison of all chains is presented, assuming the final utilisation of both, methanol (top) and power (bottom) for all chains considered. The methanol chain is not considered with respect to the production of power, because the conversion from methanol to electricity is not a realistic option.

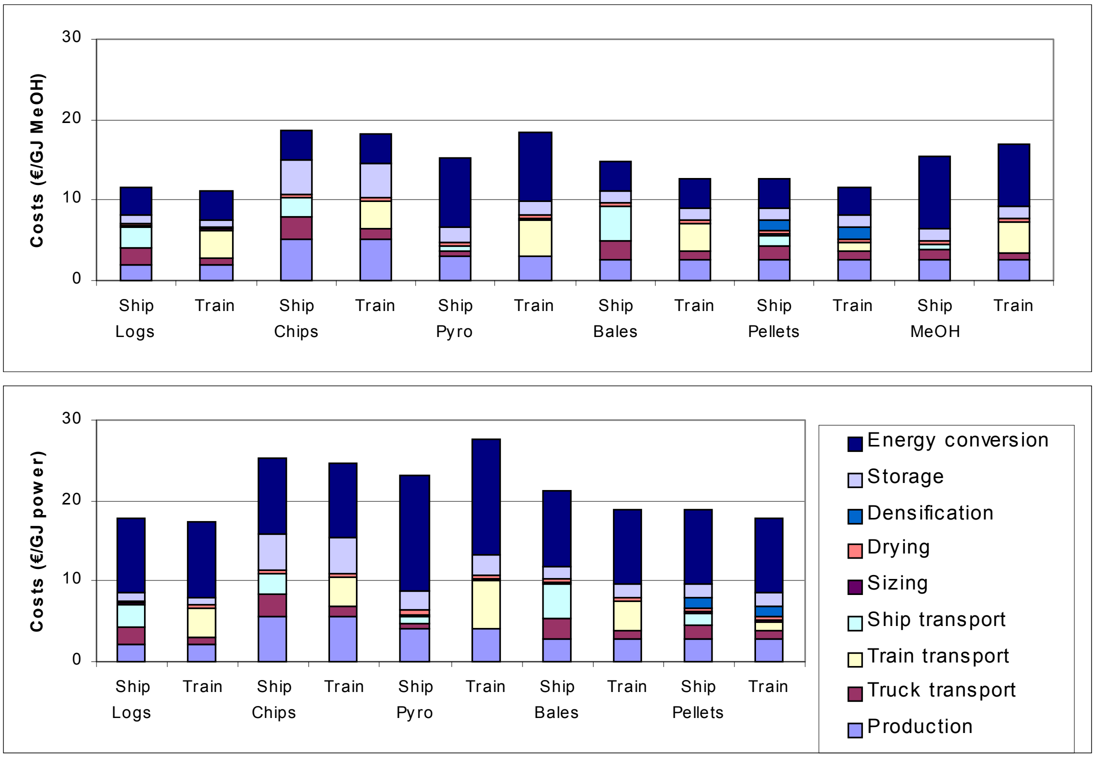


Figure 5.5: Methanol (top) and electricity (bottom) costs for a European situation with a coastal CGP in €/GJ; international transport distance 1500 km; Conversion efficiency and costs for methanol synthesis are based on a 830 MW_{th} methanol synthesis plant, except for the methanol chain, where a small scale conversion (375 MWth) is applied; For the pyrolysis-chain a special conversion has been applied (Section 3.5); conversion efficiency and costs for electricity are based on a 316 MW_{th} BIG/CC unit.

Costs for imported methanol range from 11.2-18.5 €/GJ_{MeOH} for a train transport and 13.5-21.2 €/GJ_{MeOH} for a ship transport. For electricity from imported biomass, costs range between 17.4-28.9 €/GJ_e for a train transport and 17.9-26.0 €/GJ_e for a ship transport.

The added energy conversion costs, more or less, level out the relative differences between the chains, since the share of conversion to the total costs is high, ranging from 28%-57% for methanol and 28%-62% for power. The higher end of these ranges is connected with the pyrolysis chains. A double energy conversion proofs to be a dramatically high costs factor. This seriously reduces the feasibility of the pyrolysis oil based transport chain, when producing electricity. The logs and pellets chain are still the most attractive transport options, either with the use of train or by ship.

5.1.3 Latin America

Costs

In Figure 5.6 and Figure 5.7 the financial performances of different transport chains are presented for a situation with an inland and coastal CGP respectively.

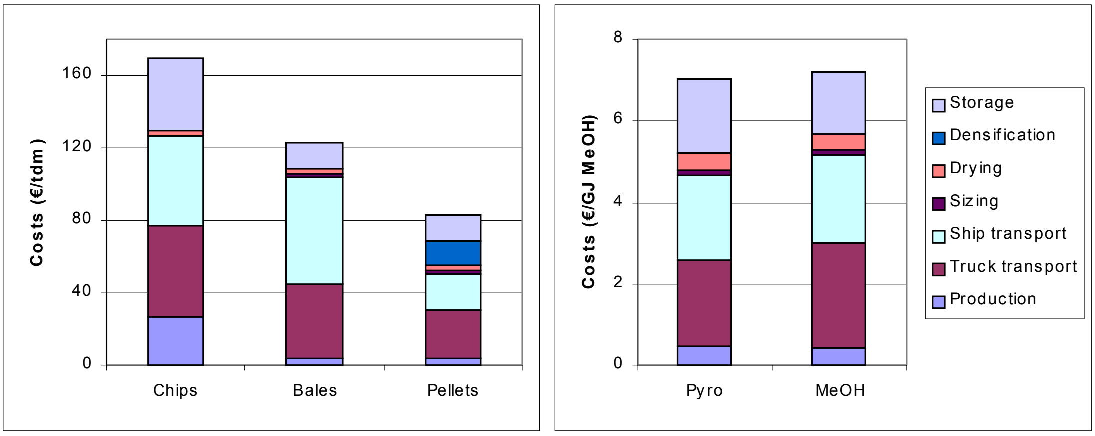


Figure 5.6: Chain costs for a Latin-American situation with an inland CGP in €/t_{dm} (woody biomass) or €/GJ_{fuel} (liquid fuels); international transport distance 10,000 km; conversion costs are excluded; ship transport only.

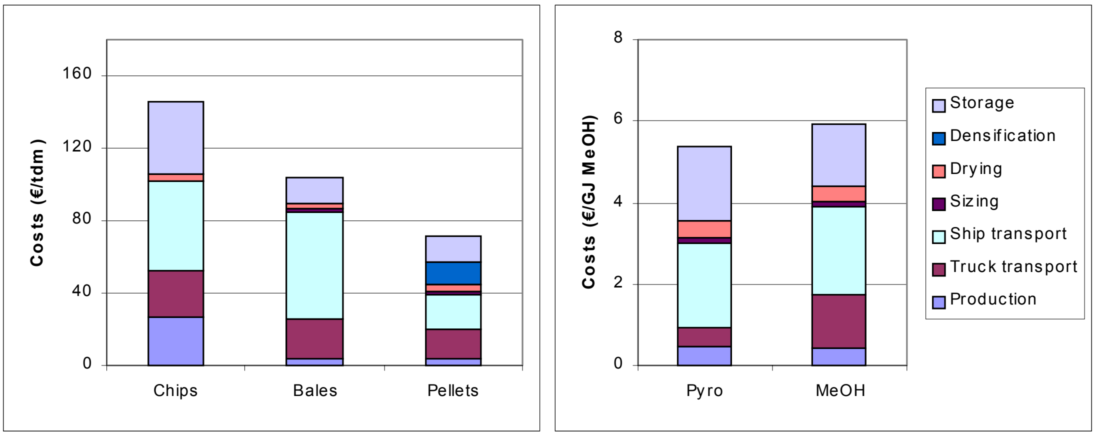


Figure 5.7: Chain costs for a Latin-American situation with a coastal CGP in €/t_{dm} (woody biomass) or €/GJ_{fuel} (liquid fuels); international transport distance 10,000 km; conversion costs are excluded; ship transport only.

Performance

For an inland CGP, the costs for delivered and ready-to-burn biomass lie within a range of 82-170 €/t_{dm} and liquid fuels are available at 7.0-7.2 €/GJ_{MeOH}. A coastal CGP situation significantly reduces the involved costs, resulting in a range of 71-146 €/t_{dm}. For liquid fuels a range of 5.4-5.9 €/GJ_{MeOH} applies.

Chain comparison

The order of chain costs performances doesn't change for the Latin American situation. Comparison of the different chains makes clear that for woody biomass, the pellets chain costs the least. Bales are more expensive and chips are even more than twice as expensive as pellets. For liquid fuels, the pyrolysis chain, is the most attractive. This is due to the higher energy density of pyrolysis oil, and the favourable situation with respect to truck transport, and especially transfer (in-field conversion renders cost intensive bulk transports obsolete). The higher costs for the chips chain, are the result of extra storage costs, which is credible. However, the high but very uncertain biomass production costs for Eucalyptus chips, also contribute largely to the extraordinary high value of the chips chain, which makes the comparison on this ground unfair.

Components contribution
The relative contribution of different system components to the chain costs is slightly different from the European situation. The most striking is the costs increase of international transport (ship) and the costs decrease of biomass production. The higher transport costs do not totally cancel out the advantage of low biomass costs. Pretreatment, storage and truck transport are still important costs determining factors, but do not strongly influence the relative chain performance.

Improvement potential
It seems that sea transport and storage are the components where the most important costs advantages are to be expected. Storage can be avoided by reducing the harvest window of the bioenergy system, for example by exploiting multiple areas, covering a full-year supply. Costs of sea transport are difficult to reduce. It might become cheaper when dedicated vessels and transfer equipment will be utilised, specially developed to carry pellets, bales or logs. A scale increase could also make things cheaper. However, the shipping industry already uses efficient cranes and for the purpose of this study the use of large vessels has already been assumed.

Energy

In Figure 5.8 and Figure 5.9 energy consumption figures are presented for Latin-American conditions, with respectively an inland and coastal CGP.

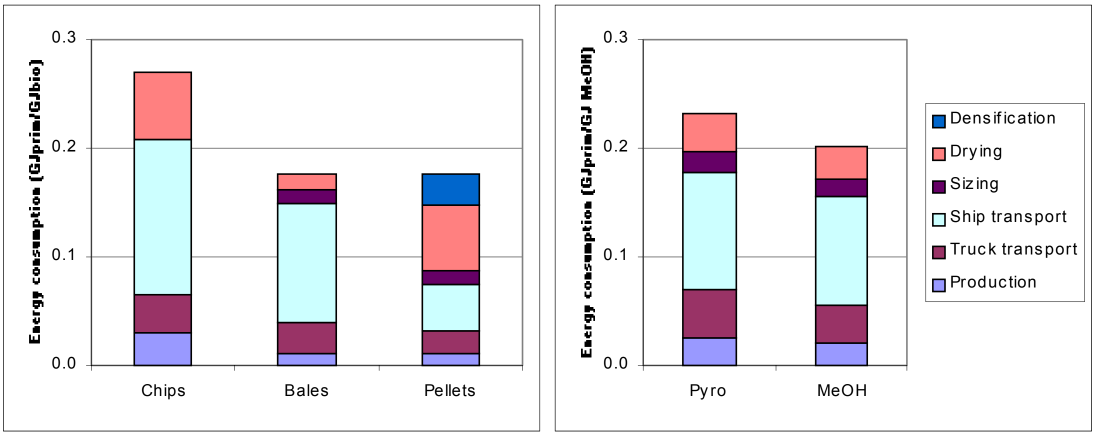


Figure 5.8: Chain energy consumption figures for a Latin-American situation with an inland CGP in GJ_{prim}/GJ_{bio} (woody biomass) or GJ/GJ_{fuel} (liquid fuels); international transport distance 10,000 km; ship transport only.

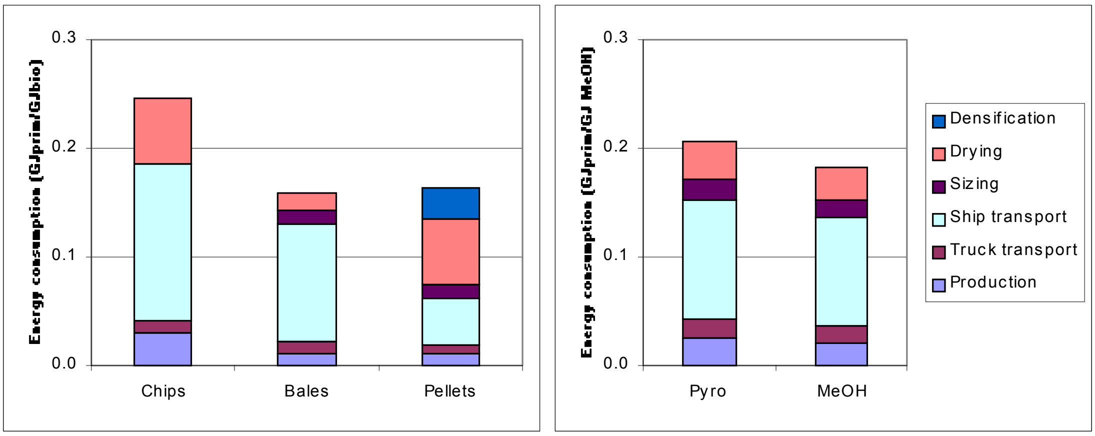


Figure 5.9: Chain energy consumption figures for a Latin-American situation with a coastal CGP in GJ_{prim}/GJ_{bio} (woody biomass) or GJ/GJ_{fuel} (liquid fuels); international transport distance 10,000 km; ship transport only.

Performance

Energy consumption figures for the chains based on woody biomass range between 0.18-0.27 GJ_{prim}/GJ_{bio} for a situation with an inland CGP. For liquid fuels a range of 0.20-0.23 GJ_{prim}/GJ_{MeOH} applies. In case of a coastal situation, figures are slightly lower, resulting in ranges of 0.16-0.25 GJ_{prim}/GJ_{bio} and 0.18-0.21 GJ_{prim}/GJ_{MeOH} for respectively woody biomass and liquid fuels.

Chain comparison

For woody fuels, the pellets or bales chains are the most favourable alternatives. Chips are more energy consuming, mostly due to the increase of fuel use during ship transport. The energy savings as a result of a high bulk density during ship transport are counter balanced by a high energy consumption during drying and pelleting.

Components contribution

Drying and pelleting operations, as well as sea transport are the major costs determining components within the chains. Energy use during biomass production is very low for all chain alternatives.

Improvement potential

Drying operations and ship transport are just like for the European situation the most influential components, with respect to energy use. Energy consumption during drying can be reduced by applying waste heat. This would seriously reduce energy input for the pellets chain. Energy savings with regard to sea transport operations is a more complicated issue and lies beyond the scope of this study.

Application

All chains are constructed to result in the production of methanol or electricity. In Figure 5.10 an integral comparison of all chains is presented, assuming the final utilisation of both methanol (left) and power (right) for all chains considered. The methanol chain is not considered with respect to the production of power, because the conversion from methanol to electricity is unrealistic.

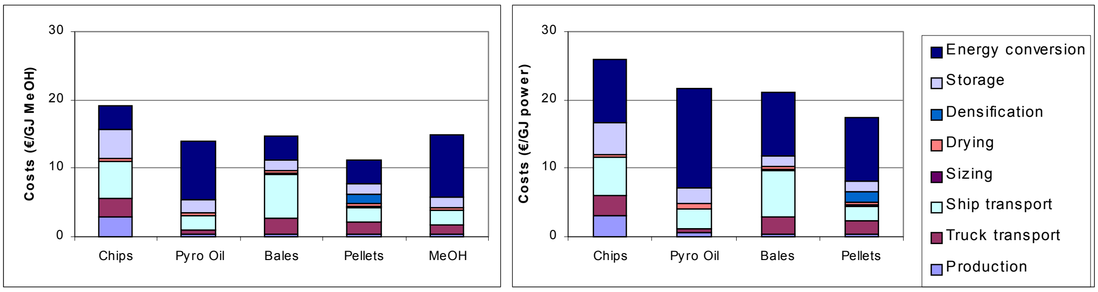
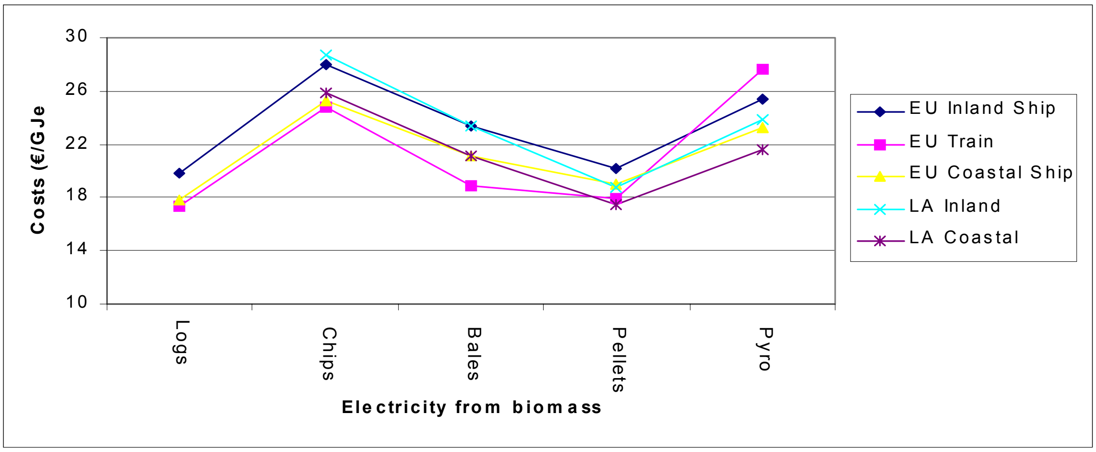


Figure 5.10: Methanol (left) and electricity (right) costs for a Latin-American situation with a coastal CGP in €/GJ; international transport distance 10,000 km; Conversion efficiency and costs for methanol synthesis are based on a 830 MW_{th} methanol synthesis plant, except for the methanol chain, where a small scale conversion (375 MWth) is applied; For the pyrolysis-chain a special conversion has been applied (Section 3.5); conversion efficiency and costs for electricity are based on a 316 MW_{th} BIG/CC unit.

Costs range from 11.3-19.2 €/GJ_{MeOH} for methanol and 17.5-25.9 €/GJ_e for electricity. Like for the European situation, it can be seen that the relative performance differences between the chains are levelled out. With regard to fuel production, the pellets chain is the cheapest. The liquid fuel chains are more expensive but still credible alternatives. As a result of the necessary extra conversion, the logistic advantages of the pyrolysis oil based chain, are compensated. The chains based on chips are the least favourable, due to high transport costs. With regard to the production of electricity, the pellets chain is the cheapest, followed by the bales chain. Pyrolysis is unfavourable, due to the high costs of the conversion of pyrolysis oil to methanol. Chips are the least favourable, due to high transport costs.

5.1.4 Scenario comparison

A complete overview of financial results is given in Figure 5.13. Total costs for European bioenergy range from 11.2-21.2 €/GJ_{MeOH} for methanol and 17.4-28.0 €/GJ_e for electricity. For Latin-America, costs ranges are 11.3-21.8 €/GJ_{MeOH} for methanol and 17.4-28.7 €/GJ_e for electricity. So it is slightly more expensive to import biomass from Latin America. The financial advantage provided by cheaper biomass production costs, is just exceeded by the higher costs for a long distance intercontinental ship transport.



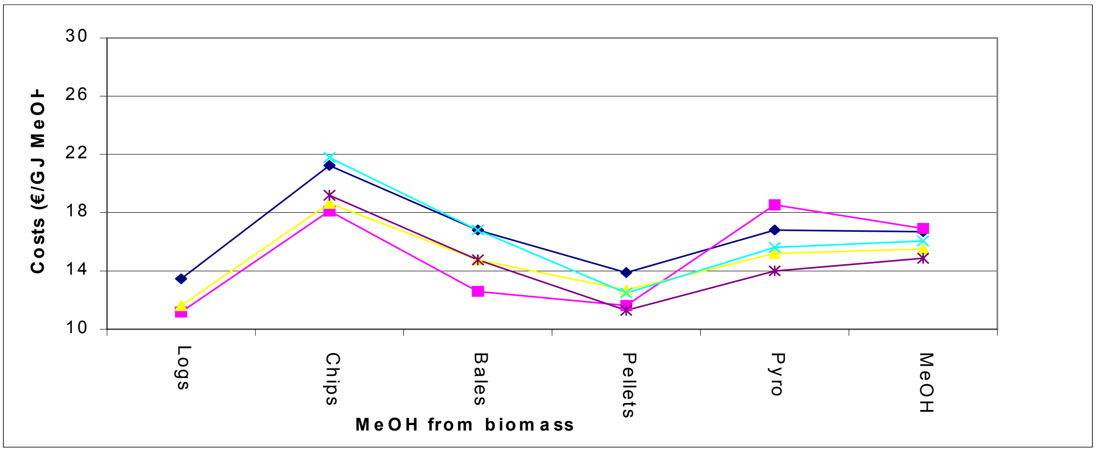


Figure 5.11: Overview of electricity (top) and methanol (bottom) costs for different chains. Situations considered are Latin-American (LA) ship transport from an inland and coastal area and European (EU) ship and train transport from an inland and coastal area. Lines serve only as a visual aid and do not indicate intermediate chain options.

5.2 Sensitivity analysis

In order to gain insight in the relative influence of variables, a sensitivity analysis is performed for the pellets chain (Latin-America coastal). In the first place because it seems to be the best choice. In the second place because the layout of this chain offers the possibility to include all pretreatment steps (i.e. also pelleting) in the analysis. Energy conversion costs are not included. A distinction is made between more or less fixed variables which are subject to a high degree of uncertainty (such as maximum weight/volume, transfer rates or port charges) and flexible variables which are more dependent on the situation considered (such as transport distances or the operation window of a system). Results are presented in spider plots, giving index values at the x-axis for various parameters (100% represents the default position) and total costs at the y-axis. In Figure 5.12 the results are presented for the 'flexible' system variables.

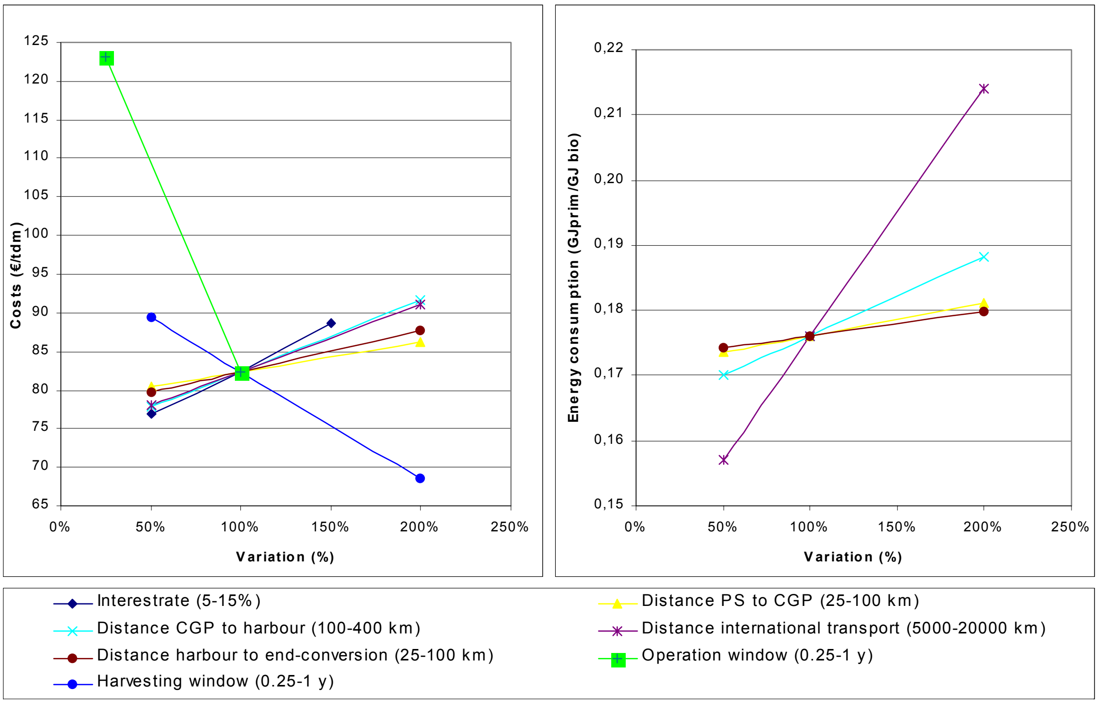


Figure 5.12: Sensitivity analysis with regard to interest rate, scale, distance production site; the default position is the pellets chain for Latin-America and an inland CGP.

Costs range from 69-123 €/t_{dm} and all parameters show a linear influence on the total costs. The most important factors of influence appear to be the operation window, the interest rate, the harvest window and the international transport distance. In order to improve chain performances, the harvest window could be increased. One possibility is to combine biomass streams from different source locations around the world, in order to prevent seasonal influences on supply and the associated high storage costs. The operation window for pretreatment facilities will then decrease to be less than a year. However, the system's operation window has a huge influence on total costs. This trade-off could still be profitable, according to the analysis above.

The distances of the segments PS-CGP and harbour-energy plant, appear to be of little importance. Still it has become clear that truck transport has a big influence on total chain costs. This is mainly due to the costs involved with transfer. Costs reduction within truck transport components is only effective when skipping transfer points.

Another point of consideration is the interest rate of a country when large capital investment decisions are to be made.

With regard to energy consumption figures, a range of 0.18-0.24 GJ_{prim}/GJ_{bio} applies. The international transport distance is the most important parameter. The sensitivity is low with regard to the segments where truck transports are used and sensitivity decreases with smaller distances.

In Figure 5.13, costs and energy consumption are presented as related to the distance of international transport for ship as well as for train.

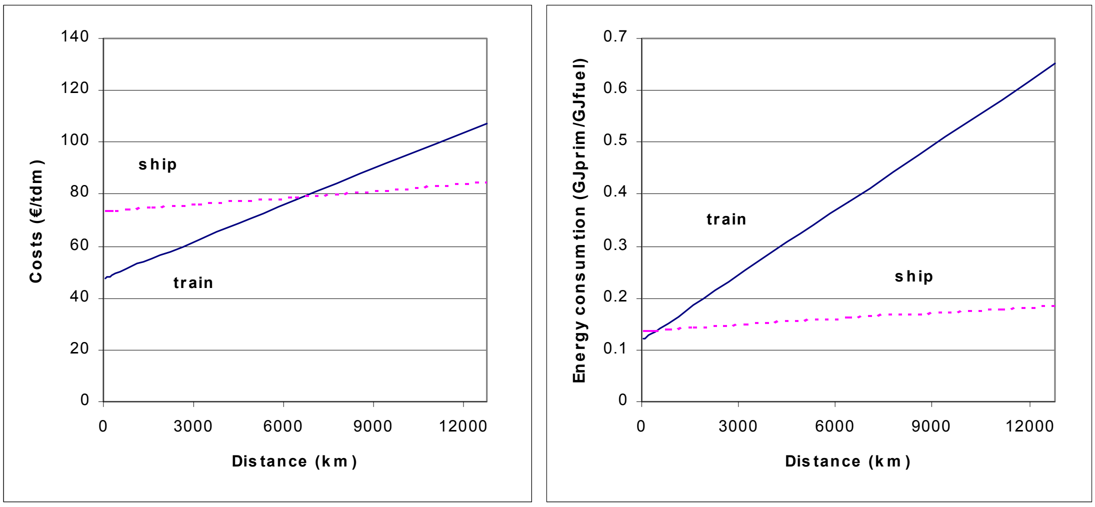


Figure 5.13: Total costs (€/t_{dm}) and energy consumption (GJ_{prim}/GJ_{bio}), excluding conversion costs, as a function of international transport distance, for train and for ship; the default position is the pellets chain for Latin-America and an inland CGP.

For a train transport the fixed costs are lower than for a ship transfer. Which means that, at relatively short distances a train transport is to be preferred. However, variable costs are higher for a train transport than for a ship transport so at a certain point a break-even distance will be reached. For the chain considered (pellets), this distance is about 7,000 km.

It must be noted that the financial information used to calculate train transport costs, is highly uncertain. The same is true for shipping, where factors like transfer costs and port charges are strongly dependent on specific location. A slight alteration in input values could shift the break-even point towards either direction, but still, for a European situation, where distances often are way beneath 2,000 km a train transport proofs to be the cheapest alternative.

With regard to energy input, a train transport is highly unfavourable. For any distance beyond 800 km a train transport is more energy consuming. At larger distances, for example beyond 6,000 km, a train transport consumes more than 0.4 GJ_{prim}/GJ_{bio}. With an energy loss this high, a long distance transport by train is unfeasible.

In order to obtain an insight in the relative influence of different 'fixed' parameters and the sturdiness of the model presented, three spider plots are presented in Figure 5.14. The first diagram presents an analysis of truck transport parameters (top left), the second diagram presents an analysis of ship transport parameters (top right) and the third diagram gives an analysis of pretreatment parameters (bottom left).

Truck transport parameters

The maximum tonnage truck capacity, has a non-linear negative influence on total costs. The explanation for this is that an increase in maximum tonnage is only effective up to a certain value, since beyond that value volume limitations determine the number of transports. Pellets possess a relatively high density, which means, the transport capacity tends to be mass limited up to high values. For most other energy carriers, an increase of maximum tonnage won't be as effective in terms of costs reduction. When the transport capacity is mass-limited, maximum tonnage strongly influences costs, giving a range of 77-95 €/t_{dm}. Truck km-costs also exert a relatively large influence on the total costs, causing a range of 74-92 €/t_{dm}. With regard to transfer costs, chain performances are not as sensitive. A range of 80-86 €/t_{dm} is found. However, it must be stressed that handling costs for pellets are low compared to other woody fuels. For other chains this range will probably be wider.

Ship transport parameters

The ship volume capacity is the most influential parameter within this category. The influence is non-linear and negative. This is due to the increase of the number of necessary vessels and the accompanying capital costs. Capital costs are annuitised, using an exponential formula, hence the non-linear curve. Total costs range between 75-93 €/t_{dm}. The system is highly sensitive to transfer costs as well. A range of 77-95 €/t_{dm} is found. Heavy fuel costs and port charges are less important, but there influence is still significant. Total costs range from 81-85 €/t_{dm} for both parameters. Ship speed and transfer rate exert a negative influence, but are practically insignificant with regard to the total chain costs. The system's dependency on both parameters is non-linear for the same reason as explained above.

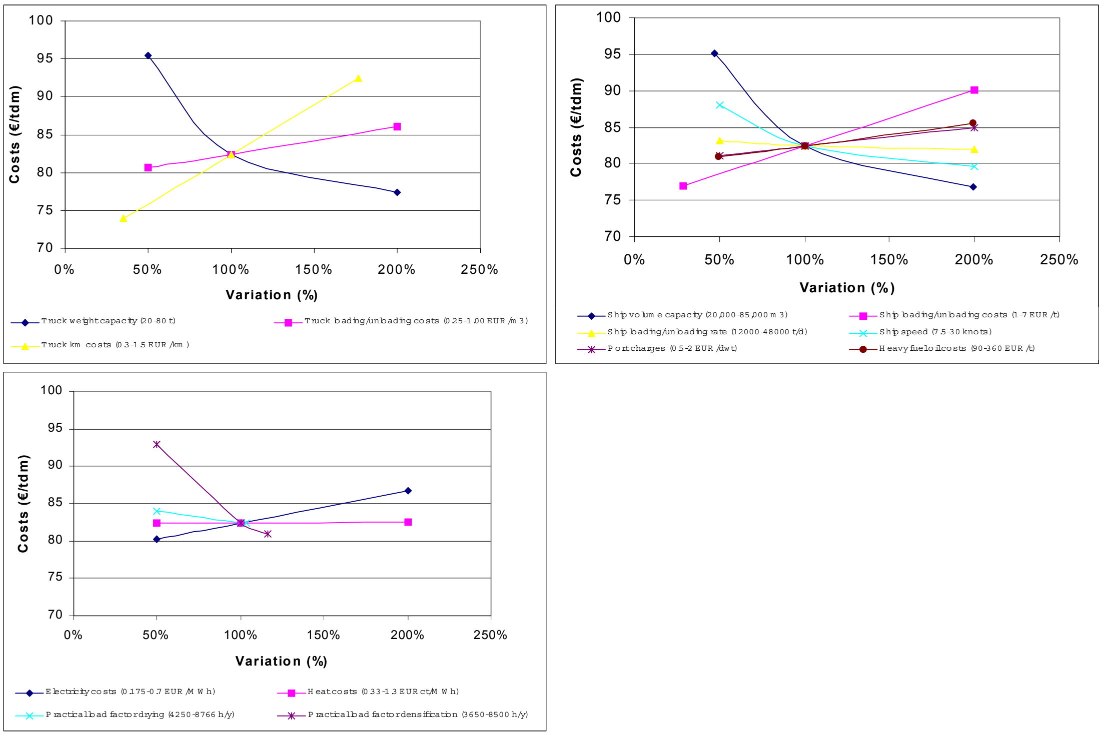


Figure 5.14: Sensitivity analysis for uncertain input data concerning truck transport, ship transport and pretreatment operations; the default position is the pellets chain for Latin-America and an inland CGP.

Pretreatment parameters

The pretreatment parameters seem to be less influential than the other parameters discussed. The biggest range to be expected is 81-93 €/t_{dm}, with regard to the practical load factor for densification. This is by far the most important parameter within this category. Electricity costs result in a range from 80-86 €/t_{dm} while heat costs are practically insignificant, lying between 82-83 €/t_{dm}. The practical load factors for drying and densification operations exert a non-linear negative influence on the total costs. Curves are negative because a larger operation time reduces capital costs for the equipment involved. A non-linear relationship is found because annual capital costs are calculated, using an exponential annuity calculation, dependent on interest rate. The load factor for densification is the most influential, probably due to the shorter life-time as compared to drying equipment.

5.3 Parameter discussion

In this section the degree of uncertainty for various input data will be discussed for each system component.

Biomass production

Biomass production costs and energy use are derived from a variety of credible literature sources. However wide ranges exist for all biomass sources considered. This is because costs and energy consumption are strongly dependent on local conditions. No detailed study has been done into biomass production systems; therefore the dependency of costs and prices of biomass on specific local conditions could not be taken into account. With respect to the feasibility of the production systems considered in this study, it must be noted that the availability of whole stem wood (logs chain) is uncertain, since this wood is normally used in the timber and pulp industry. Another factor of uncertainty is the future price development of energy crop cultivation. In this study it is assumed, that European prices for Salix will drop in the near future.

Pretreatment

Most data on pretreatment operations are derived from Pierik (1995). The results of performed costs and energy calculations were validated with other literature. Generally, the calculated values turn out low compared to other literature sources, but they are all within acceptable ranges. The only exception to this holds for calculated pelleting costs. These can not be validated easily, since literature sources are unclear and/or incomplete with regard to equipment performance figures and feedstock properties.

Transport

Costs and energy use of truck transport is largely based on Van den Heuvel (1995). For woody fuels this information is credible, however with regard to transfer operations, a more differentiated approach would have been favourable, since now no distinction is made between different types of cargo. With regard to truck transport of liquid fuels, no data was available so calculations for methanol an pyrolysis oil should be considered highly uncertain. Truck fuel consumption, speed and loading and unloading rates don’t influence the total costs in this model.
Train transport figures are solely derived from Börjesson (1996). Other useful quantitative information could not be found. Pyrolysis oil transport costs are assumed to be equal to methanol transport costs, since both substances are liquid, and hazardous during transport. However, this assumption could not be substantiated by literature or other references. Calculations on energy consumption during train transport proof to be within ranges of other literature sources.
Ship transport data are mainly derived from personal communications with people active in the Swedish harbour sector. This could result in a slight bias, caused by the regional dependency of some of the figures used. For example, transfer costs and port charges are strongly dependent on facilities available. This study was limited in time, so a more detailed analysis of harbour operations could not be done. It was assumed that only non-dedicated ships are used. In case of future developments towards large scale biofuel transports, the utilisation of dedicated ships could reduce costs, due to more efficient handling or even onboard pretreatment facilities.

Storage

A rather arbitrary time of two-days storage has been assumed for all transfer points. Another weak point is the lack of data on storage of liquid fuels. However, since storage costs are dominated by the long-term biomass storage costs as a result of seasonal biomass supply, no significant influence on total costs is to be expected.

Energy conversion

Calculations of energy conversion costs are relatively crude. For gasification and methanol synthesis of biomass, data are derived from extensive research. However, on flash pyrolysis little is known at present so the figures used, should be considered uncertain. The costs and efficiencies of gasification or methanol synthesis of pyrolysis oil, are based on crude assumptions as well. The energy conversions contribute a large share to the total bioenergy price, so it should be kept in mind that prices, based on pyrolysis chains stated are uncertain.

6 Conclusions and Recommendations

6.1 Conclusions

As a consequence of environmental advantages and increasingly progressive energy policies in various European countries, biomass energy has the potential to become one of the world's most important sources of energy. Current insights suggest that some world regions have a much larger bioenergy production potential than others. Consequently various countries may become net suppliers of renewable bioenergy to countries that are net importers of energy (Faaij, 2001b). In order for bioenergy to be available to importing regions a distribution of biofuels over long distances is necessary. This implies extra costs, complex logistics and energy losses. Hence a transportation problem exists.
When transporting biofuels, a variety of alternative chains can be constructed. Within this study a selection has been made that includes direct transport of woody biomass (chips, logs or bales), an intermediate energy carrier (pyrolysis oil) and a high quality energy carrier (methanol). Besides, factors like the production method of biomass, the transport type and the order and choice of pretreatment operations are of importance.

The composition of a logistic chain is expected to largely influence costs and energy expenditure and therefore this study has compared a variety of transport chains. An individual chain's performance is influenced by a large number of variables, such as the transport distance, fuel prices and equipment operation windows. In order to explore possibilities for improvement, the effects of such variables on costs and energy consumption within a chain, were assessed. The main objective of this study was to obtain an insight in the impact of different key factors, on chain costs and energy consumption. Scenarios analysed are Latin-America and Europe for which the distinguishing parameters were assumed to be the transport distances and biomass prices. For both regions an analysis was made for a situation where ship transports are applied for both, a coastal and an inland biomass production site. In case of European biomass, a train transport was considered as well.

Within this study, it is assumed that delivered biomass can be converted to power or methanol. Total costs for European bioenergy range from 11.2-21.2 €/GJ_{MeOH} for methanol and 17.4-28.0 €/GJ_e for electricity. For Latin-America, costs ranges are 11.3-21.8 €/GJ_{MeOH} for methanol and 17.4-28.7 €/GJ_e for electricity. The lower end of these ranges is represented by transport chains that are characterised by the use of high density energy carriers such as logs, pellets or liquid fuels.

The transport of chips should be avoided categorically. Local (small scale) chipping operations are expensive and transport is uneconomical, since most transport systems are volume limited. Besides, there is the problem of high dry-matter losses and health hazards during decomposition of wet chips.
A transport chain, based on the transport of whole stem wood (logs) appears most favourable for all situations, since costs intensive pretreatment operations like chipping and drying are only necessary at the conversion unit. However the availability of whole stem wood is limited, due to market competition with the timber and pulp industry.
A reasonable alternative for all situations considered is to use forest residues or dedicated energy crops. Salix is applied in Europe and Eucalyptus for Latin America. The most favourable way of preparing biomass, is to apply baling equipment. In this way, inefficient local chipping is avoided and road transport is relatively cheap, due to the higher density of the bales.
For all situations considered, it proofs favourable to centrally chip and dry biomass to pellets. This creates a big costs advantage with respect to transport costs for truck transports as well as for ship or train transport over longer distances. Energy use figures are pretty high for this option.
Another possibility is to convert biomass to pyrolysis oil or methanol as soon as possible, before transport by ship or train takes place. This results in very low transport and pretreatment costs. However, a chain based on methanol transport, turns out to be more expensive due to scale disadvantages during the early conversion. Energy based on pyrolysis oil is expensive because an extra conversion is necessary in order to utilise the product.

With respect to energy consumption, the transport of chips is highly unfavourable, for the same reasons as stated above. A production system based on baling seems the most feasible. Pelleting of biomass significantly increases energy input. For Latin-American chains this energy input is compensated by an equal gain in energy savings during sea transport. Energy consumption figures for drying can possibly be reduced to a large extent by utilising waste heat.

Scenario analysis

In Latin-America, biomass is cheaper than in Europe. However, this financial advantage is exceeded by the higher costs for a long distance ship transport. For long distances and intercontinental transport, a ship transport is to be preferred over a train transport. With respect to costs, the break-even distance depends on the structure of the chain considered. A train transport can be an attractive alternative up to 1,000-7,000 km. However when energy consumption is considered, a train transport becomes unfeasible already after 3,000-4,000 km. Within Europe a train transport is cheaper than a ship transport, except when liquid fuels are carried. In case a ship transport is used, costs, as well as energy can be saved by utilising coastal biomass production regions.

Parameter analysis

For the most favourable chain (based on pellets), total costs range from 69-123 €/t_{dm}, excluding energy conversion. Energy input lies within a range of 0.16-0.21 GJ_{prim}/GJ_{bio}. By far the most influential parameters are the operation window of the system and the harvest window. When these are left out of the picture, a smaller range of 78-92 €/t_{dm} remains. Other factors of importance are the interest rate and the international transport distance. Pretreatment operations do contribute an important share to the total costs and energy use, however energy costs and load factor figures, determining the application of pretreatment equipment exert a relatively weak influence.

Improvement potential

Costs could be reduced by increasing the harvest window of a biomass system. However, it is of crucial importance to maintain a large operation window, in order to keep a biomass transport system economically feasible. A significant reduction of costs, can be achieved by reducing transfer and transport costs, especially with regard to truck transport. An easy way to accomplish this, is to reduce the number of transfer points within the chains. It seems that, with regard to intercontinental distances, sea transport and storage are the components where the most important costs improvements are to be expected.

With respect to energy consumption, it seems that drying operations and long distance transport are the most influential components. During drying, energy input can be reduced by applying waste heat. This would seriously reduce energy input for the pellets chain. Energy savings with regard to sea transport operations is a more complicated issue and lies beyond the scope of this study. With regard to train transport, the potential for energy reductions is hard to estimate, because of the limited knowledge of the technology involved.

Parameter discussion

Within this study a large amount of data has been used. Some parameters are subject to a high degree of uncertainty. It remains unknown in what way the costs and prices of biomass depend on local conditions. Another factor of uncertainty is the future price development of energy crop cultivation. Calculated costs and energy consumption of pretreatment operations are validated but pelleting costs are uncertain, since literature sources are inconsistent. Train transport costs are based on a single source and could therefore not be validated. Ship transport data are mainly derived from personal communications with people active in the Swedish harbour sector. This could result in a bias, caused by the regional dependency of some of the figures used. Due to time limitations, a more detailed analysis of harbour operations could not be done. It was assumed that only non-dedicated ships are used. In case of future developments towards large scale biofuel transports, the utilisation of dedicated ships could decrease the costs. A rather arbitrary time of two-days storage has been assumed for all transfer points. With respect to storage and transport of liquid fuels, no data was available so results with respect to chains based on methanol or pyrolysis oil should be considered uncertain. Calculations of energy conversion costs are rather uncertain with respect to flash pyrolysis. The costs and efficiencies of gasification or methanol synthesis of pyrolysis oil, are based on uncertain assumptions as well. The energy conversions contribute a large share to the total bioenergy price, so it should be kept in mind that prices, based on pyrolysis chains stated, are uncertain.

6.2 Recommendations

With the outcome of this study a new insight is gained into the factors, determining costs and energy consumption during bioenergy transport. As a result, this research can be helpful for energy companies and bioenergy traders in developing actual biotrade strategies.
It is advisable to start experimenting with small scale bioenergy transport operations, using European forestry logs if available. When in the future processing scales increase, the production of dedicated energy crops like Salix or even Latin-American crops like Eucalyptus will be necessary. The application of densification equipment is highly recommended for this situation. In the long term, an early methanol conversion might also be interesting, or even the application of flash pyrolysis. However, at the moment no conclusive recommendations can be given on the feasibility of transporting liquid fuels.

Due to the limitation of time, a lot of information could not be obtained. Therefore, the results of this study, are partly based on data, with a high degree of uncertainty. Many assumptions have been made in order to cope with this problem. Especially with regard to truck transport, train transport and the storage and transfer of liquid fuels a huge lack of data exists. It would improve the credibility of the outcome of the developed model, if this information could yet be obtained and used.

A lot of progress is currently made in the field of biomass conversion technologies. Methanol synthesis, pyrolysis and BIG/CC technologies are rapidly improving. A more sophisticated conversion technology could significantly reduce calculated costs.

This study is more broad and more detailed than former studies in this field. In order to obtain actual fuel or electricity prices, the chosen general approach is unsuitable and a more specific systems study will be necessary. For this purpose, only the most successful chains need to be considered. Some Dutch energy companies are already importing large quantities of biomass. A co-operation between researchers and energy companies could be profitable.

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Appendix I: Biomass energy practice in Sweden

Compared to other countries, Swedish energy supply comes from a relatively large proportion of renewable energy sources, such as biofuels, hydro power and wind power. Sweden has a good availability of forests, an efficient forest products industry and a wide existence of district heating systems, which creates a suitable climate for biofuel energy production. In 1999 renewable sources provided 26% of the country's total energy supply. No less than 15% was made up by biofuels (94 TWh).

Of the European countries it is Sweden and Finland that have the highest proportions of biofuels in their respective energy systems. Other countries with potentially high volumes of biofuels, but in which little use is made of them in their energy systems, are Germany, France, the UK, Romania and Austria (SNEA, 2000). So Sweden is not just an important source of biofuels for the rest of Europe, but especially an example for other countries with a potential to produce biofuels themselves.

Biomass district heating and electricity

The quick development of Sweden's industrial wood fuel market is based on the development of the district heating sector[4] over a period of 20 years, from a low level in the 1970s to a substantial market of over 50% of biofuels supplied to the district heating sector, reaching 26.5 TWh in 1999 (SNEA, 2000). Of this, wood fuels accounted for 15.7 TWh which mainly consisted of felling waste and forest by-products. Approximately 3.5 TWh of biofuels were used for electricity production during 2000. Of this, about 1 TWh of wood fuels was used for the production of electricity in CHP plants. Of the remainder, 1.1 TWh of wood fuels were used in industrial back-pressure plants and 1.2 TWh in the form of black liquors (pulp industry).

The Swedish wood fuel market

Swedish market prices for wood fuels steadily decreased over the last 20 years, while consumption increased dramatically. There are many producers and there is a strong competition between them, showing transparency in the production costs. Unrefined wood-fuels (residue chips) are traded in Sweden at approximately 100 SEK/MWh. Recycled wood fuels can be imported to Sweden at 20-30 percent lower prices. As a result the domestic price level has been nominally stable for many years, which means a decrease in real value.

International competition and European policy

Prices kept dropping even below domestic production costs, mainly under the influence of international competition. The extensive waste legislation in other European countries, especially Germany and The Netherlands, make it possible to import organic waste and chipped demolition wood to Sweden at minimum prices. Therefore a few years ago Sweden started importing biofuels from abroad. Quantities are difficult to value but where estimated in 1997 to about 7-9 TWh and have increased each year since.

The utilization of wood-fuels is of course strongly dependent on the price of fossil fuels. In Sweden, the use of fossil energy has been taxed since the 1950s. There are different taxes on electricity, carbon dioxide, sulfur and NO_x, depending on a variety of factors, such as the type of use (heating or motor fuel), the location (the northern, middle or southern parts of Sweden) and the sector where the energy is used (the industrial, the domestic or the energy sector). Tax rates can be as high as 3 Eurocents per kWh_e for coal and crude oil whereas prices for biofuels and other 'clean energy carriers' are unaffected. As a result of this sophisticated tax system, bioenergy has been able to compete well with fossil fuel consumption in Sweden.

Nord Pool electricity exchange

Since the early 1990s the electricity market in Sweden and the other Nordic countries has been reconstructed and made part of the Nordic electricity market. Prior to the reconstruction, trade between the four Nordic countries (Norway, Sweden, Finland and Denmark) was controlled by bilateral agreements between purchasers and sellers. Today, this arrangement has been complemented by a Nordic power exchange, Nord Pool, on which the price of electricity for each hour of the day is determined 24 hours in advance. As a result, the production of electricity on the Nordic electrical

[4] District heating is a public heating system, intended for supplying heat in networks to mostly residential buildings but also for industrial use. Heat is produced in and supplied from hot water boiler plants and combined heat and power plants in which heat and electricity are produced simultaneously.

system is produced in those plants having the lowest production costs. Electricity can now be directly traded between the Nordic countries. The prices of electricity vary between customer categories, between urban and rural areas and between the Nordic countries. This is due to varying transmission costs across regional and local transmission and distribution systems, different taxation regimes, subsidies, national rules and the structure of the electricity market. The final price of electricity to a customer consists of a grid tariff, a price for the electrical energy itself, various charges and taxes and, finally, the profit margin applied by each link in the chain. In Europe the development will be towards a common market, with electricity being produced wherever it is physically and economically most appropriate.

Future potential

So it has become clear that Sweden presently imports more and more biofuels, mainly because of the high taxes on fossil fuels and the extensive waste legislation in some densely populated European countries (Germany and The Netherlands). Energy policies have up to now mainly been national, however the European communion is moving towards one common policy, regarding energy and environment. This means energy taxes and waste legislation will be the same for most countries. The future economic potential of Swedish forest energy production is therefore promising to say the least.

Analyses of the Swedish biomass potential vary greatly depending on the assumptions used. Börjesson (1997) have calculated biomass potentials based on different intensities in logging residue and straw recovery, present and estimated future productivity of energy crops and forest trees, different balances between forest increment and demand for wood products, and different amounts of arable land available for energy crop production. A number of scenario's were considered, diverging from optimistic to pessimistic future perspectives concerning the above mentioned factors.

When considering forest fuels the amount of productive forest land in Sweden was assumed to be the same around 2015 as today, i.e. 23 million ha. Different production intensities were taken into account, resulting in varying yields. For example optimized fertilisation regimes and the application of ash recirculation could increase the potential yield drastically. Future energy crops cultivation (2015) was assumed to be realized on 200.000 to 800.000 ha, which constitutes respectively 7% to 30% of Sweden's current arable land.

Taking these factors into account, predictions for 2015 ranged from 30 to 170 TWh/y for forestry wood and from 14 to 59 TWh/y for energy crops. (Börjesson et al., 1997) shows that in the most optimistic case the future utilization of biomass, together with wind power (estimated to be 7 TWh in 2015), could replace a major part of fossil fuels and nuclear power production in Sweden.

Appendix II: Financial chain performances

Conversion costs are excluded

Scenario Europe

Table II.1: Ship transport, inland CGP

	Logs (€/t_{dm})	Chips (€/t_{dm})	Bales (€/t_{dm})	Pellets (€/t_{dm})	Pyro oil (€/GJ $_{MeOH}$)	Methanol (€/GJ $_{MeOH}$)
Production	18.60	48.04	24.30	24.30	3.09	2.61
Truck transport	35.71	49.98	41.19	27.12	2.11	2.59
Train transport	0.00	0.00	0.00	0.00	0.00	0.00
Ship transport	24.71	22.25	38.61	12.25	0.67	0.63
Sizing	1.41	0.00	1.41	1.41	0.12	0.10
Drying	3.56	3.70	3.56	3.70	0.45	0.38
Densification	0.00	0.00	0.00	12.63	0.00	0.00
Storage	8.07	39.75	13.99	14.15	1.78	1.51
Total	92.06	163.72	123.06	95.56	8.22	7.84

Table II.2: Ship transport, coastal CGP

	Logs (€/t_{dm})	Chips (€/t_{dm})	Bales (€/t_{dm})	Pellets (€/t_{dm})	Pyro oil (€/GJ $_{MeOH}$)	Methanol (€/GJ $_{MeOH}$)
Production	18.60	48.04	24.30	24.30	3.09	2.61
Truck transport	18.43	25.87	22.08	16.07	0.46	1.33
Train transport	0.00	0.00	0.00	0.00	0.00	0.00
Ship transport	24.71	22.25	38.61	12.25	0.67	0.63
Sizing	1.41	0.00	1.41	1.41	0.12	0.10
Drying	3.56	3.70	3.56	3.70	0.45	0.38
Densification	0.00	0.00	0.00	12.63	0.00	0.00
Storage	8.07	39.75	13.99	14.15	1.78	1.51
Total	74.78	139.61	103.96	84.51	6.57	6.57

Table II.3: Train transport

	Logs (€/t_{dm})	Chips (€/t_{dm})	Bales (€/t_{dm})	Pellets (€/t_{dm})	Pyro oil (€/GJ $_{MeOH}$)	Methanol (€/GJ $_{MeOH}$)
Production	18.60	48.04	24.30	24.30	3.09	2.61
Truck transport	7.04	12.32	8.86	8.86	0.00	0.95
Train transport	31.86	31.86	31.86	10.02	4.48	3.79
Ship transport	0.00	0.00	0.00	0.00	0.00	0.00
Sizing	1.41	0.00	1.41	1.41	0.12	0.10
Drying	3.56	3.70	3.56	3.70	0.45	0.38
Densification	0.00	0.00	0.00	12.63	0.00	0.00
Storage	8.06	39.41	13.96	14.12	1.78	1.51
Total	70.52	135.33	83.95	75.04	9.91	9.36

Scenario Latin America

Table II.4: Ship transport, inland CGP

	Chips (€/t_{dm})	Bales (€/t_{dm})	Pellets (€/t_{dm})	Pyro oil (€/GJ $_{MeOH}$)	Methanol (€/GJ $_{MeOH}$)
Production	26.93	3.80	3.80	0.48	0.41
Truck transport	49.98	41.19	27.12	2.11	2.59
Train transport	0.00	0.00	0.00	0.00	0.00
Ship transport	49.32	58.92	19.61	2.05	2.18
Sizing	0.00	1.41	1.41	0.12	0.10
Drying	3.70	3.56	3.70	0.45	0.38
Densification	0.00	0.00	12.63	0.00	0.00
Storage	39.75	13.99	14.15	1.78	1.51
Total	169.67	122.87	82.42	7.01	7.17

Table II.5: Ship transport, coastal CGP

	Chips (€/t_{dm})	Bales (€/t_{dm})	Pellets (€/t_{dm})	Pyro oil (€/GJ $_{MeOH}$)	Methanol (€/GJ $_{MeOH}$)
Production	26.93	3.80	3.80	0.48	0.41
Truck transport	25.87	22.08	16.07	0.46	1.33
Train transport	0.00	0.00	0.00	0.00	0.00
Ship transport	49.32	58.92	19.61	2.05	2.18
Sizing	0.00	1.41	1.41	0.12	0.10
Drying	3.70	3.56	3.70	0.45	0.38
Densification	0.00	0.00	12.63	0.00	0.00
Storage	39.75	13.99	14.15	1.78	1.51
Total	145.57	103.76	71.37	5.35	5.91

Appendix III: Chain energy consumption

Scenario Europe

Table III.1: Ship transport, inland CGP

	Logs (GJ_{prim}/GJ_{bio})	Chips (GJ_{prim}/GJ_{bio})	Bales (GJ_{prim}/GJ_{bio})	Pellets (GJ_{prim}/GJ_{bio})	Pyro oil (GJ_{prim}/GJ_{MeOH})	Methanol (GJ_{prim}/GJ_{MeOH})
Production	0.03	0.03	0.03	0.03	0.06	0.05
Truck transport	0.03	0.03	0.03	0.02	0.04	0.03
Train transport	0.00	0.00	0.00	0.00	0.00	0.00
Ship transport	0.01	0.03	0.02	0.01	0.03	0.02
Sizing	0.01	0.00	0.01	0.01	0.02	0.02
Drying	0.02	0.06	0.02	0.06	0.04	0.03
Densification	0.00	0.00	0.00	0.03	0.00	0.00
Total	0.10	0.15	0.10	0.16	0.19	0.16

Table III.2: Ship transport, coastal CGP

	Logs (GJ_{prim}/GJ_{bio})	Chips (GJ_{prim}/GJ_{bio})	Bales (GJ_{prim}/GJ_{bio})	Pellets (GJ_{prim}/GJ_{bio})	Pyro oil (GJ_{prim}/GJ_{MeOH})	Methanol (GJ_{prim}/GJ_{MeOH})
Production	0.03	0.03	0.03	0.03	0.06	0.05
Truck transport	0.01	0.01	0.01	0.01	0.02	0.01
Train transport	0.00	0.00	0.00	0.00	0.00	0.00
Ship transport	0.01	0.03	0.02	0.01	0.03	0.02
Sizing	0.01	0.00	0.01	0.01	0.02	0.02
Drying	0.02	0.06	0.02	0.06	0.04	0.03
Densification	0.00	0.00	0.00	0.03	0.00	0.00
Total	0.08	0.13	0.09	0.15	0.16	0.14

Table III.3: Train transport

	Logs (GJ_{prim}/GJ_{bio})	Chips (GJ_{prim}/GJ_{bio})	Bales (GJ_{prim}/GJ_{bio})	Pellets (GJ_{prim}/GJ_{bio})	Pyro oil (GJ_{prim}/GJ_{MeOH})	Methanol (GJ_{prim}/GJ_{MeOH})
Production	0.03	0.03	0.03	0.03	0.06	0.05
Truck transport	0.01	0.01	0.01	0.01	0.01	0.01
Train transport	0.10	0.06	0.10	0.06	0.09	0.06
Ship transport	0.00	0.00	0.00	0.00	0.00	0.00
Sizing	0.01	0.00	0.01	0.01	0.02	0.02
Drying	0.02	0.06	0.02	0.06	0.04	0.03
Densification	0.00	0.00	0.00	0.03	0.00	0.00
Total	0.16	0.16	0.16	0.20	0.22	0.17

Scenario Latin-America

Table III.4: Ship transport, inland CGP

	Chips (GJ_{prim}/GJ_{bio})	Bales (GJ_{prim}/GJ_{bio})	Pellets (GJ_{prim}/GJ_{bio})	Pyro oil (GJ_{prim}/GJ_{MeOH})	Methanol (GJ_{prim}/GJ_{MeOH})
Production	0.03	0.01	0.01	0.03	0.02
Truck transport	0.03	0.03	0.02	0.04	0.03
Train transport	0.00	0.00	0.00	0.00	0.00
Ship transport	0.14	0.11	0.04	0.11	0.10
Sizing	0.00	0.01	0.01	0.02	0.02
Drying	0.06	0.02	0.06	0.04	0.03
Densification	0.00	0.00	0.03	0.00	0.00
Total	0.27	0.18	0.18	0.23	0.20

Table III.5: Ship transport, coastal CGP

	Chips (GJ_{prim}/GJ_{bio})	Bales (GJ_{prim}/GJ_{bio})	Pellets (GJ_{prim}/GJ_{bio})	Pyro oil (GJ_{prim}/GJ_{MeOH})	Methanol (GJ_{prim}/GJ_{MeOH})
Production	0.03	0.01	0.01	0.03	0.02
Truck transport	0.01	0.01	0.01	0.02	0.01
Train transport	0.00	0.00	0.00	0.00	0.00
Ship transport	0.14	0.11	0.04	0.11	0.10
Sizing	0.00	0.01	0.01	0.02	0.02
Drying	0.06	0.02	0.06	0.04	0.03
Densification	0.00	0.00	0.03	0.00	0.00
Total	0.25	0.16	0.16	0.21	0.18

Appendix IV: Methanol costs

Scenario Europe

Table IV.1: Ship transport, inland CGP

€/GJ $_{MeOH}$	Logs	Chips	Bales	Pellets	Pyro oil	Methanol
Production	2.00	5.17	2.61	2.61	3.09	2.58
Truck transport	3.84	5.38	4.43	2.92	2.11	2.55
Train transport	0.00	0.00	0.00	0.00	0.00	0.00
Ship transport	2.66	2.39	4.15	1.32	0.67	0.62
Sizing	0.15	0.00	0.15	0.15	0.12	0.10
Drying	0.38	0.40	0.38	0.40	0.45	0.38
Densification	0.00	0.00	0.00	1.36	0.00	0.00
Storage	0.87	4.28	1.51	1.52	1.78	1.49
Energy conv.	3.58	3.58	3.58	3.58	8.60	9.00
Total	13.48	21.19	16.82	13.86	16.82	16.72

Table IV.2: Ship transport, coastal CGP

€/GJ $_{MeOH}$	Logs	Chips	Bales	Pellets	Pyro oil	Methanol
Production	2.00	5.17	2.61	2.61	3.09	2.58
Truck transport	1.98	2.78	2.38	1.73	0.46	1.31
Train transport	0.00	0.00	0.00	0.00	0.00	0.00
Ship transport	2.66	2.39	4.15	1.32	0.67	0.62
Sizing	0.15	0.00	0.15	0.15	0.12	0.10
Drying	0.38	0.40	0.38	0.40	0.45	0.38
Densification	0.00	0.00	0.00	1.36	0.00	0.00
Storage	0.87	4.28	1.51	1.52	1.78	1.49
Energy conv.	3.58	3.58	3.58	3.58	8.60	9.00
Total	11.62	18.60	14.76	12.67	15.17	15.47

Table IV.3: Train transport

€/GJ $_{MeOH}$	Logs	Chips	Bales	Pellets	Pyro oil	Methanol
Production	2.00	5.17	2.61	2.61	3.09	2.58
Truck transport	0.76	1.33	0.95	0.95	0.00	0.94
Train transport	3.43	3.43	3.43	1.08	4.48	3.74
Ship transport	0.00	0.00	0.00	0.00	0.00	0.00
Sizing	0.15	0.00	0.15	0.15	0.12	0.10
Drying	0.38	0.40	0.38	0.40	0.45	0.38
Densification	0.00	0.00	0.00	1.36	0.00	0.00
Storage	0.87	4.24	1.50	1.52	1.78	1.49
Energy conv.	3.58	3.58	3.58	3.58	8.60	7.66
Total	11.17	18.14	12.61	11.65	18.51	16.88

Scenario Latin-America

Table IV.4: Ship transport, inland CGP

€/GJ $_{MeOH}$	Chips	Bales	Pellets	Pyro oil	Methanol
Production	2.90	0.41	0.41	0.48	0.40
Truck transport	5.38	4.43	2.92	2.11	2.55
Train transport	0.00	0.00	0.00	0.00	0.00
Ship transport	5.31	6.34	2.11	2.05	2.15
Sizing	0.00	0.15	0.15	0.12	0.10
Drying	0.40	0.38	0.40	0.45	0.38
Densification	0.00	0.00	1.36	0.00	0.00
Storage	4.28	1.51	1.52	1.78	1.49
Energy conv.	3.58	3.58	3.58	8.60	9.00
Total	21.83	16.80	12.44	15.61	16.07

Table IV.5: Ship transport, coastal CGP

€/GJ $_{MeOH}$	Chips	Bales	Pellets	Pyro oil	Methanol
Production	2.90	0.41	0.41	0.48	0.40
Truck transport	2.78	2.38	1.73	0.46	1.31
Train transport	0.00	0.00	0.00	0.00	0.00
Ship transport	5.31	6.34	2.11	2.05	2.15
Sizing	0.00	0.15	0.15	0.12	0.10
Drying	0.40	0.38	0.40	0.45	0.38
Densification	0.00	0.00	1.36	0.00	0.00
Storage	4.28	1.51	1.52	1.78	1.49
Energy conv.	3.58	3.58	3.58	8.60	9.00
Total	19.24	14.74	11.26	13.96	14.82

Appendix V: Electricity costs

Scenario Europe

Table V.1: Ship transport, inland CGP

€/GJ $_{electricity}$	Logs	Chips	Bales	Pellets	Pyro oil
Production	2.12	5.47	2.77	2.77	4.10
Truck transport	4.07	5.69	4.69	3.09	2.81
Train transport	0.00	0.00	0.00	0.00	0.00
Ship transport	2.81	2.53	4.40	1.40	0.89
Sizing	0.16	0.00	0.16	0.16	0.16
Drying	0.41	0.42	0.41	0.42	0.60
Densification	0.00	0.00	0.00	1.44	0.00
Storage	0.92	4.53	1.59	1.61	2.37
Energy conv.	9.33	9.33	9.33	9.33	14.48
Total	19.82	27.98	23.35	20.22	25.41

Table V.2: Ship transport, coastal CGP

€/GJ $_{electricity}$	Logs	Chips	Bales	Pellets	Pyro oil
Production	2.12	5.47	2.77	2.77	4.10
Truck transport	2.10	2.95	2.52	1.83	0.62
Train transport	0.00	0.00	0.00	0.00	0.00
Ship transport	2.81	2.53	4.40	1.40	0.89
Sizing	0.16	0.00	0.16	0.16	0.16
Drying	0.41	0.42	0.41	0.42	0.60
Densification	0.00	0.00	0.00	1.44	0.00
Storage	0.92	4.53	1.59	1.61	2.37
Energy conv.	9.33	9.33	9.33	9.33	14.48
Total	17.85	25.24	21.17	18.96	23.22

Table V.3: Train transport

€/GJ $_{electricity}$	Logs	Chips	Bales	Pellets	Pyro oil
Production	2.12	5.47	2.77	2.77	4.10
Truck transport	0.80	1.40	1.01	1.01	0.00
Train transport	3.63	3.63	3.63	1.14	5.95
Ship transport	0.00	0.00	0.00	0.00	0.00
Sizing	0.16	0.00	0.16	0.16	0.16
Drying	0.41	0.42	0.41	0.42	0.60
Densification	0.00	0.00	0.00	1.44	0.00
Storage	0.92	4.49	1.59	1.61	2.36
Energy conv.	9.33	9.33	9.33	9.33	14.48
Total	17.36	24.75	18.89	17.88	27.66

Scenario Latin-America

Table V.4: Ship transport, inland CGP

€/GJ $_{electricity}$	Chips	Bales	Pellets	Pyro oil
Production	3.07	0.43	0.43	0.64
Truck transport	5.69	4.69	3.09	2.81
Train transport	0.00	0.00	0.00	0.00
Ship transport	5.62	6.71	2.23	2.73
Sizing	0.00	0.16	0.16	0.16
Drying	0.42	0.41	0.42	0.60
Densification	0.00	0.00	1.44	0.00
Storage	4.53	1.59	1.61	2.37
Energy conv.	9.33	9.33	9.33	14.48
Total	28.66	23.33	18.72	23.80

Table V.5: Ship transport, coastal CGP

€/GJ $_{electricity}$	Chips	Bales	Pellets	Pyro oil
Production	3.07	0.43	0.43	0.64
Truck transport	2.95	2.52	1.83	0.62
Train transport	0.00	0.00	0.00	0.00
Ship transport	5.62	6.71	2.23	2.73
Sizing	0.00	0.16	0.16	0.16
Drying	0.42	0.41	0.42	0.60
Densification	0.00	0.00	1.44	0.00
Storage	4.53	1.59	1.61	2.37
Energy conv.	9.33	9.33	9.33	14.48
Total	25.91	21.15	17.46	21.60