Techno-economic modeling of the supply chain for torrefied biomass

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Abstract
Torrefaction and densification of biomass can provide an important piece in the puzzle of phasing out fossil fuels in favor of renewable alternatives. This new energy carrier shares many of the advantages with fossil coal in terms of energy density, hydrophobicity and burner feeding but is carbon neutral and renewable. It also lacks the challenges of many other renewable alternatives, especially irregular availability.

A model was developed in Excel as sales support for BioEndev, one of the leading actors in the process of taking torrefaction to a commercial market, assessing the black pellet supply chain from feedstock to end user and comparing it to white pellets. Data was obtained from literature, industry and BioEndev. The model can be used for different parameters for price of feedstock, capital and operating expenditures, transport and handling costs and analyze 28 different cases. It also includes simplified calculations for energy input and greenhouse gas emissions.

A case study for two different supply chains was performed with the model. One assessed a production facility in northern Sweden with distribution to a consumer in Denmark. The other a torrefaction plant in southeastern USA with distribution to a consumer in the Netherlands.

The cost for delivering black and white pellets from Sweden to Denmark was found to be 33.0 €/MWh and 35.3 €/MWh respectively. For the case of delivering from USA to the Netherlands, the total supply chain cost was 27.6 €/MWh for white pellets and 24.7 €/MWh for black pellets.

Suggestions for further work are to 1) develop the model outside this study’s limitations, for example by adding integration options for the torrefaction facility or by different end user configurations, and 2) expand the scope to also comparing black pellets to coal to see how big the gap is and which political incentives that could shrink this gap.
Foreword and acknowledgements

This thesis has been written during the spring semester 2014 for the Master’s Degree Programme in Energy Engineering at the Department of Applied Physics and Electronics at Umeå University on behalf of BioEndev AB.

Several people have been essential in completing this thesis and deserve to be mentioned.

First, I would like to thank the people at BioEndev for their cooperation and support. Special thanks to my supervisor Anders Nordin whose expertise and encouragement has helped and inspired this work greatly.

I thank my university supervisor Katarina Åberg for constructive feedback and an observant eye on my attempts to use the English language.

Thanks also to all the people outside this project who has assisted with time and knowledge.

Finally, I would like to thank my family and friends for their support.

Umeå, May 2014.
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1 Introduction

In this chapter, the background to the development of torrefaction is described to put this thesis in a wider context and motivate the need for it. From this purpose, application and delimitations of the study in presented, as well as the disposition of and abbreviations used in the study.

1.1 Background

There is a wide consensus among climate scientists that the combustion of fossil fuels by humans causes changes in the Earth’s climate by increasing the global mean temperature [1] [2] [3]. To limit the likelihood of irreversible disruptions in the global ecosystems it is necessary for mankind to keep the anthropogenic influence on the climate to a temperature increase below 2 °C compared to pre-industrial levels [4].

Today, there is no legislation on international level for limiting greenhouse gas emissions. However, there are a variety of policies and mandates on national and regional level. For example, the European Union has from December 2010 established a goal called the 20-20-20-objective in the 2009/28/EC directive. This means that the EU countries must achieve 20% reduction of greenhouse gases, increase energy efficiency by 20% and reach 20% renewable energy in 2020, compared to 1990 levels [5].

These policies have accelerated the development of renewable energy resources. Some of these alternatives, such as solar or wind energy, struggle with intermittency (i.e. irregular production depending on weather conditions). Another alternative, which do not have this problem, is generation of energy by combustion of biomass. The biomass market is growing rapidly. The large-scale markets are growing in UK and the Netherlands, while countries such as Austria and Italy has a rapidly growing market for residential use [6]. The market is driven by the rising demand in Europe, and an increasing share of the European consumption is supplied by imported biomass [6]. Today, only 40% of the potential for using biomass for energy purposes is utilized. The full potential of sustainable use of biomass for energy is estimated 100 EJ/year, which is about 30% of today’s global energy consumption [7].

Although biomass has several advantages as a renewable source of energy, it still struggles with inherent problems. For example, it has low bulk density, is heterogeneous, hydrophilic and has high moisture content [8] [9]. It also suffers from problematic ash behavior and high biological activity. These issues are most tangible when large quantities are transported long distances. In some cases the logistics can account for more than half of the cost of delivered biomass [10]. The increasing use of biomass is believed to result in even longer transport distances [11].
A way to mitigate these issues is to employ a pre-treatment technology for the biomass. One such refinement method is called torrefaction. It gives an enhanced product, in this study referred to as “black pellets”, which compared to white pellets and other traditional forms of biomass have significantly improved characteristics in terms of transportation, handling and storage [11].

One of the actors in the front-line of developing commercial torrefaction technology is BioEndev AB, who also is the initiator of this thesis. The company was founded in 2007 by scientists at Umeå University, and has since developed a state of the art proprietary technology in pilot scale. During 2014 the technology will be scaled up to achieve a proof of concept in large scale by an industrial demonstration unit [12]. BioEndev has very high knowledge and proficiency in the torrefaction technology, but has expressed an interest in improving the understanding of the downstream and upstream supply chain and to acquire a tool for supply chain modeling and analysis. Some earlier work has been done on this subject, but the used models are not generally available or presently do not fulfill the needs for BioEndev.

1.2 Objectives
The objectives of this study were to identify important parameters in the biomass supply chain and develop a model with data for quantitative analysis of the cost, energy input and greenhouse gas emissions from feedstock to end user of black and white pellets.

1.3 Application
BioEndev will use the model in sales support for commercial torrefaction units. By gaining control of the upstream and downstream costs, BioEndev will be able to show potential customers an indication of to which price they will be able to deliver black pellets to an end user as well as how the improved qualities benefit cost reduction over the whole supply chain. The study will also increase the general conceptual knowledge of the supply chain effects for BioEndevs employees.

1.4 Delimitations
To create a completely accurate model for the back pellet supply chain is not possible within the time constraints of this thesis. Therefore, distinct delimitations and assumptions were made.

First, the study has a holistic perspective on the supply chain and will not go too deep into details. Thus, the model will give approximate rather than exact results. One could argue this as a weakness, but for giving an answer to the delivery cost of black pellets, looking deep into one single part of the value chain is not as beneficial.

There is a difference between price and costs. In this study, the focus is on costs as there is yet no commodity market price for black pellets. The focus on costs is also more relevant for the comparison of white and black pellets.

The focus in this study is on pellets transported in bulk for industrial use, and excludes the market for residential pellets commonly sold and transported in bags of 15-25 kg each. The main savings and therefore largest incentives for converting from white to black pellets are most significant for industrial users.
An interesting opportunity for many possible customers is to integrate torrefaction with other processes. For example, a power plant could benefit from using residual heat to dry the biomass, and use the gases from the torrefaction process in the combustion [12]. This possibility will not be considered in the present study due to the increased complexity. Instead, a so-called “green field” plant will be used as the base case.

There are several different technologies for torrefaction of biomass (see discussion in Chapter 3.5). In this study, the process is limited to the torrefaction technology developed by BioEndev.

There are many possible end user applications for torrefied biomass. For example it can be used for co-firing with fossil coal, in entrained-flow gasification processes for electricity or liquid fuel production or for very specific industrial applications, for example steel or cement production [13]. As there are so many different uses for torrefied biomass, these will not be included in this study. Instead, only up until delivery to the gate for the end user will be considered.

An important part of this study is the financial aspects. A restriction for this study is to only analyze techno-economic costs. The costs for risk, organizational development and transaction costs will not be included.

1.5 Previous studies
Analyzing the supply chain costs, energy input and greenhouse gas emissions have previously been done, both academically and for commercial purposes. To give the reader an introduction to the state of the art, the studies of greatest importance and relevance are hereinafter summarized.

An early study by Bergman [14] compared black and white pellets for the case of South Africa to North Western Europe with the result of black pellets being 25% more cost efficiently delivered to an end user on a GJ basis.

Hamelinck et al [15] developed a model for analyzing bioenergy transport costs from Latin America and Europe to Western Europe from an economical, environmental and energy perspective. The study found biomass from Latin America being significantly more cost efficient compared to biomass being traded within in Europe. Only white pellets were considered.

British wood-, pulp and biomass consultancy company Hawkins Wright published a comprehensive study in 2012 analyzing the supply chain economics of biomass torrefaction. It covers the current market situation, gives a conceptual introduction to the supply chain and analysis of seven supply chains with different configurations for both black and white pellets. The results show significant cost savings for black pellets compared to white pellets delivered to an end user. Locations for torrefaction plants were in North and South America, South Africa and Australia, and the end users were located in the Netherlands, Japan and South Korea [16].

A recent study performed by Ehrig 2014 investigated three different cases with pellet plant locations in Canada, Australia and Russia with the consumer in Europe. Costs, energy input and greenhouse gas emissions were analyzed. It also considers effects of policy making and price risks for supply chain economics. Further, it includes a comparison between black and white
pellets. The results indicate higher costs for delivering black compared to white pellets for all cases. The author discussed that this difference in the results compared to other studies originates from the more restricted assumptions about black pellets product qualities applied in this work. [17].

A study by Svanberg in collaboration with Umeå University and BioEndev scientists has analyzed supply chain costs for torrefaction under Swedish conditions. Focus is on comprehensive sensitivity analyses on one case rather than comparing different cases. No comparison to white pellet production was included [18].

Uslu et al [19] has performed a techno-economic evaluation of different pre-treatment technologies and their effects on international bioenergy supply chain logistics, including torrefaction, fast pyrolysis and pelletizing. Black pellets produced by torrefaction were found to be the most cost efficient pre-treatment method.

Comparisons of the supply chain for black and white pellets has also been performed by for example Wild [20], Ekborn [21] and Koopejan et al [13], all reaching the conclusion that black pellets is more cost efficient than white delivered to an end user.

The study field of the torrefaction supply chain is, as shown, not new. However, the results from the previous studies are not entirely univocal and not based on BioEndevs technology for torrefaction. Many of the assumptions included are not disclosed or have changed since the study was performed. Thus, the research gap motivating this study is in part a commercial interest for BioEndev to own the information and adapt it to their own conditions, but will also contribute to the academic body of knowledge for the supply chains for black pellets and solid biomass in general.

1.6 Disposition
The first two chapters of the present master’s thesis gives an introduction to the background and scope of this study, and the method used to fulfill the purpose.

The theoretical framework for this study is presented in Chapter 3 and 4, dealing with torrefaction and biomass supply chains respectively. These describe torrefaction and biomass supply chains with focus on qualitative descriptions.

The results are also presented in two separate chapters, one presenting the model with design, function and the gathered data. The other present the result from the case studies conducted using the model.

In the last chapters, the results, potential sources for errors and suggestions for further work are discussed. The thesis ends with conclusions and recommendations to BioEndev.
1.7 Terminology and abbreviations
To a reader new to the torrefaction technology and supply chain management, this chapter serves as an orienting introduction. Specific terminology and abbreviations needed to fully understand this study are explained.

Black pellets
Black pellets is the protagonist in this study, and the term is used as a generic name for torrefied and pelletized biomass, what also is called “Torrefied pellets”, “TOP”, “TDB”, or “TCB”. The term “torrefied pellets” is somewhat misleading as it gives the impression that the pelleting is happening before the torrefaction, which rarely is the case. In this study, “black pellets” is referring to biomass that has first been torrefied and then densified by pelletizing, unless otherwise specified.

White pellets
White pellet is in this study used as a reference for comparison with black pellets. It refers to traditional densified biomass that has not been pre-treated further than being dried and pelletized.

GHG emission
GHG is an abbreviation of Greenhouse Gases. The reason for not only considering CO₂, is that other gases with similar effect on the global climate is emitted from the supply chain. These include methane, nitrous oxide and ozone, although they are emitted in much less extent than carbon dioxide. The total effects of these gases are expressed in so called CO₂ equivalents, or CO₂eq.

Ex Works, FOB and CIF
In the discussion of product prices somewhere in a supply chain, it is important to distinguish between what is called incoterms. It is a set of pre-defined terms for international trade, and explains who is responsible for which part of the supply chain. The four most commonly used is the present study are Ex Works (EXW), Free On Board (FOB), Cost, Insurance and Freight (CIF) and Delivery Duty Unpaid (DDU). The responsibility boundaries are shown in Table 1 [22].

Table 1. Summary of relevant incoterms

<table>
<thead>
<tr>
<th>Term</th>
<th>EXW</th>
<th>FOB</th>
<th>CIF</th>
<th>DDU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Export packing</td>
<td>Seller</td>
<td>Seller</td>
<td>Seller</td>
<td>Seller</td>
</tr>
<tr>
<td>Loading at seller’s premise</td>
<td>Buyer</td>
<td>Seller</td>
<td>Seller</td>
<td>Seller</td>
</tr>
<tr>
<td>Inland freight in seller country</td>
<td>Buyer</td>
<td>Seller</td>
<td>Seller</td>
<td>Seller</td>
</tr>
<tr>
<td>Terminal handling charge</td>
<td>Buyer</td>
<td>Seller</td>
<td>Seller</td>
<td>Seller</td>
</tr>
<tr>
<td>Loading on vessel</td>
<td>Buyer</td>
<td>Seller</td>
<td>Seller</td>
<td>Seller</td>
</tr>
<tr>
<td>Main carriage</td>
<td>Buyer</td>
<td>Buyer</td>
<td>Seller</td>
<td>Seller</td>
</tr>
<tr>
<td>Customs clearance in buyer’s country</td>
<td>Buyer</td>
<td>Buyer</td>
<td>Buyer</td>
<td>Buyer</td>
</tr>
<tr>
<td>Delivery to destination</td>
<td>Buyer</td>
<td>Buyer</td>
<td>Buyer</td>
<td>Seller</td>
</tr>
</tbody>
</table>

In the case study in this report, the comparisons will be carried out for CIF and DDU prices, which generally also is the case for previous studies.
2 Method

In this chapter, the method used for developing the model will be presented. It will help the reader to interpret the results presented in Chapter 5 and 6 and to make a reproduction of the study possible.

2.1 Methodological approach

Based on the objectives described in Chapter 1.2, the costs, energy input and GHG emissions will be calculated. This is achieved by developing a model, which in turn is based on compiled data and relations from a literature study. This is illustrated in Figure 1 below.

![Diagram](https://via.placeholder.com/150)

Figure 1. The methodological approach

2.2 Literature study

A comprehensive literature study was performed serving two purposes. Firstly, to give a deeper understanding for biomass supply chains, both for developing a good model and to disperse conceptual knowledge into BioEndev. The theoretical framework from this study focused on qualitative data and was descriptive in its nature. Secondly, to compile the findings in similar studies for validation of the model. Academic papers, books, articles and consultant reports about torrefaction and supply chains for biomass was included. The most relevant work was presented in Chapter 1.5.

2.3 Data collection

The supply chain of international biomass trade is complex and depending on a wide range of variables. As a model never will be better than its database, much effort was put into finding credible and recent data. Too generous assumptions in the input data would give unreliable output and the model rendered useless. Although not fully achieved, the goal was to justify each data point with more than two of each other independent sources. Whenever a triangulation between available data was made, it was adjusted for inflation and currency. The data sources have been made available in the model database when possible to make the user able to make adjustments in the future and to double-check any data.
Data for feedstock prices was collected from secondary market data from analysts and branch organizations, and in dialogue with professionals in the forest industry. Some of these data was ranging in a wide span even for small geographical areas, and in these cases an average value was used unless one source seemed more trustworthy than the others.

BioEndev was naturally an important source for data regarding the torrefaction process. For the process costs, i.e. capital and operational expenditures, most data was received from earlier works performed by BioEndev in-house. Calculations for torrefaction units in different sizes were available, and were compared to results from estimations available in academic papers.

Data for logistics was obtained from a variety of sources including academic papers on biomass logistics and dialogue with industry professionals.

2.4 Model development

The model was developed in Microsoft Excel, with a main document linked to two separate documents based on Invest for Excel®, which is a plug-in software used for capital budgeting and financial modeling. These calculated the investment and process costs for black and white pellets respectively.

To make the tool as user friendly as possible, macros and Visual Basic programming was used. For example, the user can get default values from a database by simply clicking a button instead of searching for the values themselves.

All costs were calculated in euro. To make black and white pellets comparable, all costs were presented on a MWh basis rather than per ton. This is also a common base for pricing of wood pellets in industrial scale while ton is more commonly used for the residential market. As the model will be used as sales support, the output was made aesthetic and easy to understand, even for someone with relatively low prior knowledge in biomass and its supply chain.

2.5 Case study simulations

A case study comparing two supply chain configurations were conducted using the model. The first was for production in USA and consumption in the Netherlands, primarily to validate the model against earlier studies and the actual market price, which is available for Rotterdam CIF prices. The second case study investigated production in northern Sweden and consumption in Denmark, as it is a highly relevant case for BioEndev. The case study was quantitative and focused on the costs and CO₂ emissions rather than qualitative descriptions of the similarities and differences in the value chains.
3 Torrefaction

As torrefaction is a relatively new and emerging technology, this chapter aims to introduce the concept of torrefaction. After a short history, the principle and different technologies will be explained. The advantages and disadvantages are presented.

3.1 History

Torrefaction resembles the process of roasting coffee beans, and the earliest patents for the process originate in this development in the late 19th century. During the first half of the 20th century, sporadic research was performed of which only some were patented. Modern work on torrefaction occurred during two periods; first in France during the 1980’s [23], where the first demonstration plant was built [21], and in more recent years by a group of researchers in the Netherlands. The latter led to massive interest in the academic and industrial fields, and much of today’s knowledge has been accumulated during the last ten years [24].

During 2010 to 2012 there was an industrial hype around torrefaction and many commercial projects was presented. Some of them were built but many fell through. Of the ones built, only a few are still producing black pellets today and the interest around torrefaction has somewhat cooled due to high initial expectations, unexpected challenges and unfulfilled promises. However, some actors are now coming in a second wave with improved technology and more reliable processes, and one of these are BioEndev [12].

3.2 The principle of torrefaction

Torrefaction is the name of the pre-treatment process of heating biomass to 200-350°C in an environment with atmospheric pressure and reduced or zero oxygen [14]. The residence time differs depending on feedstock, technology and temperature and range from 2 to 120 minutes [24]. About 30% of the mass is converted into so called torrefaction gases during the process. However, these gases only contain 10% of the original biomass’s energy, resulting in an increase of energy density in the torrefied biomass by a factor $0.9/0.7 = 1.3$ [14]. The process is simply described in Figure 2 [14], which is commonly used to illustrate the torrefaction process.

![Figure 2. Energy and mass balance for the torrefaction process](image)
An important factor for technologically and economically feasible torrefaction is high mass and energy yields. Typical mass yield for torrefaction is, as mentioned above, 70% and energy yield above 90%. These values are not set in stone but depend on the desired product quality and operating temperature and residence time [24].

From a biological perspective, all three components of biomass (cellulose, hemicellulose and lignin) are affected by the torrefaction process settings and they react in different ways [9]. The thermal decomposition and reactions can be divided into different regimes; drying, depolymerization, volatilization and carbonization. These processes occur in different temperature spans for cellulose, hemicellulose and lignin [25]. An illustrative summary of the decomposition regimes is presented in Figure 3.

![Figure 3. The paradigms of torrefaction [25]](image-url)
3.3 The torrefaction process

The torrefaction process is, at a first glance, very simple. The maxim can be expressed as drying followed by a more extensive drying and heating, but the process is more difficult than it appears. One challenge is to keep the process and exothermal reactions under control, and achieve a uniform temperature gradient. If some of the biomass particles experiences a temperature above the preferred span, there is a risk for thermal runoff, where the material will ignite and the temperature rises ~50 °C [12].

Parameters affecting the torrefaction process are temperature, heating rate, oxygen concentration, residence time, ambient pressure and the feedstock characteristics (e.g. species, particle size, moisture content) [9]. An example of how different temperatures affect the end product is shown in Figure 4.

![Figure 4. Different end products sorted by temperature](image)

As the biomass moves through the torrefaction reactor, it will undergo different processes depending of time and temperature. Figure 5 shows a schematic illustration of a desired temperature profile in the biomass as a function of time.

![Figure 5. Temperature profile for the torrefaction process](image)
3.4 Torrefaction technology

The general principle of torrefaction has been explained in Chapter 3.2 and the process in Chapter 3.3. To produce torrefied biomass, a wide variety of technologies have been proposed and developed as illustrated in Figure 6. Some reactors are horizontal, some vertical. Some use a moving bed while other use a rotating screws. One developer uses microwaves to heat the biomass [13]. Common for all the technologies is that solid biomass is heated to a target temperature during a period of time with some kind of transportation of the biomass through the process. In most cases, the torrefied biomass is densified by pelletizing after the process, although briquetting might be the preferred densification technology in the future [12].

![Figure 6. Different torrefaction technologies [21]](image)

A principle sketch for the torrefaction and densification process is shown in Figure 7.

![Figure 7. Principle sketch of the torrefaction and densification process](image)
3.5 Advantages of torrefaction
There are several significant advantages with torrefied and pelletized biomass compared to untreated or traditional wood pellets. It is not only an improved version of traditional pellets, but also have a wider range of applications. Utility companies such as Vattenfall, RWE and E.ON have made comprehensive testing in the application of co-firing black pellets with coal [27]. Each advantage will be described in Chapter 3.5.1 to 3.5.5. The disadvantages and challenges for torrefaction will be presented in Chapter 3.5.6.

3.5.1 Energy and bulk density
As less than 30% of the mass but only 10% of the energy typically leaves during the torrefaction process, the energy density is significantly improved. It is also possible to achieve an even higher degree of energy density when pelletizing torrefied biomass by higher bulk density. Table 2 shows the different properties for wood, white pellets, torrefied pellets and coal [6] [10] [16] [19].

Table 2. Characteristics of different fuels

<table>
<thead>
<tr>
<th></th>
<th>Wood</th>
<th>White pellets</th>
<th>Black pellets</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorific value (MJ/kg)</td>
<td>9-12</td>
<td>17-18</td>
<td>20-24</td>
<td>23-28</td>
</tr>
<tr>
<td>Bulk density (kg/m³)</td>
<td>200-250</td>
<td>620-670</td>
<td>650-800</td>
<td>800-850</td>
</tr>
<tr>
<td>Energy density (GJ/m³)</td>
<td>2-3</td>
<td>10.5-12</td>
<td>15-18.7</td>
<td>18.4-23.8</td>
</tr>
<tr>
<td>Moisture content (%)</td>
<td>30-45</td>
<td>7-10</td>
<td>1-5</td>
<td>10-15</td>
</tr>
</tbody>
</table>

The increase in energy density has significant benefits for the handling and transport costs compared to traditional pellets. The effect of densification and torrefaction on the cost of transporting biomass is shown in Figure 8, where transport cost as a function of energy density and bulk density is illustrated for white and black pellets [28]. On a weight basis, black pellets has an advantage of about 20-30% and about 35-55% on a volume basis [6], but these figures depend on the torrefaction degree.

Figure 8. Transport cost as function of energy and bulk density [28]
3.5.2 Hydrophobicity
One of the most significant advantages of torrefied biomass is that it is hydrophobic, i.e. water repellent. During the torrefaction process, the OH groups in the biomass are destroyed, which decreases the capacity for forming hydrogen bonds and thereby to absorb water [14]. The hydrophobic character of torrefied biomass has been demonstrated in several studies [14] [29] [30]. It should be noted that these were performed on torrefied but not densified material [24]. If black pellets could be produced completely hydrophobic, significant cost savings over the whole supply chain can be achieved. During the transport, there is no need for covering the goods. For interim and end user storage, eliminating the need for expensive storehouses can result in significant savings [16].

3.5.3 Biological degradation
A common problem with biomass is biological degradation that leads to self-heating and in some cases spontaneous combustion. After the torrefaction process, the biological degradation is significantly reduced. One reason for this is the decrease of water, which plays an important role in microbial reactions [9]. The elimination of biological degradation allows for longer storage times [14], which could make black pellets less sensitive to price volatility than white pellets.

Another consequence, which is yet to be proven in large scale experiments, is the reduction in CO and CO$_2$ off-gassing. Early studies on wood chips have shown that torrefaction can reduce off gassing by two thirds compared to non-torrefied wood chips [9].

3.5.4 Homogeneity
Torrefaction can be used for almost any form of lignocellulosic biomass [13]. It can also create a homogenous end product from a heterogeneous feedstock [31]. This opens the opportunity for the use of a wider range of feedstocks than for producing white pellets [16], which may ultimately lead to lower feedstock prices for black pellet production. However, the homogeneity of the end product is depending on the torrefaction degree [6], and will be a subject for trade-offs in production decisions.

3.5.5 Grindability and feeding characteristics
By undergoing the process of torrefaction, the cell wall in biomass is weakened [32]. This makes the end product more brittle, which decrease the energy consumption when grinding the material before end use in powder burners [8]. The magnitude of the energy saving differ, but is in the range of 50-90% for black compared to white wood chips before pelleting [13] [33], but there are also savings to be made at the at the end user if a powder mill is required for their application. Figure 9 illustrates how the milling energy decreases when the degree of torrefaction is increased [34].
Figure 9. Milling energy for torrefied wood chips as function of torrefaction temperature [34]

In many cases, when converting a coal plant to biomass feed, investments must be made in additional milling equipment to handle untreated biomass. These are in the area of 70-80 million € per plant, so if black pellets can be used in the existing feeding systems significant savings can be made for the end user [6].

The torrefaction process also influences the resulting particle distribution of the fuel powder, in which the particle size decrease and become more spherical. This makes the powder better suited for feeding in for example gasification processes [24] [35].

3.5.6 Disadvantages and challenges
Only a handful of the initiatives have emerged to production of torrefied biomass in large scale. To this day, none of these seem to have fully achieved their objectives with sufficient availability and pellet product quality. Many of the problems can be derived from lack of process control and homogeneous quality, resulting in low utilization and unfulfilled customer requirements [12]. These are probably a result of commercial torrefaction still being in its infancy and should be compared to the five to ten years of similar utilization problems white pellet production experienced two decades ago.

If these issues are solved and the technology live up to its potential, the main disadvantage of torrefaction of biomass over white pellets production is higher investment costs. As the torrefaction process means an additional reactor to a traditional pellets process plant, it will require higher capital expenditures. Black pellets will primarily compete on the white pellets market initially, and is therefore challenged with being superior in terms of product quality and resulting logistic and end user advantages to overcome the added production costs. As the overall mass yield is higher for white than black pellets, the torrefaction process will require more biomass for producing the same amount of end product on a MWh basis. Thus, the total feedstock costs may increase for black pellet production, putting even higher pressure on achieving superior characteristics for logistics [6]. However, with a wider range of feedstocks being available for the torrefaction process, this issue could be reduced and in some cases theoretically eliminated.
3.6 BioEndev
In addition to the general advantages of torrefaction, BioEndev claim to have a few additional advantages over other manufacturers of torrefaction processes.

BioEndev has a very slim and cost-efficient technology with several technical solutions for cost reduction, improved process control and enhanced product quality. This results in fewer components and thus lower investment costs [12]. For competition reasons, there is no reliable information about the actual investment costs for other torrefaction facilities.

These claims have not yet been proven in commercial scale, but are assumed to deliver as promised in the present study.
4 Biomass Supply Chains

This chapter consists of an introduction to biomass supply chain and logistics, and gives a theoretical background. It provides a conceptual understanding of the supply chain applied on the biomass trade chains.

4.1 Introduction to Supply Chains

In its widest perspective, this study deals with creating value from a raw material and delivering it to a customer with specific requirements. This is called a supply chain, which has been defined by Bhatnagar [36] as:

“[…] a network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these products to customers”.

Handfield and Nichols [37] have also defined the concept as following:

“The Supply Chain encompasses all organizations and activities associated with the flow and transformation of goods from the raw materials stage, through to the end user, as well as the associated information flows. Material and information flows both up and down the supply chain.”

All of the definitions have in common the focus on a flow of materials from one part of the chain to another, with a type of transformation occurring during the transition. In contradiction from logistics, the supply chain is the entire network of logistics operators and includes enhancement of the delivered goods. Thus, logistics activities are components of a supply chain. They all affect each other and all nodes in the supply chain plays a role in deciding the cost of delivering a product to a customer.

4.2 The Supply Chain of biomass

The definition of supply chains by Bhatnagar [36] can be put in the context of wood pellets. The procurement of materials is the harvesting of woody biomass, which is then transformed and refined into an intermediate product in the form of wood chips and later to a finished product in the form of wood pellets (black or white). The product is then distributed by truck, rail, ship or a combination of these to the customers, for example an energy utility company.

As pointed out by Svanberg [11], there is no one-size fit all solution to biomass supply chains. The configuration is highly dependent on the feedstock, operating decisions in the processing and the distribution conditions. A generic supply chain for biomass for energy can be described as follows:

1. Lignocellulosic biomass is harvested and often chipped, before it is transported to a refinement plant (in this study pellets or torrefaction plant).
2. At the plant, the untreated biomass is usually stored for some time before it is refined. The process increases the value of the biomass and makes it more suitable for transport.
3. After being upgraded, the biomass is distributed to a consumer. Depending on the distance and the conditions, the distribution can consist of several transports with transshipment and storage between them. For the example of transatlantic exports, it can
consist of truck transport to a port, ocean shipping and rail transport to and end user in the importing country.

4. When delivered, the biomass is stored and then consumed. Depending on the end user application, the handling is different. The application also has major implication for the implementation of biomass in for example co-firing with coal or industrial processes.

The system outline for this study can be seen in Figure 10.

![System outline for this study](Figure 10)

Thus, the price for delivering pellets to an end user can be divided to three parts; price of feedstock, processing costs and logistics costs.

4.2.1 Raw fiber sourcing

Feedstock price is a major part of the total cost of delivered pellets, and one of the most difficult to give a precise cost indication for. The price of round wood or wood chips vary geographically and over time, and is one of the major drivers behind the pellet production expansion [38]. Svanberg has identified four parameters as important for feedstock as a part of the supply chain; geography, competition and integration, cost and quality [11].

In some cases the feedstock comes from residues from another industry. For example, several pellet mills are built in direct proximity to sawmills where they use the sawdust falling from the wood industry process as feedstock for the pellet production.

The procurement area from which it is profitable to harvest wood products is dependent on the size of a pellet mill. For example, a large refinement plant must have a large harvest area, and therefore the price will rise. For the case of BioEndev, a plant with annual capacity of 150 kton has a harvest area of 50-100 km depending on the yield [12]. Whether there are other actors in the forest sector competing for the same feedstock is also influencing the price [11].

In this study, the price of feedstock is considered as delivered to the gate of the consumer, i.e. including transport from the harvesting source. This is due to most available market data being given including transport, and it is sometimes difficult to separate the cost contributions.

4.2.2 Inland transport

Unless the end user is in absolute proximity to the pellets facility, some kind of inland transport is required. In the case of overseas customers, up to three different transportation distances may be necessary: from the feedstock to the torrefaction plant, from the torrefaction plant to the
sending port and from the receiving port to the end user. The two far most common methods for inland transporting of pellets is by truck or by rail.

The two have different pros and cons, but in general it could be said that rail is more viable for long distances, whereas truck is the better choice for flexibility and shorter distances. The breakpoint for when rail is more viable is strongly depending on infrastructure conditions, but is suggested in literature to somewhere between 60-100 km [15] [16] [39].

4.2.2.1 Truck transport

Truck transport is a flexible way of transporting goods, both in terms of travel route and adaption to different type of goods. In 2000, it was used for 75% of all inland transports in the EU and EFTA countries [39].

When calculating transport costs, truck deviate from ship as the capacity is more significantly limited by weight rather than volume. In most countries, the maximum load for trucks is regulated to decrease the stress in the roads [40]. Some examples of different legislations are shown in Table 3. Worth mentioning in the discussion of maximum load is that there are plans of investigating the possibility of using an additional wheel axis to decrease the stress on the roads, which could potentially enable for heavier transport and thereby lower kilometer costs [12].

Table 3. Weight limitations for trucks

<table>
<thead>
<tr>
<th>Country</th>
<th>Gross vehicle weight limit (t)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>36.3</td>
<td>[41]</td>
</tr>
<tr>
<td>Sweden</td>
<td>60.0</td>
<td>[42]</td>
</tr>
<tr>
<td>Canada</td>
<td>62.5</td>
<td>[43]</td>
</tr>
</tbody>
</table>

The total costs for truck transport consists of several cost centers. The two most important are fuel and labor costs, which add up to over half of the total cost. A summary of the costs for truck freight is presented in Table 4.

Table 4. Cost centers of truck transport [44]

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>Cost percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>28%</td>
</tr>
<tr>
<td>Labor</td>
<td>27%</td>
</tr>
<tr>
<td>Tires</td>
<td>8%</td>
</tr>
<tr>
<td>Maintenance &amp; Repair</td>
<td>7%</td>
</tr>
<tr>
<td>Overhead</td>
<td>8%</td>
</tr>
<tr>
<td>Interest</td>
<td>6%</td>
</tr>
<tr>
<td>Depreciation</td>
<td>6%</td>
</tr>
<tr>
<td>Oil</td>
<td>3%</td>
</tr>
<tr>
<td>Insurance</td>
<td>2%</td>
</tr>
<tr>
<td>Others</td>
<td>5%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>
Fuel price represent the largest portion of the cost, which is strongly related to the oil price. Figure 11 illustrates the truck diesel prices in USA and Sweden between 2009 and 2014 [45] [46]. They follow a similar pattern, but due to higher taxes the prices are significantly higher in Sweden. It follows that the prices for truck transport is higher in Sweden, ceteris paribus.

Figure 11. Diesel prices in Sweden and USA [45] [46]

Because the cost for the driver accounts for nearly a third of the cost, the speed of the truck and the hourly cost for the driver are important factors for the trucking costs. In this study, average speed is assumed to be 65 km/h as suggested by Suurs [47].

Whether the truck can be used for return transportation after delivering the pellets is also critical for achieving good economics in truck transport. The driver cost is constant and the fuel mileage almost the same for driving fully loaded as for driving the truck empty, so if the truck returns to the terminal empty the overall cost almost doubles. This is called the backhaul problem, and is a well-known phenomenon in logistics and is defined by Demirel et al as

“the situation where the volume of transported goods or persons is not in balance between two (or more) locations, which means that transport flows are mainly in one (or more) dominant direction(s)” [48].

For example, if BioEndev delivers black pellets from the Swedish inland to the coast, they would benefit from finding another application for the truck on the way back and get the return trip paid by a company who need to get goods from the coast to the inland. As a drawback, truck transport have high GHG emissions compared to other freight methods [39], which in a way contradicts the purpose of using torrefied biomass to reduce said emissions.
4.2.2.2 Rail transport

Rail freight is more large-scale than truck transport and suitable for medium to long distances [15]. The kilometer cost is generally lower for rail than truck transport, but handling costs are higher. A typical 4-axis rail wagonload has a net payload capacity of 64-88 t and size of 168-310 m³ [49], giving a full load bulk density in the range of 280-380 kg/m³. With the bulk densities of white and black pellets, weight will be the limiting factor also for rail transport. A train set can consist of up to 120 railcars in USA [35], where the average payload per train is 2624 ton compared to 490 tons in Sweden [49].

Rail transport is more dependent on the proximity to existing infrastructure than truck transport, which is more flexible. The backhaul problem described in Chapter 4.2.2.1 is also important for rail freight and should be considered in all decisions regarding inland transport.

From a sustainability perspective, the net carbon emissions are generally significantly lower for rail than for truck freight [44], and result in five to eight times lower emissions of CO₂ equivalents compared to truck transport [16]. For the Swedish case with electrified trains and almost carbon neutral electricity production, the emissions approach zero.

4.2.3 Ocean Shipping

For very long distances, ocean shipping is the most cost efficient method for transporting goods. Unlike the case for truck and rail, shipping of biomass is in most cases limited by volume and not weight. The breakpoint for when weight becomes limiting is for a bulk density of 750-800 kg/m³, so this could become an issue for black pellets [16]. Therefore, any efforts to achieve bulk densities over this limit could be unnecessary if it requires additional costs.

Table 5 shows the capacity of a Handymax ship to illustrate the effect of a limiting volume. The assumptions for bulk density and calorific value is based on averages from Table 2. Neither black nor white pellets can, due to low bulk density, reach the ships’ maximum weight limits before it exceeds its volume limit. As black pellets has a higher bulk density about 16% more weight on the same volume, and as the calorific value also is higher about 50% more energy can be transported under the maximum volume capacity of the ship.

Table 5. Ship capacity for black and white pellets (Handymax ship)

<table>
<thead>
<tr>
<th></th>
<th>White pellets</th>
<th>Black pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship max capacity (ton)</td>
<td>45 000</td>
<td>45 000</td>
</tr>
<tr>
<td>Ship max capacity (m³)</td>
<td>56 250</td>
<td>56 250</td>
</tr>
<tr>
<td>Max pellets weight (ton)</td>
<td>36 300</td>
<td>42 200</td>
</tr>
<tr>
<td>Capacity (GWh)</td>
<td>176</td>
<td>264</td>
</tr>
</tbody>
</table>

In general, the ships used for transport of biomass can be divided into three size categories [39]; Panamax, Handymax and small vessels. Panamax ships are large ships designed to pass through the Panama Canal, and the capacity is ranging from 65 to 80 kton. Handymax are smaller but can still carry some 35-55 kton and are primarily used for somewhat shorter distances, but is still used for transatlantic freights. Handymax ships are well suited for transporting biomass from medium size harbors and often have integrated handling equipment, making them less dependent on the port infrastructure than Panamax ships [50]. Small vessels are used for
transportation during shorter distances and are significantly smaller than the Panamax and Handymax ships, handling around 3000-5000 tons.

The prices for shipping are very volatile and are dependent on the vessel size and the transport distance as well as supply and demand [51]. The distance from Vancouver to Rotterdam serves as a good example of the volatility, where the prices increased from $35/ton in 2004 to nearly $100/ton only three years later [50]. The supply and demand is in turn controlled by seasonal variations and the available tonnage [44]. Measures to reduce shipping costs are to use larger ships, reduce the number of handlings operations, streamline the necessary handling operations and to keep the stock as small as possible by having have a just-in-time delivery [51]. Further, the cost of transport is very dependent on whether a port is on a common route or not [52]. For example, a considerable volume of pellets is moved 14 000 km from Vancouver (western Canada) to major European ports like Rotterdam. A smaller quantity of pellets is transported from Halifax (eastern Canada) to Europe, yet the cost is almost the same [50]. As for inland transport, backhaul is also a major issue for achieving cost effective sea transport.

The average costs worldwide for ocean freight is tracked by the Baltic Dry Index. They assess prices for dry bulk transport directly from shipping brokers and provide an index for comparing freight prices over time [50]. It covers 23 shipping routes based on a time charter basis [53]. Figure 12 illustrate how the index has varied over time since 2000, and shows clearly how much the freight prices can vary over time.

![Figure 12. Baltic Dry Index (BDI), year 2000-2014 [54]](image)

Today, nearly 5 million tons of wood pellets are transported long distances by overseas shipping [55]. Figure 13 illustrates the flows of international wood pellet trade 2012. Europe is the center of attention with Sweden, the Netherlands, Denmark, UK and Italy being the most intense pellets users [10]. Canada, USA and Russia are major exporters of wood pellets, and new producers are emerging from Brazil, South Africa and Australia and New Zealand. Japan and South Korea is emerging as consumers, with expectations to grow over the coming years [10]. There are no signs of a decrease in intercontinental pellets freight.
From a sustainability perspective, ocean shipping has relatively low GHG emissions because of its very large volumes. If the demand for imported biomass continues to grow, torrefaction will decrease the carbon footprint for overseas shipping. Energy input, in the form of fuel for the ship which in turn generates GHG emissions, will be approximately the same for black and white pellets but a black pellet delivery will contain 265 instead of 176 GWh as shown in Table 5. Hence, the carbon emissions per delivered energy unit will be about 34% lower with black pellets.

4.2.4 Processing
A black pellet plant is basically a white pellet plant with the addition of a torrefaction reactor. Otherwise the drying, grinding, pelletizing and cooling processes can be considered quite similar.

The total cost for producing pellets is the sum of fixed and variable costs, where fixed costs are a function of the plant size and maximum production capacity and the variable costs depend on the actual production.

To achieve high utilization, shift-operating workers constantly staff the pellet plant. The cost of the labor is a function of the size of the plant but is not linear. A plant with 100 kton annual production can have the same number of shift workers a 150 kton plant, and the cost is the same independent of whether any of these plants has a utilization of 30% or 95%.

Costs for insurance, maintenance and administration are fixed and is often set to be a percentage of the investment cost in capital budgeting. The annual depreciation cost of the assets is a significant part of the fixed costs. In this study, a linear depreciation over 20 years was considered. To calculate approximations of investment cost, up- or downscaling from an existing plant with known size and investment cost is commonly used [57]. However, the relationship between size and specific investment cost is non-linear, therefore a scale factor is required. This effect is called “economy of scale” and is important to consider when planning a
torrefaction unit. To calculate the investment cost $I$ for a plant of size $S$ from the base of a known plant size $S_0$ with investment $I_0$ the following formula is used,

$$I = I_0 \times \left( \frac{S}{S_0} \right)^f$$

where $f$ is the scale factor, which is suggested to be 0.6-0.8 for pellet plants [58]. As torrefaction is a new technology, this factor will probably be higher initially but reach the same values for an n:th facility as the technology matures. An illustration of seven torrefaction units in different sizes, their investment costs and the scale factor of 0.75 is presented in Figure 14.

![Investment cost as a function of annual capacity for torrefaction units](image)

**Figure 14. Investment cost as a function of annual capacity for torrefaction units**

A torrefaction plant has been suggested to be from 13% to, in worst case, over 100% more expensive than a white pellet plant [16] [18]. The difference between a white and black pellet plant is illustrated in Figure 15. However, calculated on an energy basis the white pellets plant must have about 25% higher tonnage capacity to produce energy carriers with the same amount of energy as a black pellet plant.

![Comparison of a white and black pellet process](image)

**Figure 15. Comparison of a white and black pellet process**
Variable costs are functions of the actual production and not the name place capacity. For example, if a 100 kton plant has a utilization of 50%, the price for biomass, heating and electricity are half of what it would be at full availability.

As there are fixed costs for a pellet plant, the utilization or availability is critical for achieving profitable production. If the production is down, there are obviously lost revenues but also fixed costs regardless of production levels. Common utilization for pellet mills is suggested to be 91% by the Pellet Handbook [35]. However, during the first two years of production, it is common with lower availability levels. In a study of Svanberg this is suggested to 65% year one and 85% year two [18].

GHG emissions from the process can be attributed to the input of heat and electricity. This input is depending of the size and utilization of the plant, but the GHG emissions per unit of consumed energy depend on the energy mix in the country in which the plant is located. For example the emissions of CO$_2$ equivalent per kWh electricity is 0.04 in Sweden and 0.6 in Italy [59]. The choice of energy source to the drying process also influences the emissions. If it is heated by combustion of biomass the net emissions was estimated by Ehrig [17] to 2.92 kg CO$_{2eq}$ per ton delivered pellets, while it is 192 kg CO$_{2eq}$ per ton if the heating is by combustion of natural gas.

4.2.5 Storage and handling

A challenge when handling pellets is the balance between fast handling, and thereby reduced costs, and the durability of the pellets [44] [50]. If the pellets are handled with too much caution, it becomes slow and the costs for handling become high. But when the process is rushed, the pellets are damaged and therefore unsalable, which generate high handling costs. Pneumatic loading is a fast way of handling large quantities of pellets, but create a lot of damage. Belt conveyors are gentler but slower and have a higher risk of fires [39]. At large ports, pellets are handled either by large grab cranes or pneumatic handling (Figure 16), and the capacity can vary from 10 to 2000 ton per hour [39]. When comparing the transshipment costs for white and black pellets, it can be assumed that cranes are limited by volume whereas pneumatic solutions are limited by weight.

![Figure 16. Loading of biomass on a Handymax ship](image)
5 Results – The model

In Chapter 5.1, the model is presented with focus on design and function. Chapter 5.2 present information on where data were obtained and how the default values in the model were decided. Pictures of the model in action are presented in the appendix. Validity of the model is discussed later in Chapter 7.1.

5.1 Description and structure of the model

The model was developed in Excel and the plugin Invest for Excel®. An illustration of the general principle for how it was built is presented in Figure 17.

The user begins at the Input sheet, where every value is initially empty. By checking the “Default” boxes, the model add the value with pre-defined and, when applicable, country-specific data from the database. It is also possible to use any value and disregard the database if the user knows actual case-specific data. Some values, for example locations for producer/consumer or type of ship, are added by lists with fixed choices. When the input table is completed, it connects data to two separate documents for calculating capital and operational expenditures (CAPEX and OPEX) for a black and white pellet plant respectively. The results from these are returned to the supply chain calculation, which also collects information from the input table. The empty input table facing the user at start-up is shown in Figure 1 in Appendix 1.

The database was built to contain corresponding values to the input table. The values are requested from the above-described input table and find the correct value using multiple LOOKUP functions linked to macros. The data has been collected as described in Chapter 5.2, and is country specific whenever possible. For further development of the model, it is possible to add new countries as well as data points without changing the macros. Sources to each data point are shown using commenting on cells. An illustration of the database is shown in Figure 2 in Appendix 1.

When the input table is complete, the data is transmitted to a new sheet containing the supply chain calculations and to two separate Invest for Excel® documents for the processing costs, one for white and one for black pellets. The results from these are then sent to the main document and the sheet for supply chain calculations. All calculations are based on the data in the input table and performed for black and white pellets respectively, and with costs, energy
input and GHG emissions as output data. The supply chain calculations sheet is presented in Figure 3 in Appendix 1.

The supply chain calculations sheet is linked to the Result sheet, where the final data is aggregated and presented in graphs. It is presented for black and white pellets respectively, and both per activity and accumulated for the value chain. A Result sheet example is presented in Figure 4 in Appendix 1.

The model is able to analyze the supply chain costs for 28 different cases, with seven feedstock locations and four end user locations. Figure 18 illustrates the presently included areas for production (green) and for consumption (red).

![Figure 18. Producing and consuming areas available in the model](image)

5.2 **Input data**

A significant part of this study has been to find, compile and evaluate data for costs, energy consumption and carbon emissions. The sources used, assumptions made and potential sources of errors is discussed in the following chapters.

5.2.1 **Feedstock prices**

Data for feedstock prices was difficult to obtain. Whenever a price was available, it was in most cases uncertain whether this price was for dry or green feedstock, or if it was free delivered at production site or not. The prices also have a tendency to vary over time depending on the current supply and demand, so prices in different countries are difficult to compare. However, when using the model in the indented application as sales support, the feedstock price will probably be the easiest to find for the specific location being analyzed.

For Swedish prices, comprehensive data was available from the Swedish Energy Agency, providing quarterly assessments of the prices of wood chips, recycled wood and by-products [60]. However, the price have local variations, so data gathered from dialogue with people in the
forest industry was used for wood chips prices. From BioEndevs’ contacts, reliable and recent prices for southeastern U.S. was obtained and used in the model. This was compared to the detailed but somewhat outdated prices in the North American Wood Fiber Review, which also contributed with data on prices in Canada. An example of the data available in this report is shown in Figure 19 [61].

![Map of wood chip prices in North America](image)

**Figure 19. Wood chip prices (US$/oven dry million ton delivered) in North America [61]**

Feedstock price data for other countries such as Brazil, Russia and South Africa was obtained from an assessment of delivered feedstock prices by Pöyry [62], presented in Figure 20.

![Bar chart of feedstock prices in selected countries](image)

**Figure 20. Feedstock prices in selected countries [62]**
5.2.2 Logistics

Costs for truck transport was obtained from contact with people in the Swedish forest industry and from secondary sources, primarily academic articles. In the model, 0.56 €/ton including handling and transshipment costs was used as a default value and was calculated from three different sources from the Swedish forest industry. The prices for the other countries were calculated from this value with adjustments for labor and fuel prices. Weight was assumed to be the limiting factor for both white and black pellets.

For rail freight, costs were calculated based on an average from six different secondary sources. 0.027 €/ton was used as a default value, and no adjustments for specific costs in different countries was used due to lack of information. Weight was assumed as the limiting factor for both white and black pellets. For transshipment, 1.98 €/ton was used as default value and was calculated as an average of four different sources ranging from 1.5 to 2.97 €/ton.

The cost of shipping was divided into three categories; Panamax (0.0014 €/ton), Handymax (0.0021 €/ton) and for small vessels (0.12 €/ton). Volume was assumed to be the limiting factor for both white and black pellets. For Handymax transport, the following data points were collected and aggregated in a plot graph to see if there are any scale benefits for long distances. The result, presented in Figure 21, shows no significant variation in the price when the distance changes. Transshipment costs are excluded in the figure.

![Plot graph showing shipping costs as a function of distance](image)

Figure 21. Shipping costs as a function of distance

Shipping distances was calculated, converted into kilometers from nautical miles and pre-set into the database from Ports.com [63]. A list of the ports used is presented in Table 6 [64], and were chosen from the selection criteria of: in the area and being large ports with existing terminals for, preferably, wood pellets or at least other biomass, or wood products.
Table 6. List of ports used in the model

<table>
<thead>
<tr>
<th>Country</th>
<th>Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>Port of Umeå</td>
</tr>
<tr>
<td>Russia</td>
<td>Port of St Petersburg</td>
</tr>
<tr>
<td>Canada (BC)</td>
<td>Port Metro Vancouver</td>
</tr>
<tr>
<td>Canada (East)</td>
<td>Port of Belledune</td>
</tr>
<tr>
<td>USA</td>
<td>Port of Savannah</td>
</tr>
<tr>
<td>Brazil</td>
<td>Port of Belem</td>
</tr>
<tr>
<td>Germany</td>
<td>Rostock</td>
</tr>
<tr>
<td>Netherland</td>
<td>Port of Rotterdam</td>
</tr>
<tr>
<td>Denmark</td>
<td>Port of Aarhus</td>
</tr>
<tr>
<td>Poland</td>
<td>Port of Kolobrzeg</td>
</tr>
<tr>
<td>South Africa</td>
<td>Port of Durban</td>
</tr>
</tbody>
</table>

Handling and transshipment costs were aggregated for different countries, where the variation mainly comes from the capacity and the utilization of the port. Handling in South Africa is for example twice as expensive per ton as in the larger port in Vancouver, and receiving costs in Rotterdam is significantly lower than in Poland.

To calculate freight costs of delivered energy (MWh), assumptions about the end product of black and white pellets were used. Data for black pellets came from BioEndev’s product sheet for the industrial demonstration unit and data for white pellets from an average of large pellets suppliers.

Table 7. Assumptions for product characteristics

<table>
<thead>
<tr>
<th></th>
<th>White pellets</th>
<th>Black pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density (kg/m³)</td>
<td>650</td>
<td>750</td>
</tr>
<tr>
<td>Calorific value (MJ/kg)</td>
<td>17.0</td>
<td>21.5</td>
</tr>
<tr>
<td>Energy density (kWh/m³)</td>
<td>4.8</td>
<td>6.0</td>
</tr>
<tr>
<td>Hydrophobic</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

A functioning and mature market for both black and white pellets with high demand was assumed, and any seasonal price variations considering shipping prices were neglected.

5.2.3 Torrefaction process

Data for mass and energy yield as well as energy consumption etc. for the torrefaction process was obtained from in-house knowledge in BioEndev, and made available as default options for the model. For up- and down scaling of the investment and operating costs, BioEndev’s industrial demonstration unit was used as a starting point. The scale factor for investment was set to a default value of 0.7, as suggested in earlier studies [18] [65] [66], but was easily adjusted in the model. Investment costs were assumed to be equal in all countries, as suggested by Hawkins Wright [16] stating that equipment is likely to be imported to otherwise low-cost countries. The torrefaction plant is set to be 23% more expensive than a white pellets plant on a ton basis.
The financial assumptions for the black and white pellet production plants are presented in Table 8 and are based on BioEndev’s calculations for the industrial demonstration unit. These are assumed to be the same for production of white and black pellets.

Table 8. Assumptions in the model

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability, %</td>
<td>95</td>
</tr>
<tr>
<td>Mass yield (torrefaction), %</td>
<td>70</td>
</tr>
<tr>
<td>Maintenance, % of investment</td>
<td>2</td>
</tr>
<tr>
<td>Insurance, % of investment</td>
<td>0.5</td>
</tr>
<tr>
<td>Cost of capital, %</td>
<td>6</td>
</tr>
<tr>
<td>Depreciation time, years</td>
<td>20</td>
</tr>
</tbody>
</table>

Labor costs were differentiated between different countries with data from Swedish Trade Union Confederation [67]. These include payroll taxes and reflect the total costs for the employer, not just the salary for the employee. The number of shift workers and salaried employees as a function of the plant size was calculated based on the work of Svanberg and Olofsson [18].

Electricity prices for the concerned countries were obtained from various sources, mostly from the respective countries’ authorities for statistics and adjusted to 2014 years price level with 2% inflation. Water prices were obtained from Global Water Intel [68] and were also adjusted by 2% yearly inflation. For the heating price, data from the Swedish District Heating Association [69] was used. Price levels for heating were assumed to be equal in all producing countries in the model.

5.3 Energy input and GHG emissions

As requested by BioEndev, the main focus of the model was on finding comprehensive data for the costs. However, energy input and GHG emissions were also requested as a part of the analysis. Data was aggregated from life cycle analyses of biomass transport and earlier studies of the white pellets value chain. Energy input for the process was calculated in the Invest for Excel® files for white and black pellets respectively from BioEndev’s own data for the processes. No country-specific differentiation of the GHG emissions was performed.

An average of the collected data was used. Most data was found in the work of Sikkema et al [59], Meagelli et al [70], Ehrig, [17] and Hagberg [64]. Sources for all data points are commented in the Excel model. A summary of the used input data is presented in Table 9.

Table 9. Input data used for calculating GHG emissions and energy input

<table>
<thead>
<tr>
<th>Input component</th>
<th>kgCO₂eq</th>
<th>MJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock (/ton)</td>
<td>1.6</td>
<td>48.2</td>
</tr>
<tr>
<td>Truck transport (/ton*km)</td>
<td>0.12</td>
<td>2.3</td>
</tr>
<tr>
<td>Rail transport (/ton*km)</td>
<td>0.01</td>
<td>0.2</td>
</tr>
<tr>
<td>Shipping (/ton*km)</td>
<td>0.004</td>
<td>0.03</td>
</tr>
<tr>
<td>Process (/ton)</td>
<td>10.5</td>
<td>3804</td>
</tr>
<tr>
<td>Handling (/ton)</td>
<td>1.4</td>
<td>18.4</td>
</tr>
</tbody>
</table>
6 Results - Case studies

In this chapter, the results from the case studies are presented. The total costs for delivering black and white pellets to an end user is presented and broken down to the different parts in the supply chain. Approximations of GHG emissions and energy input are also presented.

6.1 Case 1 - Sweden to Denmark

With high ambitions of decreasing CO$_2$ emissions, strong forest industry and excellent infrastructure, Sweden was a pioneer country in the early days of the white pellet industry and is now one of the leaders in terms of production, consumption and experience. BioEndev has its headquarters in Umeå in northern Sweden and has plans of building its first commercial scale torrefaction plant in the region for access to gain experience by follow-up studies and development possibilities.

Denmark is also a country with high climate goals, however they still have a significant degree of coal in their energy mix. Danish energy utilities are converting coal plants into biomass, but Denmark has little biomass production itself and is dependent on import.

This case will study delivery from a fictive plant in Storuman with 100 000 ton annual production of black pellets and its equivalent in energy for white pellets. From there the pellets are transported by train 305 km to the Port of Umeå in Holmsund where it is transshipped to a small vessel (3500 ton) and shipped 1503 km to the Port of Aarhus. From Aarhus, the pellets are shipped by truck 16 km to a nearby coal/biomass plant in Studstrup.

The result for this supply chain is a cost of delivered pellets of 35.3 €/MWh for white pellets and 33.0 €/MWh for black pellets, which make the black pellet 7% more cost efficient for delivering from Storuman to Studstrup. An illustration of the costs per activity is presented in Figure 22. With its higher energy density, the black pellets, as seen in the lines for accumulated costs in Figure 22, approach and overtake the white pellets curve during the distribution phase. Black pellets is 50% more expensive per energy unit to transport in ship and 29% more expensive for truck and rail, due to the weigh/volume limit issue discussed in Chapter 4.

![Figure 22. Costs in €/MWh per activity for the supply chain from Sweden to Denmark](image-url)
For this supply chain, the raw fiber production costs (harvesting, chipping, transport to pellet mill), processing (heating, electricity, labor etc.) and shipping are the three most expensive activities. Raw fiber production and processing sum up to 75% of the total costs, while the distribution makes up the remaining 25%.

![Cost distribution per activity for the supply chain of black pellets from Sweden to Denmark](image)

The GHG emissions from the black and white pellets were found to be 15.0 and 16.7 kgCO₂eq/MWh product respectively, which is shown in Figure 24. Highest emission per MWh product comes from the processing, which can be explained by the use of natural gas heating in this data.

![GHG emissions for black and white pellets, from Sweden to Denmark](image)

The total energy input was 618.6 MJ/MWh product for white pellets and 613.7 MJ/MWh for black pellets, as shown in Table 10. Most energy per MWh product is put into the process, where the biomass is dried and torrefied.
### Table 10. Energy input in MJ per MWh product for black and white pellets, from Sweden to Denmark

<table>
<thead>
<tr>
<th></th>
<th>White pellets</th>
<th>Black pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw fiber production</td>
<td>9.9</td>
<td>9.9</td>
</tr>
<tr>
<td>Processing</td>
<td>573.3</td>
<td>578.0</td>
</tr>
<tr>
<td>Transport to port</td>
<td>11.3</td>
<td>8.8</td>
</tr>
<tr>
<td>Load port handling &amp; storage</td>
<td>3.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Shipping</td>
<td>9.1</td>
<td>6.1</td>
</tr>
<tr>
<td>Receiving port handling &amp; storage</td>
<td>3.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Transport to final user</td>
<td>7.4</td>
<td>5.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>618.6</strong></td>
<td><strong>613.7</strong></td>
</tr>
</tbody>
</table>

### 6.2 Case 2 - USA to the Netherlands

With one of the lowest feedstock costs in the world, southeastern USA has become a significant exporter of wood pellets to fulfill the increasing demand from Europe. The east coast has large ports with good infrastructure for biomass handling.

Regardless of the lack of native forest assets, the Netherlands has been one of the leading countries in conversion from coal to biomass, almost all of it imported. The port of Rotterdam is one of the largest in the world and has excellent infrastructure for biomass handling.

This case will study a pellet plant in Tifton, Georgia, with 100 000 ton annual production. The pellets are transported by rail 149 km to the port of Savannah where it is transshipped to a Handymax ship with 45 kton capacity. It is shipped 8709 km to the Port of Rotterdam, from where it is shipped by truck the last 55 km to a combined coal and biomass plant in Geertruidenberg.

The cost of delivering pellet from Tifton in USA to Geertruidenberg in the Netherlands is 27.6 €/MWh for white pellets and 24.7 €/MWh for black pellets. The difference is 12% in the favor of black pellets. An illustration of the cost per activity is presented in Figure 25.

![Figure 25. Costs in €/MWh product for the supply chain from USA to the Netherlands](image-url)
The raw fibre production, processing and shipping are the most expensive parts of the supply chain. A pie chart with the cost distribution for the activities is presented in Figure 26 below.

**Figure 26. Cost distribution per activity for the supply chain from USA to the Netherlands**

The GHG emissions from the black and white pellets were found to be 20.8 and 21.1 kgCO₂eq respectively, which is shown in Figure 27.

**Figure 27. GHG emissions for black and white pellets, from USA to the Netherlands**

The total energy input was 673.3 MJ/MWh product for white pellets and 651.4 MJ/MWh for black pellets, as shown in Table 11.
Table 11. Energy input in MJ per MWh product for black and white pellets, from USA to the Netherlands

<table>
<thead>
<tr>
<th></th>
<th>White pellets</th>
<th>Black pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw fiber production</td>
<td>9.9</td>
<td>9.9</td>
</tr>
<tr>
<td>Processing</td>
<td>573.3</td>
<td>578.0</td>
</tr>
<tr>
<td>Transport to port</td>
<td>11.1</td>
<td>8.7</td>
</tr>
<tr>
<td>Load port handling &amp; storage</td>
<td>3.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Shipping</td>
<td>52.8</td>
<td>35.3</td>
</tr>
<tr>
<td>Receiving port handling &amp; storage</td>
<td>3.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Transport to final user</td>
<td>18.6</td>
<td>14.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>673.3</strong></td>
<td><strong>651.4</strong></td>
</tr>
</tbody>
</table>

6.3 Summary of the case studies

A summary of the results are presented in the figures below, where Figure 28 presents the total supply chain costs, Figure 29 the GHG emissions and Figure 30 the energy input. The costs are lower for black than white pellets within the cases, but because of the low feedstock price in USA, white pellets can be delivered to a lower price than black pellets from Sweden.

Figure 28. Summarized supply chain costs for the case study
The carbon emissions mainly come from the processing and the shipping, where there is a significant difference between the two cases. With 50% more energy per volume, transport of black pellets causes much less GHG emissions than transport of white pellets, but the emissions from the production in somewhat higher due to higher energy input, as illustrated in Figure 29.

![Figure 29. Summarized supply chain GHG emissions for the case study](image)

The energy required for the processing account for the highest energy input during the supply chain. An explanation to the difference between these results for energy input in Figure 30 and the results for GHG emission in Figure 29 is that electricity and heating has much lower GHG intensity, i.e. the emissions per unit energy input is lower.

![Figure 30. Summarized supply chain energy input for the case study](image)
7 Discussion

7.1 The supply chain model

The objective of this study was to “identify important parameters in the biomass supply chain and develop a model with data for analyzing the cost, energy input and GHG emissions from feedstock to end user of black and white pellets”. The resulting model contains a database with country specific prices for feedstock, transport and processing cost, which fulfills the purpose of identifying the parameters. The model uses the data to calculate the cost, energy input and GHG emission for black and white pellets, and present the results in a comprehensible way.

The main sources of errors are not in the rather rudimentary calculations, but in the input data. As discussed in the method, no model is better than its input data and some of the required data has been difficult to find from a reliable source. This is primarily in regard to the data for feedstock price, the single most important variable for the total costs. There is no, for example, “South Africa wood chip price”, but rather a “wood chip price for the southeast Gauteng province in April 2014” which was purchased at different prices for different type of contracts.

The time aspect is of great importance when discussing the validity of this model. Some of the data used are over a year old and has historically been very volatile. There are uncertainties with how these has changed since, and above all a question regarding how they will change in the future. Price volatility for shipping has been discussed in Chapter 4.2.3, and a sudden change could quickly make the model outdated, as will future changes in transport fuel price. This is unavoidable, but the model has been made easy to adjust when market conditions change.

A way to test the validity of the model was to compare the results to actual market data for the CIF price for white pellets in Rotterdam (see Chapter 7.2). The result is a 3% difference, although the cost distributions for supply, process and distribution had bigger variations (up to 15%) within this difference. A comparison to earlier studies was also performed, but the fact that others have reached similar results with Excel models is no guarantee of the model being accurate. Furthermore, some data in this model was obtained from those earlier studies making the comparison of limited value for ensuring validity.

As the prices for feedstock and logistics for white and black pellets are based on the same assumptions, potential errors can be assumed to be systematic. Thus, the comparison between the two alternatives can be assumed to be more accurate than the actual price for delivering pellets to an end user. However, as the price is a function of the production cost and the transport distance there is still risk for inaccuracies.
7.2 The case studies

Despite the distance for the USA to the Netherlands case (Case 2) being almost five times as long as for the Sweden to Denmark case (Case 1), the significantly lower feedstock price result in a 21% lower delivered cost for the longer distance USA case. The low costs of transporting goods in the large Handymax ships also has a significant impact on the lower delivered cost, which is not as beneficial for the Sweden to Denmark case due to the limited capacity of the available ports.

Case 1 can be compared to a study by Svanberg et al [18], who calculated the cost of delivering black pellets under Swedish conditions. The result was a total price of 31.8 €/MWh, of which 18.9 €/MWh was feedstock supply, 9.9 €/MWh processing and 2.8 €/MWh distribution. The result from this study found the price of delivering black pellets to be 33.0 €/MWh, of which feedstock supply/processing/distribution was 16.0/8.5/8.5 €/MWh. The shipping distance is much longer in this study and has more transshipment, which can explain the higher distributions costs. The cost for feedstock supply can be explained by different methodological approaches, and to some degree potentially changed market prices with low wood chip prices after a warm winter in Sweden 2013/2014 [71].

Case 2 can be compared to the actual market CIF price for white pellets in Rotterdam, which was 27.4 €/MWh for Q1 2014 [72]. This study show a cost of delivering white pellets to Rotterdam of 25.6 €/MWh, which would give a not unreasonable profit margin of 7% (the profit margin in the logging industry is on average 2.5%, but generally higher in the energy industry [44]). Hawkins Wright analyzed a similar supply chain in 2013, with the result of a black pellet cost to Rotterdam being 28.4 €/MWh [16] which is 9% higher than the results from this study. The difference can mostly be explained by a lower process cost calculated in this model, possibly a result from advantages in BioEndevs technology. However, the details of the assumptions in Hawkins Wrights’ calculations are insufficient to make any definite conclusions. Hawkins Wright also has somewhat higher distribution costs, which may originate from changed market conditions and/or assumptions regarding back haul for all transport types.

Looking at the distribution of the costs for the different activities, there are interesting differences between the two cases. For Case 1, feedstock supply and processing together makes up 75% of total costs, compared to 62% for Case 2.

Due to the longer shipping distance and the relatively high GHG intensity of ocean shipping, the total GHG emissions are lower for transporting between Sweden and Denmark than from USA to the Netherlands. If GHG calculations were based on country specific CO₂ intensity for electricity, the difference would be even more pronounced. From a GHG perspective, a shorter supply chain seems to be a better alternative.

7.3 Black vs. White Pellets

In this study, the cost of delivering black and white pellets have been compared for two different cases. For transatlantic import, black pellets were 12% more cost efficient than white pellets. For a shorter transport distance but from a country with high feedstock prices, black pellets was found to be 7% more cost efficient than white pellets. Within the delimitations and assumptions made in this study, there is no doubt black pellets is a superior alternative to white pellets with BioEndevs technology and that the supply chain effects from torrefaction is an
added value. From the results, it can be assumed that longer transport distances increase the advantages for black pellets.

In addition to the cost savings for black pellets examined in this study, there are savings for the consumer not considered in the model. These depend on the end user application, existing infrastructure and handling systems, but has been suggested to be as high as a 5€/MWh cost saving in the specific case of co-firing with coal [20]. In this study, the supply of feedstock and the processing are the most expensive activities, both for the intercontinental (Case 2) and the intracontinental (Case 1) supply chains. Therefore, effort should be put into reducing CAPEX and OPEX for the process to lower the refinement cost and to find less expensive feedstocks. With feedstock cost being very dependent on geography and competition, portable torrefaction units might be a good idea for BioEndev to investigate.

So, if black pellets are superior in terms of costs and GHG emissions, why are they not already a commodity competing with white pellets? The answer is simple; torrefaction is a difficult process to control and has yet succeeded in commercial scale.

As the GHG emissions from coal combustion is a strong driver for the development of biomass refinement methods, another interesting discussion when comparing different fuels is the comparison between biomass pellets and coal. 41% of the coal consumed in Europe is imported, a large share to the port of Rotterdam [73], with a supply chain that resembles the supply chain for solid biomass to a large extent. The CIF price of coal in Rotterdam is 57 €/ton [72], which is about 7 €/MWh. Thus, black pellets, while having lower cost than white pellets to Rotterdam, are still over three times more expensive than coal (if political incentives and instruments not are considered). For biomass to replace coal in large scale at the present time, political incentives are required. Concerning the GHG emissions, the consumer application is of great importance. Compared to the approximate 20 kg CO₂ equivalents per MWh emitted from transport from USA to the Netherlands (Case 2), the savings from converting completely from coal to biomass in the Amer plant could decrease the total GHG emissions by 1000 kg CO₂ equivalents/MWh [74].

Based on the results in this the study, BioEndev is making a good decision pursuing plans to build a commercial torrefaction plant. In the long term, export of the technology to countries with low feedstock prices is a good strategy with today’s market conditions.

7.4 Recommendations for future work
This chapter will be divided into two separate parts: one discussing improvement possibilities for the model, and the other suggestions of separate research questions raised during this work.

7.4.1 Development possibilities of the model
Due to the limited time frame of this thesis, there is room for improvement of this model. During the model development, assumptions and simplifications were made to achieve a functioning model. Therefore, it should be further developed to contain more options and accuracy. Most urgent is implementation of cost saving possibilities by integration of the torrefaction and pelletizing processes with other industries or district heating, and making different end user applications available to be included. The latter is difficult because the cost saving is different depending on whether the product is used for industrial applications like steel or cement production or if it is used in co-firing with coal. For both cases, the existing handling
system must be accounted for, so this is a process that should be performed in small steps, one at the time.

The database will always be a subject for readjustments as feedstock and logistics prices will vary over time. Although the prices can be entered manually without using the database, I suggest updating the database whenever possible to retain the ability to make fast approximations.

More options for torrefaction operating decisions can be added. The torrefaction degree is dependent on supply chain and customer requirements and affects the energy consumption. The data for energy input and GHG emissions are simplified in this model. To improve results, these should be investigated further and especially adapted to country specific emission intensity for heating and electricity.

More geographical options can also be added. For example, Australia, New Zealand, Chile and Argentina are areas with good supply of biomass and are interesting producer options. Although Europe is the main consumer of biomass today, Japan, South Korea and maybe even China may be interesting options as consumers in the model.

More options for handling and transport may also be added. For example, different costs for pneumatic handling and conveyors and the exact prices for different ports could be used instead of using generalized approximation from secondary data. A wider range of trucks with different load capacities could be added, as well as ability to choose the backhaul utilization.

The model can also be improved to determine the profitability of a torrefaction plant. Choices for financing, market price for black pellets and financial risk should then be implemented.

7.4.2 Further research questions
In this study, white and black pellets have been compared. An interesting addition to this would be a comparison to the value chain of coal, to see how big the difference in price is between refined biomass and coal and from where in the supply chain these differences are derived. The regional subsidies making biomass cheaper or coal more expensive should be taken into consideration.

Costs and benefits for the end user were excluded from this study. Except from incorporating it into the model, a comprehensive assessment of savings for different types of end users would fill a knowledge gap in the torrefaction value chain.

To evaluate the possibilities in making more economic benefits from the torrefaction gas is an important task. The gas can be transformed to liquid fuels or green chemicals, which has a higher product value. If the torrefaction process can generate both wood pellets with high quality and renewable liquid fuels, it has implication on the supply chain from both an economic and environmental perspective.
8 Conclusion

The model developed for analyzing supply chain costs, energy input and GHG emissions with BioEndevs technology is fully functional, easy to use and the result are acceptably consistent with earlier studies on biomass supply chains and market prices.

If black pellets are produced in commercial scale, at the assumed costs and with the promised product quality, they will be more cost efficient than white pellets with BioEndevs technology (without considering the additional savings at the end user). However, there is still a significant gap to the CIF price of coal with the current economic instruments and incentives.

The advantages of black pellets increase with longer distribution distance. As the import of white pellets is increasing, the opportunities for long distance supply chains of black pellets are significant and should be interesting to BioEndev.

Feedstock and processing are the most expensive parts of the supply chain, and efforts should be directed toward reducing these in order to achieve optimal production and distribution costs for black pellets.

With the results and discussions above, recommendations to BioEndev from a supply chain perspective are to:

- Export the technology to countries with low feedstock prices when the technology has been proved in commercial scale.
- Focus on finding solutions to the backhaul problem when distributing black pellets.
- Investigate the opportunity to build mobile torrefaction units that could continuously realize the cheapest possible feedstock available at a certain time.
- Aim to achieve a high bulk density of the pellets, but do not bother to reach over the limiting bulk density for Handymax ships (between 750-800 kg/m$^3$).
9 References


Appendix I

Input table

<table>
<thead>
<tr>
<th>Location data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock location</td>
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<td>End user location</td>
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<tr>
<td>Mass yield (torrefaction)</td>
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<tr>
<td>Heating price</td>
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<td>Water price</td>
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<tr>
<td>Maintenance, % of inv.</td>
<td></td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Insurance, % of investment</td>
<td></td>
<td>%</td>
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</tr>
<tr>
<td>Inventory turnover</td>
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<td></td>
</tr>
<tr>
<td>Depreciation time</td>
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<tr>
<td>Bulk density</td>
<td></td>
<td>kg/m³</td>
</tr>
<tr>
<td>Energy density</td>
<td></td>
<td>GJ/m³</td>
</tr>
<tr>
<td>White pellets</td>
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<td></td>
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<tr>
<td>Bulk density</td>
<td></td>
<td>kg/m³</td>
</tr>
<tr>
<td>Energy density</td>
<td></td>
<td>GJ/m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Logistics</th>
<th>Default</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Primary transport</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport method</td>
<td></td>
<td>km</td>
</tr>
<tr>
<td>Distance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rail km cost</td>
<td></td>
<td>€/(ton*km)</td>
</tr>
<tr>
<td>Secondary transport</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport method</td>
<td></td>
<td>km</td>
</tr>
<tr>
<td>Distance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost per km</td>
<td></td>
<td>€/(ton*km)</td>
</tr>
<tr>
<td>Shipping</td>
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<tr>
<td>Ship type</td>
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<td>Capacity</td>
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<tr>
<td>Distance</td>
<td></td>
<td>km</td>
</tr>
<tr>
<td>Cost per km</td>
<td></td>
<td>€/(ton*km)</td>
</tr>
<tr>
<td>Tertiary transport</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport method</td>
<td></td>
<td>km</td>
</tr>
<tr>
<td>Distance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost per km</td>
<td></td>
<td>€/(ton*km)</td>
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</table>

Figure 1. Empty input table
### Figure 2. The database used in the model

<table>
<thead>
<tr>
<th>Export countries</th>
<th>Import countries</th>
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<tbody>
<tr>
<td>Brazil</td>
<td>Russia</td>
</tr>
<tr>
<td>Feedstock:</td>
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<tr>
<td>Wood chips</td>
<td>18.5</td>
</tr>
<tr>
<td>Recovered wood</td>
<td>n.a.</td>
</tr>
<tr>
<td>Solid by-products</td>
<td>n.a.</td>
</tr>
<tr>
<td>Sawdust</td>
<td>n.a.</td>
</tr>
<tr>
<td>Truck:</td>
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<tr>
<td>C/ton</td>
<td>0.38</td>
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<tr>
<td>Truck loading:</td>
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</tr>
<tr>
<td>€/ton</td>
<td>1.4</td>
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<tr>
<td>Rail:</td>
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</tr>
<tr>
<td>C/ton</td>
<td>0.02756825</td>
</tr>
<tr>
<td>Rail handling:</td>
<td></td>
</tr>
<tr>
<td>C/ton</td>
<td>1.38</td>
</tr>
<tr>
<td>Handling at export port:</td>
<td></td>
</tr>
<tr>
<td>€/ton</td>
<td>8.95</td>
</tr>
<tr>
<td>Handling at import port:</td>
<td></td>
</tr>
<tr>
<td>€/ton</td>
<td>n.a.</td>
</tr>
<tr>
<td>Storage:</td>
<td></td>
</tr>
<tr>
<td>Handysize (45 kton)</td>
<td>0.00015</td>
</tr>
<tr>
<td>Handysize (20 kton)</td>
<td>0.0013</td>
</tr>
<tr>
<td>Small vessel</td>
<td>0.0016</td>
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<tr>
<td>Cost per km:</td>
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</tr>
<tr>
<td>€/MWh</td>
<td>0.69</td>
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<tr>
<td>Cost of labour:</td>
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<tr>
<td>€/MWh</td>
<td>n.a.</td>
</tr>
<tr>
<td>Electricity price:</td>
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</tr>
<tr>
<td>€/MWh</td>
<td>6.5</td>
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<tr>
<td>Heating price:</td>
<td></td>
</tr>
<tr>
<td>€/MWh</td>
<td>22</td>
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<tr>
<td>Water price:</td>
<td></td>
</tr>
<tr>
<td>€/MWh</td>
<td>0.22</td>
</tr>
</tbody>
</table>

### Figure 3. The Supply Chain Calculations sheet
Figure 4. An example of the Result sheet

Figure 5. Calculations sheet for black pellet production costs