MASTER

Pre-treatment of biomass and its consequences

the influence on the energetic- and economic performance and ecological impact of the bio energy supply chain

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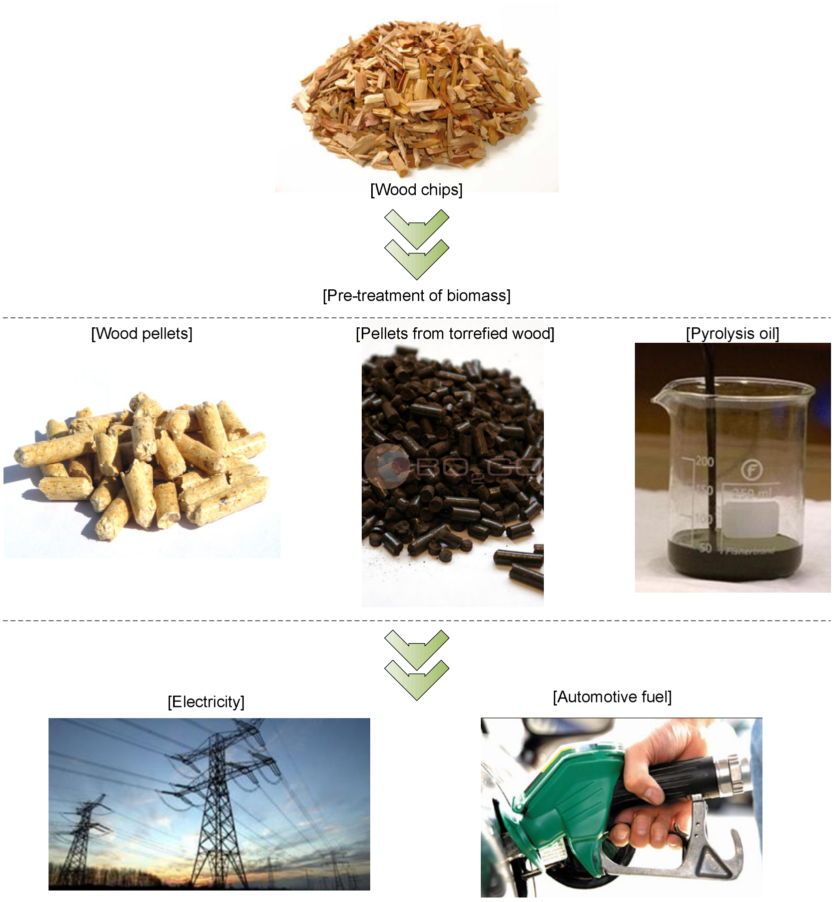

Eric van der Putten

Pre-treatment of biomass and its consequences

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Summary

This study discusses the energy production from imported biomass for two cases: electricity production (by co-firing) and automotive fuel production (by entrained flow gasification and synthesis to Fischer-Tropsch diesel). The discussion focuses upon the energetic- and economic performance and ecological impact of the bio energy supply chain (biomass pre-treatment, logistics and energy conversion), for three different biomass pre-treatment methods; pelletisation, torrefaction and pyrolysis. The supply chain is discussed within the framework of the BO_2GO project of the study sponsor Ecofys. In this project wood chips are imported from Canada and converted to energy in the Netherlands.

Pre-treatment of biomass is applied to improve the supply chain. Uncertainty exists about which biomass-pre-treatment results in the best performing chain for three performance indicators; energetic- and economic performance and ecological impact. The main research question of this study is therefore: ***Which biomass pre-treatment method results in the best energetic- and economic performance and ecological impact for the overall bio energy supply chain***?

The relevance of this topic is based on the ongoing development of biomass import for large scale energy production and the expectations that this is not a temporary phenomenon. This requires optimisation of the supply chain to utilise the full potential of bio energy in the future.

Untreated (raw) biomass hampers the energetic, economic and ecological feasibility of the bio energy supply chain. Wood chips are not a desired fuel due to problems with logistics and energy conversion. Wood chips have a low energy density (3 GJ/m³, based on LHV), high ranged product characteristics and are vulnerable to fungal growth, which causes mass loss and can cause self ignition. This makes it a very difficult product to handle in large quantities. Furthermore have wood chips disadvantages for energy conversion in existing fossil fuel based energy conversion technologies. Biomass pre-treatment is applied to overcome these drawbacks.

Pre-treatment of biomass is in essence the conversion of biomass into an intermediate product, which has advantages for logistics and energy conversion. Three promising and upcoming biomass pre-treatment methods are of interest in this study. The first method is a *physical pre-treatment*, which only alters the physical conditions of biomass. Pelletisation is drying, grinding and compression (the actual pelletisation process) of biomass into small packages with a higher mass density. The result is a uniform product (*pellets*) with higher energy content (10-11 GJ/m³) compared to raw wood.

The other two methods are *thermo-chemical pre-treatments,* which alter the chemical composition of biomass and thereby the biomass characteristics. The second pre-treatment method is the combined result of torrefaction and pelletisation. First, biomass is severe dried (roasting), which causes some mass loss while the energy content is approximately preserved. Subsequently the torrefied wood is pelletised. The resulting product (*BO_2pellets™*) is hydrophobic and has higher mass and energy densities (14-15 GJ/m³) compared to pellets.

The third pre-treatment method is pyrolysis. Biomass is liquefied through a high thermal breakdown. The resulting product (*pyrolysis oil*) is a liquid and has higher energy density (18-19 GJ/m³) in comparison with the other solid intermediate products. All three biomass pre-treatment methods result in energy carriers with different forms and product characteristics. These differences result in varying (dis)advantages during logistics and energy conversion.

Especially the energy conversion technologies set demands on the fuel characteristics of the intermediate products. There is a strong desire to capitalise on the existing knowledge and infrastructure of fossil fuel based technologies. The suitability of the intermediate products for the existing infrastructure depends therefore strongly on their compatibility with fossil fuels (coal).

Biomass pre-treatment affects, by the creation of intermediate products, all the chain elements (logistics and energy conversion).

To identify the pre-treatment method with the best chain performance, first the consequences of biomass pre-treatment are analysed for *each chain element,* i.e. the performance of pre-treatment itself and the performance of the intermediate products during logistics and energy conversion. Next the performances of the *overall supply chain* are compared to identify the biomass pre-treatment method with the best performance and to gain insight into the comparative relations. So in total six chains are compared; three for co-firing and three for Fischer-Tropsch diesel production, varying with the biomass pre-treatment method.

This is done on basis of a *literature study and examinations with experts* in the field. With this data a reference model of the supply chain is modulated in a *spreadsheet*. This spreadsheet is used next, to calculate the performance and influence of factors on the chain (-elements).

This analysis demonstrates that each chain element has its own best performing technology. At the biomass pre-treatment stage, pelletisation results in the best performance. From the intermediate products results BO_2pellets™ in the best performance during logistics and pyrolysis oil results in the best performance during energy conversion. In addition the amount of energy produced differs with the intermediate product. This leads to the following eventual performance:
<u>For chains which produce electricity</u>, pelletisation and torrefaction results in chains with a similar energetic performance, but pelletisation has lower ecological impact at higher costs, compared to torrefaction. Pyrolysis has the worst chain performance on all three indicators.
<u>For the chains which produce F-T diesel</u>, torrefaction is the most suited biomass pre-treatment method as it scores best on all three performance indicators. Chains with pelletisation can compete on costs, but not on the other performance indicators. The chain with pyrolysis results in a similar ecological impact, but at lower efficiencies and higher costs.

<u>The chains with pelletisation</u> set the benchmarks in energetic- and economic performance and ecological impact during biomass pre-treatment. However pellets have a worse performance during logistics and energy conversion compared to the other intermediate products.
<u>The chains with torrefaction</u> are able to catch up with the performance norms because of two reasons. The differences in performance during biomass pre-treatment remain limited and the improved characteristics of BO_2pellet™ result in better performance during logistics and energy conversion. This results in the best chain performance.
<u>The chains with pyrolysis</u> as biomass pre-treatment method are not able to compensate the high expenses in energetic- and economic performance and ecological impact by advantages in transport and energy conversion. Chains with pyrolysis result therefore in the lowest performance.
<u>In general</u> this study demonstrates that the logistics play a marginal role in the differences between chains. The differences in performance result mainly from factors in biomass pre-treatment and energy conversion of the intermediate products. The most important factors which explain the differences between the chains during pre-treatment are the heat demand and use of natural gas. During energy conversion, the investment costs for co-firing and the electricity use during F-T diesel production are decisive for the differences between chains.
Given these observations it is recommended, in case of wood chip import from Canada for electricity production in the Netherlands, to use pelletisation or torrefaction as biomass pre-treatment for electricity production and torrefaction as pre-treatment method for F-T diesel production.

The findings of this study are restricted to a certain extent. The comparative character of this study is a main cause for this. The comparative conditions may not result in the most optimal conditions for the biomass pre-treatment methods and thereby the best outcome for the whole chain. Another main reason for the restrictions arises from the fact that the biomass pre-treatment methods are new promising technologies under development. Because of this, factors of uncertainty, confidentiality and fast progress result in values, which have to be used as indicators rather than absolute values.

Preface

Bio energy is a promising renewable energy source. However, serious complaints arise about the sustainability of energy from biomass and its feasibility. This makes bio energy a complex field with many socio-technical developments and barriers. These dynamics have triggered my interest; on the one hand there is this natural growing ‘green’ energy source and on the other hand there are these feasibility restrictions.
I’m therefore grateful that I got the opportunity to explore the field of energy from biomass within Ecofys. This made it possible to analyse this matter within a respectable company in this field. The result of my voyage of discovery is this report, which marks the end of my study Innovation Sciences at the Eindhoven University of Technology.

This report would not have been accomplished without the contributions of several people. I would like to thank therefore my supervisors for their involvement and support: From the Innovation Sciences department Frank Veraart for his comments and organising my thoughts in plain understandable English; Geert Verbong for comments regarding the overall structure of the report; and from Ecofys Berry Meuleman for its contributions regarding the content and showing me around in the world of bio energy.

I also would like to thank my fellow students and friends who helped me out with MS office issues, geographical designs and final checks in the last month.

Last but not least I would like to thank my father and mother, brothers and Nienke for their unconditional support throughout my study, for which I’m very grateful.

Eric van der Putten
Eindhoven, May 2009.

Table of Contents

List of figures, tables, symbols and abbreviations

1.1 List of figures

1.2 List of tables

1.3 List of symbols and abbreviations

min	Minutes.
sec	Seconds.
h	Hour.
d	Day.
g	Gram.
kg	Kilogram.
tonne	10^3 kilogram.
wt%	Mass percentage, wet based.
mc	Moisture content as percentage of wet material.
m	Metre.
mm	Millimetre.
m^3	Cubic metre (1mx1mx1m).
MJ	Mega Joule (10^6 Joule).
GJ	Giga Joule (10^9 Joule).
$GJ_{e\text{ or }F\text{-}T}$	Energy content electrical or Fischer-Tropsch diesel, in GJ.
kW	Kilo Watt (10^3 Joule per second).
kWh	Energy content of 1 hour operation in kW (3.6*10^6 Joule).
MW	Mega Watt (10^6 Joule per second).
$MW_{e\text{ or }th}$	MW in electrical or thermal form.
MWh	Energy content of 1 hour operation in MW (3.6*10^9 Joule).
t/h	Tonne per hour.
MJ/kg	Heating value, energy content of 1 kg material.
kg/m^3	Mass density, kilogram per cubic metre.
MJ/m^3	Energy density: energy content of 1 m^3 material.
^{o}C	Degrees centigrade.
F-T diesel	Fischer-Tropsch diesel.
HHV	Higher Heating Value (p. 9).
LHV	Lower Heating Value (p. 10).
pH	Measure of the acidity or causticity of a solution.
Pre-t	Pre-treatment of biomass.
n.a.v.	Not available.

1 Introduction: *The bio energy supply chain*

Introduction

1. The potential of bio energy
2. Relevance: *Pressure between local biomass supply and demand*
3. Problem statement: *The supply chain and pre-treatment of biomass*
4. Research objective, focus and questions
5. Methodoloy

1.1 The potential of bio energy

The global energy demand is growing and is expected to do so in next coming years. It is expected that the energy demand will rise from 418 EJ (in 2001) to 702 EJ (in 2030) (IEA, 2007a). This continuing growth in energy demand increases the pressure on the current energy supply. The increasing demand places several great concerns about the current fossil energy supply for several reasons.

This is especially problematic for the western world since they have limited fossil energy resources, which makes them dependent on other countries for their energy supply. Some of these energy supplying regions are political unstable which brings geopolitical issues along. The global fossil energy reserve is limited and a shift to other energy sources on the long term is needed. In addition to this, the emerging economies of China and India lead to an increasing demand of resources. The consequences of this increasing demand are increasing prices and economic concerns. Greenhouse gas emissions, which cause severe environmental problems, are another reason to shift away from fossil fuels.

All these concerns require an alternative (renewable) energy source that overcomes the limited supply of fossil fuels (i.e. high prices), shifts away from geopolitical insecure areas and is a clean resource on short term.

Many renewable energy sources are available and energy from biomass is one of the promising renewable energy sources. Bio energy can be used in the form of heat or power from the conversion of ‘raw’ biomass or from an energy carrier (bio fuel) made from biomass, like ethanol, bio diesel etc. Energy from biomass has especially a high potential for the near future for several reasons (Hamelinck et al., 2003).

First, biomass is worldwide available on a large scale (energy crops, forest surplus, residues and waste). Secondly, it can be applied for heat, power and bio-fuels purposes. Thirdly, it is applicable in the existing infrastructure with minor adaptations and it can be produced and consumed on a CO_2 neutral base.

There are also limitations and drawbacks of bio energy (Smeets et al., 2007). The cost price of bio energy is still relatively high compared to the price of fossil fuel, the current technologies are not very energy efficient and the biomass production could conflict with the food (crops) supply, animal feed supply and forests preservation. This raises questions about the sustainability of bio energy and causes in some cases a negative depiction around bio energy.

Currently new technologies are under development to overcome these drawbacks of bio energy, i.e. they have higher efficiencies and make use of biomass residues and waste streams, which gives bio energy a more sustainable character.

The problems around bio energy are however, not solved yet. A main problem will be, ironically enough, that bio energy can suffer from its own success. As the interest in bio energy increases, biomass becomes a more scarce resource and no longer worldwide available on large scale. Although the world produces enough biomass to meet the global energy demand, local shortages come up. As result location-allocation problems will arise (difference in geographical location between demand and supply), which hamper the feasibility of bio energy.

This study will elaborate on the issues related to the geographical distance between energy production from biomass and biomass growth and how the resulting bio energy supply chain can be optimised.

1.2 Relevance: *Pressure between local biomass supply and demand*

A mismatch between biomass supply and demand can be caused by many reasons. In the Netherlands this mismatch is caused by the stimulation of renewable energy by the Dutch government (Junginger et al., 2008).

In 1995 the objective was set to have a 10% contribution of renewable energy in the energy mix by 2020 (Third Energy White Paper - policy document). By signing the Kyoto Protocol, the Netherlands agreed to reduce their emission of greenhouse gasses (GHG) with 8% (UN, 2007). This resulted in the Coal Covenant between the power producers and the Dutch Ministry of the Environment, in which they agreed to reduce the CO_2 emission with 3.2 Mt (Junginger et al., 2008). To reach these targets the Dutch government implements several research, development and demonstration projects, investment subsidies, renewable electricity production subsidies and tax exemptions (Junginger et al., 2006a). These policy interventions have boosted the development of renewable energy, e.g. bio energy and thereby the demand for biomass.

On the short term, it is seen that the demand for biomass can hardly be fulfilled with local biomass. The availability of suitable local biomass is limited by economic considerations, legal restrictions and the use of biomass for other purposes (Smeets et al., 2007). To meet the domestic demand, biomass is therefore imported because of lower prices, larger quantities and a better quality of the feedstock (Hillring, 2006). In 2005 and 2006, the share of imported biomass to the total amount of biomass used in The Netherlands (for energy purposes), was respectively 31 and 28%.

An overview of the contribution of biomass to the energy production in the Netherlands is given in table 1. From this table it becomes clear that the imports of biomass is mainly related to the co-firing of biomass in power stations (almost 100% of total imported biomass) and is the main share of biomass used for co-firing, respectively 75 and 70% in 2005 and 2006. This implies, more or less, that power plant operators meet the Dutch policy goals with large amounts of imported biomass instead of local grown biomass. Import of biomass is required to deliver enough biomass for large scale energy production.

Table 1 - Share of non domestic biomass sources for the Dutch renewable energy production (Sikkema et al., 2007).

	Total biomass input (in TJ)		Import of biomass (In TJ)		Share of imports related to total biomass input (In %)	
	2005	2006	2005	2006	2005	2006
Total biomass	**74,531**	**73,197**	**23,229**	**20,584**	**31%**	**28%**
A. Waste incineration	26,659	27,109	0	0	0%	0%
B. Co-firing in power plants	30,933	28,512	23,160	19,867	75%	70%
solid biomass	-	-	11,977	8,187	-	-
liquid biomass	-	-	11,183	11,680	-	-
C. Wood industry	1,995	2,201	0	0	0%	0%
D. Households	9,316	9,316	0.2	0.5	0%	0%
E. Other biomass burning	5,628	6,059	1,069	727	19%	12%
solid biomass	-	-	1,069	727	-	-
liquid biomass	-	-	0	0	-	-
F. Biogas	0	0	0	0	0%	0%
G. Bio-fuels	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

On the long term it is not sure if the local production capacity will meet the biomass demand. A study by Smeets et al. (2007) estimated the local technical biomass production capacity in 2050 according to four scenarios varying from a low to high production capacity, taking sustainability issues into account. Depending on the local biomass for energy demand, there will be a surplus of biomass available. In the study of Smeets et al. the domestic demand and production system are compared and it appeared that several areas worldwide are capable of producing a surplus of biomass for conversion to bio energy (e.g. North America, Caribbean and Latin America and the Baltic States) whereas other locations have a shortage of biomass to fulfil the local energy demand (e.g. Europe and Japan) (Smeets et al., 2007). From this study can be observed that the import of biomass, for large scale energy production in the Netherlands, will not be a temporary development.

Given these development it can be concluded that, to reach the Dutch policy targets on the short term and to utilize the full global biomass potential on the long term, extensive biomass transport over long distances is unavoidable. The crucial factor within the field of biomass transport is that the environmental benefits and energy production that result from using biomass outweigh the environmental impacts and resource consumption that their growth and supply acquire (Allen et al., 1998). Forsberg (2000) states that the energy supply chain based on coal as fuel requires an energy input of 110% non renewable per kWh electricity delivered. As long as the resource consumption for growth and transport of bio energy supply chains remains below this threshold value, bio energy supply chains result in a reduction of the environmental impact.

Anticipating on the recent development and prediction on the long term, it is necessary to gain understanding of the important aspects in the bio energy supply chain.

1.3 Problem statement: *The supply chain and pre-treatment of biomass*

To utilise the full potential of bio energy the supply chain has to be optimised. As the main barriers that hamper the feasibility of bio energy supply chains for biomass import are mentioned energetic, economical ecological barriers (Junginger et al., 2006b).

Suurs (2002), Hamelinck et al. (2003), Uslu (2005) and Zwart et al. (2006) have analyzed and modelled the biomass to bio energy chain to get insight in the key variables influencing the energetic-and economic performance and environmental impact. Suurs (2002) has built a model that gives insights in the factors influencing the transportation costs and energy consumption of the bio energy supply chain. Hamelinck et al. (2003) refined the model of the bio energy supply chain and added an amplification of the CO_2 exhaust of the bio energy supply chain. Uslu (2005) broadened the picture by the inclusion of several new thermo-chemical pre-treatments and their effects on the energetic-and economic performance, as well as on the reduction of GHG emissions of the bio energy supply chain. Zwart et al. (2006) looked into the economics of Fischer-Tropsch diesel production for several different chains (an automotive fuel). These studies conclude that the pre-treatment of biomass is a key action to improve the energetic-and economic performance and ecological impact of the bio energy supply chain.

Several questions are left unanswered in these studies with respect to the pre-treatment methods of biomass. Uslu (2005) provided a more general insight in the bio energy supply chain, by a comparison of chains with the state of art pre-treatment methods for biomass described in literature. The described state of the art is subject to different assumptions and circumstances. In a comparison under different conditions and variables which are held not constant, the effect of a variable cannot be measured accurately. The study of Uslu provides therefore less insight in the comparative relations between supply chains with different pre-treatment methods for biomass.

Zwart et al. (2006) evaluated different bio energy supply chains for the production of Fischer-Tropsch diesel on the economic performance. The energetic performance and ecological impact were not included in the scope of the study. The energetic performance is of interest because, although enough biomass is available, its availability is not unlimited. The ecological impact is of importance as it is desired that the ecological benefit outweighs the ecological impact of production. These facets are important aspects which have to be addressed, as they can hamper the feasibility of the bio energy supply chain as well.

In general, less is elaborated on the product characteristics and their influence on the logistics and the final energy conversion. The intermediate products have (dis)advantages in comparison with raw biomass during these activities. It is therefore not clear which pre-treatment method for biomass results in the best performing bio energy supply chain. These issues need to be addressed as they appear to have substantial influence on the energetic-and economic performance of the bio energy supply chain.

Due to these issues it is not yet clear which pre-treatment method of biomass results in the bio energy supply chain with the optimal energetic-and economic performance and ecological impact.

1.4 Research focus, objective and questions

Pre-treatment of biomass is beneficial for the performance of the supply chain, but uncertainty exists about the comparative relations between the several pre-treatment methods for biomass and which pre-treatment method for biomass results in the best performing bio energy supply chain. To create clarity about this a comparison is made between three different pre-treatment methods for biomass (i.e. pelletisation, torrefaction and pyrolysis), on the key elements of the supply chain (i.e. pre-treatment of biomass, transport and energy conversion of the created products). This is done for one biomass flow and equal conditions to identify the pre-treatment method for biomass with the best energetic- and economic performance and ecological impact for the overall bio energy supply chain. This study fits in with the BO_2GO project of Econcern and ECN, which develop a commercial pyrolysis-based plant to produce biomass pellets for transport. Within this context, Ecofys (subsidiary company of Econcern and the research branch) is interested in the energetic-and economic performance and ecological impact of the bio energy supply chain.

The **research objective** of this study is: *to gain insight in (and the difference between) bio energy supply chains, with different pre-treatment methods of biomass, to make predictions about the energetic efficiency, production costs and CO_2 emissions of the whole bio energy supply chain for different end applications; co-firing and Fischer-Tropsch (F-T) diesel production*.

The bio energy supply chain exists (roughly) out of four parts: production of biomass, the pre-treatment of biomass, energy conversion of biomass and logistics to transfer the obtained materials. A general representation of the bio energy supply chain is given in figure 1. Biomass is transformed in intermediate products during the pre-treatment step at certain costs, energy losses and environmental impact. The characteristics of the intermediate products affect consequently the logistic operations and energy conversion (co-firing and F-T diesel production). This leads to the main **research question**:

- *Which biomass pre-treatment method results in the best energetic- and economic performance and the lowest ecological impact for the overall bio energy chain?*

Within this study, the energetic- and economic performance refer to the energetic efficiency and production costs respectively. The ecological impact refers to the CO_2 emissions.
Within the framework of the BO_2GO project the research focus of the bio energy supply chain is restricted to a specific geographical case. The area of interest is East-Canada as the exporting country and The Netherlands as the importing country. The feedstock type is wood. The pre-treatment techniques of interest are pelletisation (commercial applied), torrefaction (a new promising pre-treatment technique) and pyrolysis (an alternative which is under development and on the edge of commercialization). The process size of pre-treatment of biomass is set to an output of 40MW. The final energy conversion varies between co-firing (short term) and entrained-flow gasification and conversion to Fischer-Tropsch fuels (long term). For the research, a spreadsheet is designed to make the calculations and to be able to evaluate the bio energy supply chains. The research boundaries are represented in figure 1 (enclosed area by the blue box).

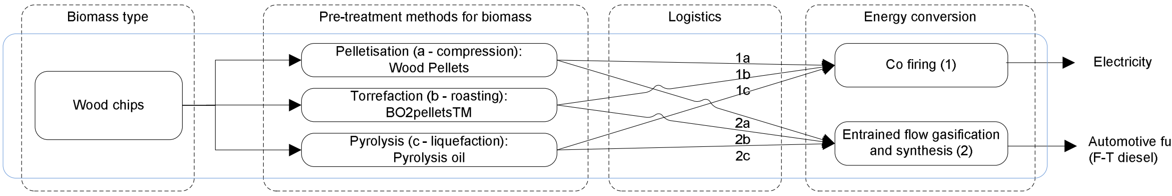

Figure 1 - Conceptual model of the bio energy supply chain.

The choice for a certain pre-treatment method for biomass affects the other activities in the chain, as the intermediate product characteristics differ from each other. The performance of the whole bio energy supply chain is therefore not solely the performance of the chosen pre-treatment method itself, but a summation of the performance of the distinctive steps in the chain. The research question is therefore split up in four sub-questions, which deal with the separate elements of the supply chain and basic starting points. These sub-questions analyse the separate chain elements in the supply chain and together add up to answer the main research question. On each sub-question a separate chapter is devoted.

Biomass type: wood chips – (Chapter 2)

The second section deals with the starting point of the bio energy supply chain: the biomass resource. Pre-treatment techniques alter the characteristics of wood in different manners and the produced intermediate products replace wood during the other stages in the chain. It is therefore desired to define the point of departure of the bio energy supply chain. The following sub-question is therefore stated:

1. *What is the basic chemical composition and physical structure of wood?*

Pre-treatment methods of biomass – (Chapter 3)

The first chain element and third section of this report deal with the pre-treatment methods for biomass. During the pre-treatment step, raw biomass is converted into an intermediate product at certain conditions and expenses.

2. *What is the energetic- and economic performance and environmental impact of the three biomass pre-treatments methods, i.e. pelletisation, torrefaction and pyrolysis?*

The conditions and expenses of this process step vary with the pre-treatment method that is used. To gain insight in the differences between the several methods the following support questions come up:

i. What are the physical and/or thermo-chemical principles of the conversion of biomass?
ii. What kind of equipment is required for the production process to convert biomass in intermediate products?
iii. What are the product characteristics of the intermediate product?

The conversion principles of the process give a fundamental understanding of the relation between the feedstock used, the required process steps and the obtained product's characteristics. In succession of the fundamental principles of the process step, an overview of the production process is required to determine the production costs and energy needed for the process equipment. Moreover, the production conditions influence the eventual product characteristics. Since the intermediate products are the input for the energy conversion process and logistic activities, the understanding of the characteristics of the specific intermediate products is crucial to determine the overall performance of the bio energy supply chain. Chapter 2 discusses these issues related to the biomass conversion principles, intermediate product characteristics, production process, and the concluding difference in energetic-and economic performance and ecological impact of the pre-treatment method itself. When the production characteristics are known, the others chain elements of the bio energy supply chain can be evaluated.

Logistics: transport of the intermediate products – (Chapter 4)

The fourth section of this report discusses the third sub-question related to the logistics and handling of the intermediate products obtained after the pre-treatment of biomass. The logistics connect the several elements of the bio energy supply chain. This results in the sub- question:

3. *What is the energetic- and economic performance and environmental impact of the logistic operations?*

The energetic-and economic performance and ecological impact are dependent on the characteristics of the product that must be transported or handled with. This refers directly to the physical and energetic values of the intermediate product, but as well to safety precautions demanded by the government for example. The following support question is therefore stated:

    i. *What are the guidelines for handling the intermediate products?*

Energy conversion – (Chapter 5)

The final element of the supply chain – the energy conversion step - is evaluated in the fifth section of this report. Energy conversion transforms the intermediate products into electricity or into an automotive energy carrier (Fischer-Tropsch diesel in this case). The different product characteristics of pellets, BO_2GO and pyrolysis oil results in differ energy conversion performances. The fourth sub-question is stated as following:

4. *What is the energetic- and economic performance and environmental impact of the energy conversion step for the different intermediate products?*

Energy conversion of biomass is done in installations especially dedicated for biomass or in conventional installations based on the proven principles of fossil fired plants. Fossil fired plants are often preferred due to economic issues and the development stage in which the biomass dedicated plants are. This leads to the following questions:

    i. *What is the difference between the conversion of fossil fuels and the intermediate products?*
    ii. *What are the implications of these differences for the production process of co-firing and Fischer-Tropsch diesel production?*

Plant operators desire materials that are alike the fossil fuels they use, as they can be fed into the existing infrastructure with minor adaptations. The (dis)similarities of the intermediate products with fossil fuels are therefore important because they determine if the production process has to be adapted. These changes influence the energetic-and economic performance and ecological benefit of the overall chain. This chapter reflects on the issues related to the use of intermediate products in fossil fired plants. The objective of this chapter is to give insight in the differences between the applications of the several intermediate products and not to give a detailed discussion of the energetic-and economic performance of energy conversion.

Chain performance: Results – (Chapter 6)

When all these sub-questions are answered, the separate chain elements can be add up to answer to the main research question This section compares the several different bio energy chains, with the different pre-treatment methods for biomass, head to head to answer the main research question: *Which pre-treatment method results in the best energetic-and economic performance and the lowest ecological impact for the overall bio energy chain?* At the end of this chapter is reflected on the casus and findings with respect to generalising of the findings.

Conclusion and recommendations – (Chapter 7)

This chapter discusses which and for what reason a certain pre-treatment method for biomass results in best energetic-and economic performance and lowest ecological impact. Furthermore it summarises the most influential factors. An insight in the effect of factors, with a high expected range in their value, on the energetic-and economic performance and ecological impact is given as well. In addition recommendations are made to improve the energetic-and economic performance and ecological impact for chains containing biomass pre-treatment methods. The gained scientific insights are presented as well.

The resulting report outline is shown in figure 2. The research framework is discussed in this chapter. (*The methodology which is used to analyse the key issues is not yet addressed and is discussed in the next section of this chapter, §1.5).* Subsequently is each chain element of the supply chain discussed in more dept in the chapters 2-5. In Chapter six, everything comes together and the overall chain performance is analysed. Chapter seven presents subsequently the conclusions and recommendations.

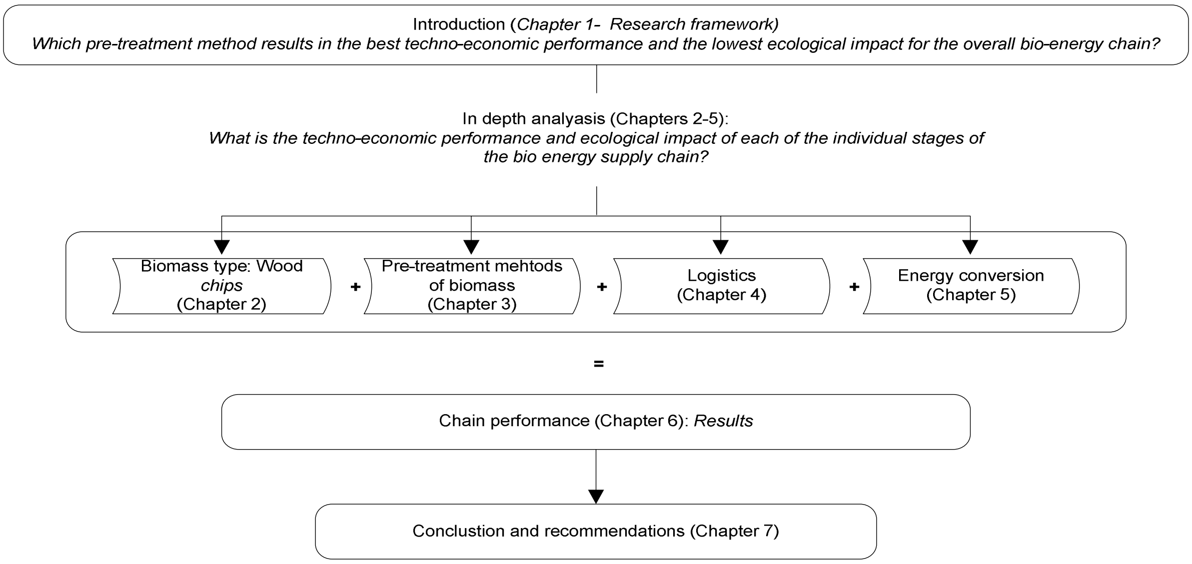

Figure 2 - Report outline.

1.5 Methodology

In order to create clarity in the comparative relations between the bio energy supply chains, with different pre-treatment methods for biomass, the research is separated in five stages.

Firstly, a literature study is performed to derive the typical characteristics of three pre-treatment methods for biomass and the created products. Subsequently the typical values for the logistics and energy conversion of the intermediate products are derived as well by a literature study. In case not all information was available, it was tried to supplement the information by inquiries with experts active in the field. *Secondly*, when all information was available, the typical values and characteristics are applied to the framework of the case study. *Thirdly,* the different elements of the bio energy supply chain are modulated in a spreadsheet. *Fourthly*, on the basis of the modulated supply chain in the spreadsheet the energetic-and economic performance and ecological impact is calculated and evaluated per element of the supply chain, i.e. pre-treatment of biomass, logistics and energy conversion. *Fifthly* and finally, the overall supply chains are compared and analysed by the energetic-and economic performance and ecological impact (three performance indicators), to give an overview of and insight in different bio energy supply chains with different pre-treatment methods of biomass.

In the supply chain, only the pre-treatment method for biomass and the energy conversion are changed, while all other conditions are held contestant. So, in total six chains are compared on basis of several variables, as represented in table 2. The actual performance definitions are given in the appropriate section, i.e. §6.2.

Table 2 - Methodological approach of the comparison between bio energy supply chains with different pre-treatment methods for biomass[1].

Supply chain		Performance indicator		
Energy conversion	Pre-treatment method for biomass	Energetic performance	Economic performance	Ecological impact
Co-firing (1) (Electricity)	Pelletisation (1a)	Variable set λ1, λ2, etc	Variable set $1, $2, etc	Variable set β1, β2, etc
	Torrefaction (1b)			
	Pyrolysis (1c)			
F-T diesel production (2) (Automotive fuel)	Pelletisation (2a)	Variable set λ1*x*, λ2*x*, etc	Variable set $1*x*, $2*x*, etc	Variable set β1*x*, β2*x*, etc
	Torrefaction (2b)			
	Pyrolysis (2c)			

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[1] *λ, β and $: Respectively related to the energetic, economic or ecological expenses.*

Case study
The typical values and characteristics are applied to the framework of the case study, which affects the outcome of the comparison between chains with different pre-treatment methods for biomass. The outcome is mostly affected by the biomass type, area of interest and conversion technology. In this study wood is chosen as biomass feedstock and East-Canada as exporting country.
Biomass exists out different types, varying with the chemical composition. The pre-treatment process conditions vary accordingly strongly with the biomass type. In this study is chosen to use wood, which makes outcome of the comparison between chains containing different pre-treatment methods for biomass only valid for wood.
The choice for East-Canada and the Netherlands as areas of interest affect the outcome in many aspects. Local conditions affect the costs and ecological impact. Each location is therefore unique and dependent on the difference between locations the outcome will vary. Other studies have focussed upon other areas, e.g. Baltic States and South America, for a comparison between pre-treatment methods.
This study only refers to coal based technologies. Other (biomass dedicated) energy conversion technologies are under development. If these technologies are used, the outcome may be different.
Finally, certain assumptions are made because of information that does not exist yet or is kept confidentially. This has as result that the outcome mentioned in this study will not be the exact value of energetic-and economic performance and ecological impact for the case used.
This study emphasises on the differences between the chains with different pre-treatment methods for biomass as objective as possible, rather than discovering the correct estimates for the performance indicators.

Modulation of the supply chain
The spreadsheet is built in several steps. First the fundamental conversion principles of the several pre-treatment methods are derived from a literature study. Next these principles are discussed with experts in the involved areas and an applied production process is stated. The choices made in the process determine eventually, the standards and norms of the created intermediate products. The characteristic values of the intermediate product are subsequently used to give an impression of the handling properties and logistic efforts. To get an impression of the behaviour of the intermediate products during the energy conversion stage, the difference in conversion between biomass (on the one hand) and coal (on the other hand) with the conversion of the intermediate products is analysed. For a more specific modulation of the different chain elements and assumptions is referred to the appropriate sections; biomass type (*§*2.5), pre-treatment methods for biomass (*§*3.5), logistics (*§*4.4) and energy conversion (*§*5.2.4 – co-firing and *§* 5.3.4 – F-T diesel production).

On basis of the obtained information and spreadsheet energy and mass balances are drawn to map the most important mass and energy flows. The estimates of the ecological impact for electricity consumption are calculated on the energy mix of the country (NL and CA), while the ecological impact of natural gas and fuels are based on literature references. The economic data is based on in-house information of Ecofys and where necessary complemented and corrected to the right scale or time. Scale factors and power factors are used to scale up the equipment to the accurate magnitude. To take account for time differences, prices are corrected with inflation or plant indexes. The capital recovery factor is used to estimate the annual depreciation.

2 Biomass type: *Wood chips*

Biomass type: Wood chips
"What is the basic chemical compostion and physical structure of wood?

1. Introduction
2. Chemical composition
3. Physical structure
4. Wood characteristics
5. Resume and assumptions feedstock

2.1 Introduction

This section discusses the main characteristics of the biomass type used in the BO_2GO casus: wood chips. The biomass type is of importance because it affects the performance of the entire chain in two ways.

Wood has a certain chemical and physical composition, which reacts different under the pre-treatment conditions. Different polymeric structures of wood are affected by the several biomass pre-treatment methods. This results in diverse decomposition pathways. The chemical and physical composition determines in this manner to a great extent the outcome and performance of the biomass pre-treatment process.

In addition, the created intermediate products replace wood during the other chain elements, i.e. logistics and energy conversion. This is especially important for energy conversion. Energy conversion takes place in on coal based infrastructures. The performance is dependent to which extent the (biomass based) intermediate products overcome the limitations and drawbacks of untreated biomass, with respect to coal. Understanding of the chemical and physical properties of biomass is required to explain advantages of the intermediate products later on in bio energy supply chain.

From this perspective wood can be seen as the starting point of the supply chain and this chapter discussed the first sub question: *What is the basic chemical composition and physical structure of wood?*

This is done by first examining the chemical properties and the thereupon based biomass classification. Secondly, the physical properties are discussed. Hereafter the main characteristics of wood are discussed. The reminder of this section refers to wood type used in this report.

2.2 Chemical composition

The chemical composition of biomass exists roughly out of organic and inorganic (minerals) materials (Klas, 1998). The typical biomass composition of representative biomass species is given in table 3.

The organic material exists out of different polymeric compositions and is called ligno-cellulose. Ligno-cellulose exists out of cellulose, hemi-cellulose and lignin. The division in the three different biomass types is made on the variations in ligno-cellulose composition. Biomass is divided in the following categories, i.e. woody (deciduous and coniferous) and herbaceous types. In general has coniferous wood higher lignin content compared to deciduous wood and herbaceous plants have very low lignin content (Kreith and Goswani, 2007).

The various biomass pre-treatment methods aim at the decompositions of different polymeric compositions. Pelletisation targets at the lignin fraction, while torrefaction aims for the hemi-cellulose content and pyrolysis affects all the ligno-cellulose compounds. Generalisations about the decomposition pathway of pre-treatment can be made therefore only per feedstock type, and then still with caution as actual composition varies per specie.

Of the organic elements, carbon (C), hydrogen (H) and oxygen (O) content are often mentioned as they influence the Higher Heating Value[2] (HHV) of biomass (Loo and Koppejan, 2002). The HHV is the heating value of bone dry biomass.

The inorganic materials of biomass affect mainly the energy conversion stage. The minerals work as a catalyst which affect the emissions. As the minerals condensate, they cause fouling of the equipment. Wood has low ash content, and therefore it is not discussed in further detail here. In the chapter of energy conversion more attention is paid to this topic.

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[2] The Higher Heating Value (HHV) is the amount of heat released by a specified quantity (initially at 25 °C) once it is combusted and the products have returned to a temperature of 25 °C.

Table 3 - Organic and inorganic (ash) compounds in the representative biomass (Klas, 1998).

Biomass type	Herbaceous	Woody	
		Coniferous	Deciduous
Name (Component (dry wt %))	Bermuda grass	Pine	Poplar
Cellulose	31.7	40.4	41.3
Hemi-cellulose	40.2	24.9	32.9
Lignin	4.1	34.5	25.6
Ash	5.0	0.5	1.0
Closure	81	100.3	100.8

2.3 Physical structure

The ligno-cellulose polymers can be seen as the bricks and cement of the physical structure of biomass. They provide the strength to the biomass fibres.

A wood cell is build out of several layers and walls to provide the strength (stiffness) to grow in height (Bergman, 2005a). The different layers and walls have different functions and their polymeric composition varies thereby. The variation in ligno-cellulose content of the wall structure is shown in figure 3. The middle layers consist mainly out of lignin. The lignin serves as a glue to bind neighbouring cells. The hemi-cellulose serves as a bounding agent for the cellulose macro-fibrils. Bounding is reached mechanically and by hydrogen bounding. The lignin content decreases cell inwards. On the other hand increases the hemi-cellulose content inwards and reaches a maximum content in S_3. The cellulose content has a maximum in the secondary layer of the secondary wall S_2. This structure of bounded chains causes the tenacious and fibrous structure of biomass. Every layer has a different fibre orientation; S_2 has a vertical orientation, while S_1 and S_2 have perpendicular fibre orientation.

The fibre orientation combined with differences in thickness of the layers causes the fibrous structure of biomass, which affects the grindability and resulting size distribution.

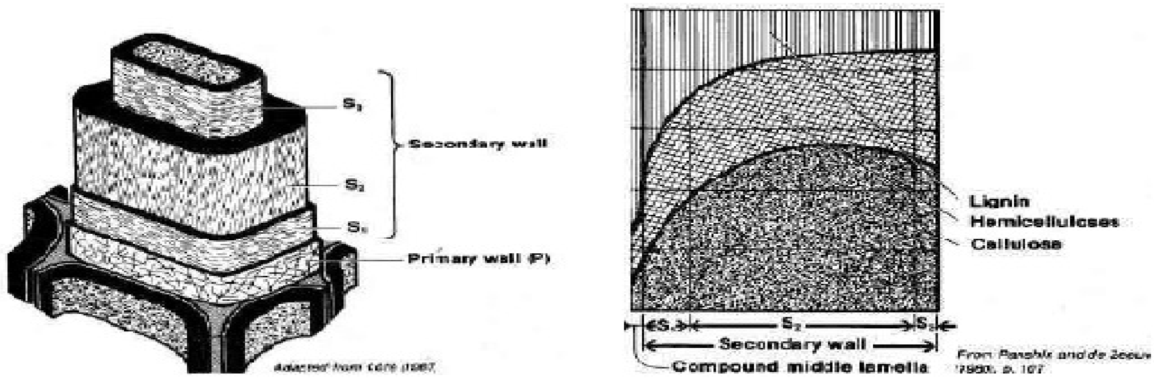

Figure 3 - Ligno-cellulosic distribution within the wall structure (Bergman, 2005b).

2.4 Wood characteristics

Having discussed the basic chemical composition and physical structure of wood the resulting characteristics can be discussed.

The most profound characteristic of biomass is its hydrophilic nature. Raw biomass has a moisture content that varies between the 45-55% (Klas, 1998). Moisture affects the vulnerability for fungal growth and plant size design (the wetter the product, the more mass for the same amount of energy, the more emissions and the bigger the boiler has to be) (Loo and Koppejan, 2002).

The most striking effect of moisture is nevertheless its effect on the energy content of biomass. Moisture reduces the HHV of biomass by the amount of energy that is required to evaporate water. The Lower Heating Value[3] (LHV) refers consequently to the energy content of the wet biomass. The HHV of biomass varies between 18-21 MJ/kg (Loo and Koppejan, 2002). The lower values apply for herbaceous species and the higher values apply to woody biomass. The relation between the moisture content, HHV and LHV is defined by:

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[3] The LHV is the amount of heat released by combusting a specified quantity (initially at 25 °C) and returning the temperature of the combustion products to 150 °C.

Equation 1 - Relation between moisture, HHV and LHV (Kreith and Goswani , 2007).

$$LHV = HHV * (1 - w) - 20{,}596 * h * (1 - w) - 2{,}3047 * w \qquad [MJ / kg]$$

w: *Moisture content of the fuel in wt%*
h: *Concentrations of hydrogen wt% (guiding value for woody fuels 6.2% d.b.)*

The bulk density is related to the moisture content as well. This is an important factor for the logistics and the process conditions of pre-treatment. In this study wet wood chips (2cm), with a bulk density of 350 kg/m³ are taken as starting point (Loo and Koppejan, 2002), the mass densities at other moisture contents is calculated by the following formula:

Equation 2 - Relation between moisture and bulk density (Avallone et al., 2006).

$$D_2 = D_1 \frac{100 + M_2}{100 + M_1 + 0.0135 D_1 (M_2 - M_1)} \qquad [kg / m^3]$$

D_x: *Mass density of wood at certain moisture content (D_1 is known and D_2 is calculated).*
M_x: *Moisture content in different cases in wt%.*

The volatile and ash content affect the conversion behaviour of biomass. Table 4 summarises the most important properties of biomass.

Table 4 - Characteristics of solid bio-fuels and their most important effects (adopted from van der Loo and Koppejan, 2007).

Characteristics	Effects
Moisture content	Storage durability and dry-matter losses, LHV, self ignition, plant design
HHV, LHV	Fuel utilisation, plant design
Volatiles	Thermal decomposition behaviour
Ash content	Dust emissions, ash manipulation, ash utilisation/ disposal, combustion technology
Ash melting behaviour	Operational safety, combustion technology, process control system
Fungi	Heath risks
Bulk density	Fuel logistics (storage, transport, handling)
Particle density	Thermal conductance, thermal decomposition
Physical dimension, form	Hoisting and conveying, combustion technology, bridging, operational
Size distribution	Safety, drying, formation of dust

2.5 Resume and assumptions feedstock

It can be concluded from this section that the chemical composition, i.e. the ligno-cellulose content, defines the feedstock type.

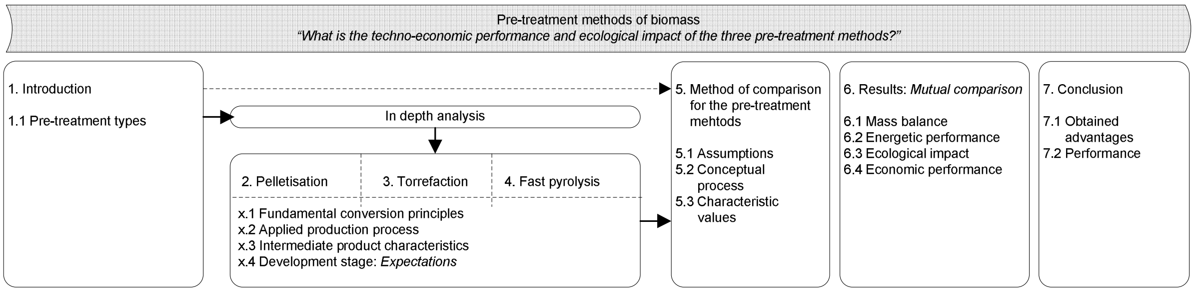
There are two woody feedstock types; coniferous and deciduous. In general wood has high lignin content and low ash content. The woody composition in this study is assumed to be, for simplicity: 40% cellulose, 30% hemicellulose, 29.5% lignin and 0.5% ash content. This composition resembles more deciduous wood, but is in between the two wood types. A HHV of 19 MJ/kg for wood is assumed, together with a moisture content of 50% for fresh wood. This results in a LHV of 7.7 MJ/kg and a bulk density of 350 kg/m³. Table 5 summarises the assumption chosen for wood chips in this report.

Table 5 - Modelling variables of wood chips.

Wood chips	Unity	Value
Cellulose	%	40
Hemi-cellulose	%	30
Lignin	%	29.5
Ash	%	0.5
HHV	MJ/kg	19
Moisture content	wt%	50
LHV	MJ/kg	7,7
Mass density	kg/m3	350

The moisture content of wood is not constant during the chain processes. Changes in the moisture content affects the LHV, mass density and thereby the process operations. These changes are recorded in equation 1 (LHV) and in equation 2 (mass density) and have to be kept in mind.

3 Pre-treatment methods of biomass



3.1 Introduction

This section will answer the second sub-question: *What is the energetic-and economic performance and environmental impact of the three pre-treatment methods, i.e. pelletisation, torrefaction and pyrolysis?*

To introduce the several pre-treatments, first the different pre-treatment methods are discussed. Next the characteristic values of the several pre-treatment processes are derived by an in-depth analysis. (Accordingly to the support questions, i.e. *what are the i. fundamental conversion principles, ii. applied production processes and iii. intermediate product characteristics?*). These values are the foundations of the modulation of the biomass pre-treatment methods.

In the method of comparison section, the characteristic values are summarised and a schematic representation of the general pre-treatment production process is given. This section describes how the energy and mass balances of the pre-treatment methods are calculated.

Subsequently the energetic-and economic performance and ecological impact are compared head to head in the result section. In this section is also elaborated on the production costs calculations. This section will give an indication of the performances and differences between the processes.

Finally is concluded at what (energetic, economic and ecological) expenses these products are created and what the most profound characteristics are of the intermediate products as they affect the later stages in the chain, e.g. the logistics and energy conversion.

3.1.1 Biomass pre-treatment types

Physical pre-treatment methods of biomass

Untreated biomass has a relatively low energy density, high moisture content and degrades biological during transport and storage (Forsberg, 1999). The low energy density causes an unwanted high number of transport activities. The high moisture content and large surface area cause fungal growth, which causes mass loss. In addition increases the temperature, which can cause self-ignition during biological degradation. Moreover suffers the quality of biomass from seasonal influences, which make biomass a highly ranged product. This highly complicates the handling of raw biomass. Physical treatments (drying, sizing and reforming) are therefore introduced to alter the physical characteristics to obtain a more uniform product. Chipping[4] and baling[5] are already widely applied and pelletisation is a strongly upcoming technique.

Thermo-chemical pre-treatment methods for biomass

The physical treatments don't affect the biomass nature, i.e. the hydrophilic character and fibrous structure. The thermo-chemical pre-treatments operate at moderate (+ 300°C) and high temperatures (+ 500°C) and thereby alter the chemical composition of biomass. This overcomes the biomass nature and is beneficial for handling and energy conversion (Bergman, 2005c and Bridgwater, 2007).The process temperature and residence time determine the decomposition process of biomass. Depending on the process characteristics biomass is decomposed in solids, liquids and gasses. The differences in temperature and residence time lead to a classification into respectively (from a low to a high temperature process): torrefaction, fast pyrolysis and gasification. An overview of the thermo-chemical processes and their typical yields are given in table 6. Torrefaction and pyrolysis are discussed in more detail in respectively §3.2 and §3.3. Gasification is discussed in less detail in the energy conversion chapter.

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[4] Chipping: Grinding of (mainly woody) biomass to reduce the size and improve handling.

[5] Baling: Compacting of (mainly herbaceous) biomass into bigger bundles.

Table 6 - Relation between thermo-chemical treatments of biomass and their typical yields (Bridgwater, 2007 and Bergman, 2005a).

Process	Conditions	Solid	Liquid	Gas
Torrefaction	Low temperature (280℃), very long residence time (20 min.)	**70%**	0%	30%
Fast pyrolysis	Moderate temperature (500℃), short vapour residence time (1 sec)	12%	**75%**	13%
Gasification	High temperature (<1000℃), moderate residence times (several min)	10%	5%	**85%**

3.2 Pelletisation

3.2.1 Fundamental conversion principles

Pelletisation is a physical treatment that compresses biomass (mainly wood) into small ´packages´, so-called wood pellets[6] (Viah, 2000). In this manner a product with higher mass density is created (kg/m3).

Pelletisation is a relatively straightforward technique. Biomass is forced through holes in a metal plate (called dies). During the compression through the dies the biomass heats up because of increasing pressure and friction. A typical temperature of around 90ºC is reached during pelletisation (Alankangas et al., 2002). This causes the lignin polymers to melt, which allows the biomass particles/ fibres to be reformed (Alakangas et al., 2002). As result the biomass is pressed together in smaller packages (pellets). As the pellets pass through the die, knifes cut the pellets in the required length. The pellets need then to be cooled to allow the lignin to set and keep the pellets together. Moreover cooling removes moisture that is released by compressing (Altener, 2002). A difference exists between the mass density of an individual pellet (<1.000 kg/m³) and the bulk density of pellets (<600 kg/m³) (IEA, 2007b). The fundamental principles are graphically displayed in figure 4.

The most used biomass resource is sawdust, also called ‘whitewood’. Whitewood is preferred because of its low ash and moisture content. Other types of raw biomass, like bark and logging residues are also suitable for pelletisation (Lehtinkangas, 2001). Rhèn et al. (2005) shows that with the appropriate conditioning and process conditions fresh biomass (higher moisture content, larger particles and higher ash content) can be pelletised as good as sawdust.

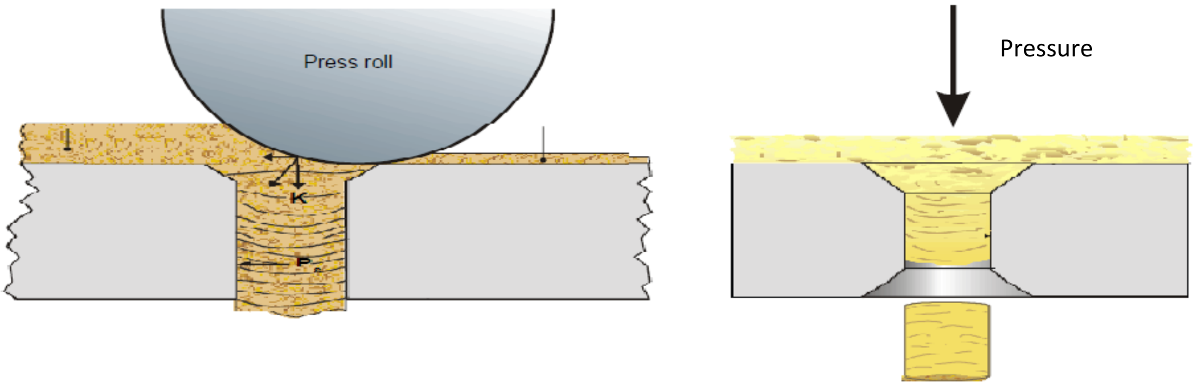

Figure 4 - Fundamental principles of the pelletisation process.

During pelletisation only the physical conditions of biomass are altered. The lignin fraction melts and the biomass particles can be reformed. Fresh biomass is not an obstacle if it is correctly conditioned. In general can be stated that the following criteria should be met to deliver high quality pellets (Viah, 2000): 1) homogenous/ uniform raw material. 2) Appropriate conditioning of the raw material, i.e. drying and grinding. 3) Right die specification to meet the required friction and pressure, i.e. heat. 4) If necessary, addition of binding agent, but this is not recommended.

3.2.2 Applied production process

Having considered the fundamental principles of pelletisation, it can be discussed what is feasible in practice. The pelletisation process can be divided in five steps as is described in figure 5. Biomass is delivered in several forms under different conditions. The biomass is therefore conditioned, dried and grinded, to obtain a uniform feed. The biomass is then pelletized and cooled to let the lignin set. Finally are the pellets screened for fines, which are send back to the pelletiser. The pellets that pass screening can be stored. The several different activities of the production process are discussed in more detail below. A summary of the typical values of the pelletisation process is given in §3.5.

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[6] In Dutch called: hout korrels.

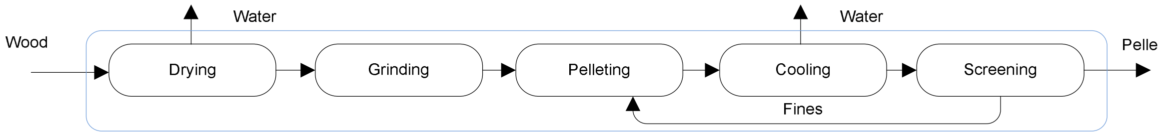

Figure 5 - Conceptual model of the applied pelletisation process (blue box).

Drying

Biomass which is too wet will slide through the dies and biomass that is too dry will plug the dies (Lehtinkangas, 2001). The optimal moisture content of wood before pelletisation would be between 10-17% according to Lehtinkagas (2001) and Karwandy (2007). The moisture left after drying ends up to a large extent in the pellet as less moisture is removed during pelletisation and cooling. Rhèn et al. (2005) states furthermore that the lower the moisture content is the more durable a pellet becomes. Less formation of fines results in lower transportation logistic losses. It is therefore chosen to dry the woodchips from 50 to 10% moisture content.

Grinding

In a similar way is the pelletisation process affected by the particle size. Particles that are too large plug the holes and if biomass is grinded too fine there are no long fibres to bind the pellet (Alakangas et al., 2002). The biomass is delivered in the form of wood chips. Wood chips have an average size of 1-3 cm. This size is too big for pelletisation. A broad range of 4-10 mm is mentioned in literature (Viah, 2000, Alakangas et al., 2002 and Karwandy, 2007). Meuleman (2008) mentions however, that in practice it is recommended to grind to size of 3 mm. Energy conversion facilities prefer particle sizes of maximal 3 mm because of combustion performance. Particles with a size bigger than 3 mm do not completely burn out (Robinson et al., 1998). Because of this reason is chosen to grind the wood chips to a size of 3 mm. The amount of energy which is required to grind chips to this size is 60 kWh/t (Gansekoele, 2000).

Steam conditioning (optional not necessary)

A somewhat more advanced pelletisation techniques makes use of steam conditioning. The pelletiser comes together with a mixing chamber, in which steam or another binding agent can be added (Alakangas et al., 2002). Mani (2006) explains that steam acts as a binder and lubricator, which would give an explanation for stronger and more durable pellets. Steam conditioning increases the moisture and heat, which allows lignin to separate and act more effectively as a binder (Mani et al., 2006). Steam conditioning is not considered necessary (Viah, 2002).

Pelletisation

Pelletisers come into different sizes and forms. Two different types of pelletisers can be distinguished (Alakangas et al., 2002 and IEA, 2007b): 1) *Flat die*, biomass falls on a horizontal circular die, over which several presses role, which push the biomass through the holes. 2) *Rotary die*, biomass falls into a vertical ring die, in which several presses role, which push the biomass from the inside of the ring through the die. Both types of dies are widely applied.

The right pressure and resistance heat the biomass up with causes the lignin to melt. The pressure and resistance can be adjusted to obtain the right quality. Alakangas et al., (2002) and Karwandy (2007) mention for example, among others, the number of holes, gap length and diameter as important factors that determine the friction and pressure as important process characteristic.

During the process also water is released, which results in a final moisture content of 6-12% (Alakangas et al., 2002). In this report is chosen to use to lower boundary of 6% moisture content for the resulting pellet. The energy required to pellet wood varies from 30–60 kWh/t (Alderliefste, 2008 and Andritz, 2008). This variation depends on the type of wood; deciduous wood types require more energy. It is assumed that the energy required for pelletisation is 50 kWh/t.

Cooling and Screening

Pellets come out of the pelletiser with a temperature of around 90^{o}C. At this temperature the lignin is still not fixed and the pellets are fragile. Cooling of the pellets is therefore required to stabilize the lignin and to obtain a durable pellet. The pelletisation process releases moisture because of the high compression. This moisture is removed during cooling. It is assumed that the eventual pellet has a moisture content of 6% (Electrabel, 2004). Finally the pellets are moved over a vibrating screen to separate the fines and redirect them back to the pelletisation process. The energy that is required for these processes is can be neglected (Alderliefste, 2008).

Alderliefste (2008) mentions however, that 40 kWh/t is required for the general process, i.e. conveyer belts and other process utilities.

3.2.3 Pellet characteristics

The applied process had several restrictions and limitations, which affect the characteristics of the pellet. Each producer has its own process conditions and as result there is wide range within the pellet conditions. End users defined therefore norms and standards to guarantee a uniform product with certain quality. Many countries have developed their own pellet standards. A European standard for solid bio-fuels CEN/TS 14961 is under development (IEA, 2007b). An overview of European pellet properties compared to the North American is given in table 7. The table shows as well the norms used by Electrabel (2004) to purchase pellets.

The pellets characteristics are discussed according the defined standards in table 7. The amount of ash and especially chlorine content are defined as they forecast the fouling phenomena during combustion. Uncertainties about the fouling phenomena of additives prohibit guidelines about the use of additives. The national policy guidelines are not decided yet, but Electrabel is not in favour of binding agents, as they complicate the combustion phenomena.

Pellets are bounded by a certain diameter and length, because of the infrastructure that is build out to handle pellets with certain dimensions. Variations of the dimensions, which are too big result in malfunction of the handling infrastructure.

The mass density, LHV and moisture content guarantee energy - off gas volume ratios, which are of high importance to streamline the combustion process. The moisture content of 6% which is chosen in this report results in a LHV of 16.5 MJ/kg. This is on the low side of the range, but is explained by the start assumption of the HHV 19 MJ/kg of this report. The mass density of 610 kg/m^3 is within the standards mentioned in table 6.

Pellets absorb moisture, due to the hydrophilic nature of biomass. As a consequence the pellet swells up, the lignin is not able to resist the increasing inner pressure anymore and the pellet falls apart in many fines.

The standards do not include durability yet. This is however an important characteristic, which explains the pellet behaviour during transport and handling. Pellets of a low quality break and produce large amounts of dust. The amount of fines is more important in the domestic small heating systems than large scale combustion facilities (Viah, 2000). Industrial process equipment is more robust and can deal with more fines.

Electrabel places also restrictions on the particle sizes of the pellets, but this complies with the combustion standard of <3.0 mm.

Table 7 - Norms and standard of the pellet characteristics (Karwandy, 2007, IEA, 2007b and Electrabel 2004).

Properties	North American Grades		Comparable European Categories	Electrabel ('04)
	Premium	Standard		
Diameter	6 mm to 8mm		6 mm to 8mm *(categories range up to 25 mm)*	4 - 10 mm
Length	≤ 38 mm		≤ 30 mm or ≤ 4 times diameter	10 - 40 mm
Mass Density	≥ 640 kg/m^3		≥ 1000 kg/m^3 (individual)	> 600 kg/m^3
LHV	-		> 17.5 MJ/kg	> 17 MJ/kg
Moisture	-		< 10 - < 12% wt	< 10% wt
Ash Content	< 1%	< 3%	≤ 0.7% to ≤ 6.0% *(>6.0% actual value must be stated)*	< 1%
Fines (passing through a 1/8" screen)	< 0.5% wt		≤ 1% wt ≤ 2% wt *(> 2% wt actual value to be stated)*	Particle size distribution <3.0mm (100%) <2.0 mm (95%) <1.5 mm (75%) <1.0 mm (50%)
Chlorides	< 300 parts per million		≤ 0.03%, ≤ 0.07% or ≤ 0.10% wt *(> 0.10% wt actual value to be stated)*	<0.03 %
Additives	-		-	Forbidden

Wood pellets are a more uniform product, with a higher mass density, higher heating value and thereby a higher energy content in comparison with wood. The moisture content is lower, which reduce the off-gasses from combustion. Moreover, the low moisture content reduces the influence of fungal growth and the sweltering behaviour.

Wood pellets have however still the hydrophilic nature of raw wood. This means that pellets must be kept free of water, otherwise the obtained advantages are undone. Standards and norms are formulated to obtain guarantee a certain quality and uniform pellet from all producers.

3.2.4 Development stage: Expectations

Pelletisation is well known process that already exists for several decades. It is the most mature pre-treatment of the three methods.

In 2006, a 7 million tonne world market existed (IEA, 2007b). The market is mainly driven by North-America and Europe. Over time the market developed and different market segments raised; an industrial and commercial sector (Rivieare et al., 2006 and IEA, 2007b). Each segment has its own norms and standards. In general industrial pellets have a lower quality. The technology is mature and Rivieare et al. (2006) observes that there is a tendency to integrate the value chain to reduce costs.

As feedstock for pellets is mainly wood used, and especially sawdust (Rivieare et al., 2006). Sawdust is the preferred resource as it is already pre-conditioned, e.g. grinded and dried. Other biomass resources can be used, but this is not common as enough sawdust is available (Viah et al., 2000). The recent trends indicate however that a shortage of sawdust can be expected (van Daalen, 2008).

An established market for pellets exists and the technology is well developed, minor changes in the production technology are expected.

As pelletisation exists already for some time, several studies investigated the production costs. Thek & Obernberger (2002) and Mani (2006) evaluated respectively a European and an American production processes. They found similar results.

The main cost factors are the raw material and drying of the raw material, followed by personnel and pelletisation costs. Sensitivity analysis showed that pellet production costs are greatly influenced (in order of magnitude) by the pellet throughput, raw material price, equipment availability, the specific heating costs, the heat demand for drying, investment costs and annual operating hours. CPM (2004) stressed the point of economies of scale, which halve the investment costs and operating costs. With increasing scale reduced the influence of capital costs and operating costs, which become constant, while the influence of the consumption costs increased. Mani (2006) found a similar scale effect. The optimum production rate would be around 15t pellets/h (CPM, 2004 and Mani, 2006).

So it can be concluded that a certain consensus is reached about the technologies, economies of scale and costs building of the pellet production process. Variations in production costs are mainly due to local conditions.

3.3 Torrefaction

3.3.1 Fundamental conversion principles

Torrefaction is a thermo-chemical treatment in the relatively low temperature range of 225-300°C, which aims to produce a fuel with an increased energy content by decomposing the hemi-cellulose fraction in biomass (Prins, 2005). In other words, biomass is heated, which causes mass to 'evaporate'. The evaporated substance has low energy content. The resulting product contains thereby relatively more energy. The process is often compared with roasting of coffee beans.

The process takes place under atmospheric conditions, in the absence of oxygen, with low particle heating rates and relatively long reactor residence times (5-20 minutes) (Bergman, 2005b). Torrefaction is an endothermic process, in which biomass is heated over a long timeframe and trough different stages (Bergman 2005b, Prins, 2005); 1) *Initial heating*, 2) *Pre-drying*, 3)*Post-drying and intermediate heating*, 4) *Torrefaction* and finally (5) *cooling*.

During the drying stages (1-2) moisture is evaporated until the critical moisture content is reached. Beyond this point, evaporation of solely moisture is not possible and some mass loss occurs due to the 'evaporation' of light volatile components (3). Increasing the temperate further above 200°C will lead to devolatilisation of biomass; *the actual Torrefaction process* (4). Cooling below 200°C is subsequently required to stop the devolatilisation of compounds (5). No mass release occurs anymore, but evaporation of absorbed reaction compounds is possible.

Under torrefaction temperatures mainly hemi-cellulose is decomposed, followed by a partial break down of cellulose and lignin (Prins, 2005). The devolatised compounds exist mainly out of CO_2, CO and H_2O (Bridgeman et al., 2008). The remaining solid has a higher concentration of carbon and lower concentrations of oxygen and hydrogen.

Due to this process, torrefied biomass approaches the structure of coal[7] (brittle structure and higher LHV). Moreover, OH-groups are broken, with as result that no hydrogen bounds can be formed. This explains the

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[7] This process is represented in the Van Krevelen diagram in appendix A.

hydrophobic nature of torrefied biomass. Torrefied biomass has however a low mass density, due to devolatisation.

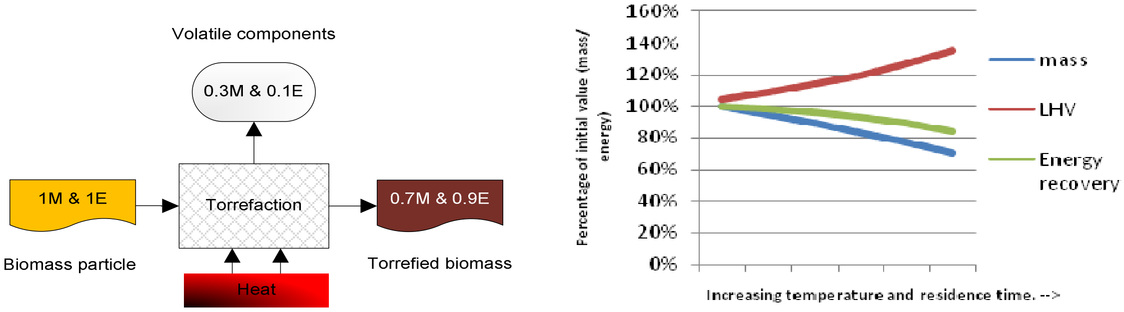

Figure 6 - Fundamental principles of the torrefaction process (adjusted from Bergman (2005a) and Prins (2006b)).

The different reactions of the polymeric structures in biomass; cellulose, hemi-cellulose and lignin, result in different yields under the same torrefaction conditions.

Many product distributions are mentioned, but for wood the division is typically in the range of 70-90% solids and 10-30% in condensable vapours and permanent gasses, mass based (Prins, 2005).

The HHV can increase, depending on the feedstock, with 5-30% (Prins, 2006 and Bridgwater, 2008). Under the same conditions an increase in LHV of 20% can be obtained for woody biomass and an increase of 30% can be obtained for herbaceous biomass (Prins, 2005b). In figure 6, this is graphically presented.

These volatiles have relatively low energy content and the LHV of the solid increases therefore. Relatively more mass than energy devolatises, e.g. 0.3 mass and 0.1 energy. The red line (LHV) is steeper than the blue line (mass left after torrefaction). As result more energy than mass is recovered and the end product (the green line is positioned higher than the blue line). This effect becomes more profound with increasing temperature and residence time.

The same mass or energy yields can be obtained for the different biomass types, but under different torrefaction temperatures and residence times (Prins, 2005, Zanzi, 2000 and Bridgeman et al., 2008).

3.3.2 *Applied production process*

To translate the torrefaction principle into a well performing industrial process requires several activities. First the raw biomass needs to be pre-dried, to make it suitable for torrefaction. After torrefaction the torrefied product is pelletised and cooled (BGP, 2005 and Bergman 2005c). An overview of the torrefaction process is given in figure 7. The figure is followed by a short description of the several process steps. A summary of the typical values of the torrefaction process is given in §3.5.

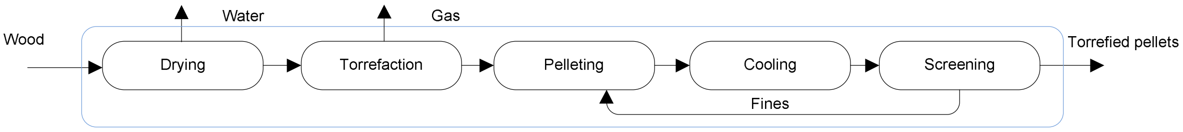

Figure 7 - Conceptual model of the applied torrefaction process (bleu box).

Drying

The moisture present in the wood will act as a heat sick during torrefaction and the evaporated moisture will end up in the torrefaction gas (Bergman, 2005b). This will reduce the efficiency of torrefaction and more important, the evaporated water will lower the HHV of the torrefaction gas. The whole torrefaction gas is combusted together with natural gas to deliver the required heat for drying and torrefaction. Typical drying to 10% (critical) moisture content is done.

Grinding (optional and not necessary)

Experiments were done to investigate the effect of particle size on the mass and energy yield. The results showed minor differences and they were inconsistent (Bergman, 2005a). The particle size varied from 0-10, 10-30, 30-50 mm. Prins (2005) discovered that internal the heat transfer does not play a significant role because devolatisation reactions are the limiting step, provided that the particle has a sufficient small size (Biot number). The sizes mentioned by Prins (2005) and Bergman (2005b) are <50 mm.

Torrefaction

A relation exists between the energy requirement, division between solid -gas and LHV's of the solid and gas. They all come together as one package. Wood has a hemi-cellulose content of approximately 30%.

The division between the products is therefore 30% gas and 70% torrefied wood. The heating values mentioned vary from 19-22 MJ/kg Pach (2002), Bergman (2005) and Bridgewater (2007). It is therefore chosen to follow Bergman (2005c), which deals with a wood type similar as the reference wood used in this report. The LHV of the torrefied wood is therefore set to 19.5 MJ/kg.

The temperature and residence time that accompany this division are respectively assumed to be 225-300°C and 5-20 minutes (Meuleman, 2008). The energy required to reach the torrefaction temperature and to obtain the required torrefaction conditions are dependent for great extent on the reactor. Not much is written about the reactors, as this is often confidential information. Bergman (2005b) distinguishes two kinds of torrefaction reactors in general; directly (rotating drum and moving bed) and indirectly heated reactors (screw reactor). The energy requirements used in this study are based on flow charts by Bergman (2005b) as the only available source. Bergman (2005b) assumes an energy requirement of 3.5% of the energy content of the feedstock entering the reactor.

The torrefaction gas exists for 50% out of water, 10% out of CO_2 and 40% out of organic vapours (Bergman, 2005b). In total contains the torrefaction gas 60% incombustible gasses, which makes it questionable if the torrefaction gas can be combusted (Bergman, 2005b).

Less is written about the actual heating value of the torrefaction gas. It is likely that the LHV of the torrefaction gas will vary with the process conditions and the content of lipids, organics, gasses and water of the torrefaction gas. Normally, it is the expected that such an off-gas has a LHV of around 4 MJ/kg (Stelt, 2008). A process variation however alters the composition of the gas and thereby the heating value. Out of confidentiality issues the process variation cannot be discussed. This results in a LHV of 6 MJ/kg for the torrefaction gas.

Another solution would be to cool the gas and let the water condensate. This is however not desirable because the polluted water has to be cleaned at high expenses (Meuleman, 2008).

Pelletisation process

The devolatisation of compounds creates a more porous structure. The mass loss and more porous structure are the cause of a lower mass density of torrefied biomass (230 kg/m3). A pelletisation step is added to increase the mass density. The mass density can be increased with a factor of 1.5-3 (Bergman, 2005c).

This process does not differ much from the pelletisation of untreated/ raw biomass, which is explained in the section of pelletisation already. The energy requirement for the pelletisation of torrefied wood is set to 30 kWh_e/t versus 60 kWh_e/t for pelletisation wood, due to the easier grindability of wood. The resulting product is called BO_2pellets™.

The lignin polymers are not affected by the torrefaction temperatures and acts therefore still as a binding agent. The lignin content is even increased and therefore stronger pellets are created.

Water is however used to ease the pelletisation process. For simplicity this is not accounted in the model and to correct the moisture content less moisture is expected to evaporate during torrefaction.

Cooling and screening

Cooling of the torrefied biomass to approximately 50-100ºC is required for four reasons (Meuleman, 2008): a) to stop the devolatisation process, b) to prevent for self ignition, c) during pelletisation rises the temperature and this could cause further devolatisation. Finally the pellets are moved over a vibrating screen to separate the fines and redirect them back to the pelletisation process. The separation of fines prevents dust formation and losses during transport and handling. The energy needed for cooling and screening is assumed to be included in the energy required to keep the process running (Alderliefste, 2008). The energy needed for the general process is set to 40 kWh_e/t raw biomass input.

3.3.3 Torrefied pellet characteristics

Now the fundamental principles and applied process are explained the torrefied pellet (BO_2pellets™) characteristics can be discussed. BO_2pellets™ are brown to dark-brown coloured and approach the characteristics of coal. A comparison between BO_2pellets™ pellets and ordinary pellets is made quickly, because of the physical form. The differences are however big. BO_2pellets™ are more uniform and have improved characteristics compared to conventional pellets. An overview of the product characteristics is given in table 8. The most important product characteristics are discussed below.

LHV and energy density

The LHV of torrefied wood is higher than the LHV of wet and dry wood. The LHV of torrefied wood is equal to the LHV of pellets made from torrefied wood as only mass increase is created during pelletisation. The higher mass density and LHV of BO$_2$pellets™ results in a higher energy density compared to wood pellets. The thermo-chemical treatment creates a more uniform product (Bergman, 2005c). With uniformity is meant the quality of the feedstock, i.e. seasonal influences like the wheatear and harvesting technique affect the quality of the feedstock.

Pellet influences

Pelletisation does not only increase the mass density, it results also in a stronger product. A higher mass density is beneficial for the logistic operations. Less transport actions are required to deliver the same amount of energy. This results also in less storage capacity at the energy conversion plant. The higher energy density also results in higher co-firing percentages. The co-firing amount is limited by the boiler capacity. BO$_2$pellets™ pellets deliver more energy with the same amount of flue gasses. A stronger pellet is created due to the relatively high lignin content and fatty unsaturated structures of BO$_2$pellets™ (Kiel, 2008). This prevents for dust formation, which reduces the danger of dust ignition and increases the handling properties as less precautions have to be taken during transport and storage.

Table 8 - Characteristics of wood, torrefied biomass, wood pellets and BO$_2$pellets™ (adopted and adjusted from Bergman (2005c).

Properties	Unit	Wood	Wood pellets	Torrefied wood	BO$_2$pellets™
Moisture content	% wt.	50	6	5	3
Heating value					
LHV (as received)	MJ/kg	7.7	16.4	19	19.5
HHV (mc 0%)	MJ/kg	19	19	20.4	20.4
Mass density	kg/m3	350	610	230	750
Energy density	GJ/m3	4.2	10	4.5	14.6
Pellet strength		-	Good	-	Very Good
Dust formation		Moderate	Limited	High	Limited
Hygroscopic nature		Water uptake	Swelling/ water uptake	Hydrophobic	Poor swelling/ hydrophobic
Biological degradation		Possible	Possible	Impossible	Impossible
Seasonal influences		High	Moderate	Poor	Poor
Handling properties		Normal	Good	Normal	Good

Grindability

This is a major advantage of torrefaction. A reduction in power consumption of 70-90% and capacity increase of 7.5-15 can be obtained, depending on the torrefaction conditions (Bergman, 2005c). Moreover become the torrefied particles more isolated and spherical, which improve the flow properties (Arias, 2007). The distribution in size and shape are also more uniform for grinded torrefied particles. Grinded raw biomass particles have a fibrous nature, with a mixture of large particles and fibres, which form links between particles. Hemi-cellulose is the bounding factor and is missing in torrefied biomass. This is shown in figure 8. The yellow and orange lines are hemi-cellulose bindings. Raw biomass has more and longer hemi-cellulose polymers, which cause a fibrous nature, while torrefied biomass breaks in loose particles.

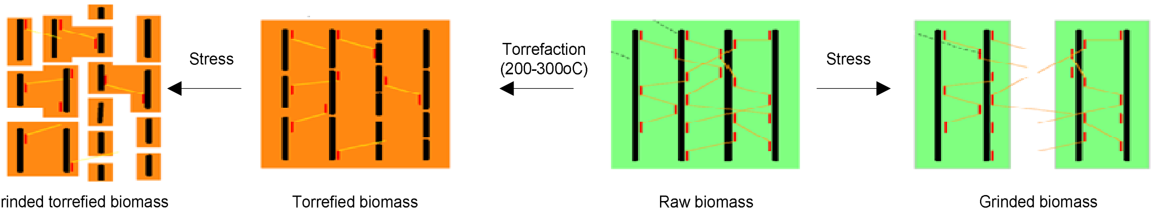

Figure 8 - Behaviour of raw biomass and torrefied biomass under stress.

Hydrophobic nature

Mainly CO_2, CO and H_2O are emitted during the disintegration of hemi-cellulose, which destroys the OH groups and form unsaturated structures, which are non polar (Bergman, 2005c). Due to these reactions is torrefied biomass unable to make hydrogen bounds, which explains its hydrophobic nature. Due to its hydrophobic nature is torrefied biomass not sensitive for biological degradation.

3.3.4 Development stage: Expectations

The development of torrefaction is, at first instant, strongly initiated by the development of biomass gasification and later on by co-firing. During the process more favourable characteristics of torrefied biomass are discovered, which boosted the interest in biomass. The coals like properties of biomass make it an attractive fuel to use in the conventional, widely applied, coal infrastructure.

A short internet search showed that more companies entered the domain of 'bio-coal'. Many activities are driven from an engineering background in related areas, i.e. drying and pyrolysis. This makes their 'torrefaction claim' not always reliable[8].

Despite the boost in interest, torrefaction is still in the research phase. Main (publically known) players are ECN and LLC for the applied process and many others are defining the exact product characteristics. Many variations can be expected in the field of production technologies and product characteristics. Consensus starts to originate however, about the torrefied biomass properties. Less is publicly written about the characteristics of torrefied pellets.

There are no commercial torrefaction plants today, but there was a torrefaction plant in operation by the firm Pechiney, France, in the 1980's (Bergman, 2005b). The factory was however, shut down due to economic considerations in the beginning of the 1990's. There is consequently little known about the investment and operation costs of torrefaction.

Bergman (2005b and 2005c) made a cost division in capital, consumption (electricity, gas, cool water and maintenance) and operating costs was made for three reactor types. The capital costs varied from €30-60 million (60 kton/a – corrected to €2008) for respectively a moving bed, rotating drum or screw reactor. In a follow up study the capital cost decreased enormously to € 6.6 – 8.7 million euro (56 kton/a –corrected to €2008) (Bergman, 2005c). No detailed cost analysis was given, so it cannot be explained why there is such a big difference.

Great uncertainty exists about the production costs of the torrefaction process.

3.4 Fast pyrolysis

3.4.1 Fundamental conversion principles

There exists a huge difference between fast pyrolysis and the other two biomass pre-treatment methods. Pelletisation and torrefaction lead to solid intermediate products, while fast pyrolysis leads to a liquid. Fast pyrolysis is *a high temperature (500°C) process in which the feedstock is rapidly (<1 second) heated in the absence of oxygen, vaporises and condenses to a dark brown mobile liquid which has a heating value of about the half that of conventional fuel oil* (Bridgwater et al., 1999a).

Pyrolysis is an endothermic process and consists out of primary (desired) and secondary (undesired) reactions (Meier et al., 1999). Pyrolysis conditions create a high heat flux, which causes such a high thermal excitation of the molecules that the material decomposes instantaneously into various products (primary reactions). The rapid heating in absence of oxygen causes a random chemical degradation. This process is described in figure 9.

The thermal breakdown decomposes the macro-polymers of cellulose, hemicelluloses and lignin into shorter components. These components are in different thermal phases at a temperature of 500°C, i.e. vapours, aerosols, gasses and solids (Bridgwater, 1999b).

By cooling the mixture, the components condensate into an organic fluid, aqueous fluid or remain permanent gasses or solids. The organic fluid and aqueous fluid form bio-oil. Due to their chemical composition they mix in such a way that they form one liquid phase and no distinctive phases can be distinguished anymore.

A disadvantage of the rapid thermal breakdown during pyrolysis is that it results in free radical compounds (Meier et al., 1999). The free radical compounds are not chemical stable and very reactive. The free radical

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[8] Transnational Technology LLC is market place for technology transfer and innovation and specialised on torrefied biomass (http://www.techtp.com).

compounds react further (during secondary reactions) into smaller compounds and/or polymerize into larger compounds. Secondary reactions create gasses, sticky fluids, aqueous fluids and solids.
This is not desired as this occurs at the expense of compounds that form the liquid and decrease the quality of the bio-oil. Rapidly quenching of the pyrolysis product avoids/ minimizes secondary reactions.

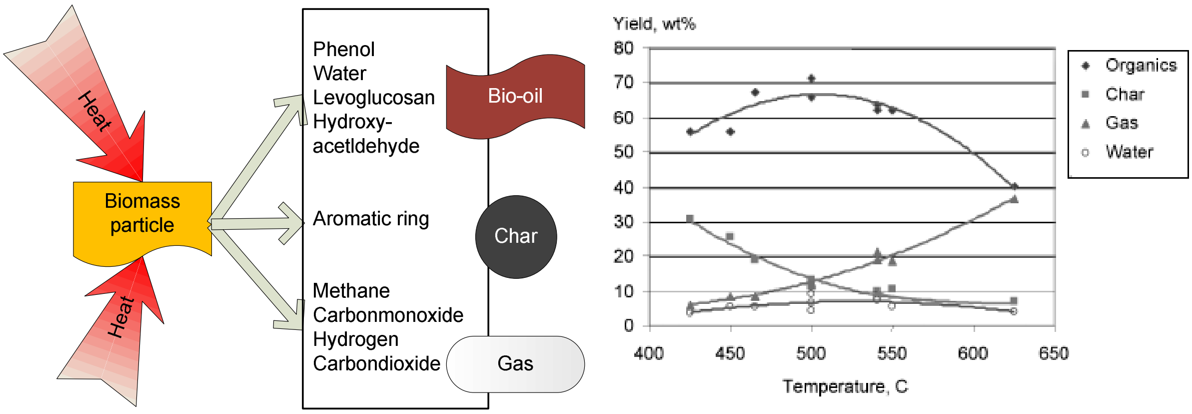

Figure 9 - Fundamental principles of the fast pyrolysis process.

In general to optimize the process circumstances and maximize the liquid yield, four essential fast pyrolysis principles should be recognized (Bridgwater, 2004): 1) Biomass has a low thermal conductivity and to reach very high heating and heat rates at the reaction interface a finely grind biomass feed is required <2mm. 2) Experimental validation concluded a reaction temperature of around 500°C for a maximum liquid yield and a vapour phase temperature of 400-450°C to prevent for secondary reactions. 3) Short reactor residence times of typically less than 2 seconds to prevent for further cracking of the compounds. 4) Rapid cooling of the pyrolysis vapours to give the bio-oil product and prevent for further reactions.

The chemical composition of biomass affects the quality and stability of pyrolysis oil. Mainly the lignin content and inorganics of the biomass affect the outcomes (Fahmi et al., 2008). The rapid degradation of lignin forms high molecular weight molecules. These, heavy weight, molecules increase the viscosity and cause a shift of the pyrolysis oil into an aqueous phase and slurry.
Ash (alkali metals) acts as a catalyst, which speeds up these processed. Moreover gasses and char are formed, which decreases the bio-oil yield. Potassium (K) has the highest influence. The effect of ash is however relatively small compared to the effect of lignin (Gerhauser, 2008).
A trade of has to be made between the two of them, because when the alkali metal content increases, the lignin content decreases and otherwise around. Any kind of biomass can be used for fast pyrolysis (Bridgwater, 2007). Mohan et al. (2006) stress however the point that the feed complexity and variability make it difficult to define standard processes.

3.4.2 Applied production process

These principals have to be translated to a good performing process. The general process set up of the fast pyrolysis (figure 10) consists out of feed preparation, fast pyrolysis, char separation from the pyrolysis vapours and cooling or quenching to obtain the bio-oil (Bridgwater, 2003). The eventual bio-oil yield dependents on the feed, reactor configuration, char separation and liquid collection. Alternations of the process characteristics change the yield and quality. A summary of the typical values of the pyrolysis process is given in section 3.5.

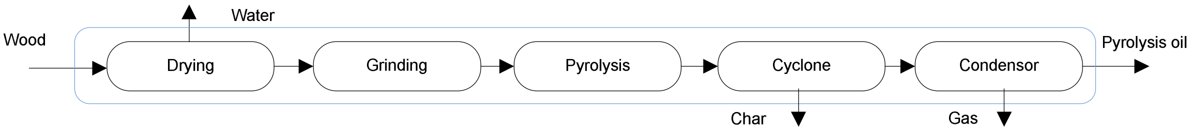

Figure 10 - Conceptual model of the applied fast pyrolysis process (blue box).

Drying

The water that is present in the in biomass feedstock will evaporate during pyrolysis and eventually condensate with the bio-oil. It is not possible to remove the water from the bio-oil with conventional distillation methods, due to complex bounding forces in the oil (Bridgwater 1999). The moisture content of the bio-oil affects its stability, viscosity, pH, LHV and other liquid properties. The pyrolysis of bone dry biomass results in bio-oil that contains 12-15wt% water. The water that is available before pyrolysis will add up with the amount of water formed during pyrolysis (NREL, 2006). Figure 11 geographical describes the relation between the LHV and moisture content. The initial moisture content determines the eventual moisture content of the pyrolysis oil and thereby the eventual LHV of the pyrolysis oil. As little as possible moisture is preferred therefore. Due to practical implications (critical moisture content) however, is the moisture content maximal reduced to approximately 10%.

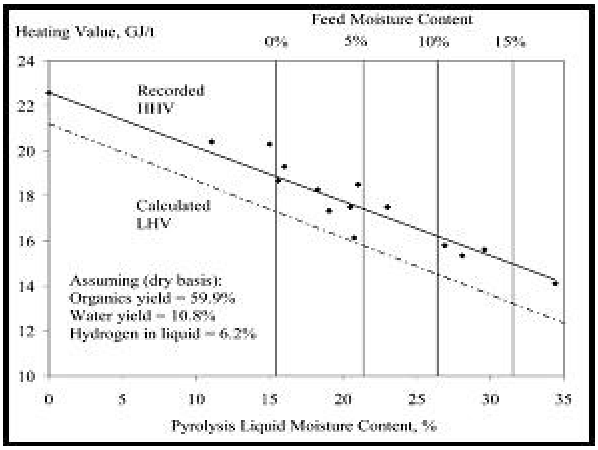

Figure 11 - The LHV of Pyrolysis oil in relation to the moisture content (Bridgwater et al., 2002).

Grinding

A size reduction is required. Small particles, with a relatively large surface area to volume ratio, are required to obtain a high heat flux. The biomass is therefore grinded to particles with a size of 2mm. Grinding in 2 phases could be more energy efficient (Gansekoele, 2000). This information is however not available and chosen is to do it in one stage. The energy required for a size reduction to 2 mm is estimated at 95 kWh/t (Gansekoele, 2000).

Reactors

The reactor is the crucial and problematic factor in the fast pyrolysis process. Heat transfer and heat supply are the essential factors. A universal heat flux to the biomass is required. This can be done in several ways, by convection, conduction and/or radiation. A short description is given of the several reactors in appendix B and for amplifications is referred to the above mentioned authors.

The reactor design determines the pyrolysis conditions, product yields and consisting LHV of the solids, gas and oil. The bio-oil yield varies greatly from 30-80%. The maximum pyrolysis oil yield is 70-75% by weight on commercial scale (Bridgwater et al., 2002). The pyrolysis by-products are char and pyrolysis gasses, respectively 13-16 and 11-14% by weight. This results in a pyrolysis oil yield of 75%, char yield of 12% and a pyrolysis gas yield of 13%. The corresponding LHV's are: 14.9 MJ/kg for pyrolysis oil (Bridgwater et al., 2002), 29 MJ/kg for char (Dynamotive, 2005) and 4 MJ/kg for the gas (van der Stelt, 2008). This agrees with the wood type chosen as reference case in this report (Mohan et al., 2006).

The oil contains approximately 70% of the initial energy content, while the char and gas contain 25% and respectively 5% of the initial energy content Bridgewater (2007). As the reactor type varies every time also the energy needed for pyrolysis varies. According to Bridgewater (2007) approximately 15% of the energy content of feed entering the reactor is required for pyrolysis process itself. The by-products are combusted to deliver heat for the process.

Char removal

The alkali metals in the char act as a catalyst for cracking processes of the pyrolysis vapours (Oasmaa, 2001). Fast removal of the char is therefore desired to prevent for secondary reactions. These reactions do not only occur in the vapour phase, but also in the liquid phase and cause severe problems for the stability and quality of the bio-oil, i.e. viscosity, phase separation and changes in the LHV. Separation of the char is preferably done before the vapours are condensed (Bridgwater, 2004).

Cyclones are used to remove the char, but some fine particles pass through the cyclone and end up in the bio-oil and cause aging and instability problems (Bridgwater, 2004). Another technique to remove the char is hot vapour filtration, but the liquid yield reduced by 10-20% due to char formation on the filter that cracks the vapours that pass the filter (Bridgwater, 2004). Other techniques like in-bed filtration, rotating principle, and pressure filtration are under development, but suffer from technical problems. As result that these techniques are not mature enough to be applied in practice (Bridgwater, 2004). In this report is assumed that all char is removed when passing the cyclones.

Liquid collection

The pyrolysis product exists out of aerosols, true vapours and non-condensable gases. To collect the bio-oil the aerosols and vapours have to be cooled down. Rapid cooling is required also to minimise secondary reactions and self ignition (Bridgwater, 2004). The true vapours condensate, while the aerosols coalescence or agglomerate. Simple heat exchange can cause tar formation of lignin derived components and results in blockages. Therefore is quenching (rapid cooling) done by blowing the pyrolysis products through product oil or an immiscible hydrocarbon solvent (Bridgwater, 2004). The energy required for the pyrolysis process utilities is set to 40 kWh/t (Bridgwater et al, 2002).

3.4.3 Characteristics of pyrolysis oil

From the above came to the fore that pyrolysis oil is a complex product. Mohan et al. (2006) describes bio-oil as: *a micro-emulsion, in which the continuous phase is an aqueous solution of holocellulose*[9] *decomposition products and small molecules from lignin decomposition*. Roughly can be stated that bio-oil exists out of an organic phase and an aqueous phase. Hydrogen bounds, formation of nano-michelles and micro/micelles keep the mixture of aqueous and organic phase in the fluid together. Due to the variety of feedstock, pyrolysis methods and process conditions it is difficult to define ´the´ bio-oil characteristics. Nowadays there exists consensus about the characteristics of bio-oils produced by several wood types. The characteristics of bio-oil are discussed according the specifications displayed in table 9.

Water content and LHV

The water content of bio-oil is about 18-40 wt%, due to the moisture in the feedstock and dehydration reactions during pyrolysis. The presence of water decreases the LHV and flame temperature, but decreases as well the viscosity, which improves the fluidity (Oasmaa et al., 2001, Czernik et al, 2004).

Below moisture content of 27% *wt* an acceptable trade of between viscosity and LHV exists, as the higher heating value is acceptable (13-17 MJ/kg). The moisture content chosen in this report is 25%, with a LHV of 14.9 for the pyrolysis oil. See also the drying section in the pyrolysis process for the relation between the moisture content and LHV.

Solids and ash

Solids exist out of char and sand particles. Ash and metals end-up in the char. High solids content can cause high wear in pumps and injectors, deposits in combustion equipment, or corrosion in gas turbines due to alkali metals in the ash (Oasmaa, 2005). Ash should be avoided in all times because it acts furthermore as a catalyst in secondary reactions, which influence the bio-oil quality negatively.

Aging (homogeneity, stability and viscosity)

The most profound characteristic of pyrolysis oil is aging. Bio-oil, as produced, has a relatively low viscosity and is a single phase liquid. Over time, bio-oil becomes more viscous and shifts into more phases. Also gasses are released, which were incorporated during cooling of the pyrolysis gasses.

Aging can best be described as ticking of the bi-oil (increase in viscosity), followed by a phase separation (a heavy compounds rich phase and an aqueous phase) (Oasmaa et al., 2001). The reason for aging is that bio-oil is not a product of a thermodynamic equilibrium (Diebold, 1999). Through rapid cooling/ quenching is a condensate obtained that is not in a thermodynamic equilibrium at storage temperatures (25°C).

The several oxygenated organic compound react further towards a thermodynamic equilibrium at room temperature. As result increases the water content the decreases the volatility content, which affect the viscosity, molecular weight and co-solubility of the aqueous and organic compounds in the fluid. In this manner shifts bio-oil into various tarry, sludgy, waxy and thin aqueous phases (Diebold, 1999). The inorganics in the char act as catalyst for this process[10].

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[9] The total polysaccharide fraction of biomass, which is composed of cellulose and hemicelluloses and is obtained when the extractives and the lignin are removed from the natural material.

[10] There are several methods, chemical and physical, to slow down the aging process (appendix C).

Phase separation has little influence on the energy content and weight. Some mass is lost due to volatile components, but this is neglectable (Gerhauser, 2008). Aging of bio-oil is mainly a problem for handling. A more viscous liquid is not so easy to transport as a more lubricous fluid. It is stated by Dynamotive that the slurry can be mixed again into the aqueous phase, but Gerhauser (2008) alleviates this. Due to chemical changes the slurry underwent the mix ability is strongly reduced and precipitation of the organic phase will occur much faster.

Table 9 - Required bio-oil norms and standards boilers for engines and turbines (adopted from Oasmaa et al, 2005).

Property	Specification to be met:	Current value by present technology	Problem(s)	Possible solution(s)
Variation	max. 10%	>50%	Changes in feed and process parameters	Quality control system
Water	<27 wt%	18-40	Inhomogeneity, phase separation (>30 wt% water)	Feedstock drying, increase (<50oC) of condensation temperature
Solids	<0.01 wt%	≤0.05 wt%	Wear of injectors, increased liquids instability, high CO emissions	Homogeneous particle size distribution of the feed, hot vapour filter, three cyclones on reactor exit, liquids filtration/ centrifugation
Ash	<0.01 wt%	<0.1 wt%		Feedstock choice, hot vapour filter, three cyclones on reactor exit, liquids filtration/ centrifugation
Homogeneity	Single-phase	Variation	Uneven liquid quality	Feedstock moisture <12 wt%, liquid water content <27 wt%
Stability	Max. 100% increase in viscosity during aging test	50%-150%	Changes in liquid properties during storage and use	Alcohol addition (methanol preferred, but ethanol/2-propanol safer to user)
Flash point	Dependents on country	>40°C	Safety regulation for transportation	Adjusting the liquid condensation temperature
pH	n.a.v.	2-3	Corrosion of fuel lines	All pipe work, vessels and gaskets must be acid resistant
HHV	n.a.v.	13-21 MJ/kg	50% lower than fuel oil, does not auto-ignite at start -up	Increase pump pressure to injectors, increase diameter of fuel lines, dual fuelling, combustion chamber modification
Viscosity	n.a.v.	>50cst at 20oC	Too high for most fuel injectors	Preheat liquids to reduce viscosity, add co solvent (alcohol), sue of emulsions
Lubricity	n.a.v.	Not determined	Build-up of lacquer on the injection needle and fuel pump plunger	Improvement in lubricity/ flow properties, additives

Flash point

Due to the volatile distribution have bio-oils different boiling points. A high amount of low-boiling compounds are the reason for a low flash point. The flash point is an indicator for self ignition.

Acidity

The high acidity (pH of 2-3) makes bio-oil very corrosive (Oasmaa et al., 2001, Czernik et al, 2004). Elevated temperatures and increased water content enforces the corrosiveness. This stresses for more requirements on the construction, storage and transportation materials.

3.4.4 Development stage: Expectations

Pyrolysis is method to produce a liquid energy carrier of ligno-cellulosic material, whereas liquid bio-fuels are mainly produced from the cellulosic component of biomass (sugar). Because of this ability fast pyrolysis gained interest since the oil crisis in the mid-1970s (Mohan et al., 2006). Moreover there is a strong interest in liquid fuels because they can be stored and transported more easily than solid fuels (Bridgwater, 2007).

There is a huge attention from researchers who analyse all kinds of pyrolysis oil of different feed stocks. This results in a quite good overview of the pyrolysis oil properties, yields and process on lab scale. Commercial applications are there only a few and little information is available about the process. There are only a few producers of which Ensyn, Dynamotive and BTG are the biggest.

Although the promising expectations, pyrolysis did not had his commercial break through yet. This is partly due to economic reasons, some challenging properties of bio-oil and a lack of standardization of bio-oil properties, which delayed the application possibilities for pyrolysis oil (Oasmaa, 2005). A relatively good overview of the technology exists and therefore no radical variations are expected in the technology field.

The cost estimates for pyrolysis vary greatly. Only a few companies are active and are reluctant to reveal information. All the commercial producers are approached, but none of them was willing to provide information out of confidentiality.

The New Hampshire office of energy and planning (2005) mentions the most concrete numbers. Installations of Dynamotive (corrected to €2008) would cost about in the range of €2.3 - €11.7 million for respectively 0.75- 12 t/h bio-oil output. Plant sizes above 12 t/h are considered modular. A detailed cost split up is however not given. In 2002 Bridgewater et al. performed a linear regression on data from different plants at that time.

Several regression models are derived and this would result in €18.8 million (corrected to €2008) for a 40MW output plant. Solantausta (2004) performed a similar study with the data from Aston University (UK), VTT (FIN), and Kemiinformation AB (SE). A deviation was found in the 40 to 60 MW output (LHV based) range. This deviation was assigned to the little industrial information available. The cost estimation of Solantausta shows many similarities as the estimates of Bridgwater et al. (2004). Both studies are based on similar data (Aston University – Bridgwater). A great uncertainty in production costs exists for that reason.

3.5 Method of comparison for the pre-treatment methods

The preceding sections have introduced the fundamental principles, applied process and product characteristics of the several biomass pre-treatment methods. These foregoing sections verified the characteristic values of the several pre-treatment methods. These values are used to calculate the energetic- and economic performance and ecological impact of the several pre-treatment methods. These typical values are in this way the foundations for the performance of pre-treatment.

In this section is described how the performance of the several pre-treatment processes is calculated using these values. First several process assumptions are discussed, which guide the process. Hereafter the conceptual model of the several pre-treatment methods for biomass is discussed, followed by a summary of the typical values.

3.5.1 Assumptions

Several assumptions are essential for the calculations in this study. The first assumption is to use biomass and the by-products to fulfil the heat demand of the process.

The second assumption is based on a technical constraint. The gaseous by-products have low energy content and require a secondary energy carrier for a good combustion performance (Meuleman, 2008). Out of ecological perspective is bio gas desired, but in practice this is not likely. The pre-treatment plant has to be build in the vicinity of a bio gas plant or the other way around and the bio gas plant has to be of a respectable size. Natural gas is therefore chosen as secondary energy carrier[11].

The last assumption affects the process size. Each process is designed at an output of 40 MW. This could affect the economic performance as each pre-treatment method has an optimal process size (economies of scale).

3.5.2 Conceptual process

The conceptual model of the pre-treatment methods for biomass is in essence a flow model. Wood chips enter the process and are converted to an intermediate product throughout several production steps. The basic process diagrams are already given in the several applied production process sections.

In this section this process diagram is extended with several ingoing or outgoing flows and internal flows to represent the actual production process. All these flows are based on the fundamental principles and applied production process sections of the several pre-treatment methods for biomass. The resulting conceptual model of the pre-treatment processes is given in figure 12.

Depending on the biomass pre-treatment method, the process components are used. Some are used by all three of the methods (black box) and some of them are used by only one or two of them (blue dotted boxes). Pelletisation requires: drying, grinding pelletisation and cooling. Torrefaction requires: drying, torrefaction reactor, pelletisation and cooling. Pyrolysis requires: drying, grinding, pyrolysis reactor and cooling. Biomass for product enters the process, is dried, grinded (if required) and converted into the intermediate product and by-products.

The by-products are together with biomass for heat combusted in a boiler for heat generation. The combusted components leave the process as flue gas or ash. The generated heat is used for drying and in the thermo-chemical processes for the reactor. Drying results in release of water.

Additional energy inputs are natural gas (technical constraint) and electricity (to power the process components.

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[11] Although the use of natural gas doesn’t minimise the ecological impact, still a reduction in the CO_2 emissions per GJ_{fuel} is reached. From section 3.6.3 will become clear that the pre-treatment method with the highest ecological impact (6.6 kg CO2/GJ) is neglectable with the ecological impact of coal, 94 kg CO2/GJ (IEA, 2007).

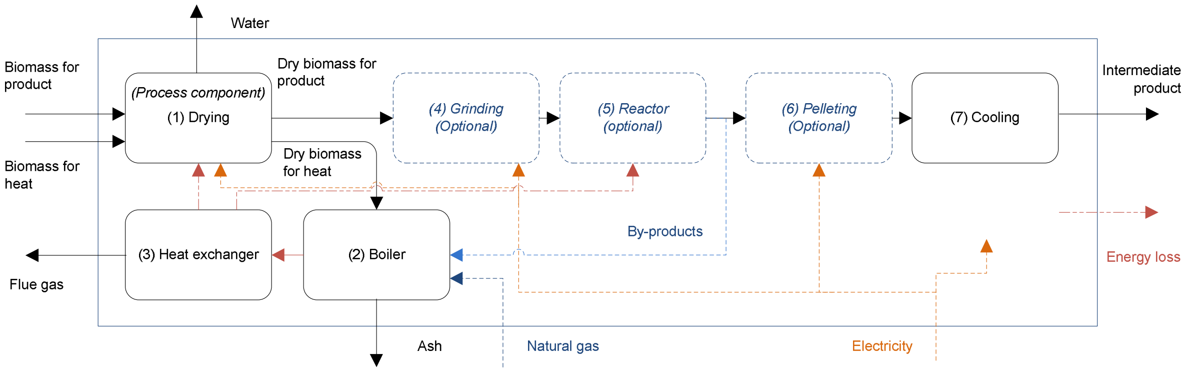

Figure 12 - Conceptual model of the applied production process of the several pre-treatment methods for biomass.

3.5.3 Characteristic values

In table 10 the characteristic values of the different pre-treatments method for biomass are summarised. The table defines per process component in the production process the typical energy requirements and process conditions. Furthermore the typical intermediate product characteristics are given. All these values are already discussed in the previous sections, except for the general variables and ecological impact.

The general variables exist out of heat for drying and the combustion system, i.e. boiler and heat exchanger. Heat for drying exists out of three factors, heating and evaporation of water and the heating of wood. With moisture content of 50%j, this result in a heat demand of 2.6 MJ/kg per kg water evaporated.

The boiler efficiency and heat exchanger efficiency are set to respectively 87% and 70 % (Faaij et al., 1998). The ecological impact of natural gas is set to 56kg/GJ$_{\text{natual gas}}$ (Vreuls, 2006). The ecological impact of electricity is calculated by the electricity mix and a more complete calculation is given in appendix D. A more arbitrary case is the ascribing of zero CO_2 emission to the use of biomass as certain emission occurs during growth and harvest of biomass.

These flows, collectively, determine the mass & energy balance of the process. The flows which cross the process boundaries (the blue box) determine the energetic-and economic performance and ecological impact, which are discussed in the next section.

Table 10 - Modelling variables of the several pre-treatment methods for biomass.

		Modelling variables						
General process								
	Drying (1)	Water	Wood		Total required			
Heat capacity	MJ/kg℃	0,0042	0,0017					
Heat of evaporation	MJ/kg	2.26	-					
	MJ/kg				2.6			
Electricity	kWh/t water evaporated				20			
Boiler (2) & Heat exchanger (3)								
Boiler efficiency	%				87%			
Heat exchanger	%				70%			
Production process specific		Pelletisation		Torrefaction			Pyrolysis	
Grinding (4)								
Size	mm	3		-			2	
Electricity	kWh/t	60		-			95	
Reactor (5)								
Reactor	% of energy content feed	-		4%			15%	
Natural gas	% of energy input	-		10%			10%	
Division products:								
Solid	%	100%		70%			75%	
Gas	%	-		30%			12%	
Liquid	%	-		-			13%	
Pelletisation (6)								
Pelletisation	kWh/t	50		30			-	
General & Cooling (7)								
Process	kWh/t	45		45			40	
Intermediate product		Pellets	Torrefied wood	Torrefaction gas	BO_2pellets™	Char	Pyrolysis gas	Pyrolysis oil
Moisture content	%	6%			3%	0%		25%
LHV	MJ/kg	16.5	20.4	6,2	19.5	29	4	14.9
Density	kg/m3	610	230	0,6	750	250	1,2	1,200
Ash content	%	Calculated	Calculated	-	Calculated	Calculated	-	0,001

Ecological impact[12]		NL	CA
Natural gas	kg CO_2/GJ	56	56
Electricity	kg CO_2/GJ	106,5	51,2

3.6 Results: *Mutual comparison*

Each biomass pre-treatment method has its own energetic- and economic performance and ecological impact, depending on the fundamental principles and applied production process (§3.2-4). The foregoing section (§3.5) described the boundary conditions for the calculations according to the BO_2GO case and in this section the results are presented. The results are presented head to head for the different pre-treatment methods to gain insight in the differences in energetic- and economic performance and ecological impact between the several processes.

The results are discussed according to the following format; mass balance, energetic performance, ecological impact and economic performance. In the reminder of this section the intermediate product characteristics are discussed in relation to raw biomass and which intermediate product is produced at the lowest energetic-and economic and ecological expenses.

3.6.1 Mass balances

Mass balance is calculated to support the calculations for the energetic-and economic performance and ecological impact. The mass flows influence the magnitude of the process and thereby the energy requirements and costs. The mass flows of the production processes are presented in Figure 13. First the ingoing flows are discussed, followed by the outgoing flows. The reminder of the mass balance reflects on the biomass input and variations in the mass and volume output of intermediate products.

Ingoing and internal flows

The different pre-treatment methods for biomass require different amounts of biomass for product to achieve an equal energy output of 40 MW in intermediate product. This is due to the LHV of the intermediate product and the product yield, i.e. division between intermediate product and by-products.

The lower the LHV of the intermediate product is the more output is required to achieve the desired energy content of 40MW. Consequently more input is required. In addition the lower the product yield, the more by-products are created, the more input is required. Pyrolysis oil has the lowest LHV and a middle high product yield, which results in the highest biomass for product input. Pyrolysis requires approximately 42% more biomass input and torrefaction requires approximately 16% more input than pelletisation.

Biomass for product is only one part of the total biomass input. The biomass for heat input to generate the process heat is the second biomass input. Biomass for heat is influence by the heat demand and created by-products. The created by-products are not lost, but are used for heat generation. The use of by-products lowers thereby the input of biomass for heat. Pelletisation creates no by-products and uses therefore only biomass for heat.

The total biomass input is however still more for the thermo-chemical processes, but the differences in input have become smaller between the pre-treatments. Torrefaction requires 5% and pyrolysis requires 31% more biomass input compared to the pellet process.

A part of the heat is generated by natural gas in the thermo-chemical processes. Although natural gas is neglectable on the mass balance is has a substantial influence on the energy balance. The input of natural gas was set to 10% of the heat demand. As consequence that natural gas lowers as well the biomass for heat input for the thermo-chemical processes and thereby the total biomass input.

The internal flows exist out of dry biomass for heat and by-products. Pelletisation has smallest internal mass flow (dry biomass for heat). The internal mass flows are of the similar order for torrefaction and pyrolysis, respectively 90 and 119% higher internal mass flow. Torrefaction has a lower product yield and produces therefore almost as much internal mass flows as pyrolysis.

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[12] Ecological impact: calculated by the energy mix for the country of interest. See Appendix D for the more detailed calculations.

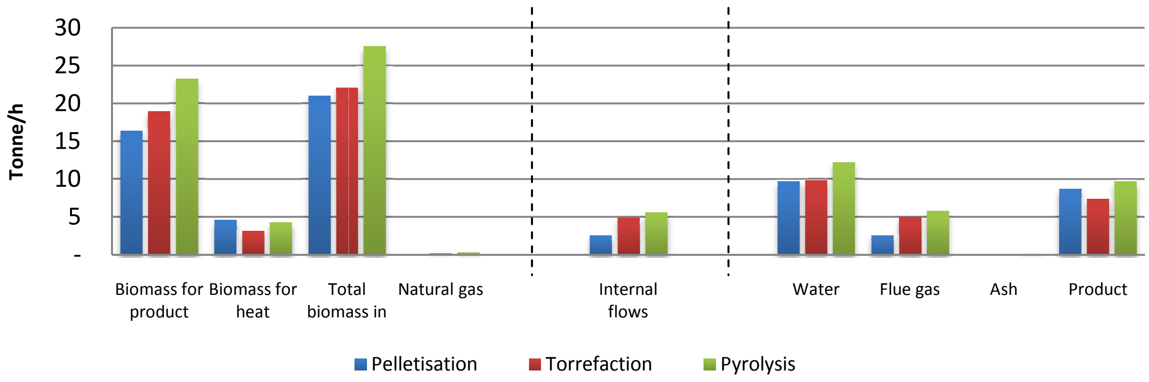

Figure 13 - Mass balance of the different pre-treatment methods for biomass.

Outgoing flows (except the intermediate products)

The amount of water is mainly related to the evaporated moisture during drying. The amount of water produced varies therefore with the amount of raw biomass which is needed for the process. Pelletisation has the lowest total biomass input and therefore the lowest amount of water produced, followed by torrefaction and pyrolysis.

The amount of flue gasses is related to the combustion of biomass for heat, natural gas and by-products. Pelletisation only consumes biomass for heat, which results in a low amount of flue gasses. Torrefaction combusts more internal flows (by-products and natural gas) and produces more flue gasses, followed by pyrolysis.

The ash amount is dependent on the combustion of biomass and by-products. Of the by-products contains the pyrolysis char all the ash of the biomass for product. In contrast contain the gaseous by-products no ash at all. Pyrolysis produces therefore the highest amount of ash, followed by pelletisation and torrefaction (lower biomass input compared to pelletisation).

Intermediate products

The mass output of the intermediate products is determined by the LHV. Figure 14 shows the different LHV's and energy densities of the intermediate products. For comparison the values of raw biomass and dry wood are given as well.

BO$_2$pellets™ have the highest LHV and requires the lowest output to achieve 40 MW (mass based). Based on the LHV pellets require approximately 18% and pyrolysis oil requires approximately 31% more mass output.

On volumetric basis however, the order changes because of the different mass densities (kg/m^3). In this case pyrolysis oil has the lowest output, followed by BO$_2$pellets™ (22% more) and pellets (77% more) volume.

The major increase is energy density of intermediate products comes forward clearly. An increase of 10 times the energy density can be achieved during pre-treatment (pyrolysis oil) and an increase of 1.5 times the LHV (BO$_2$pellets™).

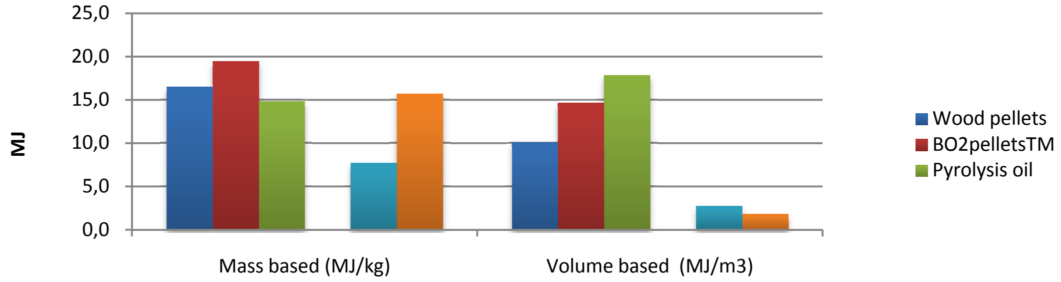

Figure 14 - LHV's and energy densities of the different intermediate products.

- *The total biomass input is the largest for pyrolysis, followed by torrefaction and pyrolysis.*
- *The creation of by-products results in higher biomass for product flows and lower biomass for heat flows.*
- *In the pyrolysis process leave all the inorganics (in the biomass for product flow) the process as ash.*
- *The product output (mass based) is the largest for pyrolysis oil, followed by pellets, BO$_2$pellets™.*
- *The product output (volume based) is the largest for pellets, followed by BO2pellets™ and pyrolysis oil.*

3.6.2 Energetic performance

The energetic performance of the process is based on the energy flows entering and leaving the process. The size of the energy flows passing these boundaries is however influenced by the underlying internal energy flows. Understanding of the internal heat demand and heat flows is needed to interpret the energetic performance.

First the in- and outgoing flows are discussed, followed by the heat demand and internal flows. The reminder of this section shows the energetic performance over the different stages in the production process.

In- and outgoing energy flows

It is chosen in this report to evaluate the process on the energy flows passing the process boundaries, i.e. the 'blue box' in figure 12. The flows that enter and leave the blue box are summarized in figure 15, together with the heat demands.

The ingoing energy flows dominated by biomass for product (70-80% of total energy input), followed by biomass for heat (10-20% of the total energy input). The differences in biomass input are related to the fundamental principles and applied process as explained in the mass balance section.

Natural gas and electricity are in order of magnitude equal to each other and respectively between the 0-4% and 3-5% of the total energy input.

The electricity demand is mainly related to grinding and the general process. Pyrolysis requires the smallest particles and has therefore the highest electricity consumption (grinding), followed by pelletisation. Torrefaction contains no grinding step and therefore the electricity consumption is the lowest. Figure 17 gives a more detail overview of the electricity consumption.

Compared to the biomass input, the energy input of natural gas and electricity can be neglected.

The outgoing intermediate product flows are equal as the output is set to 40 MW. The difference between energy input and output is energy loss as heat to the surroundings, warmed up water and flue gasses. Pyrolysis has the biggest energy loss.

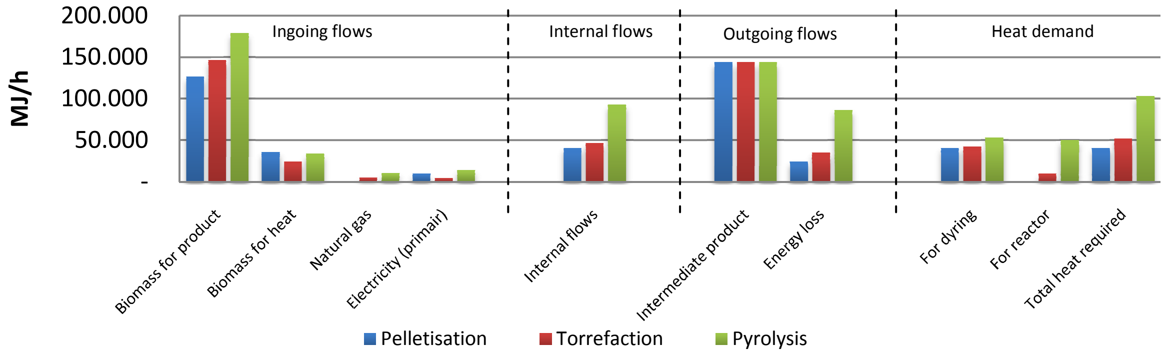

Figure 15 - Energy balance of the different pre-treatment methods for biomass.

Heat demand and internal flows

The heat demand of the process exists out of heat for drying and heat for the reactor. The amount of heat for drying is the largest heat factor. Only for the pyrolysis process the heat demand for drying and reactor are of similar magnitude.

The heat demand of the pre-treatment processes is partially fulfilled by the internal energy flows. The internal flows reduces the amount of ingoing energy flows (biomass for heat and natural gas). The thermo-chemical pre-treatment methods produce by-products and reduce thereby the biomass for heat input, but compensate this by a higher biomass for product input.

Figure 15 shows the internal flows, biomass for heat and by-products, fulfil to a large extend the heat demand. It is argued by some authors (Bergman, 2005b and Cottam et al., 1994) that the process could be self-sufficient, i.e. the total heat demand could be totally fulfilled by the by-products (and natural gas). The calculations presented here do not support this for the case of a moisture content of 50%; an additional energy input in the form of dry biomass for heat is required. Also the calculations for the case of 35% did not support the claim of an energy self-sufficient process.

Performance during the process

To gain insight in, and differences between, the energetic performance four energy efficiency measures are introduced (figure 16):

a) The energetic product yield; percentage of energy recovered in the intermediate product of the initial energy content of the feedstock. This indicator shows that the division in by-products and related LHV determine to a great extend the captured energy in the intermediate product. During pelletisation 100% of the energy content of the feed is recovered. BO_2pellets™ contain approximately 87% and pyrolysis oil contains approximately 71% of the energy content of the feed.

b) The conversion efficiency; percentage of energy recovered in the intermediate product and by-products of the initial energy content of the feedstock, shows that the thermo-chemical pre-treatment methods recover almost all the energy content. The by-products contain the energy which is not captured in the intermediate product. The torrefaction gas contains approximately 12% and the pyrolysis char and gas contain approximately 27% of the energy content.

c) The thermal efficiency; the energy content of the intermediate product divided by the initial energy content of the raw biomass and the required thermal energy for the process. The big difference in energetic performance during pre-treatment comes forward here. It is already seen that the pyrolysis process has a high heat demand and as not all the heat can be recovered the pyrolysis process has high efficiency losses here.

d) The net efficiency primair: the energy content of the intermediate product divided by the summation of all ingoing energy flows and taking the electric conversion efficiency into account. The electricity consumption was relatively low compared to the total energy consumption and this indicator shows therefore minor variations with the thermal efficiency. The difference between pelletisation and torrefaction becomes smaller due to the lower electricity consumption of the torrefaction process.

Figure 16 displays the several performance indicators. It can be seen that the order in energetic performance is: pelletisation the best (84%), followed by torrefaction (80%) and pyrolysis at a distance (60%). In conclusion: pelletisation has the highest net primary efficiency because it has the highest thermal efficiency.

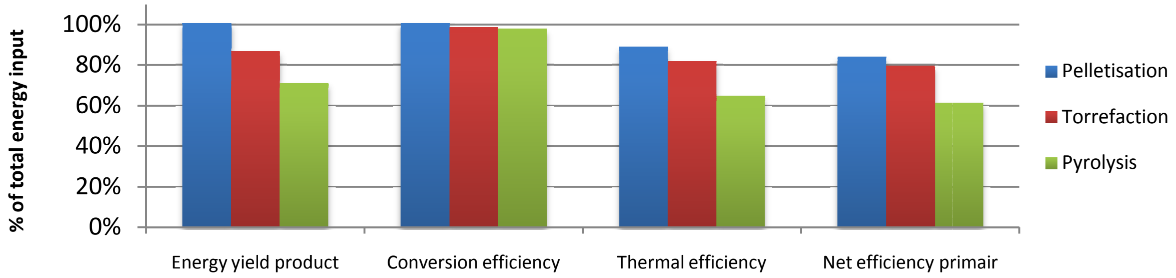

Figure 16 - Overview of the energetic performance indicators of the different pre-treatment methods for biomass.

- *The energetic performance is the highest for pelletisation, followed by torrefaction and pyrolysis.*
- *The difference in energetic performance between the pre-treatment processes come forward from the thermal efficiency, i.e. heat demand.*
- *The pre-treatment processes cannot be self-sustaining according to the calculation is this study.*
- *The biomass for product flow has a dominant impact on the overall energy input.*
- *This is partially distorting, because this flow contains as well the energy content of the by-products.*

3.6.3 Ecological impact

The ecological impact and the energy flows are strongly related. The ecological impact is determined by the energy delivered by the consumption of fossil fuels. During the process electricity and natural gas are used. The biomass (based) flows are of no influence, as they are accounted as carbon neutral in this report. Figure 17 shows the CO_2 emissions caused by the several pre-treatment processes.

The first part of the figure shows the electricity consumptions. The electricity consumption is the most influenced by grinding and the general electricity consumption. In the pelletisation process is pelletisation itself also an important factor. Torrefaction has the lowest CO_2 emissions due to the electricity consumption. Pelletisation produces 79% and pyrolysis 123% more CO_2 by electricity.

The use of natural gas is required in the thermo-chemical processes and shown in the second part of figure 17. Although natural gas only delivers 10% of the total heat demand, it has a rather high impact on the CO_2

emissions. Pyrolysis consumes twice as much natural gas as torrefaction and the CO_2 emissions are twice as much for pyrolysis.

Pelletisation has the lowest ecological impact, followed by torrefaction (54%) and pyrolysis (220%). The use of natural gas is devastating for the eventual ecological impact and should therefore be as low as possible. Grinding is another crucial factor in the ecological impact.

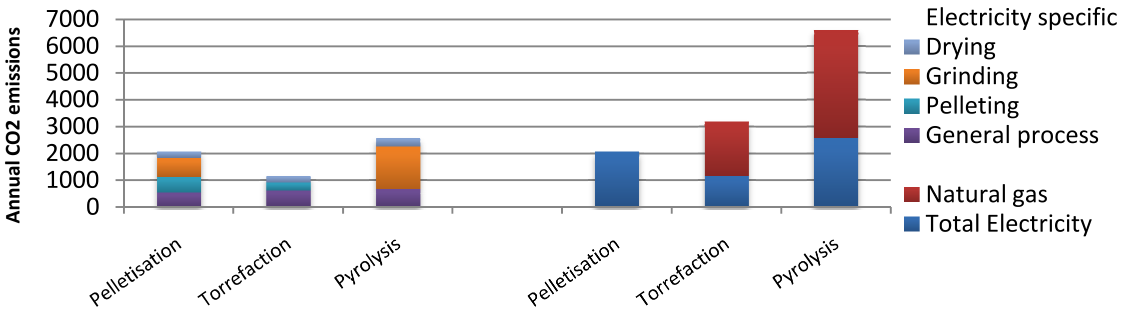

Figure 17 - Annual CO_2 emissions of the different pre-treatment methods for biomass.

- *The ecological impact is the lowest for pelletisation, followed by torrefaction and pyrolysis.*
- *Natural gas is devastating for the ecological impact of the thermo-chemical pre-treatment methods.*
- *Grinding is an electricity consuming process step and has thereby a high ecological impact.*

3.6.4 Economic performance

A preliminary prospect on the production costs of the several biomass pre-treatment methods is given in the stage of development sections. Problematic is that not much is known about the production costs. Moreover the mentioned costs estimates in literature differ strongly from the in house information of Ecofys. It is therefore chosen not to use the available literature estimates, but to estimate the production costs ourselves.

First the investment costs are discussed, followed by the operational costs. Next the production costs are examined. The production costs are split up in four categories: capital related costs (maintenance depreciation costs), total biomass costs, utilities and labour costs. In the reminder of this section is the economic performance of the several pre-treatments evaluated.

Investment costs

The investment costs are estimated for the several pre-treatment methods on basis of the known investment costs for a pellet plant. This is possible because the pre-treatment methods contain similar production equipment. Appendix E gives a more detailed overview of the production equipment of the several production processes. In this way is tried to estimate the investment costs of the several processes as accurate as possible. The resulting investment costs may not have the exact value, but the comparative relations will be correct. This makes it possible to compare the pre-treatments. An 8-10 tonne/hour pellet plant is taken as reference case and scaled up to fit the production process of torrefaction and pyrolysis.

The investment costs of the pellet plant are estimated at €14.9 million turnkey delivered[13] (van Dalen and Meuleman, 2008). Looking at the production equipment, the torrefaction process doesn't require a grinder, but needs a torrefaction reactor. For the pyrolysis process applies that it does not need pelletisers, but requires a pyrolysis reactor, cyclones and a quench. Bergman (2005c) and Gansekoele (2000) make costs estimations about the required production equipment for respectively a torrefaction reactor and pyrolysis reactor.

The main difference in production processes are the process size (biomass throughput) and need for a reactor. This requires an additional investment cost of €4.1 million for torrefaction and an additional investment of €7.7 million for pyrolysis. The investment costs for a torrefaction plant are calculated at about €19 million. The pyrolysis plant will cost slightly more, approximately around €22.6 million.

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[13] Turnkey delivered: Arrangement under which a private contractor designs and constructs a project, building, etc., for sale when completely ready for occupancy or operation.

Operational costs

This section discusses the assumptions which are related to the operational costs of biomass pre-treatment plant. The maintenance costs are estimated as 10% of the installed equipment. This rule of thumb (7-11%) is given by Peters and Timmerhause (2005) and is used as no information is available about the maintenance costs of the processes.

The consumption costs exist out of biomass for product, biomass for heat, natural gas and electricity. These flows are discussed in the mass and energy balances. The biomass costs are estimated at approximately $can55/tonne (van Daalen, 2008).

The natural gas price is estimated at €0.37/nm^3 and the electricity price is estimated at €64.24/MWh (Goes, 2008)[14].

The labour costs are based on a study by NREL (2006). The labour costs are calculated at €0.78 million a year and are not expected to vary between the different processes as they operate at approximately equal scales. Table 11 summarises the several assumptions.

Table 11 - Production costs assumptions of the different pre-treatment methods for biomass.

Cost factor		Pelletisation	Torrefaction	Pyrolysis
Additional investment	m€	-	4.1	7.7
Turnkey	m€	14.9	19.0	22.6
Lifetime	Years	15		
Interest rate	%	8%		
Operation time	hours	7,000		
Maintenance	% installed equipment	10%		
	Country	NL	CA	
Feedstock	€/t	-	35.5	
Natural gas	€/m3	0.37		
Electricity	€/MWh	64.24		
Labour	m€	0.78		

Results: production costs of biomass pre-treatment

Taking this all into account the annual production costs are calculated and graphically displayed in figure 18. The annual production costs are estimated at €9.4 million for pelletisation, €10.7 million for torrefaction and €13.9 million for pyrolysis. The production costs are dived in four cost factors: capital related (depreciation[15] & maintenance), total biomass (biomass for product & ~ heat), utilities (natural gas &electricity) and labour.

The capital related costs are approximately 30% of the total costs. The biomass costs have the most impact on the production costs, i.e. approximately 50% of the total costs. The biomass costs are dominated by the biomass for product costs (75-85%). The utility (natural gas and electricity) costs are similar to each other and represent 8% of the total costs for pelletisation and torrefaction. Pyrolysis consumes more electricity and natural gas and the utility costs are approximately 14% of the total costs. Labour are approximately 7% of the total costs.

In conclusion, the capital costs are approximately 33% of the total costs, while the feedstock costs are approximately 50% of the total costs. The production costs are mainly affected by the consumption costs, i.e. biomass, natural gas and electricity.

The difference in the production costs between pelletisation and torrefaction is however for 65% based on the capital related costs. The difference in costs between pelletisation and pyrolysis is more based on the consumption costs. Approximately 63% of the difference in production costs is explained by higher costs for biomass, natural gas and electricity.

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[14] These prices depend on the contract time and amounts. Specific calculations methods are used by energy companies to determine the prices. It was therefore not able to determine the Canadian prices without help from energy companies. The Dutch prices are consequently used for the Canadian case. This will affect the outcome. It is however seen that the utility costs have a marginal effect on pre-treatment (§3.6) and the impact on the total chain performance can be neglected (chapter 6).

[15] A simple annual depreciation formula is used: $A = F ((i*(1+i)^N) / (1+i)^N-1))$

A: annual depreciation, F: total investment costs, i: interest rate and N: life time (Sullivan et al., 2008).

In conclusion, pelletisation has the lowest production costs followed by torrefaction and pyrolysis. The difference production costs between pelletisation and torrefaction is however small (+ €1.3 million). Pyrolysis is most expensive of the three (+ €4.5 million), which is caused by the high consumption costs.

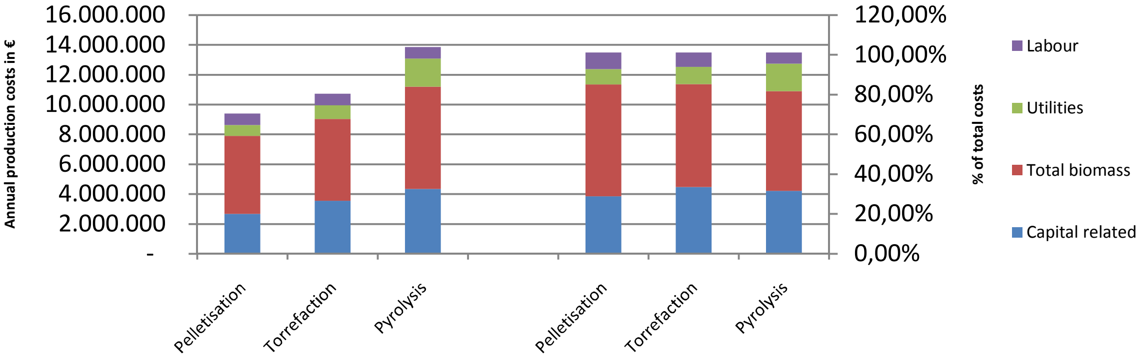


Figure 18 - Annual production costs of the different pre-treatment methods for biomass.

- *Pelletisation has the highest economic performance, followed by torrefaction and pyrolysis.*
- *Pelletisation has the lowest investment costs and thereby the lowest capital related costs, followed by torrefaction and pyrolysis.*
- *The difference in capital related costs is the main reason for a difference in performance between pelletisation and torrefaction.*
- *Pyrolysis has relatively high consumption costs compared to the other pre-treatment methods and is therefore the most expensive pre-treatment method.*

3.7 Conclusion

3.7.1 Energetic- and economic performance and ecological impact

Now the several biomass pre-treatment methods are evaluated an answer can be given to the second sub-question: *What is the energetic- and economic performance and environmental impact of the three pre-treatments methods for biomass, i.e. pelletisation, torrefaction and pyrolysis?*

In table 12 the energetic-and economic performance and ecological impact of pre-treatment is summarised. Pellets are produced at the lowest energetic-and economic expenses and ecological impact. BO_2pellets™ are the second best pre-treatment, followed by pyrolysis at a certain distance. The differences in performance are to a large extent explained by variation in heat demand of the several production processes.

Table 12 - Summary of energetic-and economic performance and ecological impact of the different pre-treatment methods for biomass.

		Pelletisation	Torrefaction	Pyrolysis
Mass input	t/ GJ_{out}	0.15	0.15	0.19
Energetic performance	GJ_{in}/ GJ_{out}	1.2	1.3	1.6
Ecological impact	kg CO_2/ GJ_{out}	2.1	3.1	6.6
Economic performance	€/ GJ_{out}	9.3	10.6	13.8

Energetic performance

Pelletisation has the highest energetic performance because of two reasons. The main reason is that the pelletisation process has a lower energy demand, i.e. no heat demand for a thermal reaction.

The second reason is related to the fact that the electricity consumption has, compared to the heat demand, no substantial influence on the total energy input. Torrefaction requires approximately 6% and pyrolysis requires approximately 37% more energy for the pre-treatment process compared to pelletisation.

A larger biomass throughput, as result of a low product yield, result also in a higher heat demand for drying. Electricity has the largest share in the energy input for pelletisation, but its share is relatively small (6%). The most influential factors on the energetic performance are the biomass for product and biomass for heat input. Natural gas and electricity consumption have a similar impact.

Ecological impact

Pelletisation has the lowest ecological impact of the three pre-treatment methods. The ecological impact is therefore divided between emissions caused by the use of electricity and natural gas. No emissions are accounted to the use of biomass. Pelletisation doesn't require natural gas and has therefore the lowest ecological impact. Torrefaction produces approximately 55% and pyrolysis produces approximately 220% more CO_2 emissions.

Based on the electricity consumption alone, torrefaction would have the lowest ecological impact, followed by pelletisation and pyrolysis. The most influential factors for the CO_2 emission are natural gas, followed by the electricity consuming activities grinding and general process utilities.

Economic performance

Pelletisation comes forward as the pre-treatment method with the lowest production costs because of two reasons. Pelletisation requires the lowest investment costs and has lowest consumption costs. Compared to pelletisation is torrefaction approximately 14% and pyrolysis 47% more expensive.

The capital costs are the main cause for the difference in production costs between pelletisation and torrefaction. The difference with pyrolysis is the most influenced by the difference in consumption costs. A higher heat demand results in a higher biomass throughput which increases the related costs substantial.

The largest cost factors are biomass, and the capital related costs (depreciation and maintenance).

3.7.2 Obtained advantages of the intermediate products

Pre-treatment of biomass results in intermediate products with different characteristics, which are important for the performance during logistics and energy conversion. Table 13 summarises the most profound characteristics of the intermediate products.

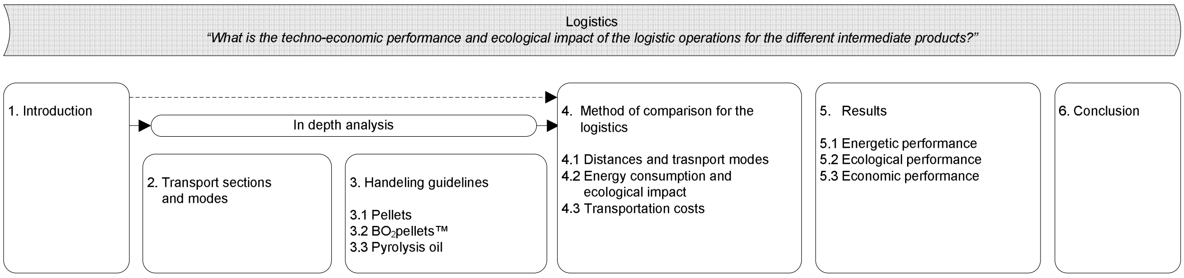
Compared to wood the intermediate products have improved energetic values, i.e. LHV and energy density. In addition the mass densities increased. Torrefaction has the highest LHV, but pyrolysis oil reached the highest energy density due to its high mass density. The pre-treatment overcome the major drawbacks of raw wood, low LHV and high moisture content. A higher 'quality' product is obtained, which makes handling easier.

Pellets keep however their biomass nature, which have some disadvantages. Much is expected from the easy grindability of BO_2pellets™. Pyrolysis oil reached the higher energy density, but gained for it some difficult characteristics, e.g. its high acidity and its aging.

Table 13 - Most important characteristics of the intermediate products

Characteristics		Raw wood	Dry wood	Pellets	BO_2pellets™	Pyrolysis oil
Moisture content	% (wb)	50%	10%	6%	3%	25%
LHV	MJ/kg	7.7	15.7	16.5	19.5	14.9
Mass density	kg/m³	350	114	610	750	1200
Energy density	GJ/m³	2.7	1.8	10.1	14.6	17.8
Most striking characteristics		> Moisture content	Hydrophilic		Hydrophobic	Low pH
		Low LHV	Biological degradable		Easy grindability	Unstable

4 Logistics



4.1 Introduction

Energy production from imported biomass implies that the several chain elements are scattered around distant locations. Consequently several logistic actions are required to connect the several chain elements. In this chapter is tried to answer the second sub question: *What is the energetic- and economic performance and environmental impact of the logistic operation?* As stated in §1.4, the outline of chain elements is discussed within the framework of the BO_2GO project; wood is grown in Canada, subsequently pre-treated, transported and converted to energy in the Netherlands.

To answer the sub-question, first the different transport sections and transport methods are discussed. When the distances and transport forms are clear, the transport conditions are discussed. The intermediate products require certain handlings, special materials or safety precautions, which affect the transport conditions. The following support question is therefore stated: *What are the guidelines for handling the intermediate products?* These guidelines are subsequently used to define the transport conditions, typical values and modulation the logistic activities of the supply chain. In the follow up section the energetic- and economic performance and ecological impact of the transport activities are described. The reminder of this section explains which intermediate product has eventually the lowest costs, energy consumption and CO_2 emissions during the logistic operations.

4.2 Transport sections and modes

The bio energy supply chain and the different stages are introduced in chapter 1.4. In this section a more geographically outline of the supply chain is given. Figure 19 shows the bio energy supply chain as chosen in this report.

The bio energy supply chain starts with the *'production' of biomass (1)*; this includes growth and harvesting or industrial residues. This aspect is not included in the analysis of this study. After harvesting, biomass is collected at a central *gathering point (2).* The central gathering point is the starting point of the analysis in this study. Depending on the local conditions (availability of biomass) pre-treatment (3) can be done at the production site, at the central gathering point (2) or at the *export harbour (4)*. In this study is chosen to pre-treat biomass at a location between the central gathering point and the export harbour as not all the biomass can be delivered by one central gathering point and the central gathering points are located too far from the export harbour. After pre-treatment of biomass, the intermediate products are transported to the export harbour. From the export harbour, the intermediate products are transhipped to the *energy conversion facility (5).*

The choice for the method of transportation is given by economic costs versus the distance. Several studies, which investigated different methods for transport, stressed that with increasing distance larger transport methods are preferred. E.g. truck, train and ship with increasing distance (Suurs, 2002, Mahmudi et al., 2006, Searcy et al., 2007 and Den Oude (2008). The 'raw' biomass has to be transported by *truck* as no other transport modes are possible because of a lacking infrastructure. The location of the pre-treatment facility is chosen strategically (hypothetically), aside a railway. The intermediate products are transported by *train* to the export harbour and from there by *ship* to the energy conversion facility in the Netherlands. In this way four different transport sections are distinguished (Suurs, 2002):

- Production location – Central gathering point (not included in the analysis)
- Central gathering point – Pre-treatment location (truck)
- Pre-treatment location – Export harbour (train)
- Export harbour – Energy conversion facility (ship)

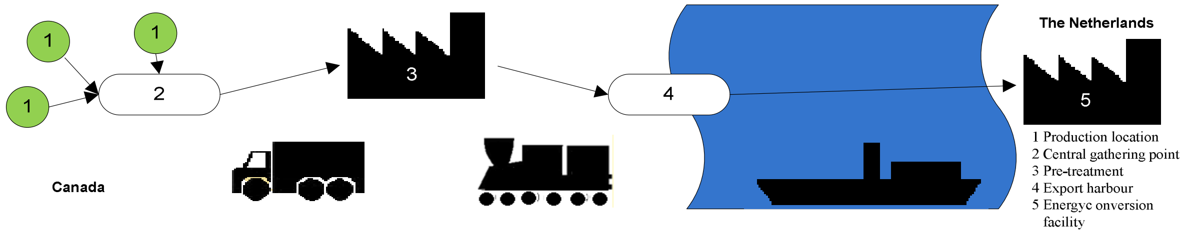


Figure 19 - Geographical model of the bio energy supply chain.

4.3 Handling guidelines

Out of safety precautions the International Maritime Organisation (IMO) has defined the potential hazards of many goods and substances. Subsequently they defined safety precautions (to comply with) during handling to prevent for accidents.

These risks and guidelines are written down in The Code of Safe Practice for Solid Bulk Cargoes (BC code) and International Maritime Dangerous Goods (IMDG) Code. The BC code and IMDG code define certain general categories, but variation within a category exists between products of different producers. Therefore each supplier is obliged to hand over more product specific information in the form of a Material Safety Data sheet (MSDS) and Shipper Cargo Information Sheet (SCIS). This general and more specific cargo information should make the transport of goods safe.

The guidelines affect however the energetic- and economic performance and ecological impact as they demand for certain actions, materials or for restrictions. This section gives on overview of the risks and handling guidelines per intermediate product.

4.3.1 Wood pellets

Large amounts of wood pellets are shipped already and a quite good overview of the handling issues of wood pellet exists. The most profound issues are oxygen depletion, self heating and dust explosions (Svedberg, 2008 and Canadian wood pellet association, 2008). The potential hazards and safety precautions are based on SCIS of Peterson (2008) and the BC code.

Oxygen depletion is the result of oxidation of compounds in the wood pellets. During this process carbon monoxide is created. Carbon monoxide is a very dangerous gas as it cannot be smelled and leads to asphyxiation.

All cargo spaces should therefore be ventilated prior to entry by personnel. In addition measurements of oxygen and carbon monoxide levels in the enclosed cargo space are advised. In case of entering cargo spaces without ventilation, self-contained breathing apparatus are obliged.

Self heating is the result of heating, exposure to droplets and water. In all cases swelling of the wood pellets occurs and the pellets cannot resist the internal pressure anymore and break. As result a layers exist, which covers the underlying cargo. This leads to fermentation over time. A flammable and asphyxiating gas is created and moreover the process is self heating, which can lead to self ignition.

Removal of wet material is required and, if un-removable, secure ventilation of wet material is strongly advised. The best solution is to take pre-cautions to avoid moisture ingress or heating during voyage.

Dust explosions are the result of handling of the pellets. Pellets break during handling and create dust. Wood dust can lead to fire of even risk of explosion, when exposed to heat, open light or direct fire.

The handling of material should therefore generate low concentrations of dust. This is accomplished for example by sucking out the pellets instead of using a crane.

4.3.2 BO_2pellets™

As BO_2pellets™ do not exist in large quantities, no BC, IMDG codes, MSDS and SCIS exist yet. It is however expected that BO_2pellets™ have characteristics in the range of wood pellets and coal and the material types which fall within this category are lignite and charcoal (as explained in §3.3.1).

A discriminating variable between the products is the self ignition temperature (Ostermeier et al., 2008). Self ignition tests at ECN showed that the self ignition temperature of BO_2pellets™ is higher than the self ignition temperature of charcoal (Meuleman, 2008). The handling characteristics of BO_2pellets™ vary therefore between wood pellets and lignite. For comparison the handling guidelines of lignite (derived from the BC code) are given here, the handling guidelines of wood pellets are given in the previous section (§4.3.1).

Lignite is subject to oxidation, leading to depletion of oxygen and an increase in carbon monoxide in the cargo space. This is also seen for the wood pellets and the same guidelines apply here. Moreover fumes from lignite are harmful by inhalation, in contact with skin and if swallowed. The guidelines should therefore be applied even more strictly.

Lignite is liable to self heating, which can lead to spontaneous combustion in the cargo space. It is therefore recommended that lignite is stored for seven days prior to loading. Seven days storage ensures self heating processes are not present anymore and if present the fire starts on shore, where it better can be controlled. This substantially reduces the risk of spontaneous combustion during transport, storage and handling. In addition the boundaries of the cargo spaces where lignite are stored should be resistant to fire and liquids.

4.3.3 Pyrolysis oil

Pyrolysis oil exists for some longer time and small quantities are already produced. Producers and researchers have therefore already some indication of the handling properties of pyrolysis oil. Based on the MSDS of Dynamotive (2008) and a more fundamental report of CIRAD (2005) the potential hazards and handling guidelines for pyrolysis oil are derived. The most profound issues are aging, flash point and corrosiveness.

The aging processes of pyrolysis oil and their effects are already discussed in §3.4. Phase shifting of pyrolysis oil in a slurry and aqueous mixture has as disadvantages that the slurry is hard to handle and the cargo spaces are hard to clean.
To maintain a good homogeneity, it is recommended to keep the pyrolysis oil between the 14-40ºC and to stir the pyrolysis oil continuous. Another solution would be the addition of methanol, but this is too expensive (Gerhauser, 2008).
Since pyrolysis oil is not in thermo-chemical equilibrium at room temperature, pyrolysis oil may either consume oxygen, and create thereby an under pressure in the cargo space, or may emit vapours and create in that way an overpressure in the cargo space. It is therefore recommended to use cargo spaces, which can be kept tightly closed at temperatures between 14-40ºC.

The flash point of pyrolysis oil lies between the 50-70 ºC for the liquid as produced. It is therefore also advised to keep the temperature below 40 ºC. In addition it is recommended to keep pyrolysis oil away from sources of ignition. It is mentioned by Ostermeier et al. (2008) that the temperature can raise to above 100ºC in cargo spaces located next to the engine room. So maybe not all cargo spaces can be used or cooling should be applied.

The high corrosive nature (pH 1.5-3) of pyrolysis oil poses limitations on the use of materials. The cargo walls should be suitable for combustible liquids and resistant to acids. Recommended storage materials are acid-proof steel (stainless steel) and plastics (PETE, PP, and HDPE).
The high corrosiveness of pyrolysis oil, and vapours of the combusted of heated liquid, are harmful by inhalation, in contact with the eyes, skin and respiratory system. It is also stated that pyrolysis oil contains potentially carcinogenic compounds. The impact of these compounds is according to Gerhauser (2008) marginal. It is however recommended to avoid continuous exposure to pyrolysis oil. When handling pyrolysis oil, protective gear is advised, e.g. gloves, full eye protection, coveralls and an organic vapour filter mask is case of significant spillages. Furthermore is a good ventilation of the space, when handling the pyrolysis oil, recommended.

4.4 Method of comparison for the logistics

The previous sections described the transport modes and conditions for transport. In this section is tried to modulate the transport sections taking the guidelines into consideration. The estimates for the logistic activities are very dependent on the equipment used, amount and contract between transporter and supplier. In addition the transport of the intermediate products is an unknown phenomenon, with as result that the estimations for the handling of intermediate products are highly speculative. It is tried to capture these aspects in the estimates, but this was not always possible.
Several studies have investigated the costs, energy consumption and throughput of biomass during the logistic handlings. Based on these studies, it is tried to derive the costs, energy consumption and ecological impact of

the several transport sections. A summary of the derived modelling variables of the transport modes and sections is given in table 14. In the upcoming sections the energy consumption and ecological impact of the several transport modes are discussed. The logistic actions exist out of two stages, (un)loading and the actual transport stage. Subsequently the logistic costs are discussed per transport mode.

Table 14 - Modelling variables of the transport modes and sections.

		Truck	Train			Ship		
		Wood chips	Pellets	BO_2pellets™	Pyrolysis oil	Pellets	BO_2pellets™	Pyrolysis oil
Distances	km	50		400			5,000	
Max Capacity	tonne	38		1,700	1,700		75,000	75,000
Max Capacity	m³	170					85,000	85,000
Speed average	km/h						25.93	26.85
Load/unload costs	€/t	4.36		2.45				
Load/unload speed	t/h						694	1200
Charter costs	€/d						19,976	25,969
Charter costs	€/wt-km	0.076		0.016	0,032			
Energy-f (MJ/km)		15.4		489	489		2,362	2,281
Ballast days	d						5	5
Port charges	€/t						1.95	1.95
Fuel consumption	t/d						35	35
Fuel price	€/t						266	266
Brokers fee	€						26,635	26,635
CO_2-emission	g/MJ	73		73	73		73	73

4.4.1 Distances and transport modes

In 4.2 the different transport modes are given. The respectively distances travelled are given here. It is assumed that the distance between a central gathering point and the pre-treatment location is 50 km. Next is presumed that the intermediate products for 400 km have to be transported by train from the pre-treatment location to the export harbour. Subsequently, the distance between Canada and the Netherlands is set to 5000 km.

4.4.2 Energy consumption and ecological impact

Energy consumption

The energy consumption and ecological impact are mainly derived from Essen et al., (2003), who did a thorough investigation of the average energy consumption and related emissions of the transport modes for passengers and bulk freights.

Essen et al. (2003) state that a truck consumes 15.4 MJ/km fully loaded. This is approximately equal to a fuel consumption of one litre gasoline per three km.

Train transport is assumed to be powered by a diesel. A fully loaded train consumes approximately 489 MJ/ km.

The energy consumption is estimated according to the cruise speed of the ship. According to MANdiesel (2007) a ship speed average varies from 25.9 km/ h, for bulk carriers, to 26.9 km/ h, for oil tankers. A ship consumes approximately 30 tonnes of Heavy Fuel Oil (HFO) a day, which results in an energy consumption of respectively 2.2-2.4 GJ/ km for respectively and oil tanker and a bulk carrier (Engels, 2008).

Ecological impact

The related CO_2 emissions are estimated at 73 g CO_2/ MJ for both types of fuel; gasoline and HFO (Essen et al., 2003 and Vreuls, 2006).

4.4.3 Transportation costs

Truck (wood chips)

Biomass is picked up at a central gathering point as explained in section 4.2. Here biomass is loaded on the truck and transported to the pre-treatment facility for biomass. A Central gathering point is often located in a wooded area, with primitive roads.

The load capacity and speed of the trucks are therefore limited. The volume of a truck can be adjusted by increasing the cargo space, but weight is the limiting factor due to the engine and road capacity. The mentioned load capacity for such type of truck transport varies between the 35-40 tonnes. In this report is chosen to follow Tampenier et al. (2006), which mention a typical Canadian load capacity of 38 tonnes.

The cargo capacity determines the amount of trips and thereby the costs, energy consumption and ecological impact. The costs estimates for truck transport vary greatly. Many authors mention a fixed estimate for the transportations and (un)load costs. The actual costs are however dependent on the amount of tonnes cargo and distance travelled. Tampenier et al. (2006) and Verkerk (2008) state both an equation to capture these nuances. It is chosen to follow Verkerk (2008) who quotes McDonald (2007). The data of McDonald are less outdated and the findings are based on a thorough research by Forrest Engineering Research Institute of Canada (FERIC). According to them, the truck transport costs including (un)load costs are given by the following relation: transport costs are €0.076/ wt-km + €4.36/ wt.

Train transport (intermediate products)

It is hypothetically assumed that the pre-treatment facility for biomass is located aside a railway. Without additional costs, it is possible to capitalise on the existing railway infrastructure.

The train transport costs are derived from Tampenier et al. (2006), who interviewed several specialists active in rail transport with respect to transport costs of the intermediate products. The differences in handling properties between pellets and BO_2pellets™ are assumed neglectable by Tampenier et al. (2006). The transport and (un)load costs are represented by the following equation: €0.016/ t + €2.45/ t.

According to the handling guidelines of pyrolysis oil, the transport costs for pyrolysis oil are estimated by the following formula: €0.032/ t. Due to its liquid form pyrolysis oil can be pumped. The (un)load costs are assumed neglectable for pyrolysis. The more corrosive nature and aging tendency the transport costs are estimated, twice as expensive as the transport of pellets and BO_2pellets™. This falls within the range of 1.3-2 times as expensive mentioned by den Oude (2008).

The capacity of train transport is not limited by volume, but by weight according to Tampenier et al, (2006). The maximum load capacity of a train is 1700 tonnes.

Ship transport (intermediate products)

To transport goods overseas a ship is chartered (rented). Basically there are two types of chartering a ship: ‘spot prices’ and ‘time charters’, which affect the transhipment costs.

Under spot prices, a ship is chartered under lump-sum bases, e.g. a fixed fee per tonne is agreed to transport the cargo from A to B in a specific trajectory. This price is highly dependent on the changes in demand and supply. Chartering a ship under time charter means that a ship, with crew is hired for a certain period. The shipping market is a highly inelastic market (Engels, 2008). It takes generally two years to build a bulk carrier or oil tanker and it is rather expensive to take a ship out of business.

Slight changes in demand and supply result therefore in high fluctuations in transhipment prices[16]. To obtain a more stable estimation of the costs of transhipment time charter is chosen to assess the transportation costs. A ship is rented over a longer time and more stable prices can be negotiated.

The ship transport costs are not only affected by the chartering type. Other factors of influence are the vessel size, brokering fee, charter costs, travel time, unload speed and additional expenses.

The transhipment costs are influenced by the size of the ship and the energy density of the intermediate product. In this study a panama bulk carrier is used for the transport. The cargo capacity of a panama bulk carrier is 75,000 tonnes and the volume of the cargo space is 85,000 m^3.

A broker operates as an intermediary between a vessel owner and a charterer. The broker gets for its services a fee; €26,635 (Engels, 2008).

Subsequently, a vessel is rented per day. The charter costs are estimated at €19,967 for a panama bulk carrier. The charter costs are based on the Baltic Index and varied in November 2008 between the US$ 25-35,000. The charter costs are averaged and converted to €2008. The costs for an oil tanker (suitable for pyrolysis oil) are estimated as 1.3 times the costs of a bulk carrier; €25,969 (den Oude 2008).

The trip time exists out to the travel time and (un)load time. The trip time is based on the cruise speed of the vessels. A bulk carrier of the size of 75.000 tonnes has cruise speed of 25.9 km/ h and an oil tanker has a cruise speed of 26.9 km/ h (MANdiesel, 2007). The difference in cruise speed is based on the building structure of an oil tanker, which is more aerodynamic. In addition, it is common that a vessel is not located in the harbour of departure and has to travel some distance before it reaches the export harbour (Engels, 2008). These days are called ‘ballast days’ and set to five days.

The (un)load speeds for pellets and BO_2pellets™ are given by Engels (2008); 694 t/ h. The (un)load speed of pyrolysis oil is based on the (un)load speed of methanol (Hamelinck et al., 2003); 1200 t/ h.

Additional expenses are HFO and port taxes. A vessel consumes 30 tonnes of HFO a day and one tonne of HFO costs €266/ tonne (Engels. 2008). The port charges are estimated at €1.95/ tonne (Engels, 2008).

4.5 Results

It is important to keep in mind that the results presented here are based upon an equal amount of energy delivered by all three the intermediate products. A difference exists here between the transport of wood chips (truck) and intermediate products (train and ship).

To reach an equal amount of energy output in intermediate products, different amount of biomass are required as input for the pre-treatment methods. The differences performance of truck transport between the

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[16] Appendix G shows the high variability in the charter costs of a panama size vessel over the last 9 years.

pre-treatment methods relate therefore solely to amounts of biomass input required by the pre-treatment methods.

The differences in transport of the intermediate products have another cause. The intermediate products have a different form and energy density which affect the cargo capacity. The differences in performance between the pre-treatment methods of train and ship transport relate to the differences in cargo capacity (amount of energy loaded) of the intermediate products.

4.5.1 Energetic performance

The energetic performance is related to the number of trips and energy consumption per trip. The energetic performance is discussed per transport mode and shown in figure 20.

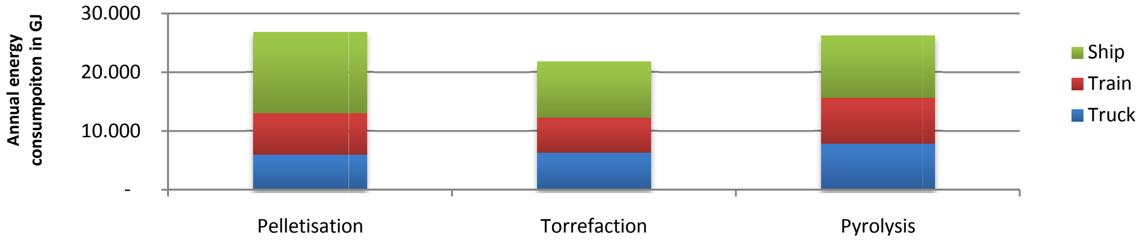


Figure 20 - Annual energy consumption of the logistic operations in the supply chain for different pre-treatment methods of biomass.

Wood chips are transported first by truck and, as explained above, the energy consumption during truck transport is related to the amount of biomass required as input in the pre-treatment process. From section 3.6.1 comes forward that pelletisation has the lowest biomass input, followed by torrefaction (16% more) and pyrolysis (31% more). Based on these biomass inputs, the energy consumption of torrefaction and pyrolysis are respectively 16 and 31% more during truck transport compared to pelletisation.

Secondly, the intermediate products are transported by train. The cargo capacity of train transport is limited by weight, which has as result that the intermediate product with highest LHV requires the lowest amount of trips to transport an equal amount of energy. BO_2pellets™ have the highest LHV, followed by pellets and pyrolysis oil has the lowest LHV (section 3.7.2). Pyrolysis oil requires therefore 31% and pellets 18% more trips and energy for train transport compared to BO_2pellets™.

Finally the intermediate products are transported by ship. The cargo capacity of a ship transport is limited by weight and volume. Based on the mass density of pellets a ship can be loaded with 52000 tonnes until it exceeds the volume limit of 85000 m^3. A ship can be loaded with 64000 tonnes of BO_2pellets™ before it exceeds the volume limit and pyrolysis oil can be fully loaded with 75000 tonnes and it hasn't reached the volume capacity. If this is expressed in energetic values, BO_2pellets™ have the highest load capacity, followed by pyrolysis oil and pellets have the lowest load capacity. BO_2pellets™ require therefore the least trips and energy, followed by pyrolysis oil (11% more) and pellets (45% more).

In the overall energy consumption is seen that ship transport has the highest influence on the energy consumption of transport, followed by train and truck. This corresponds with the distances travelled. Adding up the energy consumption of the different transport modes, the overall energy consumption for transport becomes the lowest for BO_2pellets™, followed by pyrolysis oil (21% more) and pellets (24% more).

- *The chain with torrefaction results in the best energetic performance during logistics, followed by the chains with pyrolysis and pelletisation.*
- *Ship transport has the highest ecological impact of the three transport modes.*
- *The differences in energetic performance are a result of the number of trips.*
- *The number of trips is determined by; required amount of biomass (truck transport), load capacity in weight (train transport) and load capacity in energetic capacity (ship transport).*

4.5.2 Ecological performance

The ecological impact of the transport modes is strongly related to the energy consumption. The ecological impact is calculated by multiplying the energy consumption with a CO_2 emission factor. The emissions factors are however equal for the several transport modes.

This has as result that ecological impact is a plural of the energetic performance. The differences per transport mode are therefore equal to the difference in the energetic performance as discussed in 4.5.2. In addition the order in the ecological performance is not affected and BO$_2$pellets™ have the lowest ecological impact, followed by pyrolysis oil (21% more) and pellets (24% more). The absolute values are shown in figure 21.

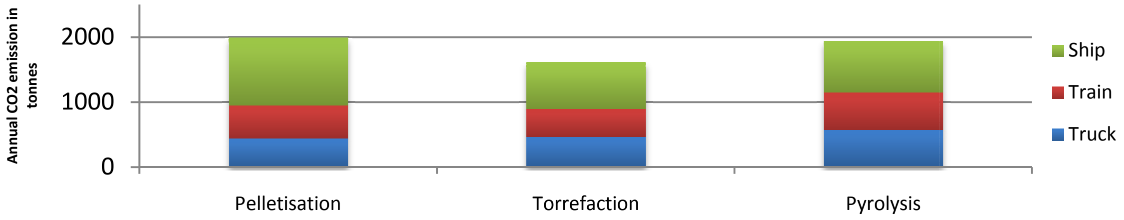


Figure 21 - Annual CO$_2$ emission of the logistic operation in the supply chain for different pre-treatment methods of biomass.

> - *The ecological impact is a plural of the energetic performance, due to the CO$_2$ emission factor.*

4.5.3 Economic performance

The economic performance is not related to the energy consumption and thereby totally different. Various factors affect the costs of the different transport modes. Figure 22 shows the annual transport costs for the different biomass pre-treatment methods.

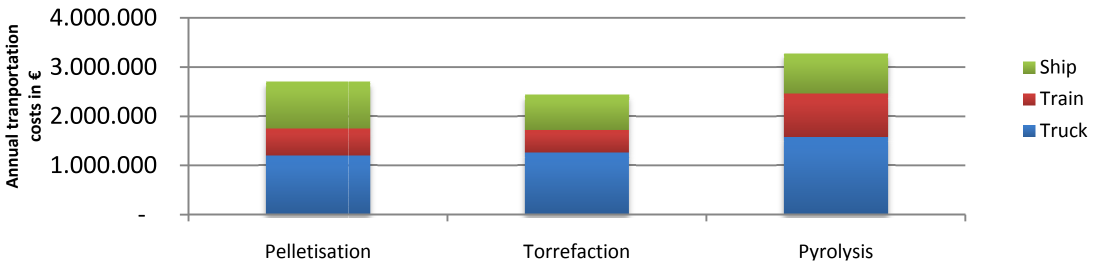


Figure 22 - Annual transportation costs of the logistic operations in the supply chain for different pre-treatment methods of biomass.

The differences in cost for truck transport are influenced by the total biomass input. As no difference in truck transport of wood chips exists between the pre-treatment methods the differences are the same; pelletisation is the cheapest, followed by torrefaction (16% more expensive) and pyrolysis (31% more expensive).

The differences in transport cost for the intermediate products are based on the amount of trips needed, to transport an equal amount of energy, and the charter costs.

The number of train trips depends on the cargo capacity. The cargo capacity of train transport is limited by weight and the highest LHV results in the lowest transport activities. BO$_2$pellets™ require the least number of trips, followed by pellets and pyrolysis oil requires the most trips. In addition, the charter costs of a pyrolysis oil train are very high compared to the train transport of pellets and BO$_2$pellets™ (similar costs). The train transport is the cheapest for BO$_2$pellets™, followed by pellets (18% more expensive) and pyrolysis oil (90% more expensive).

The ship transport costs depend mainly on the number of trips, charter costs and days a vessel has to be rented. The number of transhipment activities is limited by the cargo capacity, which is a trade-off mass density and energy density. BO$_2$pellets™ require the least number of trips, followed by pyrolysis oil and pellets require the most trips. The charter costs for a bulk carrier (pellets and BO$_2$pellets™) are lower compared to an oil tanker (pyrolysis oil). The number of days a ship has to be rented varies with the sail speed and (un)load time. An oil tanker requires the least days because it has a higher sail speed and (un)load speed. Ship transport of BO$_2$pellets™ requires more days because of a higher cargo capacity (longer (un)loading times). Taking this all into consideration, the ship transport cost of BO$_2$pellets™ are the cheapest, followed by pyrolysis oil (15% more expensive) and pellets (35% more expensive).

It is seen that truck transport has the highest impact on the transportation costs, even though it is the shortest transport distance. Ship transport has a moderate influence on the total costs. The high train transport costs of pyrolysis oil stand out. In conclusion, BO2pellets™ have the lowest transport costs because of the higher LHV and energy density. Pellets have a lower energy density and thereby a high ship transport costs, which results in the middle high transport costs. Pyrolysis has the highest transport costs because of the high train transport costs.

- *The economic performance is the highest for the chain with torrefaction, followed by the chain with pelletisation and pyrolysis.*
- *The truck transport has the most influence on the energetic performance of the three transport modes.*
- *BO$_2$pellets™ have a higher energy density and transport is therefore less expensive compared to pellets.*
- *Pyrolysis oil has rather high charter costs and is therefore expensive to transport.*

4.6 Conclusion

Now the logistic operations are evaluated an answer can be given to the third sub-question: *What is the energetic- and economic performance and environmental impact of the logistic operations for the different intermediate products?*

In table 15 the energetic-and economic performance and ecological impact of the transport modes is summarised. Torrefaction results in the best transportation performance, followed by pelletisation and pyrolysis at a certain distance. The differences in performance are to a large extent explained by variation in the load capacity (in terms of energy) and charter costs.

Truck transport has a high influence on the transportation costs and less influence on the energetic performance and ecological impact.

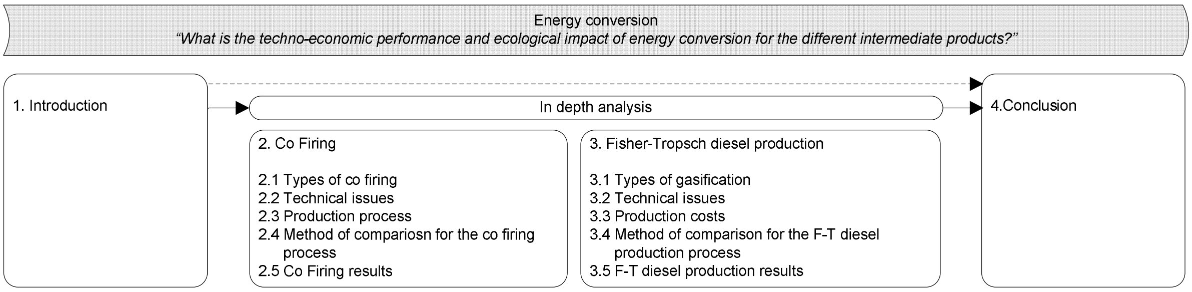
Train transport has a moderate effect on the energetic- and economic performance and ecological impact.

Ship transport has a moderate influence on the transport costs, but highly affects the energy consumption and ecological impact. The difference between train and ship transport is explained by the restriction in load capacity, respectively mass and volume.

Table 15 - Summary of the energetic- and economic performance and ecological impact of the different transport modes.

			Pelletisation		Torrefaction		Pyrolysis	
Energetic performance	GJ_{in}/GJ_{out}	Truck (wood chips)	0.01		0.01		0.01	
		Train	0.01		0.01		0.01	
		Ship	0.01		0.01		0.01	
		Total		***0.03***		***0.02***		***0.03***
Ecological impact	kg CO_2/ GJ_{out}	Truck (wood chips)	0.4		0.5		0.6	
		Train	0.5		0.4		0.6	
		Ship	1.0		0.7		0.8	
		Total		***1.9***		***1.6***		***1.9***
Economic performance	€/ GJ_{out}	Truck (wood chips)	1.2		1.3		1.6	
		Train	0.5		0.5		0.9	
		Ship	1.0		0.7		0.8	
		Total		***2.7***		***2.4***		***3.3***

5 Energy conversion



5.1 Introduction

Two types of energy conversion are discussed in this study; electricity generation (by co-firing) and production of an automotive fuel (entrained flow gasification followed by synthesis to Fischer-Tropsch diesel). This section discusses this final chain element and gives an answer to the fourth sub-question: *"What is the energetic- and economic performance and environmental impact of energy conversion for the several intermediate products, e.g. pellets, BO$_2$pellets™ and pyrolysis oil?"*

Energy conversion can be done on many ways, but what comes forward from the literature is that there is a strong desire to capitalise on the existing conversion infrastructure (Drift, 2004). This reduces the uncertainty in performance (the technology is already proven on large scale) and the production costs (only marginal investments are required).

The most common energy conversion facilities are based on coal conversion. Coal differs greatly in its chemical composition and physical structure from the biomass based intermediate products. This results in several restrictions on the use of intermediate products as fuel in the existing infrastructure. This lead to the support question: *i. "What is the difference between the energy conversion of coal and the intermediate products?*

As the intermediate products do not exist yet, less is known about the energy conversion of the intermediate products. To get an impression of the differences in energy conversion, the conversion problems of 'raw' biomass are discussed in relation to the characteristics of the intermediate products. As the intermediate products have a biomass nature their behaviour during energy conversion can be predicted by their similarity to- and differences with 'raw' biomass.

When the fundamental differences are known, an answer can be given to the second support question: *ii. "What are the implications of these differences for the production process of co-firing and Fischer-Tropsch diesel production?"* This second question will give an indication of the energetic- and economic performance and ecological impact of the energy conversion of the intermediate products.

The outlay of this section is therefore divided between an in-depth analysis, of co-firing and Fischer-Tropsch diesel production, and a concluding section. Per energy conversion is first the type of energy conversion discussed. Many (coal based) technologies are available and the outcome differs greatly with the technology chosen. This discussion will place the type of energy conversion chosen in the appropriate context. Next the technical issues related to the use of raw biomass in the chosen coal infrastructure are discussed, together with the benefits and disadvantages of the intermediate products compared to 'raw' biomass. This is followed by an evaluation the necessary adjustments in the infrastructure and production process per intermediate product. Subsequently the adjustments are summarised and a description of the modulated energy conversion process is given. When both the energy conversion processes are discussed this section is concluded with the best performing intermediate product.

5.2 Co-firing

5.2.1 Types of Co-firing

Co firing of biomass can be defined as the combustion of coal and biomass at the same time. The most common coal based power plant is a pulverised coal plant. There are several co-firing methods and due to the differences in technological combustion systems, it is impossible to indicate "the" co-firing process. In short there are three different co-firing systems (Loo and Koppejan, 2002, Baxter et al., 2004 and Maciejewskaj et al., 2006).

The most common co-firing method is direct co-firing. Direct co-firing can be divided in three options, simple mixing of the coal and biomass, separate handling systems for biomass or a separate handling system and a dedicated boiler. The later options enable a more dedicated approach towards biomass combustion issues, but requires more modification of the system and is thereby more expensive.

Indirect co-firing is the second combustion system and makes use of gasification. This approach has the advantage that it, after cleaning of the gas, cannot cause fouling or slagging in the main plant (IEA, 2002). The major disadvantage is the high investment costs.

This is also the problem with the third option; parallel co-firing. A separate combustor and boiler are use to produce steam for the power plant steam system. This enables it to deal with biomass types that contain high alkali metals and chlorine, but again at the expense of high investment costs.

These higher investment costs for the more dedicated systems explain the preference for the cheaper direct manner of co-firing. In this case the direct co-firing of intermediate products in a pulverised coal plant is discussed.

5.2.2 Technical issues

In pulverized coal plants coal is shredded to fine particles and burned in a boiler to generate steam to drive a turbine, which generates electricity. Co-firing of biomass based products poses constraints and limitations on several stages of the process: fuel preparation, combustion system and operation, flue gas cleaning and fly ash usage (Baxter et al. (2004), NETBIOCOF (2006) and Maciejewskaj et al. (2006)).

Fuel preparation

Constraints are related to the fact that existing power plants are not designed for biomass handling. Biomass has a lower bulk density, lower LHV, contains more moisture, is hydrophilic and has a fibrous structure.

The first disadvantage is that larger volumes are needed to deliver the same amount of energy input because of the lower mass density and LHV (Baxter et al., (2004), NETBIOCOF, 2006). This requires bigger storage facilities. In addition to this is installation of additional equipment is required to transport and grind biomass. In the time that these plants were build, it was not anticipated that co-firing of biomass would be an option and therefore often there is no available space for additional storage and equipment. The energy density of pyrolysis oil and BO_2pellets™ are higher than pellets and require therefore less storage facilities.

The hydrophobic nature of BO_2pellets™ doesn't require covered storage compared to pellets. Moreover consumes the grinding of pellets more energy than the grinding of coal or BO_2pellets™ (Bergman, 2005b). A reduction in energy consumption of 80-90% for torrefied materials compared to raw biomass.

Due to fibrous nature of biomass the fluidizing behaviour is not optimal (Baxter et al., 2004 and Drift, 2004). This causes challenges when transporting, pneumatically or otherwise, the biomass particles to the boiler. Pyrolysis oil has an advantage here, because it can be pumped.

Combustion system and operation

This topic addresses a crucial step in the co-firing process. Due to the nature of biomass the combustion behaviour is different. The problems that arise here are the reason why plant operators are reluctant to accept biomass for co-firing.

The lower energy density and higher moisture content of biomass result in bigger gas volumes for certain energy input and reduce thereby the output of the boiler (Baxter, 2004, NETBIOCOF, 2006 and Maciejewskaj et al., 2006). The products with a higher energy density can reach higher percentages of co-firing than the current limit of 10% for wood pellets. Pyrolysis oil and BO_2pellets™ have an advantage here.

Second is the chemical composition of biomass problematic. Alkali metals cause slagging, fouling and corrosion problems in the boiler. The issues related to slagging, fouling and corrosion are very important problems in co-firing as they damage and reduce the efficiency of the equipments. Chlorine is one of the most problematic alkali metals. Good mixing of the biomass with coal will form silicates and sulphates and minimizes the corrosion damage (NETBIOCOF, 2006). The fouling and slagging effects also cause higher maintenance costs. Pyrolysis contains no alkali metals and has no foiling or slagging effects. Pyrolysis oil has however a low pH, which is very acid. BO_2pellets™ contain relatively more alkali metals than pellets per GJ and this could lead to problems with the combustion equipment.

Flue gas clean up

Combustion of wet biomass results in greater volumes and also an increase in temperature is recorded (Baxter et al., 2004). This causes the creation of hazardous compounds, i.e. NO_x and SO_x. Moreover causes the higher alkali content aging and deactivation of the cleaning catalysts, which increase the emissions.

Solutions for these issues are under development. Different mixtures are co-fired and different catalysts are used. Torrefaction has a lower moisture content then pellet, but higher alkali content. Pyrolysis oil has higher moisture content, but lower alkali content. The effect of the thermo-chemical intermediate product on the flue gas clean up is therefore not easily to predict.

By-product utilization

The fly-ash of the coal power plant has economic value as it is used in the construction industry (NETBIOCOF, 2006). Co-firing of biomass alters the composition of the fly-ash. This conflicts with the quality standards that are set for the use of the fly-ash as material for concrete. Differences in the mineral content of fly ash from coal and biomass are the cause for this.

Separation of the fly-ash is not possible when biomass is directly co-fired or it is too expensive in case biomass is indirectly co-fired. This affects the freeze-thaw cycles of concrete. Air containment is required in the concrete as air cells relieve internal pressure by providing microscopic chambers for the expansion of water as it freezes. Another concrete property that is affected is the flexural strength. The time the concrete needs to get fixed and become strong shows however little difference.

Pyrolysis has no effect on the fly ash as it contains no alkali metals, while BO_2pellets™ contains more alkali metals and could affect the quality of the fly ash.

Conclusion: suitability for existing infrastructure

The intermediate products have several beneficial characteristics compared to raw biomass. Table 16 summaries the most important problems related to co-firing for the three intermediate products.

The compression to a dry and high mass density pellet improves the handling of biomass within the power plant. The low moisture content results in better storage condition and health risks because of reduced biological vulnerability. A disadvantage is that absorb water, which demands for covered storage and handling restrictions.

The BO_2pellets™ are compared to pellets better suited for the coal infrastructure. BO_2pellets™ have a hydrophobic nature and higher energy density, which lowers the requirements on storage and handling. Due to the better grinding properties of BO_2pellets™, the co-milling issues are less profound for BO_2pellets™ compared to pellets.

Pyrolysis oil demands as a liquid a separate infrastructure.

Pyrolysis oil is however a very acid oil and suffers from aging, which complicates handling. The corrosiveness of the intermediate products is caused by water content and pH. The effect of the corrosive behaviour is estimated as neutral for pellets, negative for pyrolysis oil and beneficial for BO_2pellets™.

In the case of pyrolysis oil, ash is removed with the char, while both pellets and BO_2pellets™ contain still the minerals. Pyrolysis is therefore expected to have less deposit formation as pellets and BO_2pellets™.

The same argument goes up for the ash utilisation. As pyrolysis contains no minerals the fly ash is less affected. It is expected that woody fuels contain such a low amount of alkali metals that is not likely to will have measurable impact (NETBIOCOF, 2006).

The co-firing ratio is expected to be the largest for pyrolysis oil, BO_2pellets™ and pellets on basis of the energy density.

Table 16 - Mitigation of problems associated with co-firing (adopted and adjusted from Maciejewskaj, 2006).

	Pellets	BO_2pellets™	Pyrolysis oil
Feeding & handling problems (hydrophilic and physical form)	o	++	+
Co-milling problems (fibrous structure)	o	+	++
Corrosion (moisture and pH)	o	+	-
Deposit formation (slagging, fouling), sintering, agglomeration (alkali metals)	o	o	+
Limited co-firing ratios (due to energy density)	o	+	++
Ash utilization (if mixed ashes are problematic)	o	o	+

5.2.3 Production process

Less is known about the energetic- and economic performance of co-firing the intermediate products. Only co-firing of wood pellets is a well-known phenomenon, but co-firing of the thermo-chemical intermediate products is an unexplored field.

BO_2pellets™ and pyrolysis oil are not yet available in large scale on the market. Due to the limited availability of intermediate products it is hard to run trial versions. One trial tests of co-firing of torrefied wood is known (Westewind, 2004) and another one is mentioned, but the results are not published (BGP, 2006). Chiaramonti et al. (2007) report three trial tests for the co-firing of pyrolysis oil. Al the papers describe the co-firing process however superficial. In all cases: the plant was operated without significant problems after cost-effective modification of the boiler to allow for co-firing. It is therefore not possible to derive information about the energetic- and economic performance and ecological impact of the thermo-chemical intermediate products.

The energetic- and economic performance of pellets is known and the energetic- and economic costs the thermo-chemical intermediate products are estimated by similarities to other fuels.

Pellets

The energetic- and economic performance and ecological impact are based on the "Onrendabele Top" calculations by de Vries et al. (2005) and van Tilburg et al. (2007). These reports give estimation of the energetic- and economic parameters of several sustainable electricity options. These numbers are used by the Dutch government to calculate the feed-in tariffs for the SDE regulation in 2008-2009.

The energetic- and economic performance of wood pellets are set in these studies at 220/kW$_{th}$ for the investment costs, ct€0.2/kWh$_e$ for the variable O&M costs and ct€0,8/kWhe for other operational costs. The electrical conversion efficiency is estimated at 37.5%.

BO$_2$pellets™

The energetic- and economic performance of co-firing of BO$_2$pellets™ is derived from Bergman (2005c).

If bo2g0 pellets are fed into the dedicated infrastructure for pellets, a cost reduction of 30% can be obtained on basis of the higher energy density of BO$_2$pellets™ compared to wood pellets. Assuming the advanced characteristics of BO$_2$pellets™, i.e. higher energy density, brittle structure, low moisture content and hydrophobic nature, it could be fed into the existing infrastructure of coal. A reduction of 100% equal to coal is obtained in this way. According to Bergman (2005c) the use of BO$_2$pellets™ compared to conventional pellets can lead to a costs reduction of 30-100% in investment costs. Higher efficiencies are obtained as well out of perspective of the advanced characteristics of BO$_2$pellets™, i.e. fewer stack loses.

This leads to the following assumptions for the co-firing process: zero investment costs and the variable O&M costs are equal to the costs of coal, ct€0.06/kW$_e$ (IEA, 2005). The other operational costs are estimated between the costs of pellets and palm oil in at ct€0.5/kW$_e$. This assumption is based on the chemical composition of B2GO, which has favourable characteristics compared to pellet (moistures), but undesired characteristics to pyrolysis oil (alkali metals). The electric efficiency is estimated equal to coal at 40%.

Pyrolysis oil

Pyrolysis oil is a separate case, as it is a liquid and therefore requires in any case a separate feeding infrastructure. This feeding infrastructure is however similar to an oil infrastructure in power plants (Chiaramonti et al., 2007). The estimates for co-firing pyrolysis oil are based on the known energetic- and economic parameters for co-firing of palm oil (de Vries et al., 2005 and van Tilburg et al., 2007).

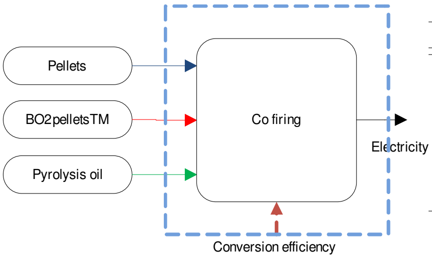
Pyrolysis oil and palm oil differ from each other. The main difference is that palm oil has a higher viscosity than pyrolysis oil, which makes it less fluid. This problem is solved by heating the palm oil to reduce the viscosity. The difference in viscosity is mainly caused by the water content. Pyrolysis has therefore better fluid properties. Palm oil, which is heated, will have a similar viscosity as pyrolysis oil. It is therefore expected that the investment and O&M costs will be the same, but that the efficiency will deviate from the proposed energetic- and economic parameters.

Pyrolysis oil requires no heat to lower the viscosity and will have therefore a higher efficiency. Moreover is assumed that a liquid requires no additional electricity to transport within the power plant (Drift, 2004). The cost estimates for palm oil are set at €5-10/kW$_{th}$ for the investment costs. Given the high acidity and handling characteristics of pyrolysis oil is chosen to use €10/kW$_{th}$ for the investment costs. The variable O&M costs are set at ct€0.05/kWh and the other operational costs are estimated at ct€0.2/kWh. The electrical efficiency is estimated at 36.7% for palm oil. Pyrolysis oil doesn't require heating to reduce the viscosity and therefore is assumed that the electric efficiency of pyrolysis oil is higher than the one of palm oil. Given the neglectable electricity consumption during gasification, the efficiency is set equal to the eclectic efficiency of coal (40%).

5.2.4 Method of comparison for the co-firing process

The previous sections derived the characteristic values of co-firing of pellets, BO$_2$pellets™ and pyrolysis oil. These numbers are summarised in figure 23 together with the corresponding modulation of the co-firing process. An input of 40 MW in intermediate product is assumed, as this amount of energy is created during pre-treatment of biomass.

The conceptual model is quite simplistic as result of the low amount of information which is available about the co-firing process of the thermo-chemical products. The intermediate products enter the process on the front and leave the process at back as electricity. This conversion takes place at certain efficiency. As no additional energy flows are distinguished the energetic performance is limited to the assumed electric efficiency. This has as consequence that the ecological impact is zero for all the co-firing process of the intermediate products. The next section will elaborate therefore mainly on the economic performance.



Assumptions co -firing		Pellets	BO2pelletsTM (Coal based)	Pyrolysis oil (Palm oil based)
General				
Lifetime	Years		15	
Interest rate	%		8	
Economic				
Investment costs	€/kWth	220	-	10
Variable O & M costs	€ct/Kwhe	0.2	0.06	0.05
Other operational costs	€ct/Kwhe	0.8	0.5	0.2
Technical				
Electric efficiency	%	37.5%	40.0%	40.0%

Figure 23 - Conceptual model of the co-firing process of the different intermediate products, together with the typical values of the co-firing process of the different intermediate products.

5.2.5 Co-firing results

As the explained in the modulation of the co-firing process section the energetic performance is estimated as the co-firing efficiency. The efficiency of pellets is empirically estimated at 37.5%. The energetic performances of the thermo-chemical intermediate products are estimated higher than electrical efficiency of pellets. Given the expected differences in product characteristics the electrical efficiency is set to 40%. This is arbitrary, but empirical evidence is required to clarify the actual efficiency, which is not available.

The ecological impact of the co-firing process is related to the fossil energy consumption during the process. The fossil energy consumption is mainly related to grinding and transportation. The power to perform these actions is delivered by electricity. Assuming that the consumed electricity is generated by the intermediate products, no CO_2 emissions are related to co-firing. The co-firing process on itself has therefore no ecological impact. In case electricity was used, the electricity generated by the intermediate product could be used and the ecological would have been assumed to be zero as well.

The resulting energetic- and economic performance of the co-firing process of the intermediate products is presented in figure 24. The production costs per GJ_e are estimated at €5.5 for pellets, €1.5 for BO_2pellets™ and €0.8 for pyrolysis oil.

Pyrolysis oil has the lowest production costs. This is mainly due to the low O&M costs. The O&M costs of pyrolysis oil are expected to be lower, as a liquid can be pumped. This reduces the operation and maintenance costs substantial.

Pelletisation is especially more expensive because of the high investment costs. A dedicated infrastructure for biomass exists out of, depending on the co-firing system: a processing line containing equipment for transportation, size reduction and feeding to a dedicated burner. High investments costs are related to such a production line.

The difference in efficiency is taken into account through the costs per GJ_e. A higher efficiency results in lower costs per GJ_e. As result, the co-firing costs of pyrolysis are the lowest. The co-firing costs of BO_2pellets™ are almost the double of the costs of co-firing pyrolysis oil. The co-firing costs of pellets are approximately five half times bigger than the co-firing costs of pyrolysis oil.

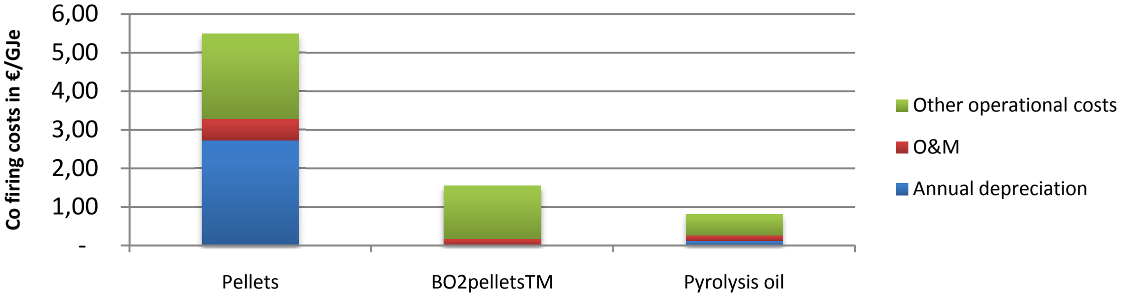


Figure 24 - Production costs per GJ_e of the co-firing process of the intermediate products.

> - *The energetic performance (conversion intermediate products to electricity) is set to 35.5% for pellets and 40% for BO_2pellets™ and pyrolysis oil.*
> - *No additional fossil energy inputs are distinguished, so the ecological impact of co-firing is zero.*
> - *Pyrolysis oil is converted to electricity at the lowest costs. This is due to the low investment costs and other operational costs.*

5.3 Fischer-Tropsch diesel production

Fossil (automotive) fuels have a high energy density because, among others, they contain hydrocarbons. Biomass is the only carbon containing renewable energy resource and therefore an attractive resource to produce automotive fuels.

Today biomass is already used to make automotive fuels. These bio fuels are made of sugars, starch and vegetable oils. These components are restricted to certain crops and represent only a minor part of the whole plant (Boerrigther, 2006). It is therefore very interesting to make use of the ligno-cellulosic components of the plant. This makes it possible to use the whole plant and more biomass types can be used.

Technologies to produce bio fuels of lingo-cellulosic material are under development. A promising method to do so is by gasification of biomass. Biomass is first gasified and subsequently the produced gas is synthesised to Fischer-Tropsch diesel.

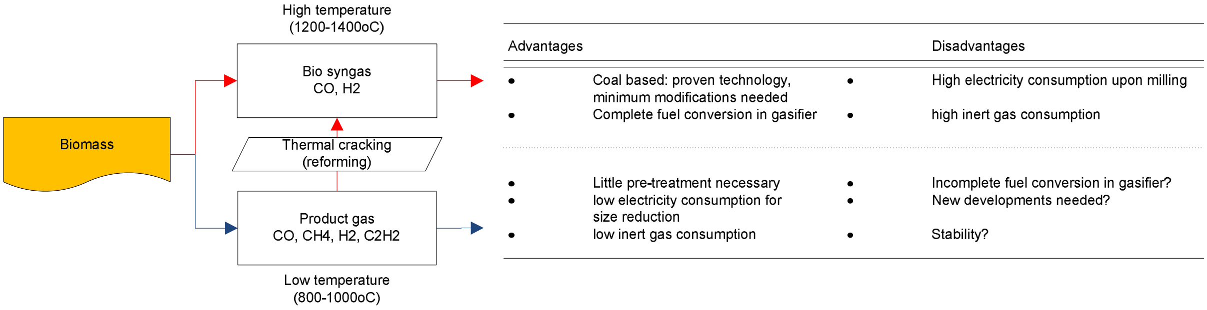
This section will go in on the advantages of pre-treatment on chains which produce bio fuels (Fischer-Tropsch diesel) by gasification of wood. First the type of gasification will be discussed, followed by the encountered technical issues. Subsequently the production costs are discussed. The Fischer-Tropsch diesel production is hereafter modulated. The results are presented thereafter.

5.3.1 *Types of gasification*

Biomass gasification can be done in two ways: gasification in a conventional gasifier or in a dedicated biomass gasifier. Figure 25 displays the several methods graphically with the belonging (dis)advantages.

Gasification in a conventional gasifier (entrained flow gasifier) produces, with addition of pure oxygen, a “synthesis gas” at high temperatures (1200-1400°C). The produced synthesis gas should not be confused with ‘product gas’, which is produced in a dedicated biomass gasifier (fluidized bed gasifier). Product gas is made at lower temperatures (800-1000°C) and contains beside H_2 and CO (synthesis gas), considerable amounts of hydrocarbons. Product gas does not meet the quality that is required to produce bio-fuels and needs additional refining before it is a suitable for the production of bio fuels. A catalyst is used to obtain the desired quality of the synthesis gas. Entrained flow gasification makes use of pure oxygen to obtain a high quality synthesis gas.

From the two thermo-chemical ways to produce synthesis gas from biomass, entrained flow gasification is preferred for 2 reasons: the technology is commercially available on large scale (mainly for coal and liquid fuels) and it can reach the highest efficiency (99%) from biomass to synthesis gas (Drift, 2004). Dedicated biomass gasification systems have some advantages, but they are still under development and have too many uncertain factors to be put in practice.



Advantages	Disadvantages
• Coal based: proven technology, minimum modifications needed • Complete fuel conversion in gasifier	• High electricity consumption upon milling • high inert gas consumption
• Little pre-treatment necessary • low electricity consumption for size reduction • low inert gas consumption	• Incomplete fuel conversion in gasifier? • New developments needed? • Stability?

Figure 25 - Different pathways of biomass gasification with the (dis)advantages of the chosen pathway.

5.3.2 *Technical issues*

Entrained flow gasification of coal is already commercial applied. A one to one comparison from coal to biomass gasification is often tried. The chemical composition of biomass however, differs from coal and therefore is a direct application to entrained flow gasification of biomass not possible.

Factors of consideration are ash behaviour, particle size and feeding and pressurizing (Drift, 2004). According to Drift (2008) is feeding the only real problem, ash and pressure are problems that can be solved. This results in two approaches, mimic coal as best as possible or adjust the entrained flow gasifier to the limitations of biomass. A geographical representation of the production process is given in figure 26. Each issue is addressed shortly below, whit the effect of each intermediate product on the production process.

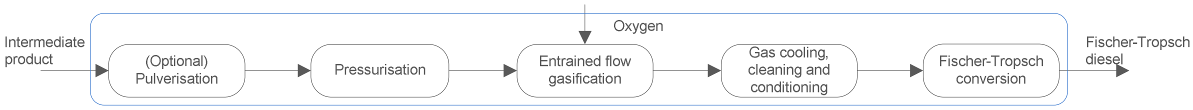


Figure 26 - Conceptual model of the applied Fischer-Tropsch diesel production process (based on Drift, 2004).

Pulverisation: Particle size

Particle size plays a key role in entrained flow gasification. The particle size is restricted by two factors in the entrained flow gasification process: the existing feeding infrastructure and the conversion efficiency and (Bergman, 2005 and Drift, 2004). Pyrolysis oil has as a liquid no need for size reduction and this discussion is therefore not of interest for pyrolysis oil. It is assumed that BO_2pellets™ are similar to coal and the characteristic particle sizes of coal are assumed to be sufficient.

The pneumatic transport lines (which feed the reactor) are based on fluidised transport. Biomass fluidisation was not possible due to the fibrous structure and the resulting cohesive forces between the biomass particles. Another problem is the size distribution due to the fibrous structure. The range is rather broad compared to coal. To overcome this problem biomass has to be grinded to 300µm. Coal requires 150 µm.
Before the intermediate particles can enter the reactor they have to be pressurised in lock hoppers. Depending on the particle size inert gasses are enclosed during the pressuring process. The access of these inert gasses to the reactor has to be minimised because these gasses result in non-continuous feeding and corresponding fluctuations in temperature and other gasification conditions. The entrance of inert gasses is minimised by more severe grinding of the particles. If the particles are sufficiently small less gas is captured during compression. For coal the required size is approximately 150µm, but this is not sufficient for biomass particles. Biomass particles have to be grinded to 100 µm.

Based on the above elaboration on the particle size it comes forward that the particle size is mainly limited by the existing feeding infrastructure. The optimal size will be 100 µm. Grinding to such a small size results in high energy consumption for wood grinding (0.08 kW_e/kW_{th}) (Drift, 2004). On primary energy base this would be around 20% of the energy content. In comparison grinding of BO2G would required 0.01 kW_e/kW_{th} (Drift, 2004 and Bergman, 2005a). Taking this size into account, compression at best performance results in a cold gas efficiency reduction for wood powder is 3.7% and 3.9% for torrefaction powder in the reactor (Drift 2004).

Pressurizing

Entrained flow gasification takes place at high pressure (20-40 bars). The solid fuels have to be pressurised before they enter the reactor because of two reasons (Drift, 2004): the large scale of the processes and for thermo-dynamical reasons. The pressure that is needed correlates with the density of the fuel and the LHV. Pyrolysis oil, BO_2pellets™ and pellets have respectively a lower density, which require more pressure and more 'batch operations' to obtain a similar energy input. This reduces the efficiency and increases the costs.
Pressurising of wood powder requires 0.027 kW_e/kW_{th} and pressuring of torrefaction powder requires 0.023 kW_e/kW_{th}. Pyrolysis is as a liquid is easy to compress as it can be pumped and the energy consumption can be neglected.

Ash behaviour

There are two types of entrained flow gasifiers, slagging and non-slagging. The ash content and behaviour determines the type of entrained flow gasifier (Drift, 2004).
In a slagging gasifier ash forming components melt in the reactor. The molten particles condense against the relatively cold wall. They form a layer, which is solid close to the wall and liquid on the inside. The liquid part is removed from the bottom of the reactor.
In a non-slagging reactor no slag is produced, which means that in practice only feedstock with low amounts of ash/ minerals are used.
Experts which were consulted by Drift (2004) had a clear preference for slagging gasifier: a little melt can never be avoided completely and slagging gasifiers are more fuel flexible. Although a non-slagging gasifier is cheaper. The ash content of the intermediate products is, because of the preference for a non-slagging gasifier, of less influence on the entrained flow gasification process.

Oxygen production

The synthesis gas exists out of CO and H2O. To produce these compounds additional oxygen is required. The ratio between fuel and oxygen is 0.25 (Drift, 2004). The energy required to produce oxygen is 0.25 kWhe/m^3 oxygen. The mass density of oxygen is 1429 kg/m^3 (Avallone et al., 2006).

Fischer-Tropsch diesel production

The synthesis gas conversion to Fischer-Tropsch diesel is for each product equal. A difference may exist between the cleaning and conditioning of the syngas. No information is available, which indicates at a difference and for simplicity is assumed that the conversion from syngas to Fischer-Tropsch diesel is equal.

Boerrighter (2006) estimates the conversion efficiency to Fischer-Tropsch diesel at 71%. Drift (2004) and Renew (2008) mention both that electricity is produced during the process. In this study the electricity production was not accounted for. As result the net efficiency will be lower and the ecological impact higher as it is related to the electricity consumption.

The intermediate products affect only the entrained flow gasification stage of the Fischer-Tropsch production process. After entrained flow gasification the synthesis gas conversion to Fischer Tropsch diesel is the same for every intermediate product.

5.3.3 Production costs

There is little information available about the costs for biomass gasification and conversion to Fischer-Tropsch fuels. Actual cost information is confidential and not publicly available. Boerrighter (2006) estimated the investment costs for a Biomass to Liquid plant (BtL) according to public available information of Coal to Liquid and Gas to Liquid plants. By extrapolating the investment cost of the production equipment of a Gas to Liquid plant, estimation is made of the capital investment costs of a Biomass to Liquid plant.

Taking the reference plant as starting point the following relation between the plant scale and investment costs is derived by Boerrighter (2006):

Equation 3 - Total capital investment for an F-T diesel plant (Boerrighter, 2006).

$$TCI : 1415 * \left(\frac{scaleX \ [bbld]}{34000 \ [bbld]} \right)^{0,7} \ [million€_{2008}]$$

TCI: *Total capital investment*
Scale X: *Scale of the desired plant*
bbld: *Fischer-Tropsch diesel production in barrels per day*

Boerrighter (2006) argues that the capital costs are of such an order that the investment costs, which are intermediate product specific, can be neglected. Given these assumptions the capital costs of a Biomass to Liquid plant can be derived for each of the intermediate products.

Renew (2008) mentions furthermore estimates for the service and operation costs of 3% of TCI, personnel costs of 0.5% of the TCI and production costs of oxygen of €0.08/m^3. The question remains now, which production scale to take? It is chosen to use the scale of the biggest Fischer-Tropsch diesel plant in operation now days (Choren - Germany). This plant is based on 5000 barrels a day Fischer-Tropsch diesel output. This results in an investment cost of 1.1 m€/MW output.

5.3.4 Method of comparison for the F-T diesel production process

The preceding sections have introduced the production process, technical issues and production costs. These foregoing sections verified the characteristic values of the distinctive Fischer-Tropsch diesel production by entrained flow gasification of the intermediate products. These values are the foundations of the performance of the different intermediate products. In this section is described how the performance of the several pre-treatment processes is calculated using these values. Table 17 summarises the modulation variables.

Table 17 - Modelling variables of the Fischer-Tropsch diesel production process of the different intermediate products.

Variable		Pellets	BO_2pellets™	Pyrolysis oil
Economic				
Capital investment (Based on Choren (334MW))	M€	369.90		
	m€/MW_{f-t}	1.11		
Costs for service and operation	%TCI	0.03		
Oxygen	€/m^3	0.08		
Personnel costs	%TCI	0.01		
Technical				
Grinding	kW_e/kW_{th}	0.08	0.01	-
Compression	kW_e/kW_{th}	0.03	0.02	-
Oxygen production	kW_e/m^3	0.25		
The equivalence ratio (oxygen/ fuel)		0.25		
Gasification efficiency	%	99%		
Reduction efficiency of gasifier	%	3.7%	3.9%	0.0%
F-T efficiency	%	71%		

In figure 27 is the conceptual production process of Fischer-Tropsch diesel production shown. The intermediate products enter the process run through several process activities. The process requires electricity and oxygen. The major conversion stages (gasification and Fischer-Tropsch diesel synthesis) are defined by the efficiency. The process throughput is based on the amount of energy which can be generated by a 40 MW input in intermediate product.

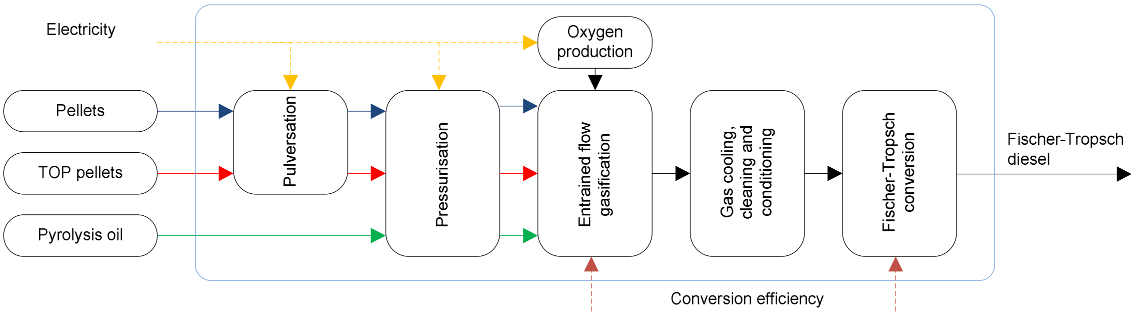


Figure 27 - The conceptual model of the applied production process of Fischer-Tropsch diesel production by entrained flow gasification of the different intermediate products.

5.3.5 Fischer-Tropsch diesel production results

Energetic performance

The energetic performance of Fischer-Tropsch diesel production process is mainly dependent on the energetic performance during gasification. The energetic performance of entrained flow gasification exists out the thermal conversion efficiency (conversion of intermediate product to F-T diesel) and the net efficiency (primary).

The thermal conversion is approximately the same for pelletisation and torrefaction. Pyrolysis oil has a higher efficiency because it has no cold gas reduction. This results in efficiency from intermediate product to synthesis gas of 95.1-99% for respectively BO_2pellets™, pellets and pyrolysis oil. See also figure 27 figure 28. The conversion to Fischer-Tropsch diesel differs therefore not much form the gasification efficiency as the conversion efficiency from synthesis gas to Fischer-Tropsch diesel is constant at 71%. The conversion efficiency to F-T diesel is 68% for pellets and BO_2pellet™ and 70% for pyrolysis oil.

The real difference in efficiency is caused by the electricity consumption. Pyrolysis requires no electricity for grinding and compression and is therefore the pyrolysis oil has the highest net efficiency (primary). Grinding of the pellets requires more power than BO_2pellets™ pellets and has therefore the lowest efficiency.

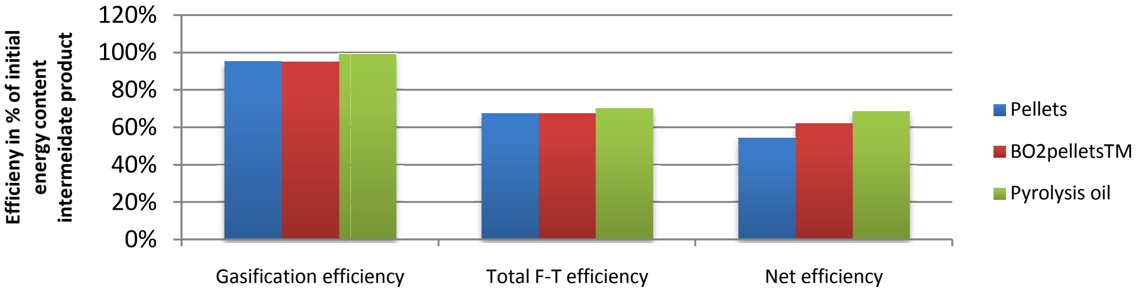


Figure 28 - Energetic performance indicators of the Fischer-Tropsch diesel production process of the different intermediate products.

> - *The F-T diesel production is approximately equal for all three the intermediate products (68-71%).*
> - *The difference in energetic performance is the result of the electricity consumption before gasification.*

Ecological impact

The electricity consumption is reflected in the ecological impact, as the production process doesn't require other fossil fuels. The ecological impact is given in figure 29.

The high CO_2 emission is related to high electricity consumption during grinding. The emissions related to the electricity consumption of compression are equal for pellets and BO_2pellets™. Pyrolysis requires slightly more electricity for oxygen production, as pyrolysis oil has more mass, but the overall CO_2 emissions are lower because the electricity consumption for grinding and compression can be neglected.

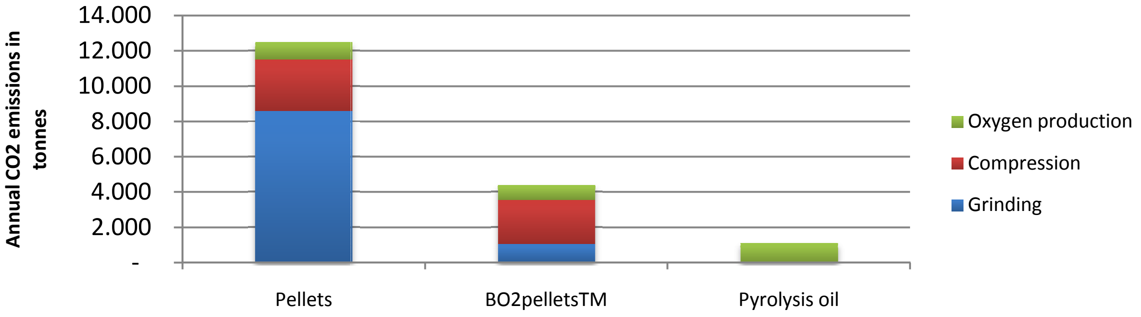


Figure 29 - Annual CO_2 emissions of the Fischer-Tropsch diesel production process for the different intermediate products.

> - *Pyrolysis oil has the lowest ecological impact during F-T diesel production due to its liquid form.*
> - *BO_2pellets™ has the second best energetic performance due to its better grindability in comparison with pellets.*

Economic performance

The economic performances are dominated by the capital costs. The capital costs are based on the output and for that reason the annual depreciation costs in figure 30 are similar for all the three intermediate products (similar conversion efficiency). The service, operation and labour costs are therefore as well equal to each other (similar investment costs). The oxygen production costs vary with the mass flow and are the lowest for torrefaction, followed by pellets and pyrolysis oil. The difference in costs is influenced by the costs for electricity. Pellets are the most expensive due to their high electricity consumption.

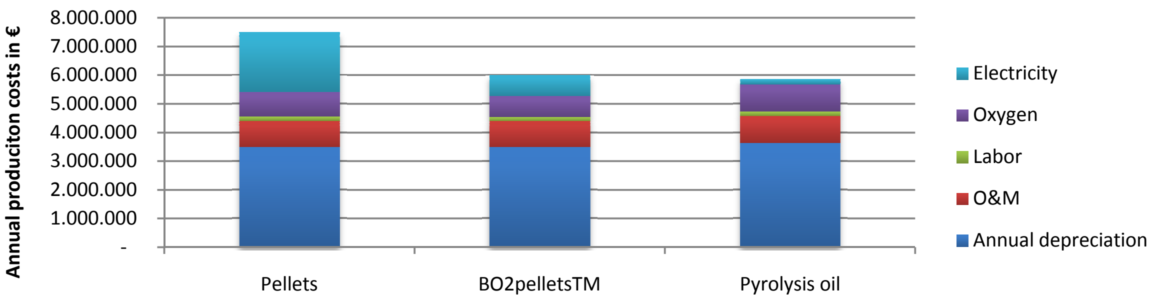


Figure 30 - Production cost per GJ of the Fischer-Tropsch diesel production process of the different intermediate products.

- *The investment costs have a high impact on the economic performance.*
- *The differences between the production costs are determined by the electricity consumption.*

5.4 Conclusion

Now the energy conversion processes are evaluated an answer can be given to the fourth sub-question: *“What is the energetic- and economic performance and environmental impact of energy conversion for the several intermediate products, e.g. pellets, BO_2pellets™ and pyrolysis oil?”*

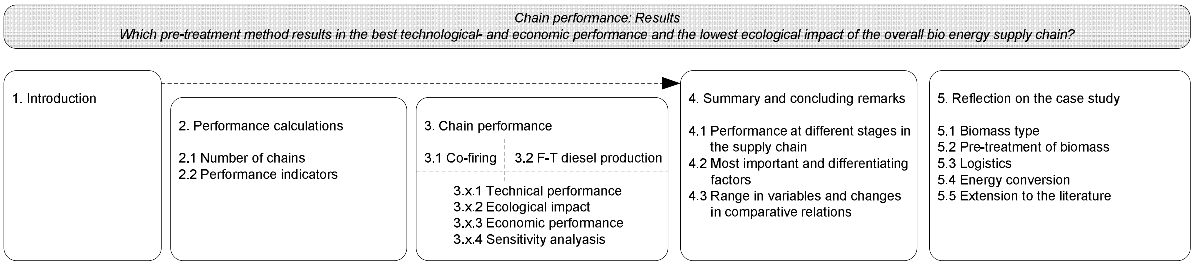
In table 18 the energetic-and economic performance and ecological impact of the energy conversion processes are summarised. Pyrolysis oil comes forward as the most beneficial intermediate product for energy conversion in both cases, co-firing and Fischer-Tropsch diesel production. This is due to the liquid form of pyrolysis. It does not require high investment costs or energy consuming handlings. This results in the highest energetic- and economic performance and lowest ecological impact for pyrolysis oil.

Table 18 - summary of the energetic- and economic performance and ecological impact of energy conversion.

			Co-firing: electricity			F-T diesel production	
		Pellets	BO_2pellets™	Pyrolysis oil	Pellets	BO_2pellets™	Pyrolysis oil
Energy produced	$GJ_{(e\ or\ F\text{-}T)}$^6	0.38	0.40	0.40	0.68	0.68	0.71
Energetic performance	GJ_{in}^6	1.01	1.01	1.01	1.26	1.1	1.03
Ecological impact	kg CO2	-	-	-	12.5	4.4	1.1
Economic performance	€^6	2.1	0.6	0.3	7.5	6.0	5.9

BO_2pellets™ have improved characteristics compared to pellets, i.e. hydrophobic nature and easier grinding. These beneficial characteristics results in a better energetic- and economic performance and ecological impact compared to pellets. BO_2pellets™ however cannot compete with the liquid advantage of pyrolysis oil. Grinding and compression are important and decisive factors in the energy conversion process.

6 Chain performance: *Results*



6.1 Introduction

The preceding sections explained in detail the energetic- and economic performance and ecological impact of the distinctive chain elements in the bio energy supply chain, i.e. pre-treatment (CH3), logistics (CH4) and energy conversion (CH5). Each element has its own energetic- and economic performance and ecological impact and the performance varied per chain element with the chosen biomass pre-treatment method.
The separate chain elements are analysed as a whole in this section. It is discussed what the energetic- and economic performance and ecological impact is of the entire bio energy supply chain. This will give an answer to the main research question: *Which pre-treatment method results in the best energetic- and economic performance and the lowest ecological impact of the overall bio energy supply chain?*
Furthermore, by and analysing the entire supply, an indication is obtained of the most influential variables and factors which cause the differences in performance between chains containing different biomass pre-treatment methods.

These issues are addressed in the following order: Firstly the method of comparison for the chain performance is described. Secondly the results are presented. The results are presented per energy conversion type; firstly co-firing is discussed, followed by F-T diesel production. In each case the eventual performance, performance structure and range in calculations per performance indicator are examined. Thirdly the results are summarised and concluding remarks are given. These remarks refer to the performance at different stages in the supply chain, the most influential factors and the effect of the range in variables for the comparative relations. Finally the limitations about the generalisation of the findings in this study are discussed.

6.2 Method of comparison for the chain performance

This section elaborates on how many chains are analysed and how the performance of a chain is defined.

6.2.1 *Number of chains*

There exists not one chain to analyse, but several ones. The number of chains which is analysed depends on the number of biomass pre-treatment methods and number of energy conversion types. In this study three pre-treatment methods (pelletisation, torrefaction and pyrolysis) and two energy conversion types are discussed (electricity production by co-firing and F-T diesel production by entrained flow gasification). So, in total six chains are discussed, three co-firing and three F-T diesel production chains, varying with the pre-treatment method. A schematic impression of the six possible supply chains is shown in figure 31 (arrows).

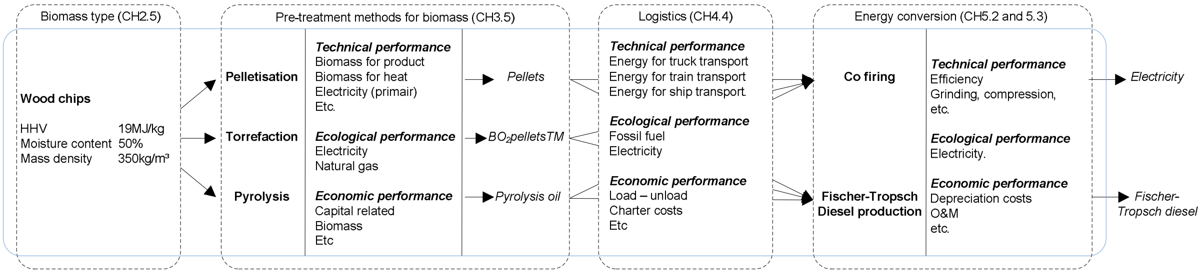


Figure 31 - Stages of the bio energy supply chain with variables affecting the energetic- and economic performance and ecological impact.

6.2.2 Performance indicators

The performance of a chain is defined by the performance of the several distinctive chain elements. The supply chain starts with, woodchips as resource. Subsequently the woodchips are pre-treated and the created intermediate products are transported and converted to energy. The eventual performance of the entire bio energy supply chain is the summation per performance of each chain element of the chain. Figure 31 shows the chain elements, together with several of the variables affecting the technological- and economic performance and ecological impact. For a more detailed discussion of the process and variables is referred to the appropriate chapters as mentioned in figure 31.

However, the absolute value of the summation cannot be compared. Each chain produces different amounts of energy and solely a comparison of the absolute values would result in incomplete comparison. Therefore the absolute value is divided by the amount of energy produced by the distinctive chain. The 'expenses' are compared per GJ produced and this is an objective factor, which can be compared.

This leads to the following definitions of the performance indicators:

1) Energetic performance $$= \frac{\sum \left(\lambda_{\Pr e-treatment} + \lambda_{Energy\_conversion} + \lambda_{Logistics}\right)}{GJ_{output\_\alpha/\mu}}$$

2) Economic performance $$= \frac{\sum \left(\$_{\Pr e-treatment} + \$_{Energy\_conversion} + \$_{Logistics}\right)}{GJ_{output\_\alpha/\mu}}$$

3) Ecological impact $$= \frac{\sum \left(\beta_{\Pr e-treatment} + \beta_{Energy\_conversion} + \beta_{Logistics}\right)}{GJ_{output\_\alpha/\mu}}$$

λ, β and \$:	*Respectively the energetic, economic and ecological expenses at chain element X in the bio energy supply chain, i.e. pre-treatment, logistics and energy conversion.*
$GJ_{output\_\alpha/\mu}$	*Respectively the amount of produced electrical energy or the energy content of the produced amount of F-T diesel for the different energy conversion types.*

The chain which scores best on the above mentioned performance indicators leads to an indication of the pre-treatment method with the best energetic- and economic performance and ecological impact.

6.3 Chain performance

The foregoing sections showed that pelletisation resulted in the best performance during the pre-treatment stage. BO_2pellets™ resulted in the best performance during transport and pyrolysis oil resulted in the best performance during co-firing. In the coming section the summation of the energy input over the stages in the supply chain are discussed per GJ produced.

Remember that the goal of thermo chemical biomass pre-treatment methods is to compensate for the higher (energetic, economic and ecological) expenses during biomass pre-treatment by a better performance during transport and energy conversion. From the results it will become clear of they succeed in their intension.

6.3.1 Co-firing

This section discusses the energetic- and economic performance and ecological impact of bio energy supply chains producing electricity.

6.3.1.1 Energetic performance

The total energy consumption per GJ_e produced is shown in figure 32 for the several co-firing chains. From this figure can be derived which biomass pre-treatment method results in the chain with the lowest energy input, i.e. highest efficiency and energetic performance.

Pelletisation and torrefaction result in chains with a similar energetic performance. The chain including pyrolysis on the contrary requires approximately 30% more energy input in comparison with the other chains.

In the energy consumption structure is seen that the energy consumption during pre-treatment is dominant and is responsible for 98-99% of the total energy input. Transport requires approximately 1-2% of the total energy input. The impact of the difference in co-firing efficiency cannot be directly retrieved from figure 32. This is indirectly seen by a 'compression' or 'extension' of the bar, as the energy input is divided over respectively more or less GJ_e output. The bar, representing the chain with pelletisation in figure 32, is 'extended' in comparison with the bars representing the chains with torrefaction and pyrolysis.

It can be concluded that the created intermediate product during torrefaction (BO_2pellets™) can undo the higher energy consumption during pre-treatment by a better performance during transport (less movements) and co-firing (higher conversion efficiency). As result the chains with torrefaction and pelletisation as biomass pre-treatment method end up with the lowest energy input.

The chain with pyrolysis as pre-treatment method is only able to compensate a part of the higher energy consumption during pre-treatment by a better performance during (mainly) co-firing and has therefore the highest energy input.

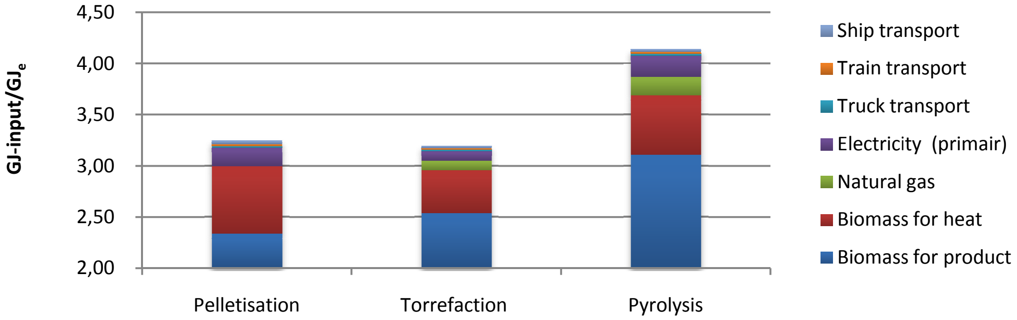


Figure 32 - Energetic performance of co-firing chains with different pre-treatment methods of biomass.

The energy consumption structure is discussed in more detail. This is done because each variable has a different impact on the energetic performance and differences between the chains. A closer look at these variables will give an indication of the factors which are decisive for the performance and differences between the chains.

From the above comes forward that the energy consumption during pre-treatment is responsible for 98-99% of the total energy input. This has as consequence that the same factors are of influence on the energetic chain performance as on the energetic performance as pre-treatment of biomass (as discussed in 3.6). Biomass for product and -heat are of the most important factors as result of the product yield and heat demand of the pre-treatment processes.

The low impact of the energy consumption during transport on the overall input of the bio energy supply chain can be explained easily. A fully loaded bulk carrier, loaded with wood pellets; the lowest energy density, contains 856 GJs. A single boat trip from Canada to the Netherlands consumes only 11 GJ. This is 1.3% of the energy content of the cargo in pellets. As consequence a low impact of transport on the energetic performance.

In conclusion, transport has neglectable impact on the total energy input, and the main variable affecting the difference between the chains are the biomass flows.

6.3.1.2 Ecological impact

The ecological impact is related to energy input of the chain, with an important feature that biomass is CO_2 neutral. As consequence that the CO_2 emissions are related to the consumption of fossil fuels during biomass pre-treatment and transport. During co-firing no fossil fuels are used. The resulting ecological impact is shown in figure 33.

The co-firing chain with pelletisation has the lowest ecological impact. The chain with torrefaction produces 11%- and the chain including pyrolysis produce 98% more CO_2.

In the ecological impact structure pre-treatment is responsible for 51-66-77% of the total CO_2 emissions, for respectively the chains with pelletisation, torrefaction and pyrolysis. Consequently, transport is responsible for 49-34-23% of the total CO_2 emissions, for respectively the chains with pelletisation, torrefaction and pyrolysis.

It can be concluded that the created thermo-chemical intermediate products cannot undo the higher CO_2 production during pre-treatment, as result of improved characteristics for transport. Pelletisation has therefore the lowest ecological impact, followed by torrefaction and pyrolysis.

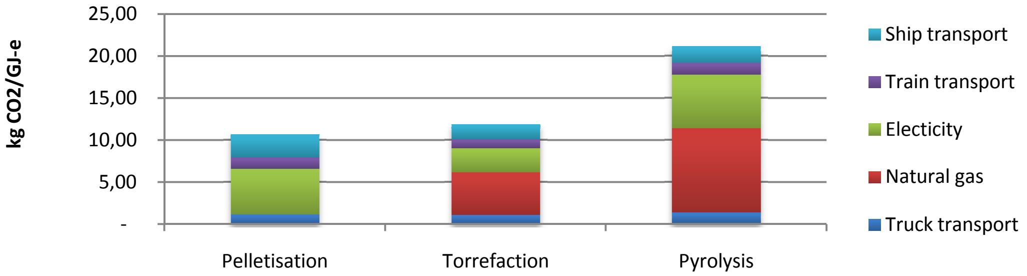


Figure 33 - Ecological impact of co-firing chains with different pre-treatment methods of biomass.

A more detailed examination of the ecological impact structure reveals the most important chain activities for the ecological impact.

What immediately stands out is the high impact of natural gas on the ecological impact. Natural gas is responsible for 42-47% of the CO_2 emissions in the chains with thermo-chemical processes, respectively the chains with torrefaction and pyrolysis). The use of natural gas is the main cause of a higher ecological impact of the thermo-chemical chains which produce electricity.

Whereas the energy consumption of transport had no substantial influence on the energetic performance, the ecological impact of transport is substantial. The individual transport activities have however a moderate ecological impact (range of 7-15%) in chains with thermo-chemical pre-treatment methods. Nevertheless ship transport has a high ecological impact (25%) on chains with pelletisation.

In conclusion natural gas is devastating for and the main cause for high the ecological impact of the chains with thermo-chemical pre-treatment methods. Transport has only a high ecological impact in case of ship transport for chains with pelletisation.

6.3.1.3 Economic performance

The production costs showed a lot of variance per pre-treatment method for the separate chain elements. Each chain element has its own champion. The overall economic chain performance is given in figure 34.

The chain with torrefaction results in the highest economic performance. Electricity produced by chains with pelletisation is 10% more expensive and if produced by chains with pyrolysis the production cost are even 27% more expensive.

The pre-treatment costs are approximately 66-78-79% of the total production costs for respectively chains with pelletisation, torrefaction and pyrolysis. The transport costs are roughly 19% of the total production costs in each of the chains. The co-firing costs of pellets are approximately 15-5-2% of the total production costs, for respectively chains with pelletisation, torrefaction and pyrolysis.

It can be concluded that the created intermediate product during torrefaction (BO_2pellets™) can undo the higher production costs during pre-treatment by a better performance during transport (less movements) and co-firing (lower investment costs). As result the chain with torrefaction as biomass pre-treatment method ends up with the lowest production costs.

The chain with pelletisation has a middle high production costs, due to the high investment costs for co-firing.

The chain with pyrolysis as pre-treatment method is the most expensive as the higher costs during pre-treatment and transport only partially can be compensated by saving during co-firing.

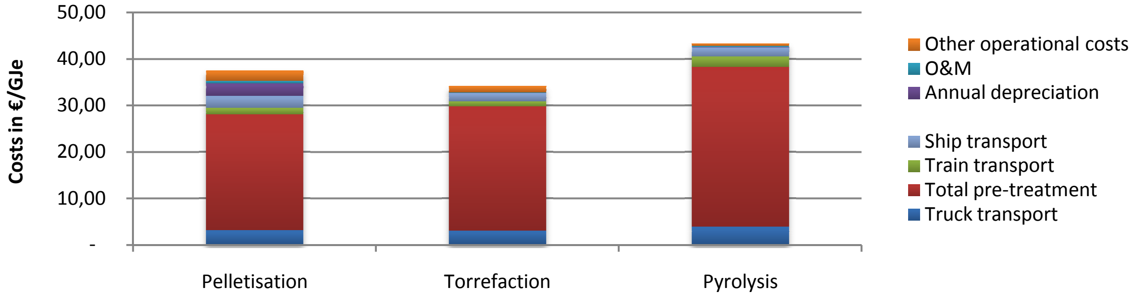


Figure 34 - Economic performance of co-firing chains with different pre-treatment methods of biomass.

A more detailed assessment of the product costs composition is discussed to identify the most important factors for the economic performance.

The highest cost factor, in all three the chains, are the total pre-treatment costs. Within this factor are the biomass costs the largest factor. Approximately 42-46-50% of the total co-firing costs for respectively the chains with pelletisation, torrefaction and pyrolysis.

Of the transport modes is the local truck transport the most expensive transport mode with 10% of the total costs. Train and ship transport account together for another 10% of the total costs.

The co-firing costs are of less influence on the total production costs, except for the chain with pelletisation. In this chain the co-firing costs of pellets are approximately 15% of the total production costs.

In conclusion, the decisive factor in the difference in production costs between the co-firing chains with pelletisation and torrefaction are the investment costs at the energy conversion stage. The chain with pyrolysis as pre-treatment method for biomass is too expensive during the production of pyrolysis oil. Although truck transport is over a short distance it is an important cost factor to reconsider.

6.3.1.4 Sensitivity analysis: tornado diagrams

The above presented results are the outcome of the values chosen in this study. The variables used in this study don't have a fixed value, but have a range. The values used in this study are chosen according to the assumptions of this study or based on the most likely value. Nevertheless there exists a range in the variables, which affects the calculated results.

To gain insight in the effect of this range in variables, the value of a variable is changed and the impact of this change is reported in this section. The influence of a variable varies with the range of the variable. Therefore, not solely a 10% range in the variable is taken, but the expected range in the variable. The resulting picture is a so called tornado diagram (Vencil, 2003). The tornado diagram shows the relative impact and order of importance of the factors (from high to low influence). The sensitivity analyses represented here are based on the chain containing torrefaction because it is the chain with the 'best' performance. The sensitivity analysis of the other chains can be found in appendix H.

First the energetic performance is discussed, followed by the ecological impact and finally the variables that affect the economic performance are discussed. In §6.4.4 subsequently, the effect on the comparative relations is discussed.

Energetic performance

In figure 35 is the effect on the energetic performance given as a result of the expected variance in the variables. On the vertical axis are the several variables mentioned, together with the range. On the horizontal axis is the change in energetic performance given as a percentage of the above calculated energetic performance of co-firing.

The default value of the moisture content is 50% (left boundary). This results in 100% of the energetic performance, as this is the value used for the calculations. The lowest expected moisture content is 35% (right boundary). The lower moisture content results eventually in a gain of 7 % in the energetic performance of the chain.

If the co-firing efficiency decreases from 40 (coal based) to 37.5% (pellets based) the efficiency reduces with 6%.

Heat recovery is lacking in the analysis of this study, but it is tried to capture heat recovery by varying the efficiency of the heat exchanger. By increasing the heat exchanger efficiency less energy is lost and 'more heat is recovered'. This results in an efficiency gain of 4%.

The heat demand of the torrefaction and pyrolysis reactors is relatively uncertain. Therefore is examined what the result will be, if the torrefaction reactor would have a similar heat demand as the pyrolysis reactor. This broad range is taken as the most extreme possibility. An increase in heat demand of 3.5% to 15% results in a decrease of 16% in the energetic performance.

The variation in the other variables is of less influence (<1%).

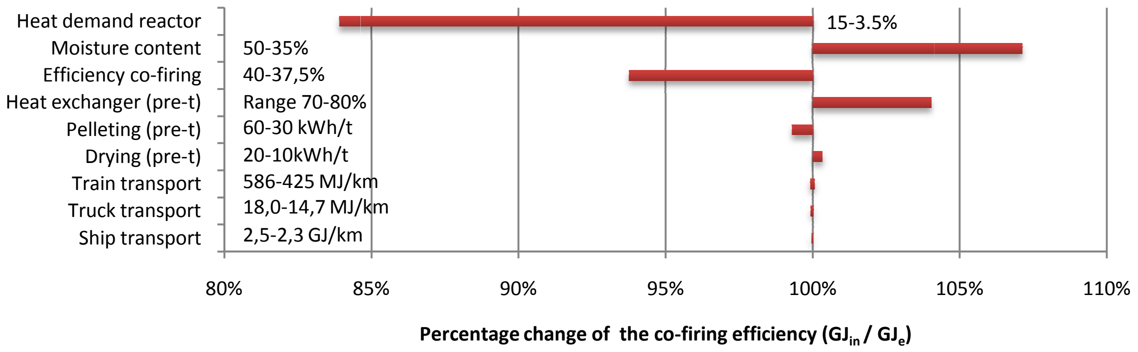


Figure 35 - Expected change in energetic performance of co-firing chains with torrefaction as pre-treatment method for biomass.

Ecological impact

Similar factors are on influence on the ecological impact as on the energetic performance. The effects are however different because only a reduction in the use of fossil fuels has an impact on the CO_2 emissions. Figure 36 shows the expected change in the ecological impact of supply chains with torrefaction as pre-treatment.

The heat demand of the reactor has the highest impact on the ecological impact. A higher heat demand increases the use of natural gas and thereby strongly the CO_2 emissions. A similar reactor heat demand as the pyrolysis reactor results in an increase of approximately 35% in ecological impact.

A lower moisture content reduces the heat demand, i.e. electricity consumption for drying and more important the use of natural gas. If the lowest moisture content is chosen, the CO_2 emissions can be reduced with 25%.

In a similar way affects heat recovery the reduction of the ecological impact. The more heat is recovered, the lower the external heat demand and use of electricity and natural gas is reduced. A reduction of 8% in the ecological impact is obtained by increasing the efficiency of the heat exchanger.

The co-firing efficiency is here of importance as it defines how the ecological impact is accounted per GJ_e produced. If the co-firing efficiency of BO_2pellets™ approaches the co-firing efficiency of pellets the ecological impact increases as the CO_2 emissions can be divided over less GJ_e.

The electricity consumption activities have pelletisation the most influence on the ecological impact. Of the transport factors has train transport the greatest variation due broad range. The other factors have less influence on the ecological impact.

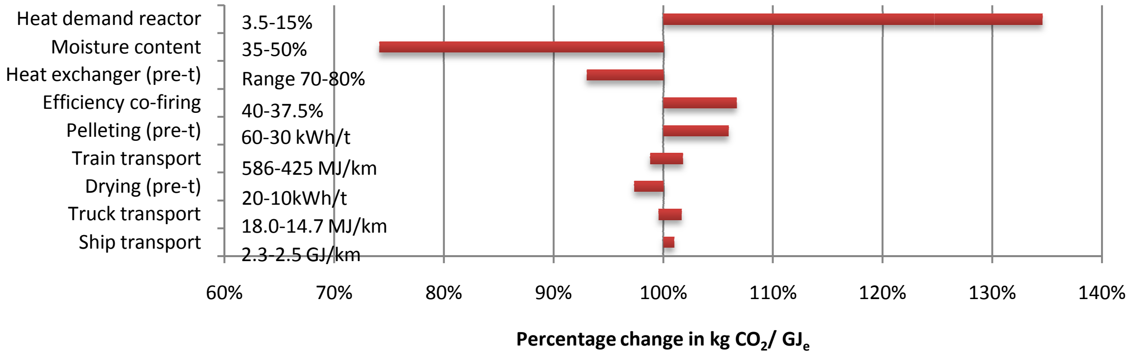


Figure 36 - Expected change in ecological impact of co-firing chains with torrefaction as pre-treatment method for biomass.

Economic performance

The economic performance is affected by different factors as the energetic performance and ecological impact. The expected variations in economic performance are shown in figure 37.

The moisture content has the most influence, followed by the raw material price. The high impact of these factors is related to the high impact of the biomass costs (40-50% of the total costs). A variation in the moisture content and raw material price reduces the biomass costs and thereby the entire chain costs. A lower moisture content result in less purchase of biomass (no moisture is less weight in the spreadsheet) and a lower biomass for heat demand, due to a lower heat demand for drying. The effect of the raw material price on entire chain production cost can be expressed by the percentage change in the raw material price multiplied by the biomass cost factor of the entire chain.

The investment costs for torrefaction have a very broad range (+40%) which causes high uncertainty in the economic performance. The parameters related to the investment cost are of influence as well because the capital costs are 25% of the total costs. For this dependency have the operation time, lifetime, interest rate and maintenance costs as well a high influence. Especially the operation time is a crucial factor. Long stagnations of the production process have to be avoided due to the large capital costs.

Heat demand has a lower impact on the economic performance. The impact of the natural gas costs are not high and thereby is the impact of the heat demand strongly reduced. Its influence is however still respectable with an increase of approximately 12%.

Ship transport is of influence by the high variability of the charter costs. High uncertainty exists about the price due to market influences.

The co-firing efficiency influences the costs, but does not affect the performance order between the chains. A co-firing efficiency of 37.5% result in €36/GJ for torrefaction, which is still below the costs of the chain containing pelletisation. If in addition, the other operation costs are set equal to the costs of co-firing, torrefaction chain becomes gets similar costs as the pelletisation chain (€37.2 vs €37.5). It seems therefore likely that the co-firing of BO_2pellets™ is cheaper than the co-firing of pellets.

Heat recovery is important as it reduces on biomass for heat and natural gas. The other factors are of less influence. Ship transport remains as well a factor for consideration as the high uncertainty of the price affects the economic performance substantial. The more 'optimistic' chosen parameters for co-firing of BO_2pellets™, i.e. co-firing efficiency and other operation costs, did not affect the order in economic performance of BO_2pellets™ and pellets.

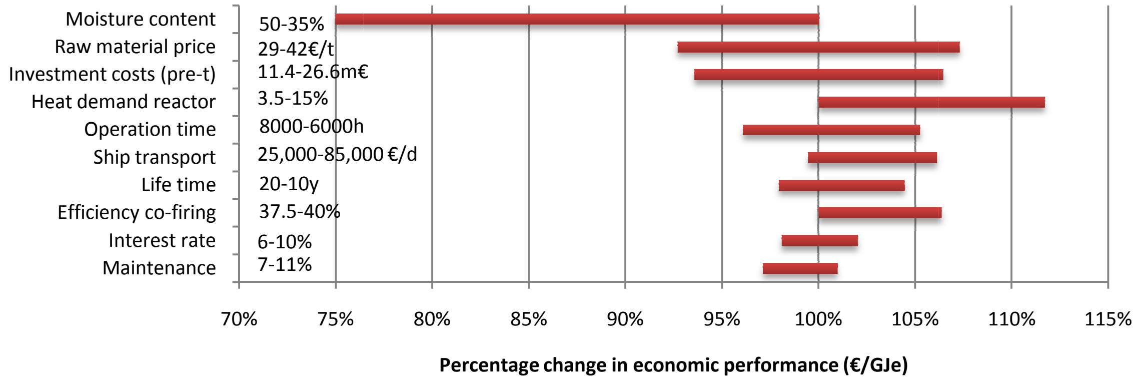


Figure 37 - Expected change in economical performance of co-firing chains with torrefaction as pre-treatment method for biomass.

6.3.2 F-T diesel production

This section discusses the energetic- and economic performance and ecological impact of bio energy supply chains producing an automotive fuel, i.e. F-T diesel.

6.3.2.1 Energetic performance

The overall energetic performances of the chains that produce Fischer-Tropsch diesel are shown in figure 38. The chain with torrefaction as pre-treatment method for biomass has the highest energetic performance. The chains containing pelletisation and pyrolysis consume respectively 8 and 18% more energy than the chain with torrefaction.

In the energy consumption structure is seen that the energy consumption during pre-treatment is dominant and is responsible for 81-92-97% of the total energy input, for respectively the chains with pelletisation, torrefaction and pyrolysis. Transport requires approximately 2% of the total energy input for all three the chains. The energy consumption during F-T diesel production varies from 17-6-1% of the total energy input for respectively the chains with pelletisation, torrefaction and pyrolysis. The conversion efficiency to F-T diesel is approximately similar (section 5.3.5) and the 'compression or expansion' effect is therefore neglectable (as in section 6.2.1).

It can be concluded that the created intermediate product during torrefaction (BO_2pellets™) can undo the higher energy consumption during pre-treatment by a better performance during (mainly) F-T diesel production. As result the chains with torrefaction as biomass pre-treatment method ends up with the lowest energy input.

The chain with pelletisation consumes a lot of energy during F-T diesel production and has therefore the second best energetic performance.

The chain with pyrolysis as pre-treatment method is only able to compensate a part of the higher energy consumption during pre-treatment by a better performance during (mainly) F-T diesel production and has therefore the highest energy input.

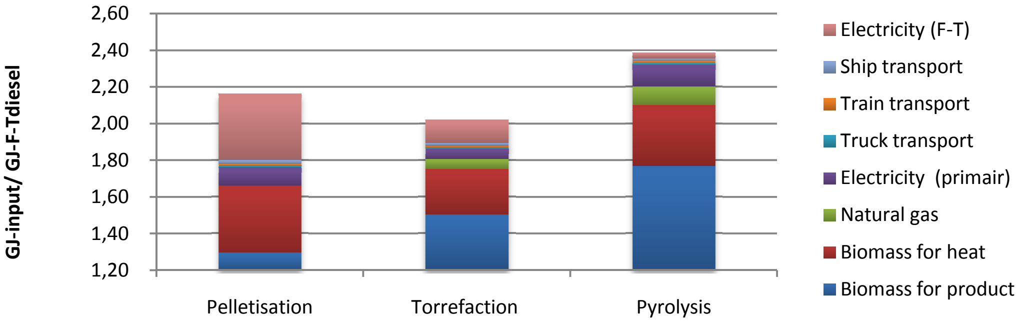


Figure 38 - Energetic performance of chains producing F-T diesel with different pre-treatment methods for biomass.

The energy consumption structure is discussed now in more detail. This is done because each variable has a different impact on the energetic performance and differences between the chains. A closer look at these variables will give an indication of the factors which are decisive for the performance and differences between the chains.

The energy consumption during pre-treatment is the lion's share of the total energy consumption (81-98%). The energetic performance is therefore dominated by the biomass flows, i.e. 77-87-88% of the total energy input for respectively the chains with pelletisation, torrefaction and pyrolysis.

The most striking variable is the electricity consumption during F-T diesel production. The electricity consumption during F-T diesel production in chains with pyrolysis can be neglected, while the energy consumption in chains with pelletisation is almost 1/5 of the total energy consumption. The improved characteristics of BO_2pellets™ reduce the electricity consumption during grinding substantial (see also section 5.35).

In conclusion the electricity consumption is a decisive factor is in the energetic performance. Out of figure 38 comes forward that BO_2pellets™ consume less electricity (grinding) and that the chain with torrefaction becomes therefore the most efficient chain.

Pelletisation transforms wood into a product which still has its biomass characteristics. This results in high energy consumption during F-T diesel production.

The chain with pyrolysis as biomass pre-treatment method is not able to compensate the higher energy consumption during pre-treatment by the low electricity consumption during F-T diesel production.

6.3.2.2 Ecological impact

The energetic performance section of Fischer-Tropsch diesel production showed that pelletisation consumed a lot of electricity during the F-T diesel production. The corresponding ecological impact of pelletisation sky rocked or the pelletisation chain as can be seen in figure 39.

The chains with torrefaction and pyrolysis have a similar ecological impact. The chain with pelletisation as pre-treatment method for biomass has approximately 80% more CO_2 emissions.

In the ecological impact composition is biomass pre-treatment accountable for 12-35-68% of the total CO_2 emissions for respectively chains with pelletisation, torrefaction and pyrolysis. The transport activities are responsible for 12-17-20% of the total CO_2 emissions for respectively the chains with pelletisation, torrefaction and pyrolysis. The F-T diesel production is responsible for 76-48-12% of the total ecological impact for respectively the chains with pelletisation, torrefaction and pyrolysis.

It can be concluded that the chains with torrefaction and pyrolysis can compensate the high ecological impact during pre-treatment because of the improved intermediate product characteristics for F-T diesel production. The chains with pelletisation have high electricity consumption during the F-T diesel production and result therefore in the highest ecological impact.

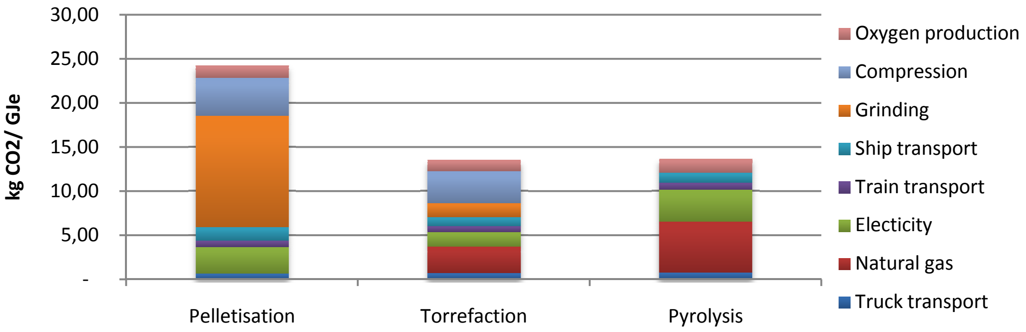


Figure 39 - Ecological impact of chains producing F-T diesel with different pre-treatment methods for biomass.

A closer look at the configuration of the ecological impact in figure 39 identifies the variables with the highest impact and differentiating factors between the chains with different biomass pre-treatment methods.

The variable with the highest impact on the ecological impact of the chain is grinding of pellets for F-T diesel production. Grinding and compression of BO_2pellets™ are factors of high impact in chains with torrefaction. Natural gas remains a factor with high influence on the ecological impact on both the chains with a thermo-chemical pre-treatment.

It can be concluded that the decisive variables between the chains with different pre-treatment methods for biomass are grinding in case of pelletisation, compression for chains with torrefaction and the use of natural gas in chains with pyrolysis.

6.3.2.3 Economic performance

The economic performance is in a lesser degree influenced by the electricity consumption during F-T diesel production as seen in the section of energetic performance and ecological impact. The production costs for F-T diesel production via different biomass pre-treatment methods are shown in figure 40.

The economical performances of the chains with pelletisation and torrefaction as biomass pre-treatment method are approximately the same. F-T diesel production via pyrolysis is approximately 15% more expensive than via torrefaction or pelletisation.

In the economic performance structure covers pre-treatment 48-56-60% of the total production costs for respectively the chains with pelletisation, torrefaction and pyrolysis. The impact of transport is approximately 14% of the total production costs for all three the chains. The cost share of F-T diesel production in relation to the total production costs is 28-27-25% for respectively the chains with pelletisation, torrefaction and pyrolysis.

It can be concluded that the chain with torrefaction is able to compensate for the higher production costs during pre-treatment by lower production costs during F-T diesel production.

The chain with pelletisation consumes ‘too much’ energy during F-T diesel production and has therefore similar production costs as the chain with torrefaction.

Pyrolysis has a better economic performance during F-T diesel production as torrefaction, but is too expensive at the pre-treatment stage and becomes the most expensive chain.

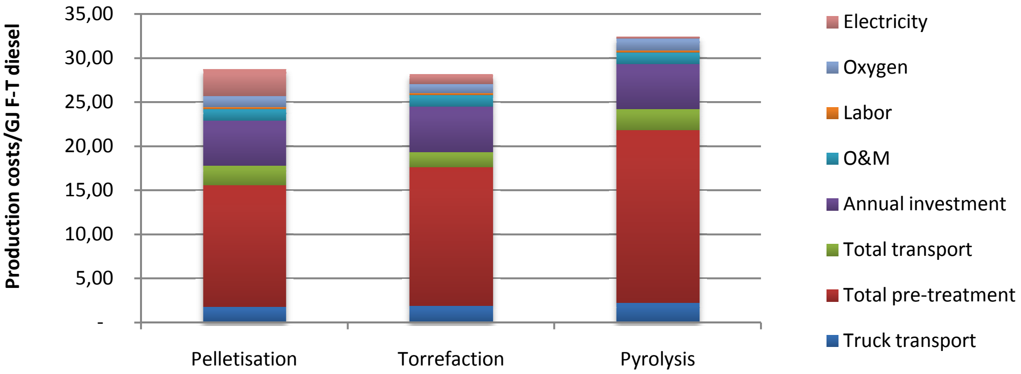


Figure 40 - Economical performance of chains producing F-T diesel with different pre-treatment methods for biomass.

A closer look at the variables with a low and high influence in figure 40 can give an indication of the most important factors for the chains producing F-T diesel.

The pre-treatment costs dominate the economic performance of F-T diesel production. This is mainly due to the purchase costs of biomass, which are approximately 27-30% of the total costs. The annual depreciation costs of the F-T plant are another important cost factor, respectively 16-18% of the total production cost. Electricity is the last cost factor to reconsider. The electricity costs have a low impact on the total costs, except for the chain with pelletisation, i.e. 1% of the total costs.
It can be concluded that although the electricity costs have a low impact of the overall costs, the electricity consumption is a decisive factors for the difference in economic performance between the chains with pelletisation and torrefaction. With respect to the chain with pyrolysis, as biomass pre-treatment method, applies that the consumption costs during pre-treatment are too high.

6.3.2.4 Sensitivity analysis

Energetic performance

The effect of variation in the variables determining the energetic performance of F-T diesel production is shown in figure 41.
The factors of high influence are the heat demand related factors, i.e. reactor heat demand, moisture content and heat recovery. The reactor heat demand of a pyrolysis reactor strongly increases the heat demand (15%). Both other variables reduce the heat demand and thereby the required energy input. An increase in the energetic performance of approximately 7 and 4% is obtained for respectively a reduction in moisture content or increase in heat recovery.
The variation in the power required for grinding is the responsible for a minor effect on the energetic performance; approximately 2% reduction in energetic performance.
The impacts of the other factors are of minor influence.

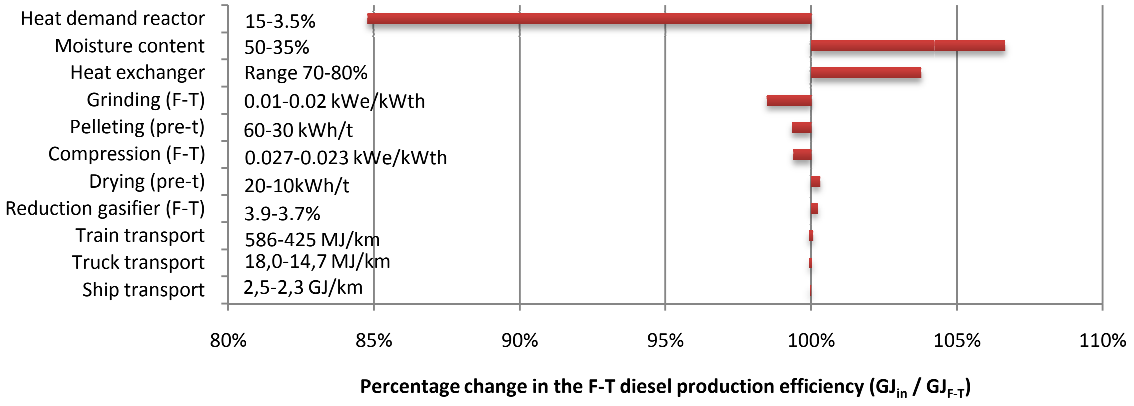


Figure 41 - Expected change in the energetic performance of chains producing F-T diesel with torrefaction as pre-treatment method for biomass.

Ecological impact

Figure 42 presents a summary of the most influencing factors on the ecological impact.
The greatest variations in the ecological impact is related to the reactor heat demand and moisture content. An increase of 17% in the ecological impact is obtained if the reactor heat demand would be equal to the heat demand of the pyrolysis reactor. A 13% reduction in CO_2 emissions can be obtained by reducing the moisture content to 35%. The same principles are at work here as explained in section 6.2.4.1. The use of natural gas and electricity are reduced and thereby the ecological impact.
Grinding is an electricity consuming activity affects thereby greatly the ecological impact. Compression affects the conversion efficiency to synthesis gas and thereby the amount of F-T diesel produced. The produced CO_2 can here fore be divided over less GJF-T diesel.
Heat recovery is important as it reduces the consumption of natural gas.
The other factors are of less influence.

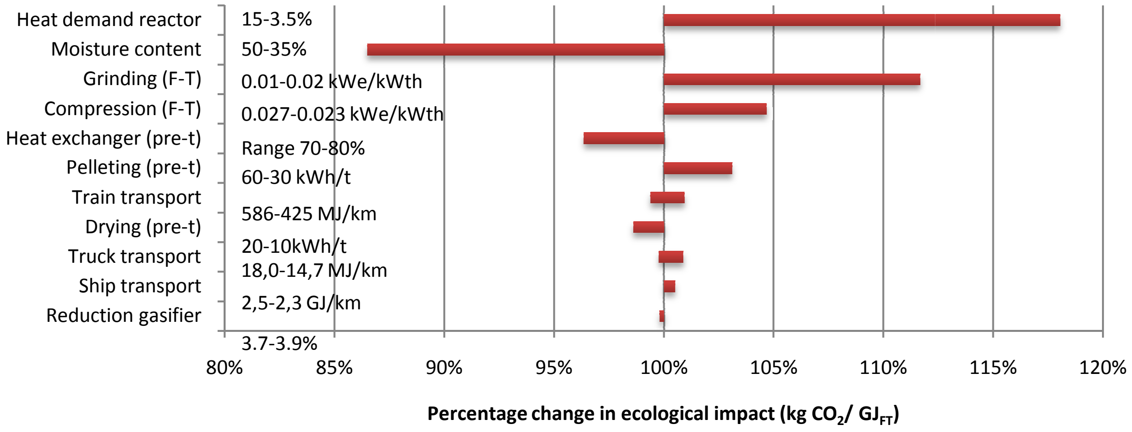


Figure 42 - Expected change in the ecological impact of chains producing F-T diesel with torrefaction as pre-treatment method for biomass.

Economic performance

Figure 43 shows the factors of influence on the economic performance of supply chains with torrefaction as pre-treatment method for biomass.

The economic performance is highly influenced by the moisture content. The moisture content reduces strongly the material throughput and heat demand.

The operation time is importance because delays during pre-treatment affect the stages upward in the chain as well. The high capital costs of the F-T diesel plant are burdensome if they are not fully exploited.

The raw material price is because of the high biomass flows also of high importance for the economic performance.

The investment costs are highly uncertain and this results in a big variation in the production costs. The capital related costs of pre-treatment have a marginal influence.

Heat demand the reactor has a lower influence here as well on the economic performance. Its influence is still considerable with an increase of 7%.

The ship costs have, due to the big variation in charter cost, a substantial influence on the production cost.

The other parameters are of less influence.

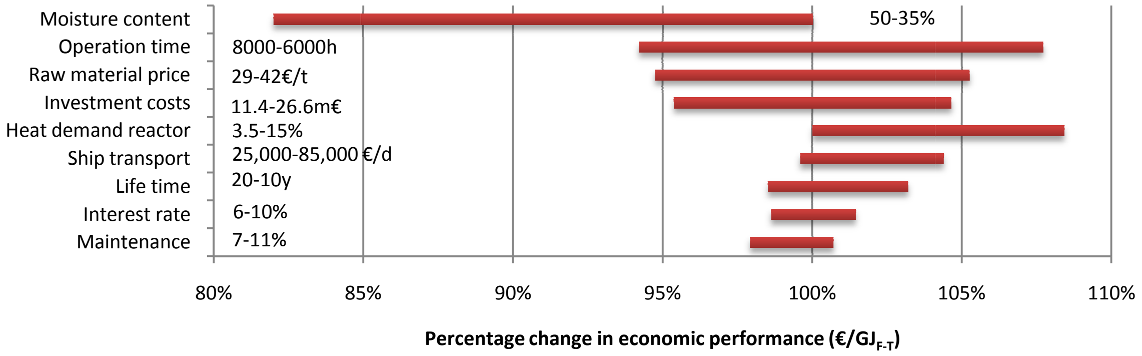


Figure 43 - Expected change in economic performance of chains producing F-T diesel with torrefaction as pre-treatment method for biomass.

6.4 Summary and concluding remarks

It is seen so far how the chains with different biomass pre-treatment methods score on the performance indicators for the two energy conversion types. In addition the factors with a high influence on the final results are identified, together with the factors which affect the difference between the chains. The main issues are summarised here per performance indicator to return to the objective of this study: *to gain insight in (and the difference between) bio energy supply chains, with different pre-treatment methods of biomass, to make* *predictions about the energetic efficiency, production costs and CO_2 emissions of the whole bio energy supply chain for different end applications; co-firing and F-T diesel production.*

First the evolvement over the chain is discussed. Followed by the most important and differentiating factor between the chains with different biomass pre-treatment methods. Finally the effect of the range in the variables and their effect on the comparative relations are discussed.

6.4.1 Performance at different stages in the supply chain

In §6.2-3 of this chapter only the end stage of the supply chain are discussed. The influence of all the variables is taken into account, which makes it harder to identify the influence of the separate chain elements on the difference in performances. The chain is therefore broken up in several stages and the performance is summarised to get a less complex impression of the chain performance.

The performance evolvement over the chain is described as following: First the performance during pre-treatment of biomass is shown in figures 44-46. Next a new term is introduced, gate delivered. Gate delivered includes the combined performance of pre-treatment and transport. Subsequently the eventual performance at the energy conversion stage is shown, as described in §6.2-3.

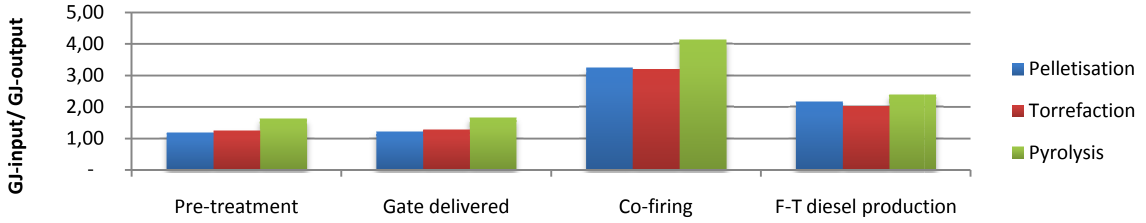


Figure 44 - The energetic performance at different stages in the supply chain for chains with different pre-treatment methods for biomass.

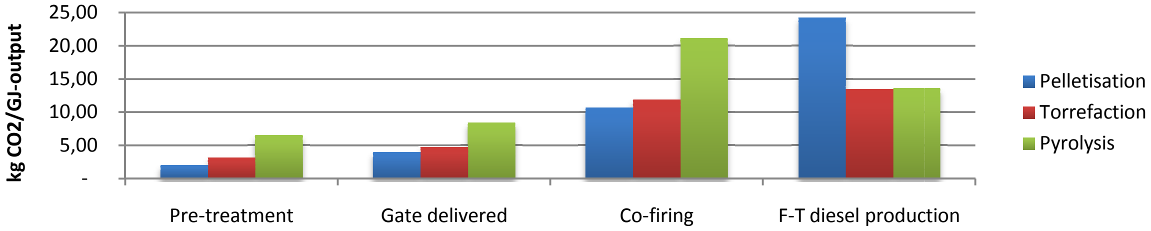


Figure 45 - The Ecological impact at different stages in the supply chain for chains with different pre-treatment methods for biomass.

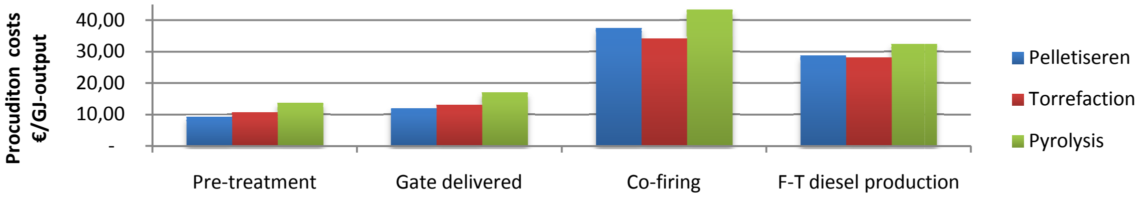


Figure 46 - The economic performance at different stages in the supply chain for chains with different pre-treatment methods for biomass.

Figures 44-46 show that the chain with pelletisation sets the benchmark during biomass pre-treatment on all three the performance indicators. The chain with torrefaction has a slighter worse performance as the benchmark, but the chain with pyrolysis follows at a certain distance.

At the gate delivered stage it is seen that the improved characteristics of the (thermo-chemical) intermediate products have an beneficial impact on the performance. This effect is however marginal and can be seen by the decrease in differences between chains.

The large changes are however seen at the energy conversion stage. During the activities in this chain element the order in performances changes between chains with different biomass pre-treatment methods. The details are discussed in §5.4 and §6.2-3.

From the performance evolvement over the chain comes clearly forward that the major differences in performance are caused by biomass pre-treatment and energy conversion of the intermediate products. Transport of the intermediate products has a low impact on the performance and does not affect the order in the case of transport from Canada to the Netherlands.

6.4.2 Most important and differentiating factors

Paragraphs 6.2.1-3 and 6.3.1-3 showed the most influential parameters. Table 19 summarises the variables which explain 90% of the value of the indicator (except for economic performance of which 75-85% of the economic performance is explained). The variables in this table are the most influential variables on the chain performance. From this table, the variables which have the largest contribution in the performance difference between chains with different biomass pre-treatment methods can be derived as well. The differentiating factors are blue shaded. The most important variables and variables which are responsible for the difference in performance between chains are discussed per energy conversion type.

Co-firing

The most influential factors and factors responsible for the difference in energetic- and economic performance and ecological impact of co-firing are mentioned in this section.
The most influential factors on the *energetic performance* are in order of magnitude: biomass for product, biomass for heat, total electricity consumption pre-treatment and natural gas. The differences in energetic performance between chains with pelletisation and torrefaction on the one hand and pyrolysis on the other hand are mainly caused by the energy flows of biomass for product and natural gas.
The most influential factors on the *ecological impact* are in order of magnitude: natural gas, electricity consumption pre-treatment and emissions during ship transport. The differences in ecological impact are mainly due to use of natural gas in the biomass pre-treatment processes.
The most influential factors on the *economic performance* are in order of magnitude: the consumption costs during pre-treatment, the capital related cost of pre-treatment (annual depreciation and maintenance), annual depreciation of the investments at the co-firing facility and the local truck transport of woodchips.

The difference in economic performance is influenced by two factors. The difference between the chain containing pyrolysis as pre-treatment method and the other two chains is mainly affected by consumption costs of pre-treatment. The difference between the chains with pelletisation and torrefaction is the result of varying investments at the co-firing plant.

F-T diesel production

The most influential factors and factors responsible for the difference in energetic- and economic performance and ecological impact of F-T diesel production are mentioned in this section.
The most influential factors on the *energetic performance* are in order of magnitude: biomass for product, biomass for heat, total electricity consumption pre-treatment and electricity consumption during pre-treatment. The differences in energetic performance are mainly the results of differences in electricity consumption during F-T diesel production.
The most influential factors on the *ecological impact* are in order of magnitude: electricity consumption during F-T diesel production, the use of natural gas and electricity during pre-treatment. The differences in ecological impact are greatly affected by the electricity consumption during F-T diesel production.
The most influential factors on the *economic performance* are in order of magnitude: the consumption costs of pre-treatment, annual depreciation of the investments for F-T diesel production, the capital related costs of pre-treatment and the electricity consumption of F-T diesel production. The difference in economic performance is mainly the result of the consumption costs during pre-treatment. The difference in economic performance between the chains with pelletisation and torrefaction is additionally influenced by the capital related costs and electricity consumption during F-T diesel production.

Table 19 - Variables with high influence on- and which are responsible for the differences in performance between bio energy supply chains, producing electricity or F-T diesel, with different pre-treatment methods for biomass.

	Co Firing (Electricity) - 1				F-T diesel production (Automotive fuel) - 2			
Performance indicator	Variables of high influence	Pelletisation 1a	Torrefaction 1b	Pyrolysis 1b	Variables of high influence	Pelletisation 2a	Torrefaction 2b	Pyrolysis 2c
Technical performance	Biomass for product	2.3	2.5	3.1	Biomass for product	1.3	1.5	1.8
	Biomass for heat	0.7	0.4	0.6	Biomass for heat	0.4	0.3	0.3
	Electricity (pre-t)	0.2	0.1	0.2	Electricity (pre-t)	0.1	0.1	0.1
	Natural gas	-	0.1	0.2	Electricity (F-T)	0.4	0.1	0.0
Ecological impact	Natural gas	-	5.1	10	Electricity (F-T)	18	6.5	1.6
	Electricity (pre-t)	5.5	2.9	6.4	Natural gas	-	3.0	5.7
	Ship transport	2.8	1.8	2.0	Electricity (pre-t)	3.0	1.7	3.6
Economic performance	Consumption cost	15.7	15.9	21.7	Consumption costs	8.7	9.4	12
	Capital related	7.1	8.8	10.8	Annual depreciation (F-T)	5.1	5.1	5.1
	Annual depreciation (Co firing)	5.5	1.6	0.8	Capital related	3.9	5.2	6.1
	Truck transport	3.2	3.1	3.9	Electricity (F-T)	3.1	1.1	0.3

From table 19 can be concluded that the differences energetic- and economic performance and ecological impact of co-firing are mainly the result of the heat demand and technical restrictions of the pre-treatment technology as explained in §3.6. In addition applies that the economic performance is highly affected the investment costs at the co-firing facility.

For the differences in (energetic, economic and ecological) performance of F-T diesel production are mainly the result of the electricity consumption during F-T diesel production.

6.4.3 Range in variables and changes in comparative relations

The above presented results are based on the typical values of the several processes and activities. As explained in §6.3.1.4 and 6.4.1.4 each variable has a range, which affects the performance calculations. The range in the variables alters the absolute values and more important it may affect the performance order between the different supply chains. In this section is therefore an overview given of the effect of the range in variables on the comparative relations between chains with different pre-treatment methods. This is done for the variables with most influential range on the performance outcome. This is done on basis of the sensitivity analysis in §6.3.1.4, §6.4.1.4 and appendix H.

First the effect of variance in the energetic performance on the comparative relations is discussed, followed by the changes in ecological impact. Finally the results of variation in the economic performance are discussed.

Energetic performance

The variables with the most influential range on the energetic performance are: heat demand of the reactor, moisture content of wood, heat recovery (varying the efficiency of the heat exchanger) and co-firing efficiency. For the F-T diesel production process applies that grinding is very important variable.

The effect of the range in a variable on the energetic performance is shown in figure 47. On the left part of the figure the effect on the energetic performance of co-firing is shown and on the right part of the figure the effect on the energetic performance of F-T diesel production is shown. The bar of “calculated value” in the figure refers to the values used in the analysis of the study. The bars of the other variables are the resulting values of the range in variable. The dotted lines in the figure are the original value as calculated in this study.

The range in heat demand for reactor is assumed to be zero for pelletisation and this bar is therefore not present. The heat demand of the torrefaction reactor is assumed to vary between its original demand and the heat demand of pyrolysis. Taking the higher heat demand of the pyrolysis reactor into account, the energetic performance of the chain with torrefaction worsens (higher input in GJ). Doing the inverse for the chain with pyrolysis (heat demand of reaction of torrefaction reactor), the energetic performance of the chain with pyrolysis improves (lower input in GJ).

The comparative relations in case of co-firing however, do not change as result of the range in heat demand of the reactor. This can be seen because the bars stay within the dotted lines in figure 47. Both chains perform however worse than the chain with pelletisation.

In case of F-T diesel production the comparative relations change. The chain with torrefaction will reach a similar energetic performance as the chain with pyrolysis as result of a higher reactor heat demand. The chain with pyrolysis will slightly perform better as the chain with torrefaction if the pyrolysis reactor heat demand is equal to the torrefaction reactor heat demand.

A reduction in the moisture content of wood from 50-35% changes the comparative relations not much. A reduction in the moisture content lowers the heat demand of the pre-treatment process. The thermo-chemical processes require still heat for the reactor. Relatively seen, a reduction in moisture content is therefore more beneficial for the chain with pelletisation than for the chains with thermo-chemical pre-treatment methods.

In contrast with the moisture content, heat recovery is more beneficial for the chains with thermo-chemical pre-treatment methods. The heat demand of these processes is much higher and therefore more heat can be recovered in comparison with the chain with pelletisation. In figure 47 this is seen by an increase in the difference between the chain with pelletisation and torrefaction and in decrease in difference between the chains with pelletisation and pyrolysis.

The range in the co-firing efficiency changes the comparative relations between the chain with pelletisation and torrefaction. The energetic efficiency of co-firing for the chain with torrefaction becomes worse than the chain with pelletisation.

The energy required for grinding does not affect the comparative relations. Only the differences between the chains become smaller.

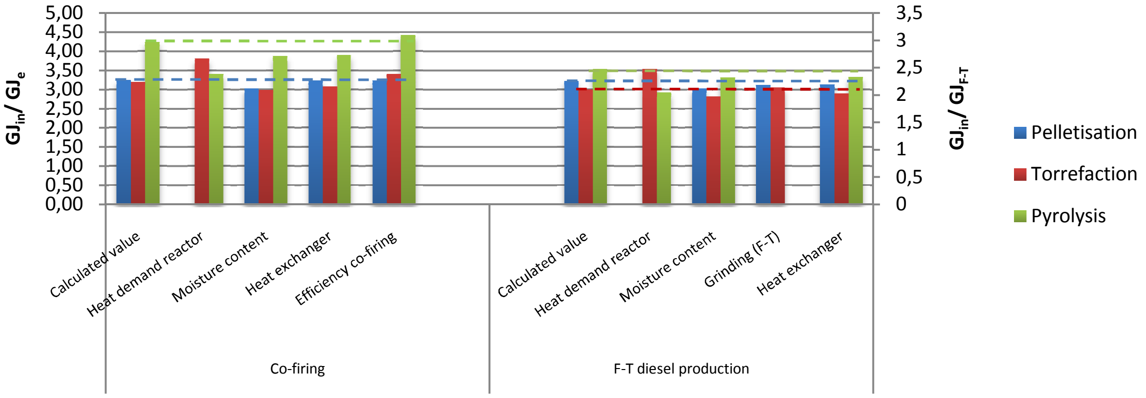


Figure 47 - The effect of the range in variables on the comparative relations in energetic performance of the bio energy supply chain with different biomass pre-treatment methods.

Ecological impact

The variables with the most influential range on the ecological impact are: heat demand of the reactor, moisture content of wood, heat recovery (varying the efficiency of the heat exchanger) and co-firing efficiency. For the F-T diesel production process applies that grinding and compression are as well important variables. The effect of the range in a variable on the ecological impact is shown in figure 48.

The heat demand for the reactor changes the comparative relations between chains. The reactor heat demand affects the demand for natural gas and thereby strongly the ecological impact. As result the energetic performance of torrefaction becomes the worst, in case its reactor heat demand is equal to the heat demand of the pyrolysis reactor. In contradiction, the chain with pyrolysis reaches the best ecological impact if its reactor heat demand is equal to the heat demand of the torrefaction reactor.

The range in moisture content changes the comparative relations as well. The effect of a lower moisture content works on a similar basis as a change in reactor heat demand. The effect is therefore more profound for the thermo-chemical pre-treatment methods. Lower moisture content reduces the heat demand and thereby as well the use of natural gas. Pelletisation doesn’t use natural gas and has therefore only a marginal reduction in ecological impact. Torrefaction has a high reduction in ecological impact because of this and becomes the chain with the lowest ecological impact. Pyrolysis remains the chains with the highest ecological impact.

For heat recovery, applies the same story as for the range in heat demand for reactor and moisture content. The effect of heat recovery on the ecological impact is however so marginal that it does not affect the comparative relations.

The range in co-firing efficiency only increases the differences in ecological impact, due to a higher co-firing efficiency for pellets and a lower co-firing efficiency for BO_2pellets™ and pyrolysis oil.

The range in electricity consumption during F-T diesel production (grinding and compression of the grinded material) affects the comparative relations also. The chain with pelletisation remains in both cases (grinding and compression) the chain with the highest ecological impact. The chain with torrefaction performs in both cases (grinding and compression) worse than the chain with pyrolysis as result of the range in these variables.

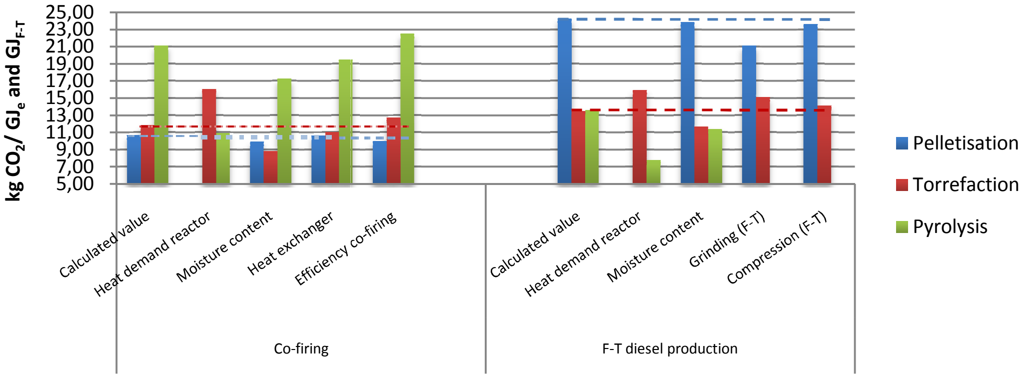


Figure 48 - The effect of the range in variables on the comparative relations in ecological impact of the bio energy supply chain with different biomass pre-treatment methods.

Economic performance

The variables with the most influential range on the economic performance are: heat demand of the reactor, moisture content of wood, the raw material price. For the F-T diesel production process applies that and operation time is as well an important variable. The effect of the range in a variable on the economic performance is shown in figure 49.

The heat demand of the reactor affects the consumption costs of the pre-treatment processes (biomass costs and utility costs). Especially the biomass costs are an important factor, as will become clear when the raw material prices are discussed. In short, the higher the heat demand for reactor the higher the consumption costs. In case the torrefaction reactor has an equal heat demand as the pyrolysis reactor, and the inverse for the pyrolysis reactor, all the chains will have a similar economic performance for co-firing.

The range in moisture content improves the economic performance, but does not affect the comparative relations. Lower moisture content reduces the heat demand and thereby the consumption costs.
In this study is assumed that wood is paid per tonne. If wood is dried, wood weighs less and the biomass costs reduce considerably.

The effect of raw material price does not affect the comparative relations. It only increased or decreases the economic performance. The effect is however more profound for the pre-treatment process which consume more biomass. The larger the cost share of biomass on the total production cost the larger the impact of a change in the raw material price.

The operation time does not affect the comparative relations. It only reduces or increases the production costs. The effect is however more profound for the capital intensive processes. The processes with a high cost share of capital are more sensitive for stand stills.

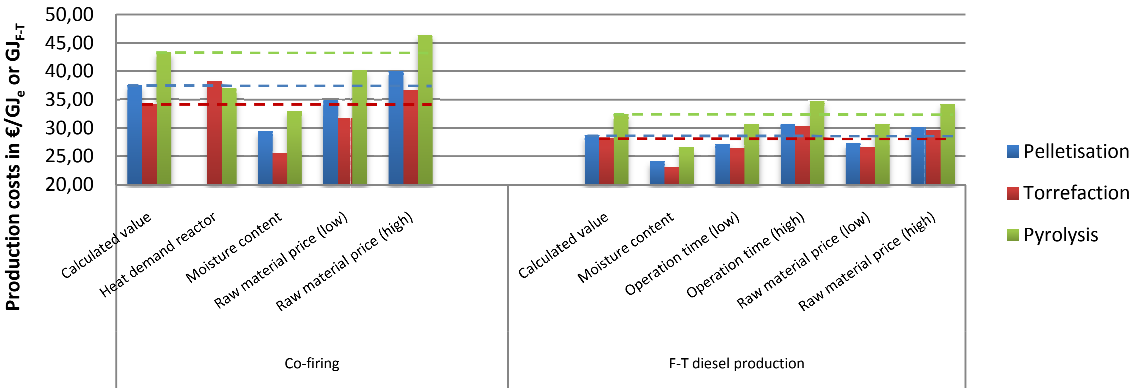


Figure 49 - The effect of the range in variables on the comparative relations in economic performance of the bio energy supply chain with different biomass pre-treatment methods.

6.5 Reflection on the case study

In this section a critical look is taken at the information gathered in this report, with respect to the calculations and outcome of this report. This is done per stage of the bio energy supply chain.

6.5.1 Biomass

The biomass type is a crucial factor in the whole supply chain. The pre-treatment methods for biomass are highly affected by the biomass composition. A reference biomass type is given in this report for wood. A wide variety of biomass types and wood exists and the outcome of the bio energy supply chain varies with the different biomass types. The created intermediate product characteristics during pre-treatment of biomass are based on similar wood types.

The biomass purchase costs are a high cost factor and varying prices over time and location are important issues. The costs price of wood mentioned in this study was the market price at that time.

Biomass is considered CO_2 neutral in this report, but this is highly disputed by many interest groups. The allocation of CO_2 emissions to biomass will affect the ecological impact substantial as a high amount of biomass is used for heat delivery. A detailed study into the biomass production systems is required to retrieve the actual CO_2 emissions of growth and harvest of biomass, but this is outside the scope of this report.

6.5.2 Pre-treatment methods for biomass

The calculations about the pre-treatment methods for biomass are based on many variables. A high variation exists in the mentioned values in the literature. Aside from the value chosen, the values are used for all three the pre-treatment methods, which result in an equal comparison. The calculations are generally on the low side to other literature references, but are in acceptable ranges and show similar patterns as in the literature.

Crucial in the calculations was the heat demand for the reactor in the thermo-chemical processes. Almost no information is available as this is reactor dependent and highly confidential. Although reliable sources are used, attention to this aspect is required.

It is not managed to retrieve the Canadian prices of natural gas and electricity. The prices of the Dutch market are used instead. This results in biased calculations. However, since the electricity price and natural gas price have a low impact on the total costs, no significant influence on the total costs is expected.

Rough indications are given about the energetic performance of pre-treatment. Viah (2000) mentions that between the 18-35% of the produced wood pellets are needed to power the pelletisation process of wood chips. Bergman (2005b and 2005c) evaluated the energetic efficiency of the torrefaction process. The mentioned range for the net efficiency was 90-96%. Solantaustra et al, (2001), Schenkeveld (2002) and CH-EU-BIO (2006) mentions a range of 40-65% for the efficiency for the pyrolysis process. The net efficiencies mentioned in this study are on the low side, which is explained by a lack of heat recovery. The estimates mentioned here do not deviate strongly from the expected range mentioned in literature, except for torrefaction. In that case however, a low heat demand for drying was assumed.

No information is available about the ecological impact of the pre-treatment processes of biomass.

The economic performance is expected to be just below the (ideal) optimal scale mentioned in literature (Mani, 2006 and Solantaustra et al., 2001). The production costs are therefore higher than in the ideal case.

6.5.3 Logistics

The energy consumption and ecological impact are largely based on Essen (2003). The energy consumption is highly affected by the load, speed and driving behaviour. A method which would take this into account would have been favourable. This is however not realistic. The ecological estimates are however confirmed by Vreuls (2006), which makes these calculations relatively robust.

The truck transport costs are based on wood chip transport. McDonald (2007) is quoted as a reliable source which takes (un)loading and transport into account. Other factors, like speed and fuel consumption, have as well influence on the transport costs and extension of the model could be desirable. The costs are however calculated for West Canada, this could result in a local bias.

The train transport estimates are solely derived from Tampenier (2006). Other reliable data sources could not be found. Pyrolysis oil is seen as a highly demanding product and is expected to be twice/ three times as expensive compared to transport of more common goods (van den Bosch, 2008). This would comply with the costs mentioned by Tampenier (2006). Uncertainty regarding the train transport costs remain therefore.

Ship transport is a highly disorderly and variable field. The costs are highly affected by the amount, time and contract. The findings for the ship transport cost are mainly derived from personal communication with Engels. It was not possible to do a detailed analysis of the harbour operations and transhipment costs as no further party was interested in sharing information. The costs estimates given by Engels are therefore not verified. Engels stated furthermore that the cost estimates are on the lower boundary, which makes the transhipment cost low and uncertain, especially for the intermediate products.

A study by EUBIONET2 (2007) concludes that pellets can be transhipped from Canada to the Netherlands for 25 US$ per tonne pellets, which is in the range of this study.

6.5.4 Energy conversion

Although data is derived from extensive research, the calculations of energy conversion are rather uncertain. The main reason for this is that the intermediate products are not yet available on large scale and many studies mention expectations of the energy conversion of the intermediate products.

For co-firing applies that the performance energy conversion of the intermediate products is derived from similar products and in this way a rough indication is obtained of the differences between the co-firing of several intermediate products. The actual values for the co-firing have to be derived by several experimental trial runs.

For Fischer-Tropsch diesel applies that this energy conversion technology is in its child shoes. Although entrained flow gasification is a well known technology for coal, less is known of the behaviour of wood gasification. The extrapolations made to the entrained flow gasification of the intermediate products are therefore uncertain. As the energy conversion has great impact has on the differences between the supply chains with different biomass pre-treatment methods, it is very important to keep this in mind. Especially the electricity consumption during F-T diesel production is important. It is stated that the process generates electricity, but this is not taken into account in this report.

This has as result that the actual energetic performance is a little bit higher for all the chains. The major result is seen in the economic performance and ecological performance. In essence it doesn't really matter if the produced electricity is used in the process or electricity generated by conventional Dutch power plant. The consumption costs and ecological impact would be lower, but on the other hand the earnings by selling and offset of fossil produced electricity would be lower.

The method applied in this process results therefore in a more negative effect for F-T diesel process with high electricity consumption. The economic assumptions are based on the Dutch standards and this can vary with other countries.

6.5.5 Addition to literature

In this report is tried to gain more insight in the differences between chains with different pre-treatment methods by a relatively detailed examination of the different stages in the supply chain. This is partially succeeded. An indication is obtained of which pre-treatment method for biomass leads to the chain with the highest technological- and economic performance and ecological impact. Furthermore the differentiating factors between the chains with different pre-treatment methods for biomass are identified.

The problem is that the actual outcome of the comparison is not very robust. This has two reasons. Firstly, a lot of unknown (not yet) and secondly, (especially) classified information is required to set up an unbiased measurement. To derive the correct conditions is a very time consuming activity and is not possible without willing contacts.

In addition to this are fluctuations over time also an important factor. The finding of this report may not apply for the next year, because of changes at different stages in the supply chain. This last aspect applies more to the economic performance as to the energetic performance and ecological impact.

These issues related to unknown-, classified information and fluctuations over time ask for caution when to generalise the findings of this study.

Many technical developments are ongoing. These developments are mainly related to the energy conversion technologies. These technical developments may alter the chain activities and the performance outcome.

The findings of this study apply to a specific aspect of bio energy , i.e. the capitalisation on the existing fossil fuel based energy conversion technologies. The technologies described in this report are seen as state of the art. The main issue in the development of biomass dedicated technologies is how to deal with the biomass nature. Dependent on the development of these other (more biomass dedicated) technologies, the activities in the chain may change.

In this case, biomass has still to be transported from Canada to generate electricity in the Netherlands. As it is not desired to transport raw biomass, pre-treatment of biomass is still required. However which biomass pre-treatment method will lead to the chain with the best technological- and economic performance and ecological impact may change.

In the case of F-T diesel production, the actual F-T diesel production could also take place in the country of origin. The produced F-T diesel subsequently would be transported. If it is still beneficial to pre-treat biomass before F-T diesel production is dependent on the amount of biomass locally available (as F-T diesel production operates at large scale) and the local technological, economic and ecological conditions. This question is influenced by many factors and a reliable answer can only be given by detailed information.

7 Conclusion and recommendations

Conclusion and Recommenadations

1. The problem: The supply chain
2. Results: Chain performance
3. Contribution to existing literature
4. Recommendations
   4.1 Methodological recommendation
   4.2 Practical recommendations

7.1 The problem: *the supply chain*

There is a growing demand for renewable energy sources in society. Within this field bio energy is a promising energy source. However, the local biomass supply cannot meet the increasing biomass demand in Western Europe (§1.2). On the short term this results in biomass import (because of prices and quality) and it is expected that this is not a temporary phenomena (production capacity). The resulting bio energy supply chain exists out of the conversion of raw biomass (e.g. woodchips) via pre-treatment processes of biomass, followed by transport (logistics) and energy conversion. See also figure 50.

Within the energy supply chain, pre-treatment of biomass has been identified as a crucial element to improve the energetic efficiency, production costs and ecological impact of the supply chain. Biomass pre-treatment is the conversion of biomass into an intermediate product, which has advantages for transport and energy conversion. Each biomass pre-treatment method creates different intermediate products which result in different performances for the chain elements. The research question of this report is therefore: ***Which biomass pre-treatment method results in the best energetic- and economic performance and ecological impact for the overall bio energy supply chain?***

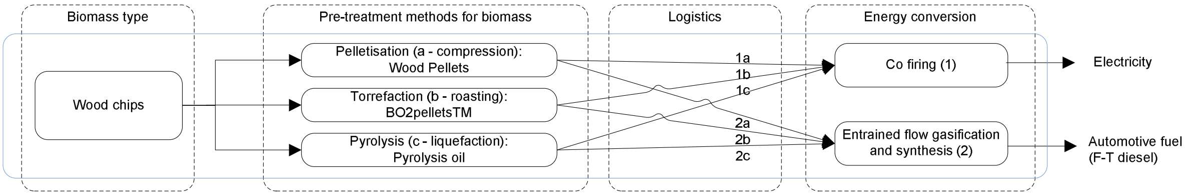


Figure 50 - Conceptual model of bio energy supply chains producing electricity or an automotive fuel by different biomass pre-treatment methods.

The methodology used to analyse this problem consists out of a literature study and the modulation of reference supply chains in a spreadsheet for calculations. The boundaries of the bio energy supply chain are set by the BO_2GO project. In this case wood chips are imported from Canada to produce electricity or an automotive fuel in the Netherlands. By comparing the chains on three performance indicators (energetic- and economic performance and ecological impact), the best pre-treatment method for biomass is identified. In this way it is possible to identify differences and their reasons, between the chains with three different biomass pre-treatment methods.

7.2 Results: chain performance

Based on the spreadsheet the energetic- and economic performance and ecological impact of bio energy supply chains are calculated, for different biomass pre-treatment methods. Table 20 summaries the energetic- and economic performance and ecological impact of the bio energy supply chains producing electricity or F-T diesel with different biomass pre-treatment methods. First the performances of the entire chain are discussed, followed by the performance outline over the chain.

Table 20 - The energetic- and economic performance and ecological impact of bio energy supply chains, producing electricity or F-T diesel, with different biomass pre-treatment methods.

		Co-firing (Electricity) – 1			F-T diesel production (Automotive fuel) - 2		
Performance indicator		Pelletisation - 1a	Torrefaction - 1b	Pyrolysis - 1c	Pelletisation -2a	Torrefaction - 2b	Pyrolysis - 2c
Energetic performance	GJ_{in}/Gj_{out}	3.3	3.2	4.1	2.2	2.0	2.4
Ecological impact	kg CO_2/GJ_{out}	10.7	11.9	21.1	24.3	13.5	13.6
Economic performance	$€/GJ_{out}$	37.5	34.2	43.3	28.7	28.1	32.5

For chains which produce electricity, pelletisation and torrefaction are the most suited options as biomass pre-treatment method based upon the performance indicators (§6.2). Both methods results in chains with a similar energetic performance, but pelletisation has lower ecological impact at higher costs in comparison with torrefaction. In other words, the chain with pelletisation produces less CO_2 per GJ_e, but at higher costs. The difference in ecological impact can be expressed in the following economic cost; 2.75 €/kg CO_2, for the chain with pelletisation. Pyrolysis is less suited as pre-treatment method for co-firing (under the conditions of this study) as it has the worst chain performance *on all three indicators*, in comparison with the chains with pelletisation or torrefaction as pre-treatment method.

For the chains that produce F-T diesel, torrefaction is the most suited biomass pre-treatment method as it scores best on all three performance indicators (§6.3). The chain with pelletisation has a high ecological impact, which makes it less suited as biomass pre-treatment method for F-T diesel production. For pyrolysis applies that the energy input and CO_2 emission are too high compared to the other chains, to be an option.

The biomass pre-treatment methods are under development and uncertainties exist about the overall- and chain element performance. Technology promoters are eager to stress the benefits of their technology, throughout the chain. Therefore it is important to know what creates the differences in performance between the chains with different biomass pre-treatment methods. In table 21, the performance structures for chains with different pre-treatment methods are presented. The absolute influence on- and belonging percentages of the total chain performance are given per chain element.

Table 21 - Performance outline over the bio energy supply chain, for different biomass pre-treatment methods (in absolute and percentages of the annual values).

Performance (Absolute)	Chain element	Co-firing						F-T diesel production					
		Pelletisation		Torrefaction		Pyrolysis		Pelletisation		Torrefaction		Pyrolysis	
		%	(absolute)	%	(absolute)	%	(absolute)	%	(absolute)	%	(absolute)	%	(absolute)
Energetic performance (Annual energy input GJ^6)	Biomass pre-treatment	98%	(1.20)	98%	(1.27)	98%	(1.64)	81%	(1.20)	92%	(1.27)	97%	(1.64)
	Logistics	2%	(0.03)	2%	(0.02)	2%	(0.03)	2%	(0.03)	2%	(0.02)	2%	(0.03)
	Energy conversion	-	-	-	-	-	-	17%	(0.25)	6%	(0.09)	1%	(0.02)
Energy produced (Annual energy output GJ^6)			*(0.38)*		*(0.40)*		*(0.40)*		*(0.68)*		*(0.68)*		*(0.71)*
Ecological impact (|Annual emissions kg CO_2^6)	Biomass pre-treatment	51%	(2.1)	66%	(3.2)	77%	(6.6)	12%	(2.1)	35%	(3.2)	68%	(6.6)
	Logistics	49%	(2.0)	34%	(1.6)	23%	(1.9)	12%	(2.0)	17%	(1.6)	20%	(1.9)
	Energy conversion	-	-	-	-	-	-	76%	(12.5)	48%	(4.4)	12%	(1.1)
Economic performance (Annual production costs €^6)	Biomass pre-treatment	66%	(9.4)	78%	(10.7)	79%	(13.9)	48%	(9.4)	56%	(10.7)	60%	(13.9)
	Logistics	19%	(2.7)	18%	(2.4)	19%	(3.3)	14%	(2.7)	13%	(2.4)	14%	(3.3)
	Energy conversion	15%	(2.1)	5%	(0.6)	2%	(0.3)	38%	(7.5)	31%	(6.0)	25%	(5.9)

The chains with pelletisation set the benchmark in energetic- and economic performance and ecological impact during biomass pre-treatment (§3.6). However pellets have a worse performance during logistics (§4.5) and energy conversion (§5.2 and 5.3) compared to the other intermediate products.

The chains with torrefaction are able to catch up with the benchmark because of two reasons. The differences in performance during biomass pre-treatment remain limited and the improved characteristics of BO2pellet™ result in better performance during logistics and energy conversion. This results in the best chain performance.

The chains with pyrolysis as biomass pre-treatment method are not able to compensate the high expenses in energetic- and economic performance and ecological impact through advantages in transport and energy conversion. Chains with pyrolysis result therefore in the lowest performance.

In general (table 21) this study demonstrates that the logistics play a marginal role in the differences between chains (§6.4). The differences in performance result mainly from factors in biomass pre-treatment and energy conversion of the intermediate products (§6.4). The most important factors which explain the differences between the chains during pre-treatment are the heat demand and use of natural gas. During energy conversion, the investment costs for co-firing and the electricity use during F-T diesel production are decisive for the differences between chains.

7.3 Contribution to existing literature

Within the field of bio energy substantial research on the supply chain is conducted; biomass resources, supply systems (harvesting and collection), conversion and end products. In this report a more comprehensive approach is followed; an energy supply- and system analysis is performed. This report builds on the existing

knowledge in this field. This study especially contributes to the possibility to capitalise on the on the existing (fossil) energy conversion facilities by the use of biomass pre-treatment methods.
A new geographical area is explored for comparing chains with different pre-treatment methods for biomass. Canada (North America) is examined in this report. Although the local conditions are different, the findings of this report are to a great extend in line with other studies. This may indicate that local conditions (truck transport and pre-treatment) do not affect which pre-treatment method results in the best performing chain.
In contrast to other studies, the entire chain is examined in more detail. This results in an indication of the crucial factors that determine the difference in energetic- and economic performance and ecological impact between chains with different pre-treatment methods for biomass.
The analysis of chains producing F-T diesel gives more insight in the CO_2 emissions caused by the activities in the chain. Especially the difference in emissions between the chains producing F-T diesel are stressed.
Studying the supply chain gave a good insight in of the most important variables of the chains including thermo-chemical biomass pre-treatment methods. This allows going beyond the notable factors per chain element and focusing on the most influential factors for the entire chain (CH 6.4.2).

The methodology which is used in this study has however also limitations. These limitations restrict the generalisations of the findings of this study. The first restrictions come from the comparative character of this study. The comparative conditions may not result in the best outcome for each of the pre-treatment methods and thereby the whole chain result. This explains the differences with other studies, which have used optimal conditions for the method of interest.
The primary comparative condition was a constant biomass type. Based on the chemical composition of the biomass type, a biomass pre-treatment method is more suited for the biomass type. The findings of this report can therefore only be generalised for wood as defined in this report.
The second pre-set value was a fixed energy output of 40 MW for the biomass pre-treatment methods. This choice affects the scale and outcome of the comparison. The chosen scale is approximately in line with the optimal process sizes for the pre-treatment methods. The findings of this study apply therefore only to supply chains with similar scale biomass pre-treatment processes.
Furthermore, restrictions arise from the fact that the biomass pre-treatment methods are new promising technologies under development. Because of this, factors as uncertainty, confidentiality and fast technology development result in values, that need to be interpret rather as indicators than absolute values. By a thorough literature research and examinations with experts in the field, it is tried to reduce the uncertainty and obtain solid reference values. There exists however ambiguity in the outcome. The uncertainty is the largest for the economic chain performance. The values in this report are therefore not precise and the comparative relations have to be interpreted with caution.
Apart from uncertainty, variables also work within ranges. The ranges are not uncertainty, but can be chosen to a certain extend. These assumptions (e.g. moisture content, product yield and heat recovery) affect the absolute value and may affect the comparative relations. This limits the findings to the conditions chosen in this report.
The final restrictions are due to the case study chosen. As biomass pre-treatment takes place in Canada, the economical performance and ecological impact are restricted to this area. The same applies for the energy conversions, which takes place in the Netherlands.

7.4 Recommendations

From this study two types of recommendations can be distracted. First a suggestion is made to improve the applied methodology. Secondly, a more practical suggestion is based upon the finding of this study, followed by several suggestions to improve the performance of the supply chain.

7.4.1 Methodological recommendation

A comparison between bio energy supply chains is used to identify the best suited pre-treatment method for biomass. As mentioned before, a key element of this comparison is a (pre determined) fixed energy output at the pre-treatment stage of 40 MW. Two other logical places to equate the chains with each other and to compare the chains which each other would be on the supply side (amount of biomass available) or on the demand side (required amount of energy output). As a fixed biomass input or energy output affect the chain size and conditions, a comparison under these conditions could lead to other findings.
Adjustment of the spreadsheet model of the supply chain, which allow limitations in the production capacity of an area or at the energy demand site, make it possible to calculate the most optimal chain under these

restrictions. The outcome of these calculations can make the findings more robust or provide for nuance in the findings for the case of import of wood chips from Canada to the Netherlands.

7.4.2 Practical recommendations

This study illustrated that the biomass characteristics are an important factor for the chain performance. Its chemical composition determines to a great extend the outcome of pre-treatment of biomass and subsequently the overall chain performance, due to the altered characteristics of the intermediate products. The biomass type especially influences the outcome of the thermo-chemical pre-treatment methods for biomass. The suitability of a biomass pre-treatment method for the supply chain may vary with the biomass type. It is therefore recommended to use pelletisation or torrefaction in chains for electricity production in the Netherlands, which are based on wood as feedstock. In chains producing F-T diesel (in the Netherlands) from wood, torrefaction is recommended as pre-treatment method for biomass. If another feedstock is available, recalculation is needed to identify the most suitable pre-treatment method.

Given this basic condition, some other (more) general suggestions to improve the performance of the supply chain can be derived. These suggestion are based on 1) the influence of a factor on the performance and 2) the range in a variable (§6.4).

Supply chain improvements by reducing the negative impact of factors

The performance of the supply chain can be improved by focussing on highly influential factors and finding ways to influence these factors (§6.4.2).

The ecological impact can be improved by reducing the amount of fossil fuels used. A simple solution is replacing natural gas with bio gas in the case of the thermo-chemical processes. Or using combined heat power systems in all three the pre-treatment process to generate ‘green’ electricity which can be used in the process. This can reduce the ecological impact with 30-60%.

The economic performance can be improved by reducing the costs of raw biomass. The most straightforward method is to use cheaper biomass resources for heat generation. The actual biomass for product can be substituted as well, but the process performances change as well as explained above.

The energetic performance can be improved by adjusting the processes or changing the technology and not simply by replacing high impact factors. Therefore no suggestion can be made for improving the energetic performance by reducing the impact of factors.

Supply chain improvements by optimising the process conditions

The second option is to improve the chain performance by investment to improve sub-processes of the chain. That is to say, for the calculations within this study typical (fixed) values are used for the different variables within the chain. These values might be improved to obtain better results. For example within the research, calculations are based upon a moisture content of 50% while the (theoretical) value fluctuates between 50-35%. These fluctuations leave room for process optimisation. Additional investments can therefore lead to improved sub-processes and -products hence increasing the eventual performance of the chain (§6.4.3).

The advice is to focus upon the following three suggestion to improve the chain performance. These suggestions are however not ready to be applied yet. Rather they need further cost benefit analyses to determine the actual feasibility, which is context specific.

A reduction in the moisture content is beneficial for all three the performance indicators and is relatively easy to obtain. Biomass can be dried by leaving it in the field for a certain time or a forced drying process at the production location can be applied. The gains and expenses vary with the chosen method of drying.

Heat recovery is another variable which improves all three the performance indicators. It saves on biomass for heat generation and natural gas. A heat recovery system complicates the process substantial and requires higher investment costs. Dependent on the system chosen and the corresponding savings, it will or will not outweigh the investments.

The production processes which are capital intensive are vulnerable for higher production costs due to stand stills of equipment (lower operation times). A possible solution would be and additional production line to cover for repairs and mall functions. This requires additional investment costs, but reduces the risks on production losses.

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9 Appendices

9.1 Appendix A: *relation torrefaction and coal*

The devolatised compounds consist mainly out of CO_2, CO and H_2O (Bridgeman et al., 2008). The remaining solid has because of this lower concentrations of oxygen and hydrogen and thereby higher concentrations of carbon. Due to these decreasing ratios approaches torrefied biomass the structure of coal (brittle structure and higher energy density). This process is represented in the Van Krevelen diagram.

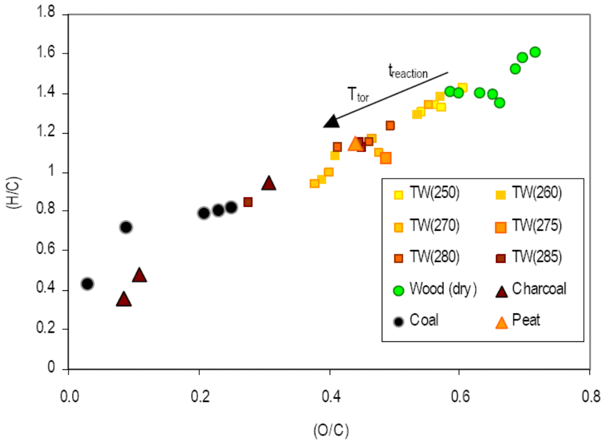

Figure 51 - Van Krevelen diagram for different biomass types at different torrefaction conditions (Bergman, 2005b and Prins, 2006).

9.2 Appendix B: r*eactor types*

9.2.1 Torrefaction reactor types

Bergman (2005b) distinguishes two kinds of torrefaction reactors in general; directly (rotating drum and moving bed) and indirectly heated reactors (screw reactor). The directly heated reactor uses a carrier gas to heat the biomass. In an indirectly heated reactor is the biomass heated by the wall, which is heated by a heat carrier. The main differences between the processes are: 1) the directly heated reactor requires a re-pressuring action to recycle the gas and 2) the heat exchange is between two gasses instead of between a gas and liquid. Disadvantages of the directly heated reactor are related to the use of the torrefaction gas. Torrefaction gas can contain dust and heavy volatile components, which can cause fouling of the equipment when they condensate. Moreover is the heat exchange between two gasses is less effective, than the heat exchange between gas and oil. The advantages of directly heated reactor outweigh however, the disadvantages. The heat exchange between a gas and a solid is much faster like the heat exchange between a solid and a solid. As result, the volume and complexity are much lower which reduce the costs of the reactor. The most is expected from a directly heated reactor. In both processes can the process heat be delivered by the combustion of the torrefaction gas and if necessary with a utility fuel. A torrefaction reactor works according to similar principles as a pyrolysis reactor. Pyrolysis reactors are longer under development and a more elaborated overview of the several reactors is given in the section of fast pyrolysis.

9.2.2 Pyrolysis reactor types

A summary is given in table 22 (Mohan et al., 2006). In fluidized bed pyrolysis, hot air flows with high speed through a bed whit sand particles. The bed behaves because of this like boiling fluid. An intensive heat exchange exists within the bed, air and biomass particles, which cause the biomass particle to degrade rapidly. This results in high mass exchanges. This process is called a bubbling fluidized bed. Through high air speeds, sand and biomass particles can be blown out of the reactor. If these particles are recovered and led back to the reactor one speaks of a circulating fluidized bed. The rotating cone process has big similarities with the fluidized bed pyrolysis, but the biomass and sand transport is carried out by centrifugal forces in the rotating cone process. Vacuum Pyrolysis is applied because it minimizes the change on secondary reactions. The process takes place under reduced pressure and therefore it requires large scale equipment and the heat and mass rates are low. Ablative Pyrolysis is fundamentally different from the other processes. It is based on the melting of biomass on a hot reactor surface and is similar to the process of melting butter in frying pan. As result the particles can be longer and is a fluidising gas not necessary. The auger reactor is a very compact reactor and therefore it does not require a carrier gas to deliver heat. It operates at lower temperatures (400ºC) and operates as a continuous process. It is designed to reduce the energy costs, but up scaling could be a problem. Until now only a few producers are able to scale up the reactor from laboratory to industrial scale. The limiting factors can be directed back to cost of scaling up and the ability to deliver a uniform high heat flux. From the table comes forward that the fluidized bed and rotating cone pyrolysis are most promising type of reactor on these factors.

Table 22 - Reactor types (Mohan et al., 2006).

Yield (%)	Method of heating	Mode of transfer	Operational unit	Strengths/advantages	Disadvantages/challenges
				Fluidized Bed reactor	
75	Heated recycle gas/hot inert gas	95% Conduction 4% Convection 1% Radiation	400kg/h at Dynamotive, 250 kg/h at Welman (U.K.), 20 kg/h at RTI	Good temperature control Easy scalability Well-understood technology	Small particle sized are needed Heat transfer to bed has yet to be proven
				Circulating Fluidized Bed Reactor	
75	Particle gasification/fire tubes	80% Conduction 19% Convection 1% Radiation	1000 kg/h at Red Arrow (Ensyn), 20 kg/h at VTT (Ensyn)	Good temperature control Large particle sizes may possibly used Suitable for large throughputs Well-understood technology	Hydrodynamics more complex than others Char is finer due to more attrition at higher velocities requires attention Heat transfer to bed has yet to be proven at large scale
				Rotating Cone Reactor	
65	Gasification of char to heat sand	90% Conduction 9% Convection 1% Radiation	120 kg/h at BTG (Netherlands)	Centrifugal force moves heated sand and biomass	Small particle sized are needed Heat transfer to bed has yet to be proven at large scale
				Vacuum Reactor	
35-50	Wall and sand heating	4% Conduction 95% Convection 1% Radiation	3500 kg/h at Pyrovac	Lower temperature required Can process larger particles than others No carrier gas is required	Not a true fast pyrolysis as solids residence time is very high Liquid yields of 35-50% on dry feed basis
				Ablative Reactor	
75	Direct contact with hot surface	n.a.v.	350 kg/h at Fortum, Finland	Large particle sizes may possibly used Inert gas is not required System is more intensive Lower process temperature (<600oC)	Reaction rates limited by heat transfer to the reactor, not to the biomass Process surface area controlled so scaling is costly Reactor is costly
				Auger Reactor	
30-50		n.a.v.	200 kg/h at Fortum, Finland	Compact, does not require carrier gas Lower process temperature (400oC)	Moving parts in the hot zone Heat transfer at large scale may be a problem

9.3 Appendix C: *Solutions to aging*

There are three methods to slow the aging in bio-oils on a chemical bases (Diebold, 1999).

The first one is by adding a solvent, which weakens the formation of polymers, and reduces thereby the viscosity and aging rate. The addition of a polar solvent like methanol, 10-20 wt%, is recommended by Diebold (1999). Dynamotive mentions an addition of 5% methanol, which is on the low side, but reduces the costs.

Another method would be mild hydration to saturate the reactive compounds. This however, increases the viscosity, which is undesired.

The third method is limiting access to air and antioxidants. The oxygen in air causes polymerization and an increase in viscosity.

The physical solution for aging is traced back to the co-solvency of bio-oil components. The co-solvency of the several compounds depends on the chemical structure, weights and relative amounts. In general are compounds with similar polarities, similar molecule structures and lower molecular weights better soluble. Aging reactions change the polarity of the several compounds and forms longer molecules during aging. This change polarity and molecular weights causes phase separations. Bio-oil shifts into a light, highly polar aqueous phase and a less polar heavier organic phase. The organic phase shifts also into lighter and heavier phases over time. The bio-oil can be seen as a liquid of as micelles, suspensions and emulsions. The solution lies in multi-polar molecules (emulsifiers), which can stabilize the emulsion.

9.4 Appendix D: *ecological impact calculations*

The ecological impact values are taken from Vreuls (2006). The ecological impact of electricity consumption is calculated by the electric mix of the country (table 23) and the conversion efficiency (table 24). The resulting CO_2 emission factors are given in table 25.

Table 23 - Electricity generation by fuel (IEA, 2008).

GW/h	Netherlands	Canada
Coal	26,926	106,188
Oil	2,262	19,442
Gas	57,856	36,324
Biomass	3,989	9,036
Waste	2,738	19
Nuclear	3,997	92,040
Hydro	88	363,626
Geothermal	-	-
Solar pv	34	17
Solar thermal	-	-
Wind	2,067	1,471
Tide	-	31
Other	262	-
Import	23,691	19,677
Export	5,398	43,528
Nett import	18,293	-
Total	118,512	628,194

Table 24 - Conversion efficiency per fuel type (IEA, 2008).

Fuel	Netherlands	Canada
Coal	40%	40%
Oil	40%	40%
Gas	55%	55%
Nuclear	33%	33%
Biomass and waste	50%	50%
Other sustainable	100%	100%

Table 25 - CO_2 emissions per fuel.

		Netherlands	Canada
Coal	CO_2 (tonne/GJ_{coal})	0.094	0.094
Oil	CO_2 (tonne/GJ_{oil})	0.073	0.073
Gas	CO_2 (tonne/GJ_{gas})	0.056	0.056
Electricity	CO_2 (tonne/GJ_e)	0.107	0.051

9.5 Appendix E: production costs

9.5.1 Investment costs

The investment costs are calculated as following: First the reference plant is taken as starting point and secondly the additional investment costs are determined (table 26). Secondly the processes are scaled up to the appropriate size and power needs according to the mass balances and assumptions. The scale and power factors are given in

table 27. The resulting investment costs for the different pre-treatment plants are given in table 28.

Table 26 - Investment costs pellet plant and additional investment costs other pre-treatment plants.

Investment costs		Additional investment costs			
Costs in (€$_{2008}$)	Pelletisation		Pelletisation	Torrefaction	Pyrolysis
Dryer					
Minimiser					
Combustion system gas/ char		k€/kW	100	100	100
Pelletiser(s) - 3					
Cooler		€			-1.000.000
Reactor		€		3,000,000	3,500,000
Land production					
Building production					
Other production investment					
Prime movers (shovel)					
Building storage (input)					
Building storage (output)					
Estimated total costs	14.9 m€				

Table 27 - Scale and power factors.

Equipment	Scale factor	Power factor
Dryer	65%	-
Minimiser	60%	60%
Combustion system	-	-
Pelletiser	65%	60%
Cooler	-	-
Reactor	-	-
Prime mover	70%	-
Building storage input	65%	-
Building storage output	65%	-

Table 28 - Calculated investment costs for the several pre-treatment plants.

k1000€$_{2008}$	Pelletisation	Torrefaction	Pyrolysis
Dryer			
Minimiser			
Combustion system gas/ char			
Pelletiser(s) – 3			
Cooler			
Reactor			
Land production			
Building production			
Other production investment			
Prime movers (shovel)			
Building storage (input)			
Building storage (output)			
Total	***14.9***	***19***	***22.6***

9.5.2 *Labour costs*

The labour costs are estimated according a study by NREL (2006). From this study the type of employee, salaries and basic shift composition are taken. The factory operates on an 8 hours shift base, i.e. 3 shifts a day are required. First the number of employees per shift is determined. To operate the plant is assumed that one supervisor, one maintenance technician and four operators are required per shift. Secondly, is estimated that one additional shift is required for continuous operation and sick leave. The resulting labour costs are given in table 28.

Table 29 - Calculated labour costs.

Employee	Amount	Salary (US$$_{2006}$)	Salary (€$_{2008}$)	Total	Per shift	
Plant/ general Manager	1	121,600	86,771	86,771	shifts a day	3
Plant Engineer	1	79,000	56,373	56,373	Supervisor	1
Lab Manager/ Chemist	1	60,780	43,371	43,371	Maintenance tech	1
Shift supervisor	4	45,000	32,111	128,444	Operators per shift	4
Maintenance Tech	4	34,000	24,261	97,047		
Shift operators	15	30,400	21,692	325,393	7 day work-week (continuous process)	
Prime mover (shift operator)	1	30,400	21,692	21,692	Additional supervisor:	1
Administrative Assistant	1	24,300	17,340	17,340	Additional maintenance tech:	1
					Additional operators:	4
Average				27,729		
Total	28			776,435		

9.6 Appendix F: *Correction factors*

Several correction factors are used and given in tables 29-31.

Table 30 - Chemical Plant Index (GE, 2008).

CPI	Year								
	2000	2001	2002	2003	2004	2005	2006	2007	2008
CE INDEX	394.1	394.3	395.6	402	444.237	468.2	499.6	525.4	552.9
Equipment	438	437.3	437.5	445.1	508.111	543.7	588	624.4	665.0
Heat Exchanges and Tanks	370.6	363.9	356.9	363.6	464.826	513.9	548	592.1	644.9
Process Machinery	439.4	439.5	444.2	450.3	490.979	519.7	549.7	598.3	621.7
Pipe, valves and fittings	545.9	548.1	555.8	570.7	600.618	623.7	708	733.6	789.6
Process Instruments	368.5	362.9	363.5	363.4	374.326	381.8	420.1	425.2	429.6
Pumps and Compressions	665.3	683.2	699.2	705.4	719.427	752.5	785.7	831.2	856.9
Electrical equipment	339.4	341.2	341.4	341.6	351.007	372.1	403.1	430.5	449.0
Structural supports	408.7	413.9	415.4	428.6	537.493	584.8	625.3	662.6	707.9
Construction Labour	299.2	302.3	305.8	309.3	307.756	305.6	309.3	315.1	317.0
Buildings	385.6	385.6	390.4	400.6	428.567	445.1	468.6	476.8	489.2
Engineering Supervision	340.6	341.5	345.3	347.3	345.185	346.8	350.9	357	354.5

Table 31 - Exchange rates (Bank of Canada, 2008).

Country	Unit	Yearly average								
		2000	2001	2002	2003	2004	2005	2006	2007	2008
Europe	€	1	1	1	1	1	1	1	1	1
Canada	$	0.73	0.72	0.67	0.63	0.62	0.66	0.7	0.68	0.65
US	$	1.08	1.12	1.06	0.89	0.8	0.8	0.8	0.73	0.67

Table 32 - Inflation.

Country	Year									
		2000	2001	2002	2003	2004	2005	2006	2007	2008
Canada[17]	€	95.38	97.78	99.99	102.75	104.66	106.98	109.12	111.45	113.94
Europe[18]	$	87.41	91.05	94.04	96.03	97.22	98.85	100.00	101.61	104.38
US[19]	$	172.20	177.10	179.90	184.00	188.90	195.30	201.60	207.34	216.04

9.7 Appendix G: *Ship charter costs*

The shipping costs are highly affected by the rental price. Over the past years the prices rise tremendously. In addition, the prices are highly affected by the changing demand. Figure 52 shows the uncertainty in price expectations.

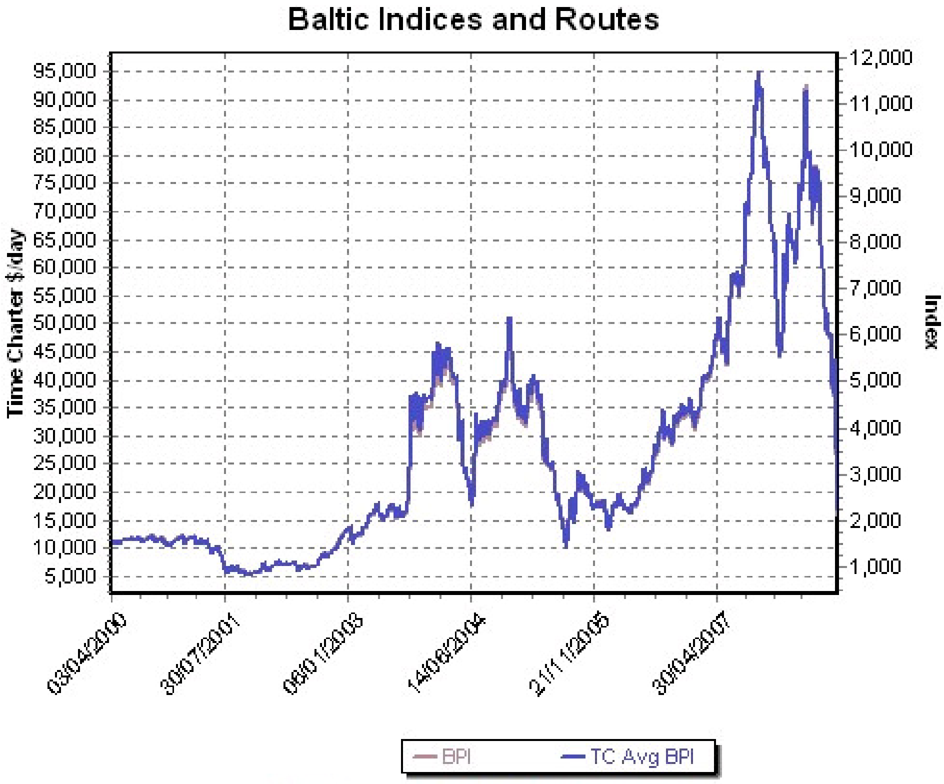

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Figure 52 - Baltic Dry Index for panama size vessels.

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[17] Bank of Canada (2008).

[18] CBS (2008).

[19] BLS (2008).

9.8 Appendix H: *Sensitivity analysis*

9.8.1 Co-firing

9.8.1.1 Chain with pelletisation

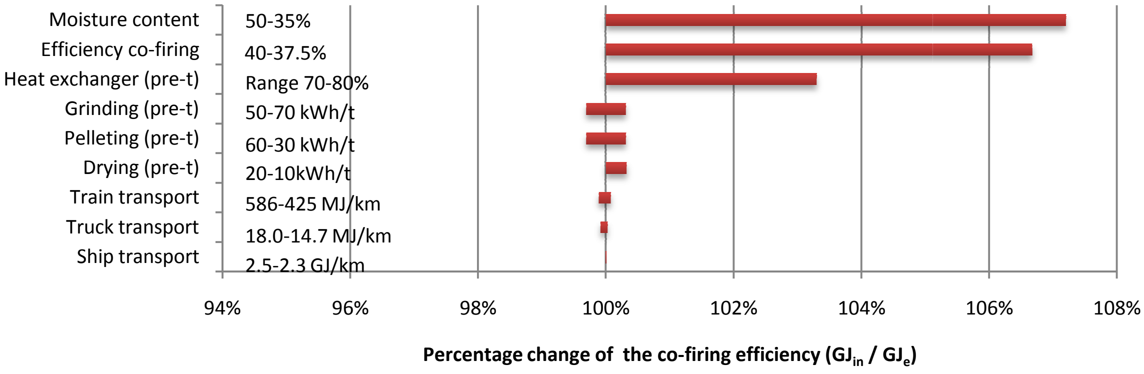


Figure 53 - Expected change in the energetic performance of the chain producing electricity with pelletisation as pre-treatment method for biomass.

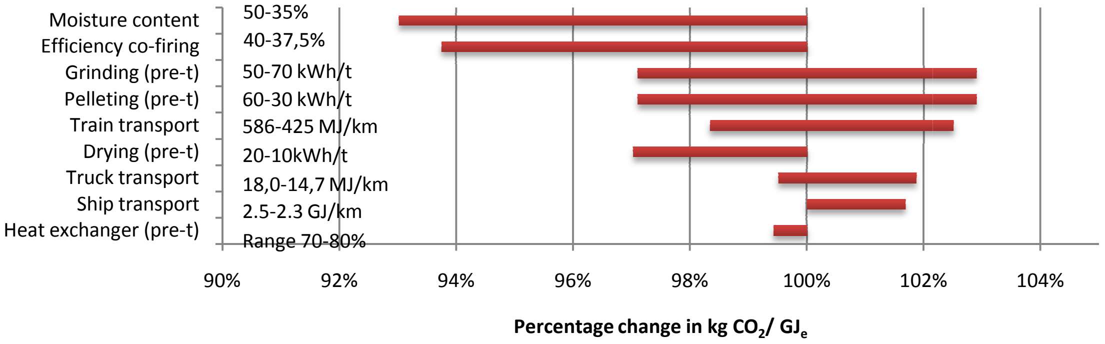


Figure 54 - Expected change in the ecological impact of the chain producing electricity with pelletisation as pre-treatment method for biomass.

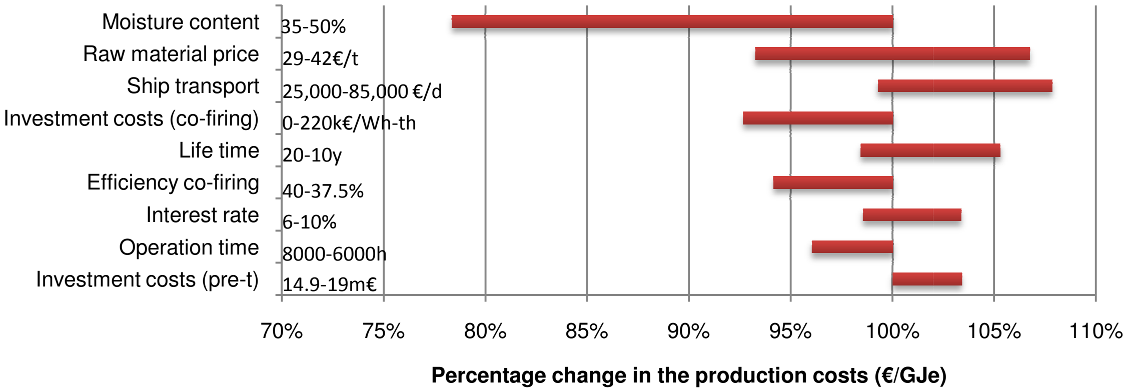


Figure 55 - Expected change in the economic performance of the chain producing electricity with pelletisation as pre-treatment method for biomass.

9.8.1.2 Chain with pyrolysis

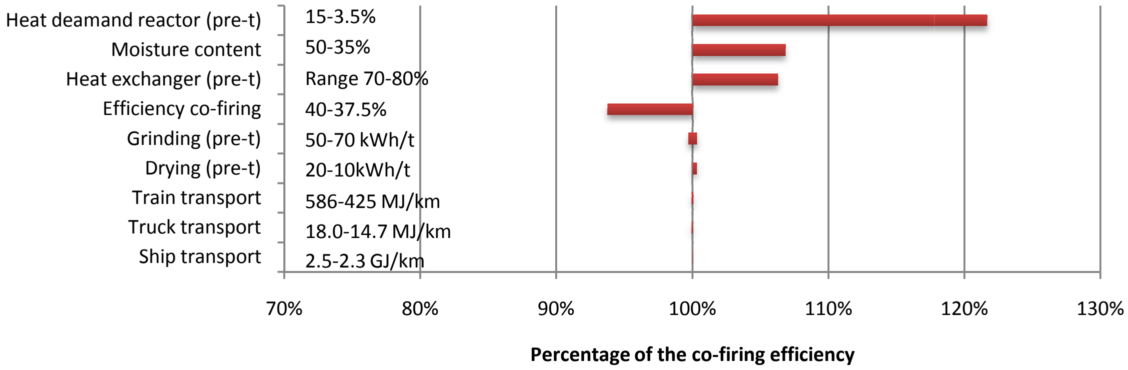


Figure 56 - Expected change in the energetic performance of the chain producing electricity with pyrolysis as pre-treatment method for biomass.

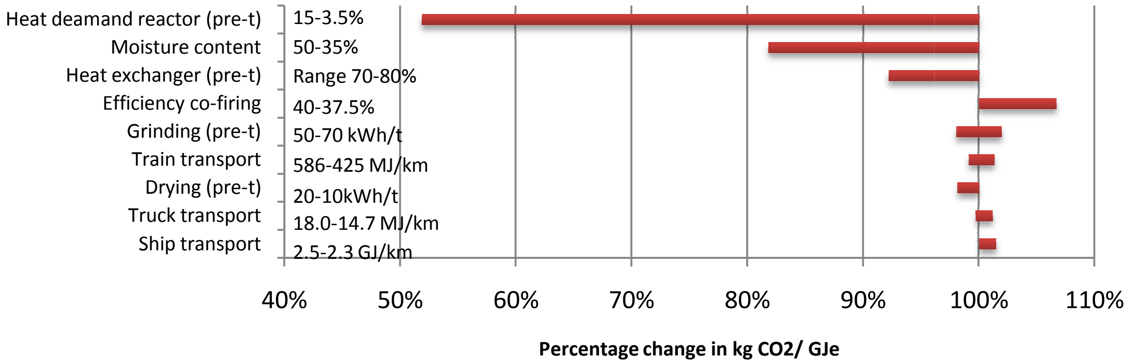


Figure 57 - Expected change in the ecological impact of the chain producing electricity with pyrolysis as pre-treatment method for biomass.

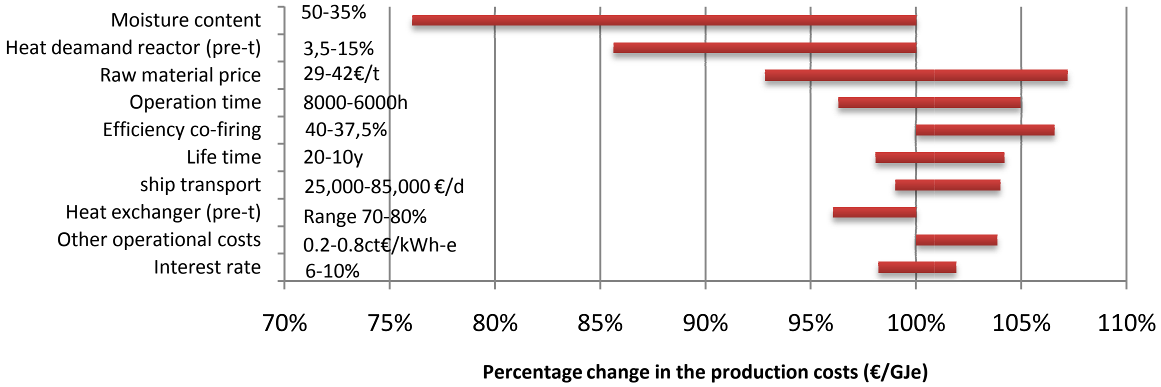


Figure 58 - Expected change in the economic performance of the chain producing electricity with pyrolysis as pre-treatment method for biomass.

9.8.2 F-T diesel production

9.8.2.1 Chain with pelletisation

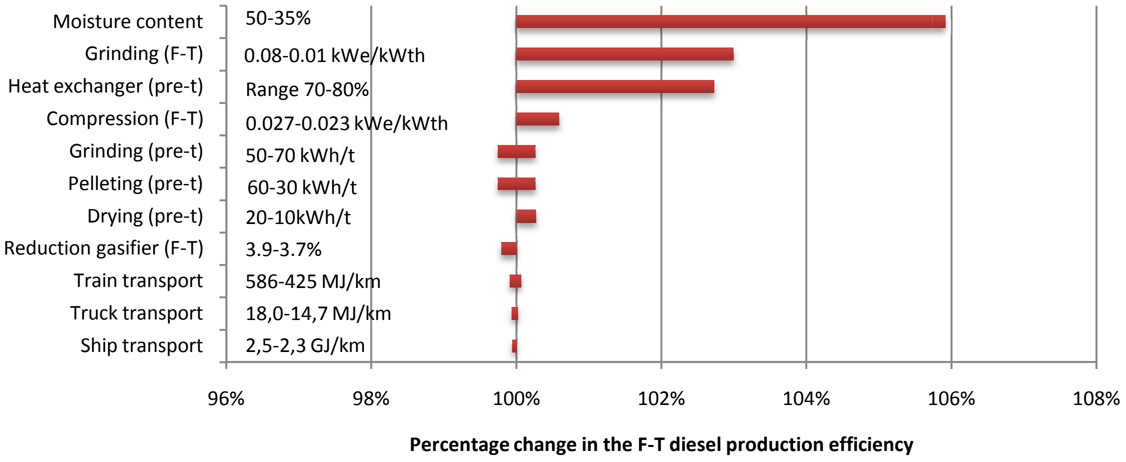


Figure 59 - Expected change in the energetic performance of the chain producing F-T diesel with pelletisation as pre-treatment method for biomass.

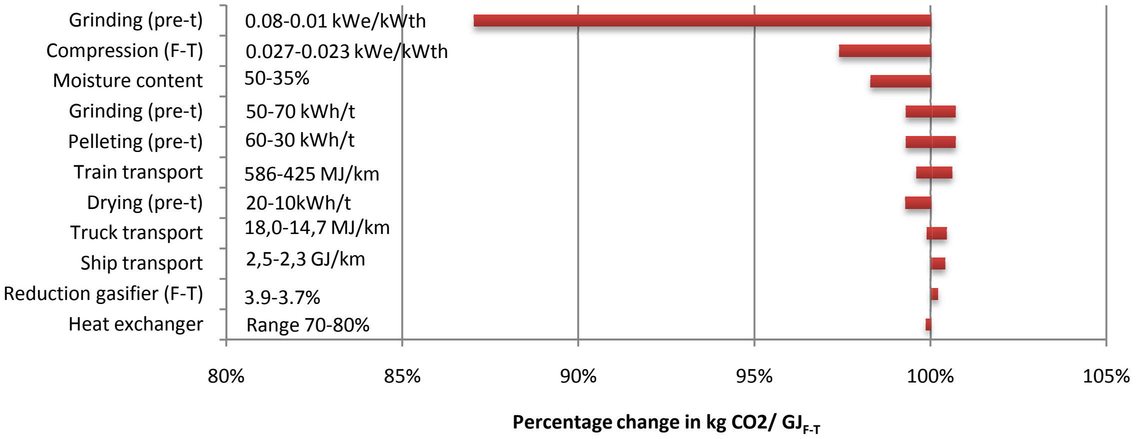


Figure 60 - Expected change in the ecological impact of the chain producing F-T diesel with pelletisation as pre-treatment method for biomass.

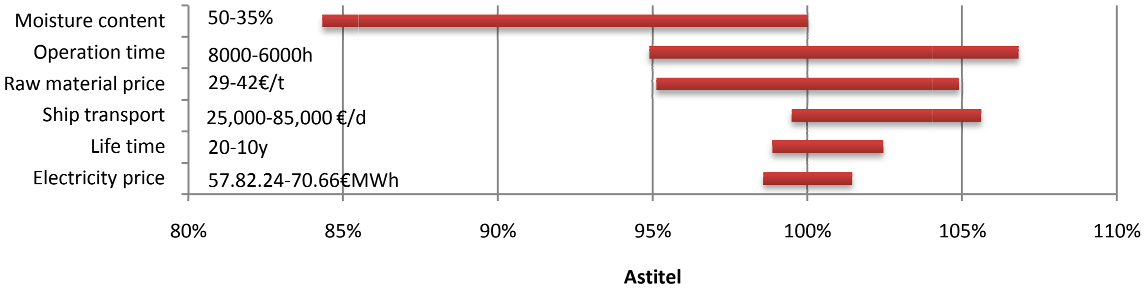


Figure 61 - Expected change in the economic performance of the chain producing F-T diesel with pelletisation as pre-treatment method for biomass.

9.8.2.2 Chain with pyrolysis

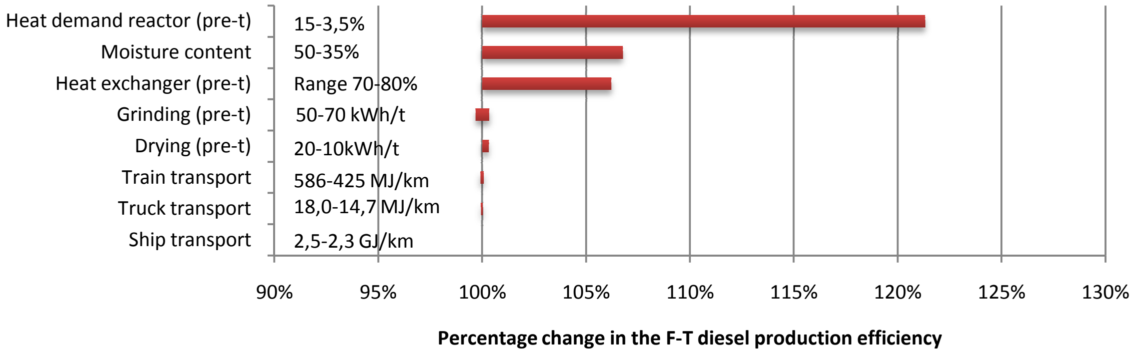


Figure 62 - Expected change in the energetic performance of the chain producing F-T diesel with pyrolysis as pre-treatment method for biomass.

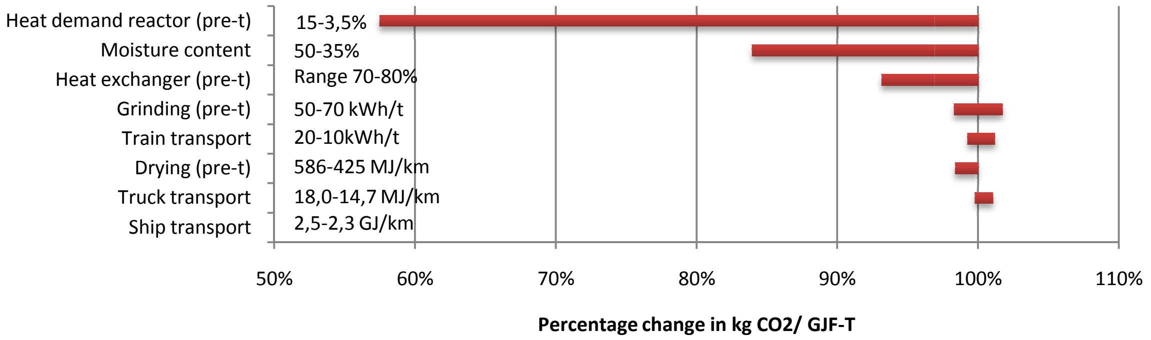
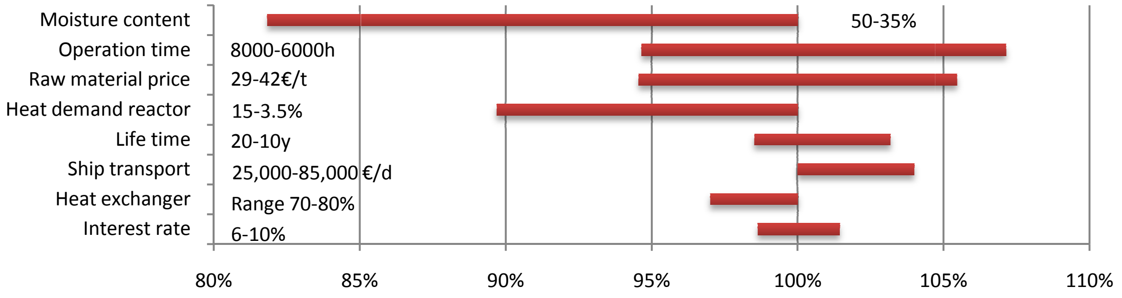


Figure 63 - Expected change in the ecological impact of the chain producing F-T diesel with pyrolysis as pre-treatment method for biomass.



Figuur 64 - Expected change in the economic performance of the chain producing F-T diesel with pyrolysis as pre-treatment method for biomass.