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A Torrefied Wood Pellet Supply Chain

A detailed cost analysis of the competitiveness of torrefied wood pellets compared to white wood pellets

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Disclaimer

This study has been performed at the companies RWE Generation NL and Blackwood Technology BV and some of the information contained in this report is confidential and is only intended for the involved parties. The confidential data is therefore left out of the public version and replaced by ''conf''.

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Abstract

The growing global demand for energy continuous to increase the pressure on scarce fossil resources and the environment. This trend calls for the further development of renewable energy sources, including biomass. In order to achieve the national 2020 goals, the use of biomass becomes unavoidable, since it can directly replace coal at the power plant. The Amer Bio CHP plant, is the former Amer 9 coal power plant and is now transformed to a biomass power plant. This study presents a detailed cost analysis to assess the cost competitiveness of torrefied wood pellets compared to white wood pellets. This analysis could help optimize the allocation of the government SDE+ subsidies, which are currently indispensable to introduce and support biomass.

The goal for the optimization of coal replacement at the power plant is to develop a solid biomass product with coal like structures. This can be accomplished with torrefaction. Torrefaction is a thermal process, producing a biomass product with a higher energy density, bulk density and hydrophobicity, resulting in significant advantages in logistics, storage and processing. For the comparison of the white wood pellets and torrefied pellets, a supply chain model was developed, focusing on the cost structure from the harvesting of the biomass up to the boiler at the power plant.

A specific case study has been analyzed, from production of the pellets at Georgia Biomass LLC (Waycross, US), up to the processing at the Amer Bio CHP plant of RWE (Geertruidenberg, NL). Two torrefaction scenarios were assumed. A scenario with *equal* feedstock input costs and a scenario with *lower* feedstock input costs. For the specific case study, the white wood pellets could be supplied up to the quay of the Amer Bio CHP plant for €150 per tonne (dry). The torrefied wood pellets could be supplied for €166 (equal) and €155 (low) per tonne (dry). Expressing the costs in €/GJ, the pellets could be supplied for €8.8/GJ, €7.9/GJ and €7.4/GJ, respectively. The storage at the power plant and further processing up to the boiler resulted in the final costs for white wood pellets of €9/GJ and for torrefied wood pellets of €8/GJ (equal) and €7.5/GJ (low). Indicating a significant saving effect for torrefied wood pellets of €1/GJ or €1.5/GJ over the whole supply chain. This result could help support the future decision making in the biomass subsidy allocation.

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List of abbreviations/units

AEBIOM	European biomass association
ARA	Amsterdam, Rotterdam, Antwerp
BTS	Blackwood torrefaction system
CAPEX	Capital expenditures
CBS	Dutch Central Bureau of Statistics
CCS	Carbon capture and storage
CFR	Capital recovery factor
CIF	Cost, insurance and freight
DB	dry basis
ESP	Electrostatic precipitator
EU	European Union
FOB	Freight on board
GHG	Greenhouse gas
GJ	Gigajoule
IPCC	Intergovernmental panel on climate change
MIE	Minimum ignition energy
NCV	Net calorific value
NIMBY	Not in my backyard
OPEX	Operational expenditures
PBL	Netherlands environmental assessment agency
RES	Renewable energy sources
RTO	Regenerative thermal oxidizer
RVO	Netherlands enterprise organization
SMES	Super conducting magnetic energy storage
US	United States
VOC	Volatile organic compound

1. Introduction

1.1 Background

Today's world relies heavily on electricity to power its industries and homes. The growing global demand for energy increases the pressure on scarce fossil resources as well as the environment. This state calls for further development and use of renewable energy sources, including biomass. In this study, different forms of woody biomass for energy use are compared in order to assess their use in the production of heat and power and as a replacement of fossil resources like coal. This analysis could help optimize the allocation of the government subsidies, which are currently indispensable to introduce and support biomass.

Presented in the Energy Agreement for Sustainable Growth report, the Dutch government aims to increase the share of renewables from 5.6% in 2014 to 14% in 2020 (SER, 2013; CBS, 2015). The government therefore is creating a more favorable investment climate and increases possibilities for renewable technologies e.g. by the SDE and the SDE+ regulation (RVO, 2016). These regulations are focused on distributing subsidies for renewable energy techniques (SER, 2013; ECN, 2014).

The Intergovernmental Panel on Climate Change (IPCC) 2014 report, stated that the burning of coal causes the highest CO_2 emissions compared to other fossil energy sources (IPCC, 2014). In order to achieve the 2020 goal of CO_2 emission reduction, the Dutch government had therefore ordered the closure of older coal power plants in the last two years and was planning to close additional coal power plants, including the Amer 9 power plant. This, however, would have proven insufficient to meet the climate goals (ECN, 2015a). RWE proposed instead to replace the coal at the Amer power plant[1] with biomass, and to increase the co-firing of biomass to 50% in the course of 2017 and to further increase it to 80% in the subsequent years (M. Bouwmeester[2], personal communication, September 13, 2016). Coal replacement by CO_2 neutral biomass could significantly contribute to the reduction of CO_2 emissions at the Amer Bio CHP plant.

From the Dutch government, the use of biomass for co-firing is stimulated in the form of subsidies in the SDE+ regulation (RVO, 2016). Subsidies that have been granted to RWE. This is where biomass could play an essential role in replacing coal. Biomass for energy use and even as material for further chemical applications, this latter however will not be discussed in this study. The national effort to decrease the emitted CO_2 emissions is an important factor in the development and continuation of the business case of power plants like the Amer Bio CHP plant. Coal replacement with biomass, is a sustainable option to substitute coal directly at the power plant. Moreover, the term co-firing seems misplaced if the share of biomass reaches up to 50%, 80% or even 100%.

Biomass for energy use is a wide concept and is described as a term for all organic material directly from plants or trees, or indirectly from plant-derived industrial, commercial or urban waste, or agricultural and forestry residues (Kurchania, 2012). Due to the different types and characteristics of biomass, it can be difficult and costly to process biomass at power plants designed for processing coal (M. Bouwmeester, personal communication, March 13, 2017; McKendry, 2002). Therefore, in order to be able to replace the coal and process the biomass at the Amer Bio CHP plant, the goal is to create a more coal like biomass product. A technology to produce a more coal like and high-grade solid biomass product is called torrefaction (Blackwood, 2017). This pre-treatment technology ensures a more coal like structure of the biomass because it increases the bulk density, energy density, durability and hydrophobicity (Blackwood, 2016a).

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[1] From April 11, 2017, the Amer 9 power plant has been converted to the Amer Bio CHP plant.

[2] M. Bouwmeester. Process Technologist, RWE Generation NL

Blackwood Technology BV is one of the companies that owns a leading and award-winning torrefaction technology, the *Blackwood Torrefaction System* (BTS). The goal of Blackwood is a worldwide roll-out of their technology. The BTS is used to produce torrefied wood pellets, a more coal like and durable biomass product with an improved hydrophobicity and usability. The combination of torrefaction and pelletizing results in the fact that the higher production costs due to the torrefaction units could potentially be offset by the lower electricity costs, transportation costs, storage costs and handling costs, which could result in a lower product price compared to white wood pellets. However, this depends on several cost components along the supply chain (Wild et al., 2016; Bergman and Kiel, 2005). Torrefied wood pellets could therefore be more cost efficient in replacing coal at power plants compared to white wood pellets.

The process of making the biomass suitable for processing requires high costs. For European countries like the Netherlands, it is indicated that it is more cost effective to import biomass from e.g. the US, than using expensive domestic resources (Hoefnagels et al., 2014a). Consequently, subsidies are required and stimulate that despite high costs, the biomass is made suitable for processing. This results in the supply chain presented in Figure 1.

Figure 1. The wood pellet supply chain

Earlier studies from Batidzirai et al. (2013) and Bergman and Kiel (2005), also presented that torrefied biomass has an improved quality compared to other biomass types. However, the study of Batidzirai et al. (2013) indicates that there are still uncertainties regarding the final characteristics of torrefied pellets. The torrefaction process improves e.g. the grindability and hydrophobicity, however, it is not clear to what extent. And precisely this data is of use for the application of commercial scale torrefied wood pellet production and for the replacement of coal.

Uslu et al. (2008) examined three different pre-treatment technologies including torrefaction, and the effect they have on the supply chain logistics. Their results presented a significant cost difference for torrefied pellets caused by transporting advantages. The advantages however, only apply when the torrefaction technology is combined with pelletization. Torrefied biomass has a low bulk density of 230 kg/ton, while torrefied and pelletized biomass has a bulk density of 750 kg/ton, reducing the transport costs (Uslu et al., 2008; Blackwood, 2016b).

1.2 Research aim

Extensive research has been done focusing on the torrefaction process. However, the effect of a torrefied wood pellet supply chain for cofiring at coal power plant is still somewhat underexposed. The development of the most optimal coal-look-a-like biomass product appears to be difficult. Therefore, the torrefaction process itself has been given a lot of attention and the next step, the changes and requirements in the supply chain are still underexposed. This study provides insight in this knowledge gap. Due to the cooperation of RWE Generation NL and Blackwood in this study, the total supply chain from tree to electricity is covered.

The aim of this study is to create a detailed cost structure of the white wood pellet and torrefied wood pellet supply chain and to calculate the final price, in euro per gigajoule. The detailed supply chain cost analysis will be covering the harvesting of the biomass up to the boiler at the power plant. The focus of this study is to provide new knowledge of the biomass (logistical) supply chain and the economic effect torrefaction will have on the supply chain compared to white wood pellets.

The added value of this study results from the fact that this study is focused on one specific supply chain and provides a detailed cost comparison based on practical data from white wood pellets use for energy and on torrefaction experience. This offers the possibility to a detailed analysis of the possible adjustments that are required along the supply chain.

In this study, the following research question will be addressed:

To what extent are torrefied wood pellets competitive compared to white wood pellets and what is the economic effect of a torrefied wood pellet supply chain for RWE's Amer Bio CHP plant?

In order to answer this research question, the following sub-questions are formulated:

1. What are the differences between white wood pellets and torrefied wood pellets and how do these affect the biomass supply chain?
2. What is the difference in production cost for white wood pellets and torrefied wood pellets under different feedstock input cost scenarios?
3. What are the required investments at the pellet plant for the production of white wood pellets and torrefied wood pellets?
4. What are the required investments at the power plant for the processing of white wood pellets and torrefied wood pellets?
5. What is the tipping point for torrefied wood pellets to be cost-effective compared to white wood pellets?

1.3 Scientific relevance

This study indicates the potential of torrefied wood pellet supply chains compared to existing white wood pellet supply chains. Extensive research has been done and is still being done regarding energy production from biomass, including assessments on what type of biomass is the most optimal and how to use it as efficient as possible. One of the problems with the current biomass pellets is the fact that they have a narrow feedstock type, i.e. there is a restricted range of the type of plants, trees or waste that can be used (Wild et al., 2016). For this, torrefaction could be a promising technology since torrefied biomass can be produced from a wider variety of biomass feedstock which can potentially lower the feedstock price (Kurchania, 2012). Therefore, torrefaction could make it possible for more biomass sources to be used as an energy source and lower the feedstock input cost.

The production costs of torrefied wood pellets increase due to the required pre-treatment process investments, the report of Blackwood (2016a) states that the transportation costs, storage costs and feedstock costs decrease. This potentially results in a lower product price for torrefied wood pellets than white wood pellets. This report could provide insight in this statement and could contribute to the indication of the economic effects of a torrefied wood pellet supply chain.

In this study, the combination of involved companies is excellent to perform the detailed cost analysis. Blackwood Technology BV, as producer of torrefied wood pellets and RWE Generation NL, as (large-scale) end-user of wood pellets, create a feasible combination to assess the potential of the torrefied pellets for coal replacement at the Amer Bio CHP plant. The result of this report could help support in the decision making of using white wood pellet or torrefied wood pellets at the Amer Bio CHP plant and the allocation of granted SDE+ subsidies.

2. Theory

2.1 Biomass

Biomass is not only a scientific term for living matter, the word biomass is also used to refer to products derived from living organisms (Kurchania, 2012). These biomass resource include organic materials obtained from agricultural crops, forest products, aquatic plants, residues, manures an wastes. For potential bioenergy there are two main resource types: biomass from agriculture and forestry (Haberl et al., 2010; Hoogwijk et al., 2003). Substituting coal by biomass can reduce the CO_2 emissions from power plants, since biomass is considered carbon neutral[3] (Tumuluru et al., 2012). The worldwide importance of biomass for power generation is increasing and biomass is recognized to be one of the main renewable energy sources (RES) for achieving EU energy and climate targets (Tumuluru et al., 2012; Bertrand et al., 2014). Currently, biomass is co-fired in the form of white wood pellets (Figure 4-A). However, the use of biomass for power generation is facing different challenges, including feedstock supply, quality, stability and comparative cost. Moreover, before biomass can be more efficiently stored, transported or co-fired at plants specifically designed for fossil fuels, it requires a pre-processing treatment (Tumuluru et al., 2012).

Earlier studies indicated an already growing trend in biomass use. According to Wild et al. (2016), the global pellet production increased from 3 million tonne in 2003 to 27 million tonne in 2014. And the European Biomass Association (AEBIOM) expects the total pellet demand in the European Union to reach 50 to 80 million tonne by 2020 (AEBIOM, 2011). A study from Hiegl and Janssen (2009) presented that in the EU the high quality biomass production, mostly for residential use, is covered by domestic production. While the industrial pellet production already depends partly on import. Hoefnagels et al. (2014a) presented in their study that, under different renewable energy supporting scenarios, this trend will continue up to 2020.

2.2 The Biomass Supply Chain

The biomass supply chain (Figure 2) is focused on processing raw material into a high value energy product. The biomass moves from one part in the chain to another, while being transformed into energy dense pellets and delivered to end-users. The biomass supply chain covers every component in the production of the white wood and torrefied wood pellets, including the logistics. Due to the significant role of the logistics in the biomass supply chain, and the impact torrefaction has on the logistics, torrefaction can have a considerable impact on the costs (Searcy et al., 2016).

The biomass supply chain (Figure 2) has the following structure: the first step is the harvesting of woody biomass. The harvested biomass is transported to a pellet plant. To reduce the handling and transportation costs, both the bulk density and energy density are maximized by drying, pelletizing and possibly torrefaction. The pellets are transported by truck or railcars to a loading port, the type of transport depends on the distance. At this port the pellets are stored and loaded on to the ocean cargo vessels (e.g. Handymax or Panamax). Then, the pellets are shipped to a receiving port. At the receiving port, the pellets are transshipped into trucks, railcars or barges, and transported to the end-user. Here the pellets are unloaded, stored and processed (Uslu et al., 2008; Hawkins Wright, 2012).

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[3] It is a fundamental requirement that the carbon release from harvesting is completely offset by forest (re)growth (WBCSD, 2015).

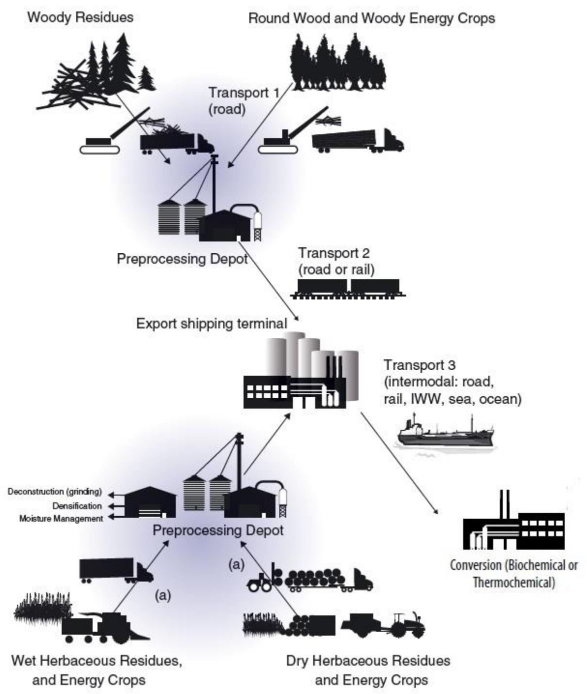

Figure 2. Biomass supply chain components
(Source: edited from Searcy et al., 2015 and Hoefnagels et al., 2014b).

It is indicated by a study from Hoefnagels et al. (2014a), that it is only cost effective for forest-rich countries to exploit the domestic biomass resources. For other European countries e.g. Germany and the Netherlands, it is indicated that it is more cost effective to import biomass than using more expensive domestic resources. Due to the lack of cheap European biomass, the Dutch biomass supply chain is internationally focused (Figure 3). Therefore, the transportation component in the biomass supply chain covers the transportation of biomass and pellets at different international stages.

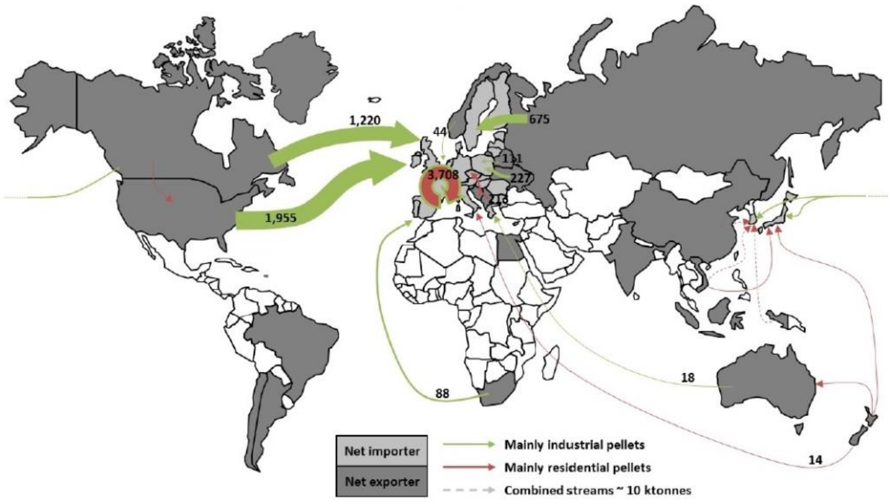

Figure 3. International wood pellet trading streams in 2012
(Source: Lamers et al., 2014)

2.3 Torrefaction

Considering biomass as a fuel has certain limitations. Raw biomass has a high moisture content, low bulk density, low calorific value and is easy to degrade (Tumuluru and Hess, 2015). In order to upgrade biomass, there are different pre-processing treatments. One of these treatment technologies is torrefaction.

Torrefaction is a thermo-chemical process that takes place under oxygen-free conditions within a temperature range of approximately 200 to 300°C (Obernberger and Thek, 2010a; Tumuluru and Hess, 2015). This creates an environment hot enough to almost completely dry the biomass an produce chemical changes. During the process (Figure 5) the biomass loses its strength by breaking up the hemi-celluloses (part C of Figure 5) and becomes more brittle due to the partial depolymerisation of the cellulose (part D of Figure 5) (Bergman et al., 2005; Obernberger and Thek, 2010a). While the lignin is largely retained during the process, even increases in share due to the mass loss of the biomass, and acts like a binder (Obernberger and Thek, 2010a).


A: White wood pellets

B: Wood chips

C: Torrefied wood pellets

Figure 4. Different types of biomass

The pre-treatment process consists of different temperature stages (Tumuluru and Hess, 2015; Wild et al., 2016). The first stage, at temperatures of 50 to 150°C, loses the water in the biomass and therefore reduces the material's overall bulk density. During the second stage, at temperatures of 150 to 200°C, hydrogen and carbon bonds begin to break. This eliminates the water that is stored in the plant's micropores, which causes the biomass to lose its fibrous nature. This makes the torrefied biomass more brittle and therefore easier to grind.

Finally, the third stage takes place at temperatures of 200 to 300°C, this stage is also referred to as the torrefaction range. At this stage, the biomass has lost most of its moisture, while it retained most of its calorific value and now the biomass experiences chemical changes. Carbonization and devolatilization occurs and the biomass acquires characteristics similar to coal (Table 1). During this last process off-gases are emitted, these are being recycled and used to help power the torrefaction process. The emission of the off-gases during the torrefaction process ensures safer transportation and combustion, due to the fact that volatiles are not emitted into the atmosphere (Searcy et al., 2016; Tumuluru and Hess, 2015).

Results from earlier studies on torrefaction , including a study by Bergman et al. (2005) and test results from Blackwood's own research (Blackwood, 2016ab), indicate that the torrefaction process results in a biomass product, which is more suitable for co-firing applications. The torrefaction technology improves the grindability of the biomass pellets significantly, therefore, the torrefied wood pellets can be used as fuel in almost any type of conventional coal power plant. (Bergman et al., 2005; Simmons et al., 2008; T. Chopin[4], personal communication, September 13, 2016).

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[4] T. Chopin, CFO – Managing Director Blackwood Technology BV.

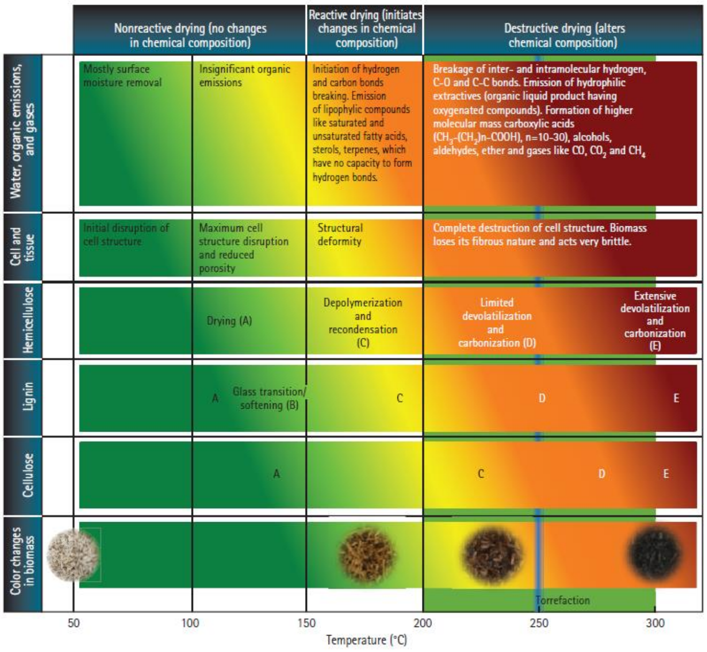

Figure 5. The chemical and structural changes of biomass at different process temperatures
(Source: Tumuluru et al, 2011 (modified version of Bergman et al., 2005)).

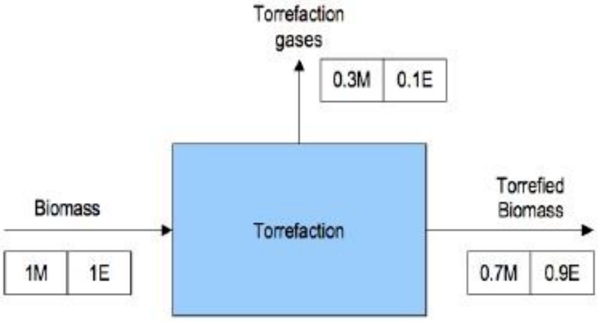

Figure 6. Mass and Energy balance of the torrefaction process. Symbols: M = mass unit, E = energy unit.
(Source: Bergman, 2005).

The end product of the torrefaction process, known as torrefied wood pellets (Figure 4-C), has approximately 70% of the initial weight and 90% of the original energy content (Figure 6). The other 30% of the weight is converted into 'torrefaction' gas, which only contains 10% of the biomass' initial energy (Bergman et al., 2005; Tumuluru et al., 2012). The advantages of torrefied pellets over white pellets, (Searcy et al., 2016; Tumuluru et al., 2012; Wild et al, 2016; Blackwood, 2016ab) resulting from the torrefaction process, can be listed as follows:

- Hydrophobicity
- Bulk density
- Calorific value
- Storage
- Feedstock
- Durability
- Handling (grindability)
- Biodegradability
- Ash and fines
- Explosiveness of dust

In Section 2.5, these characteristics are presented in more detail and in Table 1 an overview is presented of most of these advantages, comparing wood chips, white wood pellets, torrefied wood pellets and coal.

2.4 Pelletizing (compacting)

Biomass disintegrates easily during transportation and handling (Searcy et al., 2016). Therefore, densification of the torrefied biomass is required in the form of pelletization or briquetting. During the compaction or densification of the torrefied biomass, the potential hazardous dust is removed and the dust and fines production of torrefied pellets or briquettes during the loading, off-loading and conveying transportation is reduced (Wild et al., 2016; Kurchania, 2012). The key advantage of compaction, for example in the form of pelletization, is that it further increases the bulk density per volume, reaching a bulk density ranging from 650 to 800 kg/m^3 (Wild et al., 2016; Zwart et al., 2012). This results in lower transport and storage costs. Furthermore, pelletization further increases the grindability and handling, and therefore further facilitates coal replacement at power plants (Blackwood, 2016ab; Searcy et al., 2016).

2.5 Characteristics of white wood pellets and torrefied wood pellets

2.5.1 Calorific value

The heating value is defined as the amount of heat produced by the combustion of any amount of a unit of fuel (Lee et a., 2015). The calorific value is synonymous to the heating value, however, a differentiation is made between the gross and net calorific value. The net calorific value (NCV) is most commonly used for wood pellets and is defined as the energy released per unit mass (or volume) of the fuel, when the fuel is completely burned and when the water in the final product remains as vapour rather than condensed into liquid water, and thus the latent heat is not accounted for (Wild et al., 2016; Lee et al., 2015).

White pellets have a NCV ranging from 16 to 19 GJ/t (Searcy et al., 2016; Wild et al., 2016; Tumuluru et al., 2012). The NCV of torrefied wood pellets is determined by the type of feedstock and by the degree of torrefaction, i.e. the temperature and the duration time (Wild et al., 2016). Currently, after torrefaction and pelletization, torrefied wood pellets have a NCV in the range of 20 to 24 GJ/t (Searcy et al., 2016; Wild et al., 2016; Tumuluru et al., 2012). The relatively large range of these values can be the result of different initial moisture content and different torrefaction technologies. In this study a NCV of 17 GJ/t is assumed for white wood pellets and 21 GJ/t for torrefied wood pellets. This indicates the significant increase in NCV of torrefied and pelletized biomass. The exact NCV depends on feedstock properties and on the operating conditions of the process.

2.5.2 Bulk density

An important factor for biomass transportation is the bulk density (volume) (McKendry, 2002). With the compaction (pelletization) of the torrefied biomass, the bulk density (kg/m^3) is increased. Therefore, the maximum load per truck, train or ship increases, which has a significant influence on the transport and storage costs (Wild et al., 2016). With torrefaction and pelletization a bulk density is achieved ranging from 650 to 850 kg/m^3 (Searcy et al., 2016; Bergman 2005).

2.5.3 hydrophobicity

Raw biomass has a hydrophilic nature. In order to assure better fuel handling characteristic, biomass is made hydrophobic with torrefaction (Stelt et al., 2011; Uslu et al., 2008). The hydrophobicity of pellets is defined by the extent the pellets can withstand water, i.e. before cracks and rifts appear on the surface of the pellets (Blackwood, 2016a). Torrefied biomass is hydrophobic, however, in pellet or briquette form it is not necessarily waterproof (Searcy et al., 2016). The final hydrophobic quality is determined by the compacting process.

A pilot study (Blackwood, 2016a), conducted by Blackwood Technology B.V., focused on the outdoor storage of torrefied pellets, presented that torrefied pellets that were stored for more than one year in a warehouse did not show any representative increase in moisture content. The conditions in the covered, but not closed warehouse, varied from a humidity ranging from 48 to 100% and a temperature ranging from -10 to 38°C. These results demonstrate the hydrophobic properties when the pellets are not directly exposed to (rain)water. This slow degradation of torrefied pellets is an important factor in transportation and handling.

The pilot study was set up as two separate bags, each bag containing one ton of forest residue torrefied pellets. The two bags were exposed to outside weather conditions for one and two months. The results of the pilot study, present an increase in moisture content for the top layer of the torrefied wood pellets. The water percolates through the upper layer, degrading the top layer, creating a layer of fines. This layer of fines creates a buffer, isolating the pellets under it. The study (Blackwood, 2016a) shows that, although the top layer of the torrefied wood pellets suffered from the weather exposure, it still preserved the pellet shape instead of decomposing completely, as white pellets would after being exposed to outside weather conditions.

2.5.4 Storage

The storage of white wood or torrefied wood pellets is directly linked to the hydrophobicity. Torrefaction and pelletization have a significant effect on the storage of the pellets. Different studies (e.g. Wild et al., 2016; Blackwood, 2016b) presented the fact that white pellets cannot be stored outside, exposed to weather conditions, without degradation. Test results presented that the torrefied and pelletized pellets are much more resistant to the weather impact and remain their shape and. Therefore, while white pellets need storage facilities on site, e.g. silos, domes or bunkers. Torrefied wood pellets only require a basic storage investment consisting of a floor, four pillars and a roof. This result can have a significant impact on the storage costs (Hawkins Wright, 2012; Chopin, personal communication, 2017).

Another issue with the storage and also the transportation of biomass is self-heating and self-ignition due to exothermic reactions (Searcy et al., 2016). Causing the necessity for additional measurements in order to safely store and transport the biomass. After torrefaction, biomass is considered a nonhazardous product. Once cooled during the production process, no temperature increase are recorded during storage or transportation, which would imply that there is no requirement for special storage facilities (Searcy et al., 2016).

2.5.5 Feedstock

The torrefaction process results in the fact that also the bark can be used for the pellet production. Furthermore, are the feedstock cost for the torrefaction plant decreased, because due to the torrefaction process, less stringent requirements for the wood apply (Chopin, 2016).

2.5.6 Durability

The durability of pellets is an important factor for delivering pellets still in good shape. During the production processes, transport and further handling the torrefied pellets are exposed to dropping, crushing and friction, causing fractures and breaking of the pellets (Blackwood, 2016a). Tests by Wild et al. (2016) and Blackwood (2016a-b) present the importance of torrefaction and pelletization to increase the durability. The densification and the increase in share of lignin as a binder provide a pellet that can withstand handling and transportation.

2.5.7 Handling

Torrefaction has also an effect on the grindability of the biomass. The brittleness of the biomass is increased, and is therefore easier to grind and to handle at the power plant (Searcy et al., 2016). The increased grindability can result in different cost effects. For the torrefied pellets with an increased grindability, different, less heavy and cheaper hammer mills are necessary. However, the increased grindability can result in more dust generation, which results in more investments at the power plant e.g. a vacuum system above the conveyor belt (Wild et al., 2016; Blackwood, 2016a; Searcy et al., 2016).

2.5.8 Ash and fines

The ash content of torrefied pellets has a direct impact on the lifetime of certain equipment, e.g. the mills and the conveying system (Blackwood, 2016b). The average ash content ranges from 0.5 to 3% by wt, where this relatively large range is due to possible different biomass types (Searcy et al., 2016; Blackwood, 2016ab). As torrefaction increases the share of lignin in the torrefied biomass, the generation of fines is decreased. Lignin acts as a binder in the torrefied wood pellets (Blackwood, 2016b; Obernberger and Thek, 2010a). However, the generation of fines during milling is increased, resulting in the risk of causing explosions, as happens with wood dust (Wild et al., 2016).

2.5.9 Explosiveness of dust

Obernberger and Thek (2010a) describe the explosiveness of dust as a function of the particle concentration, oxygen concentration and the energy of the ignition source or the temperature of the heat on the dust. The explosiveness of the dust is classified by different parameters. The minimum ignition energy (MIE) is a guiding value to assess in which the electrical grounding has to be designed in order to avoid electrostatic ignition of the pellet dust (Obernberger and Thek, 2010a). In addition, the self-ignition temperature indicates the maximum temperature the pellet dust can be exposed to without the ignition as a result of heating (Obernberger and Thek, 2010a).

Under the TKI-BBE project, ECN has conducted different tests to determine the safety of white and torrefied pellets and pellet dust. The MIE was determined according to the European Standard EN 13821:2002 and the self-ignition temperature was determined using thermogravometric analysis (TGA) according to the European Standard EN 15188:2007 (ECN, 2015b). The results show that dust from torrefied pellets have MIE in the same range as dust from white pellets. Depending on the type of biomass, the MIE of torrefied pellet dust can be even lower than white pellet dust (ECN, 2015b). The test results also show that the self-ignition temperature of torrefied pellets is lower than for white pellets. There are however significant differences between different types of biomass (ECN, 2015b).

Table 1. Characteristics of the different biomass type: fresh wood, white wood pellets, torrefied wood pellets and coal

Property	Wood	White wood pellets	Torrefied wood pellets	Coal
Moisture content (% wt*)	40	10	3	12
Calorific value (GJ/t)	10	17	21	25
Bulk density (kg/m^3)	350	650	750	850
Energy density (GJ/m^3)	4	10	15	21
Ash content (% wt)	-	1	2	9.5
Hydrophobicity	hydrophilic	hydrophilic	hydrophobic	hydrophobic
Volatile matter (% wt db**)	80	80	60	22.5
Fixed carbon (% wt db)	20.5	20.5	28.5	52.5
Biological degradation	fast	moderate	slow	none
Milling requirements	special	special	standard	standard
Product consistency	limited	limited	high	high

*% wt: percentage by weight, **db: dry basis.
(Source: edited from: Searcy et al., 2016; Blackwood, 2016ab; Stelt et al., 2011; Bergman, 2005; Tumuluru et al., 2011; Kleinschmidt, 2011; Prins et al., 2006; Uslu et al., 2008 and Lensselink et al., 2008;).

The values in Table 1, represent the values based on Blackwood, RWE and Georgia Biomass, or an average from a range of different scientific literature sources.

3. Methodology and Data Input

3.1 Method

For the detailed cost analysis of white wood pellets and torrefied wood pellets, a (supply) chain analysis has been performed. This way, the pellet supply chain was divided into different components, creating a clear cost structure of all the different components and their influence on the final cost. In this study, the different cost components are divided over the supply chain presented in Figure 7. The supply chain is constructed out of the following components: harvesting, pellet production/torrefaction, transportation and processing. So, the analysis in this study contains the supply chain from the harvesting of the biomass up to the boiler at the power plant. The data obtained from the chain analysis was incorporated in an Excel model, which was used for the comparison of the detailed cost structure of the white wood pellets and torrefied wood pellets.

Figure 7. The case study specific pellet supply chain

For the analysis of the differences between white wood pellets and torrefied wood pellets, a clear framework with the characteristics was constructed. The focus of this assessment was on the structural improvements of torrefied wood pellets over white wood pellets, this includes among other things the bulk density, energy density, hydrophobicity, grindability and durability. The white wood pellet characteristics were determined using scientific literature. The torrefied wood pellets characteristics were determined using data from Blackwood. This data contained information of tests with torrefied pellets (Blackwood, 2016ab). Additionally, Blackwood's deliverable within the BiologikNL project, the *Torrefaction Demo Plant Model* was made available for this study.

Using a chain analysis, the pellet supply chain has been broken down to different cost components, indicating all steps from which the whole chain is constructed. The data collection for the input of this chain analysis is obtained from theoretical and practical data from RWE and Blackwood and also from expert assessments from people working at RWE, Blackwood, Innogy SE and Georgia Biomass LLC. If the data was not available due to e.g. confidentiality, it was obtained from scientific literature.

With Excel, the obtained data of the different cost components is modelled into a *Pellet Supply Chain Model*. With this model, the total cost (Equation 1) of the white wood pellet and torrefied wood pellets was calculated. The costs are expressed in euro per tonne and finally in euro per gigajoule, this way both the bulk density and energy density advantages of torrefied wood pellets are incorporated. All costs, if necessary, were converted from US $ to Euro, using the exchange rate presented in the Appendix (Table 14) and were corrected for inflation.

$$C_{total} = C_{FS} + C_P + C_{T1} + C_{S1} + C_{T2} + C_{tr} + C_{T3} + C_{S2} + C_G \quad [1]$$

Where:
C_{total} = total cost of the whole biomass supply chain
C_{Fs} = feedstock cost
C_P = production cost pellet process
C_{T1} = railway transport cost
C_{S1} = storage and handling at port of loading
C_{T2} = ocean transportation cost
C_{tr} = transshipment cost at port of receiving
C_{T3} = barge transport cost
C_{S2} = storage at power plant
C_G = cost associated with the processing of biomass at the power plant
*(all in € per tonne pellets (output)

The (specific) investment costs of the pellet plants are based on an annual production output of 750,000 tonne pellets and the (specific) investment costs of the power plant are based on a co-firing percentage of 50% or 1,000,000 tonne pellets. The costs of the supply chain are presented in the different stages: pellet production, FOB, CIF ARA, up to the power plant's quay and the processing at the power plant, resulting in the total cost of the whole supply chain. The costs are presented for the white wood pellets and for two scenarios of torrefied wood pellets. The *equal* scenario, includes feedstock input costs that are equal to the feedstock input cost of white wood pellets. And the *low* scenario, which includes a lower feedstock input costs due to the feedstock advantages of the torrefaction process.

The data for this study was obtained from different sources. This resulted in the fact that the data has a different uncertainty and variability. The uncertainty of the data is indicated in the figures by different symbols. The data that is calculated is indicated with (*), the data that is stated by experts is indicated with (+) and the data that is obtained from scientific literature is indicated with (-). The source of the data is converted into a percentage of reliability, which is used in a sensitivity analysis. The data obtained from scientific literature was given the highest uncertainty percentage of 50%, the data that is stated by experts was given an uncertainty percentage of 25% and the calculated data was given a percentage of 10%. The sensitivity analysis is conducted with the comparison of white wood pellets with the equal scenario of the torrefied wood pellets. This way, the advantages of torrefaction within the process are clearly presented.

3.2 Case study

One specific case study was analyzed in this study. The production of white wood pellets at Georgia Biomass LLC (Waycross, US) and the production of torrefied wood pellets at a greenfield torrefaction plant with the same scale and geographical characteristics as Georgia Biomass. The pellets are transported overseas and supplied to the Amer Bio CHP plant of RWE (Geertruidenberg, NL).

The woody biomass that is used as the feedstock for the case study pellet production is a mix, consisting mainly of pine pulpwood to which residuals are added (M. Dalton[5], personal communication, January 31, 2017). The harvesting grounds are situated relatively close to the pellet plant. From the harvesting ground, the wood is transported by truck over a distance of 50 km to the pellet plant. At the white pellet plant, the biomass is dried, grinded using hammer mills, pelletized and then cooled (Figure 8). After the production process the pellets are stored using the train as main storage facility (F. Etteldorf[6], personal communication, February 1, 2017). For the production of torrefied wood pellets, a greenfield pellet plant is assumed. So, a newly built torrefaction plant is assumed, with the additional torrefaction requirements and without the avoidable investments. The avoidable and required investments are extracted from the

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[5] M. Dalton. International Commercial Manager, Georgia Biomass LLC.
[6] F. Etteldorf. Dipl.-Ing. Innogy SE, Ingenieurdienstleistungen.

investments of Georgia Biomass LLC and Blackwood's torrefaction demo plant model. At the torrefaction plant, the biomass is dried, torrefied, grinded, pelletized and then cooled (Figure 9). The annual production output of the two pellets plants is based on the maximum output of Georgia Biomass, 750,000 tonne pellets.

From the pellet plant, the pellets are transported by railcars over a distance of 161 km to the port of Savannah where the pellets are stored. From this port, the pellets are loaded on to a Handymax cargo vessel and transported to the port of Rotterdam over a distance of 7160 km. At the port of Rotterdam, the pellets are loaded directly from the cargo vessel on to barges. With the barges, the pellets are shipped to the Amer Bio CHP plant, where they are unloaded, stored and processed.

The white wood pellets are stored at the power plant using a silo storage facility, while the torrefied wood pellets are stored under a simple roof construction, to cover the torrefied wood pellets from direct exposure to moisture. The white wood pellets have a complete separate conveying infrastructure from the coal, because they need to be transported to specially modified mills before they are processed into the boiler. The torrefied wood pellets require only partly a separate conveying system, to control the co-firing. The coal like structure of the torrefied wood pellets ensures that the mills do not require retrofitting for processing the pellets to the boiler.

The two main pellet characteristics that are used for this case study are the bulk density and the energy density. For the white wood pellets, these are 650 kg/m^3 and 17 GJ/tonne respectively. For the torrefied wood pellets, these are 750 kg/m^3 and 21 GJ/tonne respectively. These and the other important characteristics are presented in Table 1.

3.3 Data input

3.3.1 Feedstock cost

The price that is paid for the biomass by pellet plants is called the gate delivered price and is built up from different components: stumpage price, harvesting costs and transporting costs (Qian and McDow, 2013). The gate delivered price for Georgia Biomass is stated by M. Dalton (personal communication, January 31, 2017) and H. Pease[7] (personal communication, February 15, 2017) and comes around $30-35 per short ton wet. For the gate delivered price for the torrefaction plant, two feedstock prices scenarios are assumed. The first scenario (equal), includes a torrefied wood pellet feedstock price that is equal to the feedstock price of white wood pellets and the second scenario (low), includes a feedstock price of $28 per tonne wet. This lower feedstock price is realized due to the feedstock advantages of torrefaction (T. Chopin, personal communication, March 9, 2017). The feedstock cost were calculated in euro per tonne pellets (output) and in euro per gigajoule. The feedstock cost calculations for the white wood pellets and equal scenario of the torrefied wood pellets will be calculated with a feedstock cost input price of $30 per tonne wet (Table 2 and Table 3).

$$\frac{F_G}{(1-MC)} * \frac{feedstock\ input\ (tonne\ dry)}{pellet\ output\ (tonne\ dry)} \qquad [2]$$

Where:
F_g = price feedstock gate delivered ($/tonne wet)
MC = moisture content

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[7] H. Pease. RWE Supply & Trading GmbH, Biofuels trading – Global Solid Fuels.

Table 2. Input parameters of the feedstock cost for white wood pellets

Component	
Input feedstock wet (short ton)	1,858,700
Input feedstock dry ((tonne)	929.350
Output pellets (tonne)	750,000
Feedstock conversion factor	1.24
Total feedstock input/output ratio	2.24
Feedstock cost input ($/short ton wet)	30
Feedstock cost input ($/tonne wet)	33
Feedstock cost input ($/tonne dry)	74
Feedstock cost pellet output (€/tonne dry)	67

(Source: RWE internal report, n.d.; M. Dalton, personal communication January 31, 2017; H. Pease, personal communication, February 15, 2017)

Table 3. Input parameters of the feedstock cost for torrefied wood pellets

Component	
Input feedstock wet (tonne)	1,769,770
Additional support fuel (tonne)	175,410
Input feedstock dry (tonne)	1,069,849
Output pellets	750,000
Feedstock conversion factor	1.43
Total feedstock input/output ratio	2.36
Feedstock cost input ($/short ton wet)	30
Feedstock cost input dry ($/tonne wet)	28 and 33
Feedstock cost input ($/tonne dry)	73 and 86
Feedstock cost pellet output (€/tonne dry)	66 and 77

(Source: Blackwood's torrefaction demo plant model; M. Dalton, personal communication January 31, 2017; H. Pease, personal communication, February 15, 2017)

The feedstock input of the white wood pellets (Table 2) already include the additional support fuel. The additional fuel for the white wood pellets consists of the bark that is separated from the wood by the debarking system. For the torrefied wood pellets (Table 3), the bark is also used in the pellet production process. Therefore, the feedstock input contains the feedstock for the pellets and the feedstock for the support fuel. The fact that the bark is included in the torrefied wood pellets, has no negative effects in the further process of the pellets for co-firing (T. Chopin, personal communication, April 10, 2017).

3.3.2 Pellet production

The pellet production cost include all the cost covering the entire process of production (Equation 2). The investment cost of the pellet plants are presented in Table 4. These costs are the negotiated contract cost (exclusive groundwork, civil work, concrete- and steelworks) of Georgia Biomass (F. Etteldorf, personal communication, February 15, 2017) and the modelled torrefaction plant (T. Chopin, personal communication, March 9, 2017).

Table 4. The investment cost of the Georgia Biomass LLC and the modelled torrefaction plant

Georgia Biomass plant (white wood pellets)	Investment* ($ x million)	Modelled torrefaction plant (torrefied wood pellets)	Investment ** ($ x million)
Woodyard	conf	Woodyard	conf
Dryer island	conf	Dryer island	conf
Hammer/Pelletising/Cooling	conf	Mills/Pelletising/Torrefaction/Cooling	conf
Other	conf	Other	conf
Facility total	160	Facility total	188.5

(Source: *F. Etteldorf, personal communication, February 15, 2017; **T. Chopin, personal communication, March 9, 2017)

For the white wood pellet plant, the woodyard consists of the storage of fiber, debarking system, chipping system, screening and re-chipping system and sums up to an investment of $X million. For the torrefaction plant, the woodyard consists of the same systems except for the debarking system, this is not required for the torrefaction process (T. Chopin, personal communication, March 9, 2017), resulting in an investment of $X million. The dryer island investment is assumed the same for both plants and consists of a conveying system, furnaces, dryer drums and a wet electrostatic precipitator (ESP) system, resulting in an investment of $X million.

The main difference exists between the next step of the process. In the white wood pellet process (Figure 8) the biomass is grinded by hammer mills, before the biomass is pelletized and cooled. For Georgia Biomass, this part consists of a conveying system, 20 hammer mills, 22 pellet mills, a pellet cooling system, fiber storage bins (which have an equal size to the railcars) and another cooling air system, resulting in a total investment of $X million. During this process, generated volatile organic compounds (VOCs) are burned using a regenerative thermal oxidizer (RTO) system ($X million).

For the modelled torrefaction plant process (Figure 9), the biomass is torrefied using 10 torrefaction units. The investment of one torrefaction unit is assumed to be $6 million, resulting in a total investment of $60 million (T. Chopin, personal communication, March 9, 2017). After the biomass is torrefied, it is more brittle an requires less heavy grinding. Therefore, no hammer mills are required, but smaller, cheaper mills. After the grinding, the biomass is pelletized, cooled and stored, resulting in a total investment of $X million (T. Chopin, personal communication, March 9, 2017). The *Other* costs ($X million) of both plants consist of control rooms, overall visualization, offices, fire safety (F. Etteldorf, personal communication, February 15, 2017) and are assumed equal for both plants. This results in a total investment cost for Georgia Biomass of $160 million and for the modelled torrefaction plant $188.5 million. The total specific cost of the two pellet plants is calculated using equation 3, 4 and 5 and is presented in Table 5. For the specific investment cost, an interest rate of 6% is used and a payback period a 20 years is assumed for all the four different packages of the pellet plant (Obernberger and Thek, 2010a).

$$C_P = C_{Fs} + C_{sp} + C_F + C_V \qquad [3]$$

$$C_{sp} = \frac{C_{cap}}{annual\ output} \qquad [4]$$

$$C_{cap} = C_I * CFR = C_I * \frac{(1+i)^n * i}{(1+i)^n - 1} \qquad [5]$$

Where
C_P = production cost of the pellet process (€/t)
C_{Fs} = feedstock cost
C_{sp} = specific cost (€/t)
C_F = fixed operation cost (€/t)
C_V = variable operation cost (€/t)
C_{cap} = capital cost (€/year)
C_I = investment cost (€)
CFR = capital recovery factor
i = interest rate (%)
n = payback period (year)

Figure 8. White wood pellet production process
(Source: Edited from Bergman, 2005)

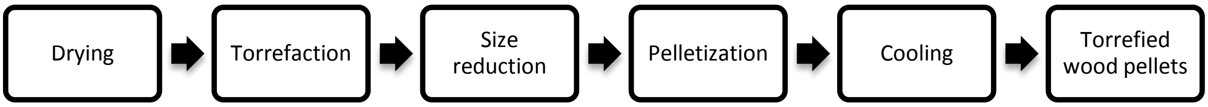

Figure 9. Torrefied wood pellet production process
(Source: Edited from Bergman, 2005)

Table 5. The different cost of the pellet plants

	Investment ($ x million)	Capital cost ($/year)	Specific cost ($/tonne)
Georgia Biomass	160	13.9	18.6
Torrefaction plant	188.5	16.4	21.9

The pellet production cost include the harvesting costs, investments cost and the fixed and variable operational cost. The fixed costs contain the personnel costs, administration cost and other cost (insurance, site, taxes). The variable costs contain the operation and maintenance (O&M) cost and variable utilities. The variable utilities consists mainly of the pellet plant's power and gas consumption (H. Pease, personal communication, February 2, 2017), and is therefore assumed to be equal to the annual electricity consumption of Georgia Biomass, presented in Table 6. To calculate the cost of the electricity use, the industrial electricity price of $5.72 ct per kWh in the Waycross area is used (NREL, 2017). Because the torrefaction process requires e.g. less extensive milling, the total electricity costs for a torrefied wood pellet plant are assumed to be lower, resulting in a total electricity use of 120,000,000 kWh per year.

Table 6. The electricity use of the pellet production process

White wood pellet plant	(kWh/year)
Woodyard	15,276,800
Drying	41,698,800
Grinding/pelletizing/cooling	121,305,600
Plant total	178,281,200
Electricity price ($/kWh)	0.0572

(Source: RWE internal report, n.d.)

3.3.3 Transportation and handling

The transportation component of the pellet supply chain consists of different stages. The first transportation stage includes transporting the feedstock from the harvesting ground to the pellet plant. These costs are often limited, as in the case of Georgia Biomass, by having the harvesting ground relatively close to the pellet factory (Georgia Biomass, 2017). The transportation of the harvested biomass is mostly done by truck, which is, together with railway, the most common method of inland transport of pellets (Sénéchal et al., 2009). This transport stage is however not considered individually in this study, since these costs are included in the gate delivered price of the feedstock.

The actual first stage of transportation includes the transportation of the pellets from the pellet plant to the port of loading. In this study, this means transporting the pellets from Georgia Biomass (Waycross) to the port of loading in Savannah over 161 km with a rail unit consisting of 40 railcars, with each railcar loaded with 97 tonne pellets (M. Dalton, personal communication, February 3, 2017; F. Etteldorf, personal communication, February 15, 2017).

The storage and handling costs at the port of Savannah are obtained from F. Etteldorf (personal communication, February 15, 2017) and were indicated to be €4 per tonne. Due to confidential contract agreements, the cost breakdown for the storage and handling was not further available. Therefore the costs for storage and handling of torrefied wood pellets at the port of Savannah are assumed equal.

The second stage of transportation is long distance ocean shipping, using cargo vessels to transport the pellets from the exporting harbor to the receiving harbor. In this case, from Savannah to the port of Rotterdam over a distance of approximately 7160 km. In this study the pellets are transported using a Handymax cargo vessel, with a maximum load of 55,000 m^3 (Table 7) . The pellet load of the Handymax is presented in Table 7. Due to confidential contract agreements, the ocean transportation costs are obtained from scientific literature (Hoefnagels et al., 2014a), and are assumed to be €11 per tonne for white wood pellets. Despite the fluctuation of ocean shipping prices (Appendix Figure 28), the ocean price is assumed to be fixed by long-term contracts. The transportation costs of torrefied wood pellets are calculated, using the bulk density and energy density improvements (Table 7).

Table 7. Maximum load of white wood and torrefied wood pellets in a Handymax cargo vessel

	White wood pellets	Torrefied wood pellets
Maximum load* (t)	48,000	48,000
Maximum load* (m^3)	55,000	55,000
Bulk density (t/m^3)	0.65	0.75
Energy density (GJ/t)	17	21
Load pellets (t)	35,750	41,250

(*Source: Maritime Connector, 2017)

Once the pellets arrive at the port of Rotterdam, the pellets are unloaded directly from the cargo vessel on to smaller dry bulk barges. The cargo vessels are unloaded using floating cranes. Due to confidential contract agreements, the transshipment costs at Rotterdam are obtained from scientific literature and assumed to be €4.5 per tonne (Sikkema, 2010).

The third transportation stage includes the barge transportation of the pellets from the port of Rotterdam to the Amer Bio CHP plant. For this transportation, a distance of approximately 100 km is assumed. The barge transportation costs are obtained from scientific literature where the parameters match the case study features, a distance of 100 km and a pellet load of 4000 tonne per barge, resulting in €5.3 per tonne (Sikkema, 2010).

3.3.4 Processing

The formula of the processing costs of the pellets on the power plant site is presented in Equation 5. The investment costs of these values are presented in Table 8 and Table 9. For the specific cost, he same calculation for the CRF (Equation 4) is used as for the plant investment. The same interest rate of 6% is used. However, for this calculation, a lifetime of 8 years is assumed. Because of the subsidy time horizon of 8 years, it is assumed that the payback period of the investment needs to be 8 years.

$$C_G = C_U + C_{S2} + C_M + C_C + C_{pnc} + C_E + C_{pc} + C_Q \qquad [6]$$

Where
C_G = cost associated with the processing of the biomass at the power plant
C_U = unloading cost
C_{S2} = storage cost
C_M = mill retrofitting cost
C_C = conveying infrastructure cost
C_{pnc} = pneumatic conveying system cost
C_E = electricity system cost
C_{pc} = process control system cost
C_Q = quay foundation cost
*(all in € per tonne)

Table 8. The specific cost of the required investments for white wood pellets at the power plant

White wood pellets	Investment (€ x million)	Capital cost (€ x million)	Specific cost (€/tonne)
Unloading	conf	conf	conf
Storage	conf	conf	conf
Mill retrofitting	conf	conf	conf
Conveying infrastructure	conf	conf	conf
Pneumatic infrastructure	conf	conf	conf
DCS system	conf	conf	conf
Electric infrastructure	conf	conf	conf
Quay foundations	conf	conf	conf
Total			conf

(Source: W. Willeboer[8], personal communication, January 30, 2017)

Table 9. The specific cost of the required investments for torrefied wood pellets at the power plant

Torrefied wood pellets	Investment (€ x million)	Capital cost (€ x million)	Specific cost (€/tonne)
Unloading	conf	conf	conf
Storage	conf	conf	conf
Mill retrofitting	conf	conf	conf
Conveying infrastructure	conf	conf	conf
Pneumatic infrastructure	conf	conf	conf
DCS system	conf	conf	conf
Electric infrastructure	conf	conf	conf
Quay foundations	conf	conf	conf
Total			conf

The cost for the storage of torrefied wood pellets is extracted from the costs for the storage of white wood pellets, which comes from RWE. It is assumed that for the storage of torrefied wood pellets a simple construction consisting of a floor, four pillars and a roof is sufficient. Because of the more coal like structure of torrefied wood pellets, it is assumed that the mills require no retrofitting. The 50% lower conveying infrastructure costs results from the fact that it is assumed that for the torrefied pellets only the first stage of conveying needs to be separate from the coal feed system. This way the percentage of co-firing can be controlled.

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[8] W. Willeboer. Strategic Engineer Process Technology, RWE Generation NL

3.3.5 Sensitivity analysis

The costs of the components of the supply chain could be vulnerable to variability's, affecting the total cost. Since the components all have a different share in the supply chain, a change in the cost of the components will have a different impact on the total cost. The range of the variability of the components is linked to the method the data is obtained.

The variable cost include the electricity cost and O&M cost. The electricity benefits for a torrefaction plant that are assumed in this study can be too optimistic. At the same time, the electricity cost for white wood pellet plant can be decreased by e.g. higher efficiency. Different scenarios for the sensitivity analysis are presented in Table 10.

Table 10. The cost difference under different scenarios

Scenario	White wood pellets	Torrefied wood pellets (equal)	Torrefied wood pellets (low)
Base	-	-	-
Electricity	50% lower	50% higher	50% higher
Torrefaction units; Grinding mills	-	50% higher	50% higher
Combined	-	50% higher	50% higher
Variable	50% lower	50% higher	50% higher

4. Results/Cost Analysis

4.1 Feedstock

Woody and herbaceous biomass are the two main types of solid biomass feedstock interesting for international traded biomass (Batidzirai et al., 2016). In the case of Georgia Biomass, the feedstock consists of a mix of woody biomass. This mix consists predominately out of pine pulpwood, with the addition of woody residuals (Dalton, 2017).

The feedstock costs (Table 11) per tonne pellet output are calculated using Equation 2, and results in the feedstock cost for white wood pellets of €67 per tonne (dry) and for torrefied wood pellets €77 per tonne (dry) (equal) and €66 per tonne (dry)(low). Despite the equal feedstock input cost, the cost per tonne pellets is higher for torrefied wood pellets compared to white wood pellets. This is the result of the higher input/output ratio of torrefied wood pellet production. However, when the costs are presented in euro per gigajoule, even the equal feedstock price scenario results in lower cost for the torrefied wood pellets compared to the white wood pellets.

Table 11. Feedstock cost per tonne output pellets under different feedstock input costs

Feedstock input cost* ($/tonne wet)	White wood pellets (€/tonne dry)	Torrefied wood pellets (equal)(€/tonne dry)	Torrefied wood pellets (low) (€/tonne dry)
28	-	-	66
33	67	77	-
38.5	78	90	-

(*Source: M. Dalton, personal communication, January 31, 2017; H. Pease, personal communication, February 15, 2017).

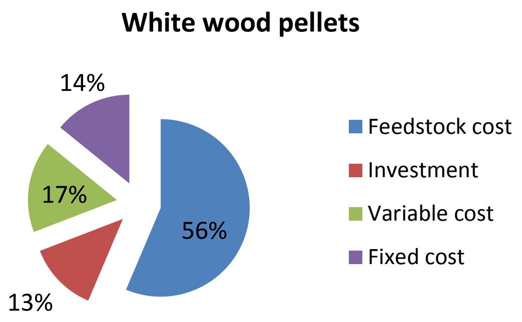

Figure 10. The share of the white wood pellet feedstock cost in the pellet production process (in € per GJ)

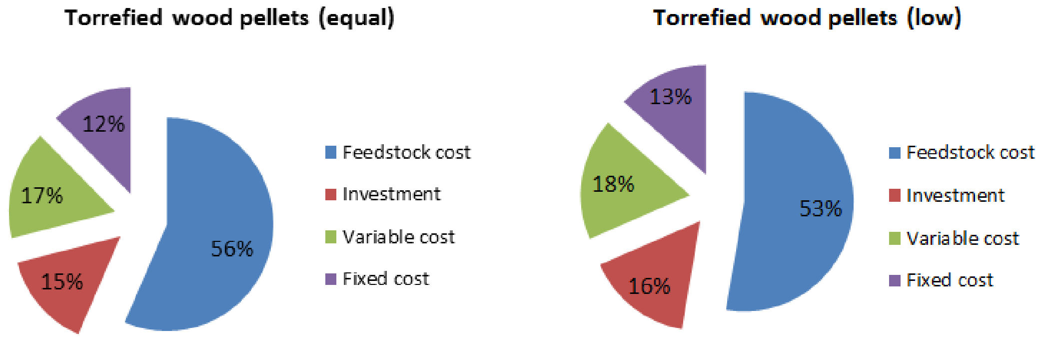

Figure 11. The share of the torrefied wood pellet feedstock cost in the pellet production process (in € per GJ)

Figure 10 and Figure 11, present the share of the feedstock cost in the pellet production process. For white wood pellets, this is 56%, while for torrefied wood pellets, this is 56% (equal) and 53% (low). These figures show the significant impact the feedstock cost have within the process.

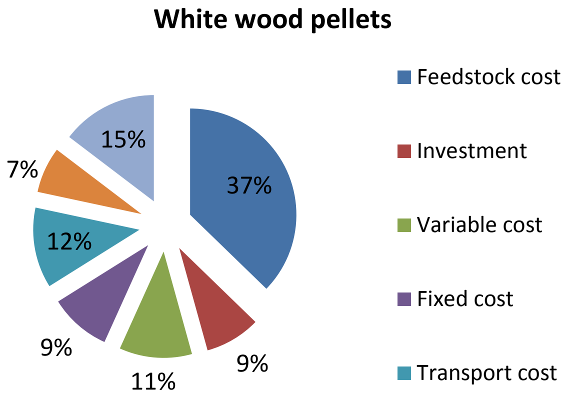

Figure 12. The share of the white wood pellet feedstock cost over the whole supply chain (in € per GJ)

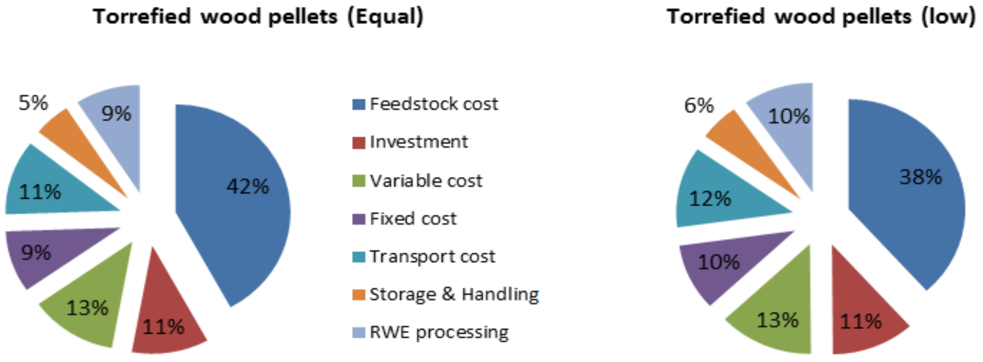

Figure 13. The share of the torrefied wood pellet feedstock cost over the whole supply chain (in € per GJ)

Figure 12 and Figure 13, present the share of the feedstock cost in the whole supply chain. The feedstock costs for white wood pellets cover 37% of the total cost. For torrefied wood pellets, the feedstock costs cover 42% (equal) and 38% (low) of the total cost. For both white wood pellets and torrefied wood pellets, the feedstock cost represent the main cost component of the supply chain.

4.2 Transportation and Handling

Since the railcars are weight limited, there is no advantage of the higher bulk density of torrefied wood pellets, only the higher energy density advantage. Each load, the rail unit transports approximately 4000 tonne of pellets to Savannah. This transportation cost from the plant to the port of loading is €6 per tonne (Etteldorf, 2017).

At the port of Savannah, the pellets are unloaded and the white wood pellets needs to be stored into two 25,000 m^3 domes (Figure 14). The handling of the pellets includes the loading of the pellets from the storage dome(s) on to the cargo vessel (Handymax). The storage and handling costs at the port of Savannah are €4 per tonne (F. Etteldorf, personal communication, February 15, 2017).

Figure 14. The railway structure and storage domes at the port of Savannah
(Source: www.dometechnology.com)

The second transportation stage includes the ocean transportation. Using a Handymax cargo vessel, the pellets are transported 7160 km (Portworld, 2017) from the port of Savannah to the port of Rotterdam. Contrary to the weight limitation for truck and railcar transport, ocean shipping is in most cases volume limited (Hawkins Wright, 2012). Therefore, the ocean transportation (Table 7) can benefit the higher bulk density of torrefied wood pellets, which results in lower transport cost for torrefied wood pellets. The cost for white wood pellet transport is €11 per tonne (Hoefnagels et al., 2014b) and for torrefied wood pellets €9,5 per tonne.

The pellets are transported to the port of Rotterdam, where the cargo vessel is unloaded. The pellets are transshipped from the cargo vessel on to barges. The costs for the transshipment at the port of Rotterdam are €4,5 per tonne (Sikkema, 2010).

The final transportation stages includes transporting the pellets over approximately 100 km from the port of Rotterdam to the Amer Bio CHP plant using barges. The transportation costs for this transportation stage are €5,3 per tonne (Sikkema, 2010).

4.3 Pellet production

The FOB (freight on board) cost are the cost up to loading the pellets on board of the cargo vessel. Figure 15 presents the FOB costs for the different supply chains in euro per tonne. For the white wood pellets, the FOB cost are €129 per tonne. For the torrefied wood pellets, the FOB costs are €146 per tonne (equal)and €135 per tonne (low). This indicates that the FOB cost in euro per tonne for torrefied pellets are higher for both feedstock price scenarios (Figure 15). However, when the price is presented in euro per gigajoule, the FOB costs for white wood pellets are €7.6 per gigajoule and the FOB costs for the equal and low scenario of torrefied wood pellets are €7 per gigajoule and €6.4 per gigajoule respectively (Figure 16). The increased energy density of torrefied wood pellets result in the fact that the FOB costs for both torrefied scenarios are lower than for white wood pellets.

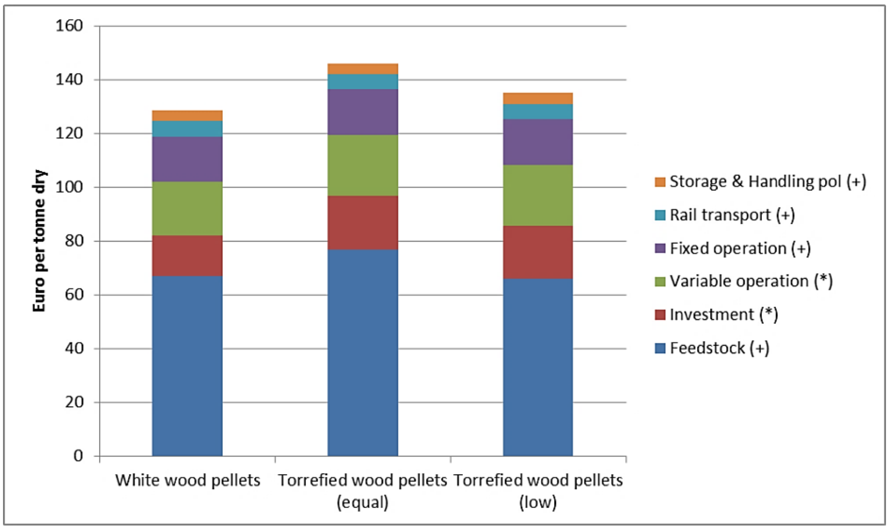

Figure 15. The FOB cost in euro per tonne

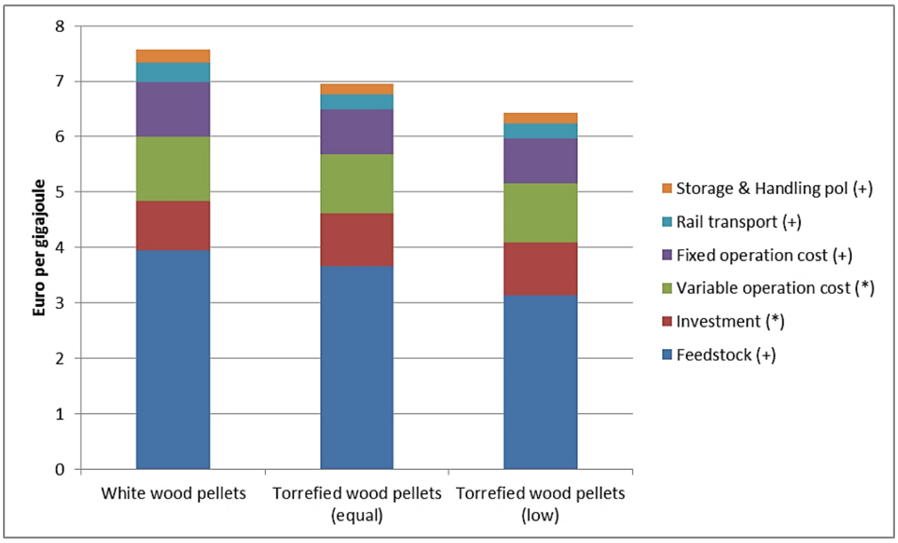

Figure 16. The FOB cost in euro per gigajoule.

The costs from the feedstock supply up to the receiving of the loaded cargo vessel at the port of Rotterdam, are called the CIF (cost, insurance and freight) ARA (Amsterdam, Rotterdam, Antwerp) costs. The CIF ARA costs for white wood pellets and torrefied wood pellets are presented in Figure 17 and Figure 18. For white wood pellets the CIF ARA costs are €140 per tonne. For torrefied wood pellets, the CIF ARA costs are €156 per tonne (equal) and €145 per tonne (low).

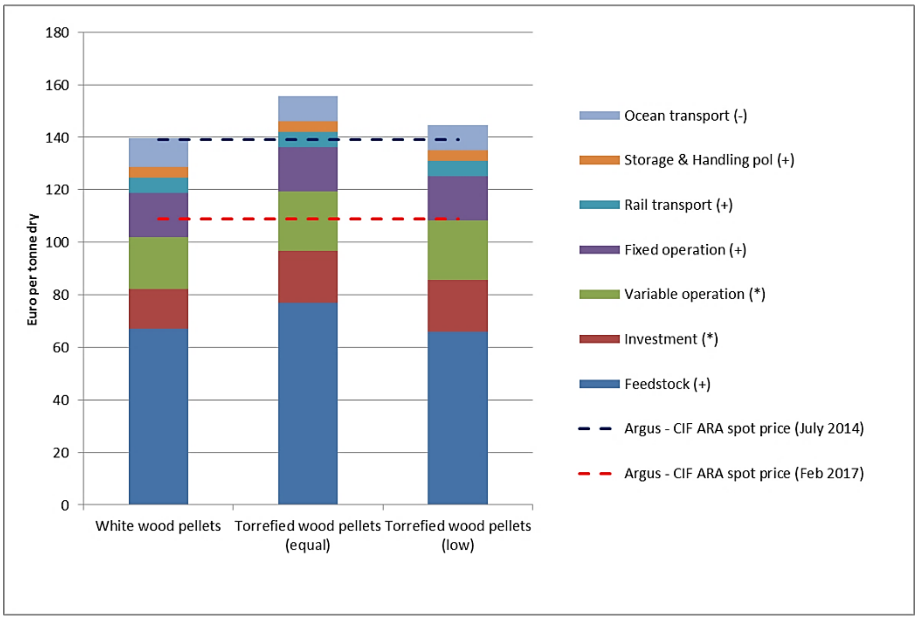

Figure 17. The CIF ARA (Rotterdam) cost in euro per tonne

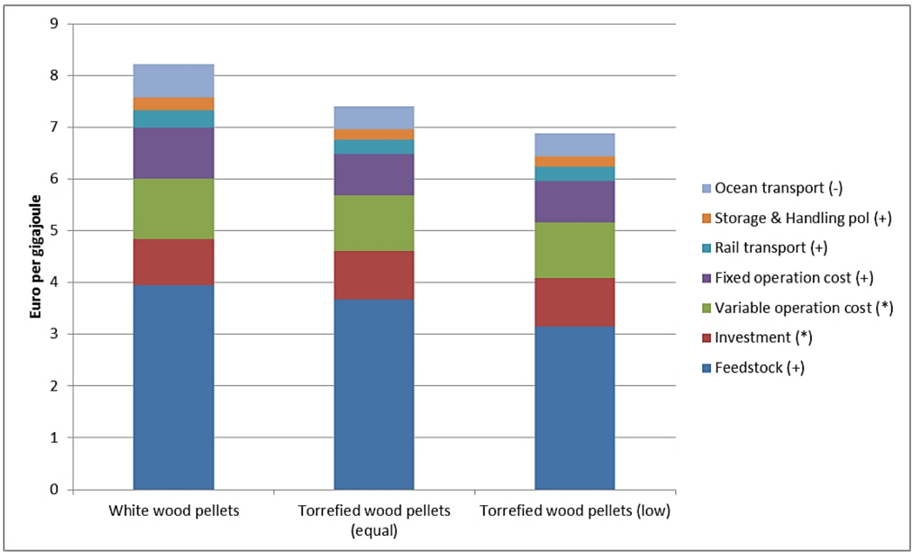

Figure 18. The CIF ARA cost in euro per gigajoule

In Figure 18, the CIF ARA costs are presented in euro per gigajoule. The cost for white wood pellets are €8.2 per gigajoule and the cost for torrefied wood pellets are €7.4 per gigajoule (equal) and €6.9 per gigajoule (low). The figure shows the increased cost difference of white wood pellets compared to the two torrefied wood pellet scenarios.

4.4 Processing

The final component of the biomass supply chain, processing (Equation 6), takes place at the power plant and includes the unloading, storage and processing of the pellets. When the barge with the pellets arrives at the power plant, the pellets are pneumatically unloaded on to the quay. The costs of unloading are €X per tonne. The cost of the quay foundations are equal for white wood and torrefied pellets and are €X per tonne. This results in the total cost up to the quay (Figure 19 and Figure 20) of €150 per tonne for white wood pellets, €166 per tonne (equal) and €155 per tonne (low) for torrefied wood pellets.

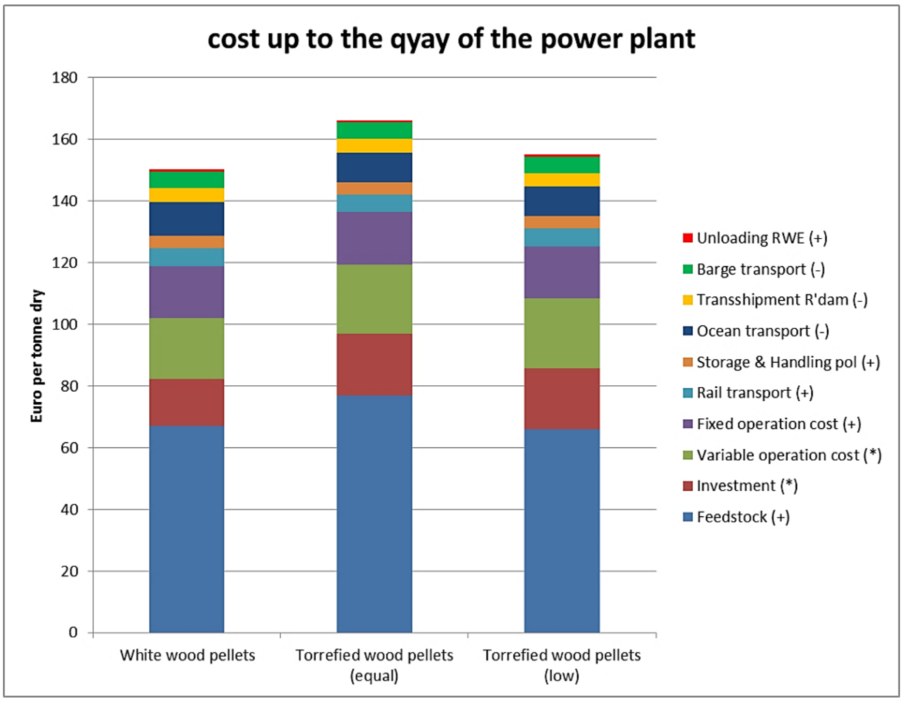

Figure 19. The cost up to the quay of the power plant in euro per tonne

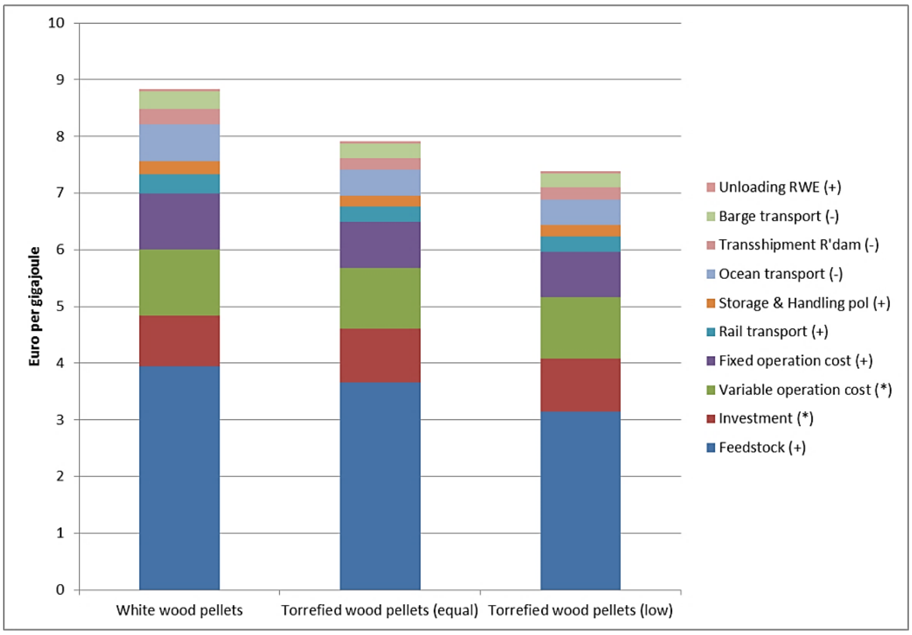

Figure 20. The cost up to the quay of the power plant in euro per gigajoule

After the unloading, the pellets are transported to a storage facility and further processed up to the boiler. With the addition of these stages, the total cost (Equation 1) of the supply chain are presented in Figure 21 and Figure 24 in euro per tonne and euro per gigajoule, respectively. The cost in euro per tonne are for white wood pellets €154 and for torrefied wood pellets €168 (equal) and €157 (low). This indicates that over the whole supply chain, the costs expressed in euro per tonne, are higher for both torrefied wood pellet scenarios compared to the white wood pellet supply chain.

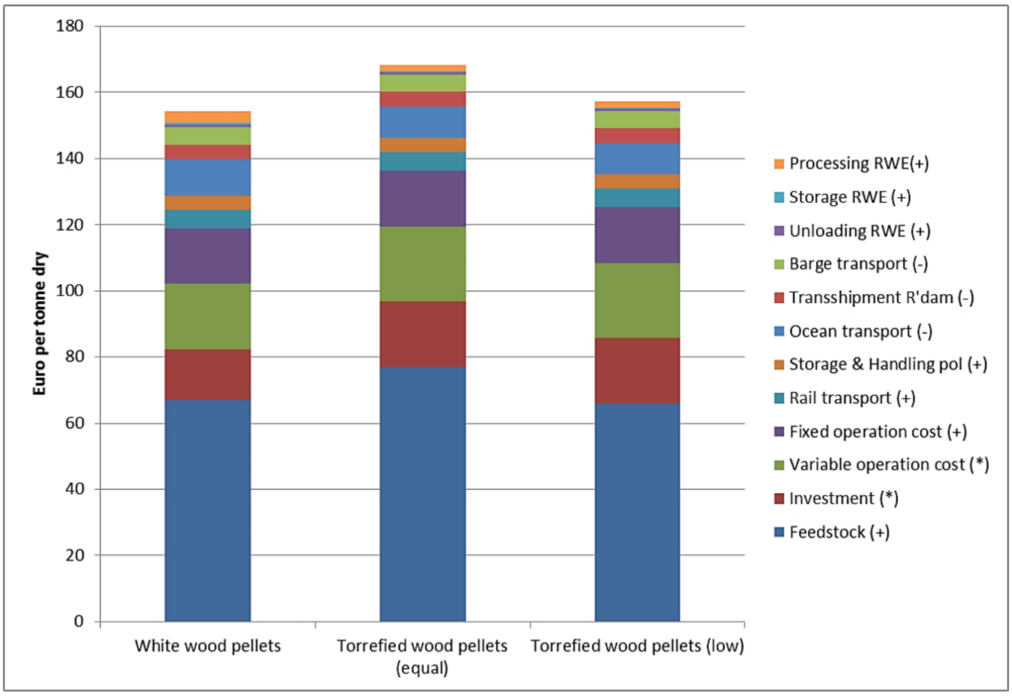

Figure 21. The total cost of the whole pellet supply chain in euro per tonne

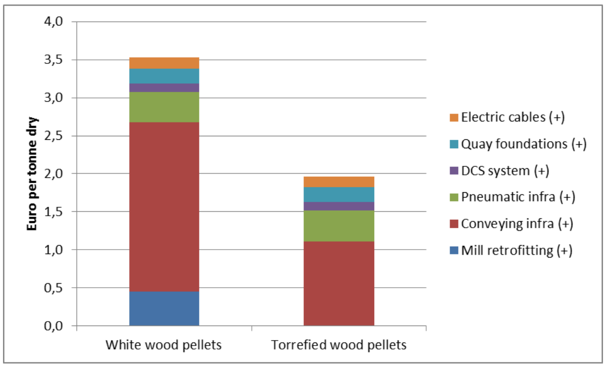

Figure 22. Breakdown of the processing cost at the power plant in euro per tonne

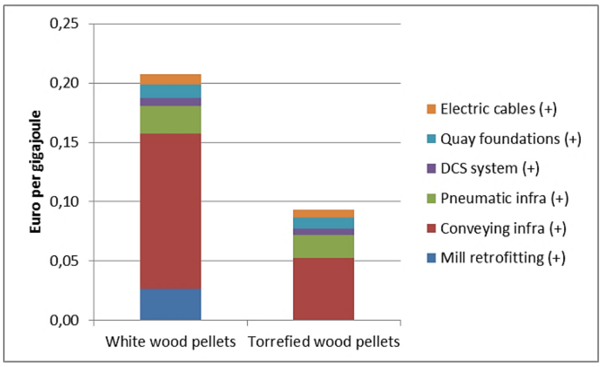

Figure 23. Breakdown of the processing cost at the power plant in euro per gigajoule

In Figure 22 and Figure 23, the cost structure of the processing costs are presented in euro per tonne (dry) and euro per gigajoule, respectively. The figures indicate that the processing costs for white wood pellets are 3.5 per tonne (dry) and €0,2 per gigajoule. For torrefied wood pellets these costs are €1.9 per tonne (dry) and €0,09 per gigajoule.

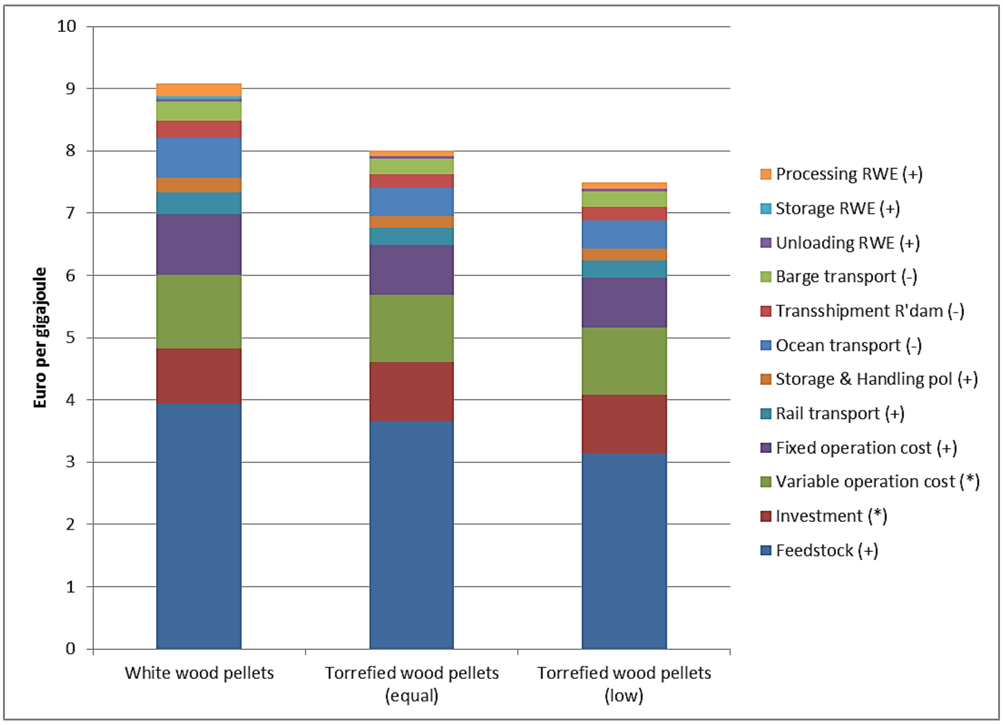

Figure 24. The total cost of the whole pellet supply chain in euro per gigajoule

In Figure 24, the total supply chain costs are expressed in euro per gigajoule. This figure indicates that the total costs for the white wood pellets are €9.1 and for the torrefied wood pellets €8 (equal) and €7.5 (low). In Table 12 and Table 13, a clear overview of all the costs of the different stages of the supply chain that are indicated in the figures are presented.

Table 12. The total cost up to the different stages of the supply chain in euro per tonne

	White wood pellets	Torrefied wood pellets (equal)	Torrefied wood pellets (low)
Production	119	136	125
FOB	129	146	135
CIF ARA	140	156	145
Quay	150	166	155
Total	154	168	157

Table 13. The total cost up to the different stages of the supply chain in euro per gigajoule

	White wood pellets	Torrefied wood pellets (equal)	Torrefied wood pellets (low)
Production	7	6.5	6
FOB	7.6	7	6.4
CIF ARA	8.2	7.4	6.9
Quay	8.8	7.9	7.4
Total	9.1	8	7.5

4.5 Sensitivity Analysis

In Figure 25, the results of the sensitivity analysis are presented. The figure shows the impact of lower and higher estimates (%) of the different components on the final cost the supply chain. The analysis shows the impact of the feedstock cost variability. For both white wood pellets and torrefied wood pellets, a 50% increase or decrease of the ocean transport cost has a smaller effect on the total cost than a 10% increase or decrease of the feedstock cost.

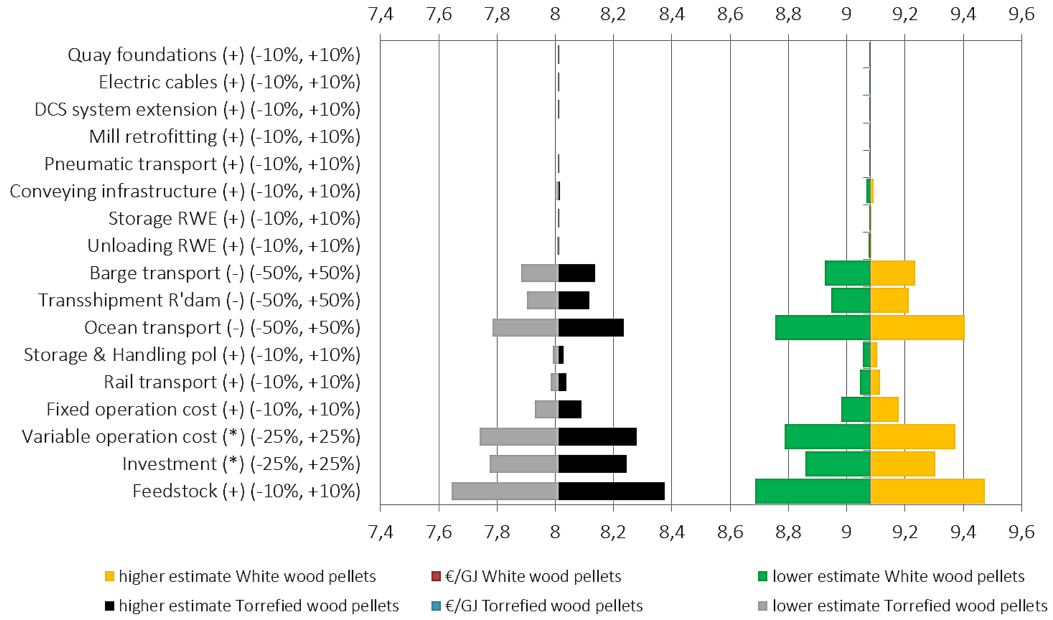

Figure 25. Sensitivity analysis of alternative costs for the components of the supply chain.

Figure 25 furthermore indicates that there are no tipping points where the torrefied wood pellet total costs are higher than the white wood pellets. Moreover, many of the components have a similar effect on the two supply chains. If the feedstock cost for white wood pellets e.g. decrease, then the feedstock costs for torrefied wood pellets also decrease. If e.g. the ocean transport increase, the same effect applies for the transportation of both white wood pellets and torrefied wood pellets. This is not the case for e.g. the variable operation cost (electricity costs and O&M costs). Figure 26 shows the results of the sensitivity analysis when only the production costs components are taken into account. A 25% increase of the variable operation cost for torrefied wood pellets and a 25% decrease of the variable costs for white wood pellets results in a tipping point, where the total costs of torrefied wood pellets are higher than the total cost for white wood pellets.

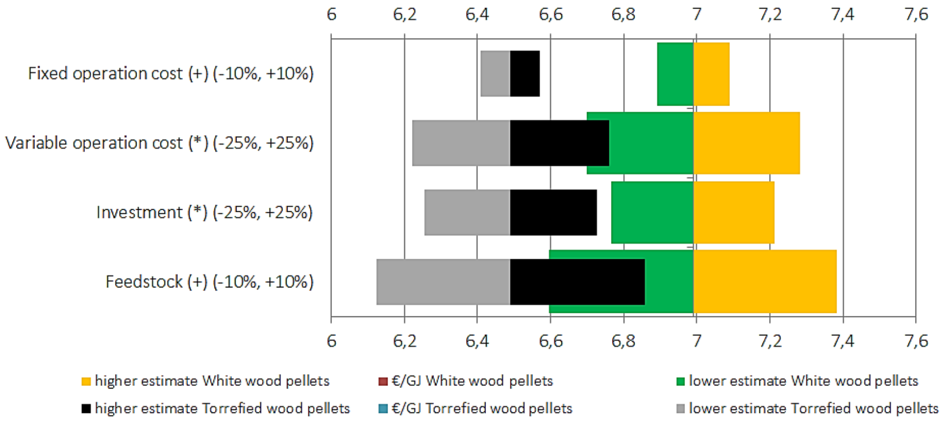

Figure 26. Sensitivity analysis of the production cost components of the supply chain

In Figure 27, the effect of five different scenarios (Table 10) is presented. This figure shows that when the electricity costs is decreased with 50% for white wood pellet production and increased with 50% for torrefied wood pellet production, the total cost expressed in euro per gigajoule are still higher for white wood pellets than for torrefied wood pellets. A 50% increase in the investment costs of the torrefaction units and grinding mills causes the total costs of the torrefied wood pellets to increase only slightly compared to the base case. The combination of higher electricity costs and higher investments costs for the torrefied wood pellet production, does not causes the total costs to be higher than for white wood pellets. The only scenario in which the total costs of the torrefied wood pellets (equal) are higher than the white wood pellets, is when the variable costs of white wood pellets are decreased with 50% and the variable costs of torrefied wood pellets are increased with 50%.

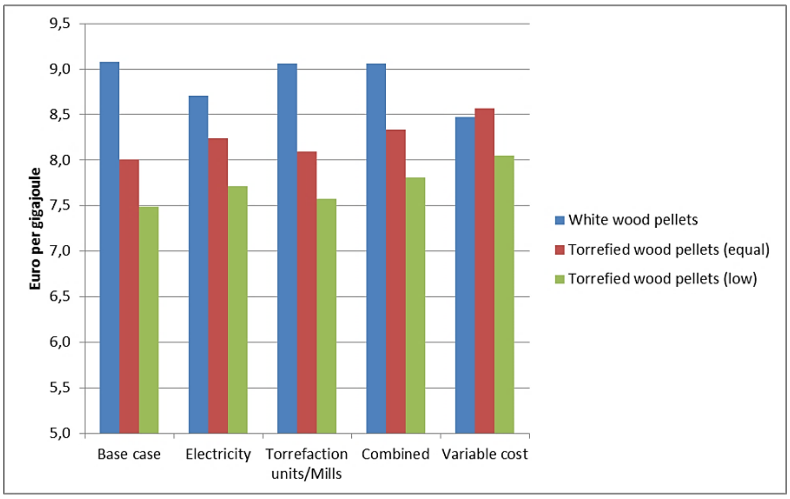

Figure 27. The total supply chain cost under different (sensitivity) scenarios

5. Conclusion

The main goal of this study was to determine the cost competitiveness of torrefied wood pellets compared to white wood pellets and to determine what the economic effect would be of a torrefied wood pellet supply chain for the Amer Bio CHP plant. For this assessment, one specific case study has been analyzed. With the combination of the developed pellet supply chain model, Blackwood's torrefaction demo plant model and data from Georgia Biomass, it was possible to perform a detailed cost analysis.

From this analysis it can be concluded that, if the white wood pellets and torrefied wood pellets are produced, transported and processed under the in this study assumed costs, the white wood pellets can be delivered up to the quay of the Amer Bio CHP plant for €150 per tonne and the torrefied wood pellets for €166 per tonne in the *equal* scenario and €155 per tonne in the *low* scenario. The storage and processing of the pellets at the Amer Bio CHP plant result in the final cost of €154 per tonne for white wood pellets and €168 per tonne (equal) and €157 per tonne (low) for torrefied wood pellets. If only the higher bulk density is assumed and the costs are considered in euro per tonne, the required investments for a torrefaction plant are not compensated by the advantages in electricity, logistics, storage and processing. Resulting in the fact that torrefied wood pellets are not cost competitive with white wood pellets.

However, if also the improved energy density is considered and the costs are expressed in euro per gigajoule, the total costs for delivering the white wood pellets up to the quay of the Amer Bio CHP plant are €8.8 per gigajoule. For delivering the torrefied wood pellets up to the quay, the cost are €7.9 (equal) and €7.4 (low) per gigajoule. The addition of the storage and processing of the pellets at the Amer Bio CHP plant result in the final cost for white wood pellets of €9 per gigajoule, while the total cost for torrefied wood pellets are €8 per gigajoule for the *equal* feedstock input cost scenario and €7.5 for the *low* feedstock input cost scenario.

The improved characteristics of the torrefied wood pellets compared to the white wood pellets is the of the cost advantage of torrefied wood pellets. The higher bulk density and hydrophobicity due to torrefaction, result in cost advantages compared to white wood pellets. However, these do not yet compensate the higher investment costs that are required for the production of torrefied wood pellets. The more than compensation of the higher investment and production costs of torrefied wood pellets is mainly the result of the higher energy density of 21 GJ per tonne compared to 17 GJ per tonne of white wood pellets. Even for the equal scenario of the feedstock input costs, where the feedstock input advantages of torrefaction are not included, the costs of the torrefied wood pellets are lower compared to white wood pellets.

The assumptions for the torrefaction process are key in this analysis. However, the sensitivity analysis showed that the electricity costs, operating and maintenance costs, torrefaction unit investment costs and grinding mill investment costs can all be increased with 50% (separately), without exceeding the costs of white wood pellets. The only analyzed scenario in which the torrefied wood pellets have a higher total cost than white wood pellets is in the case of a 50% increase in variable costs for torrefied wood pellets and a 50% decrease in variable costs for white wood pellets.

It can be concluded from this study, that the investments that are required for the production of torrefied wood pellets are more than compensated over the whole supply chain and results in a saving of €1 per gigajoule for the *equal* scenario and €1.6 per gigajoule for the *low* scenario. From this, it can be conceded that over the whole supply chain, the two torrefied wood pellet scenarios are cost competitive compared to white wood pellets. The more coal like structure of torrefied wood pellet, due to the characteristic improvements (bulk density, energy density, hydrophobicity and durability) is however a prerequisite for this conclusion.

It remains difficult to assess if some cost assumptions and presented advantages are realistic. Large scale commercial production of torrefied wood pellets, as presented in this specific case study, needs to be proven. In the end however, the results of the costs analysis appear to be promising for a torrefied wood pellet supply chain.

6. Discussion

The detailed cost analysis with the developed Supply Chain Model, required some specific data on cost components. The model contains all of the cost components, however, some assumptions had to be made due to data confidentiality or missing data. The cost analysis was based on the pellet production scale of Georgia Biomass, one of the largest white wood pellet production plants in the world. Since torrefaction is still under development, there is no commercial data on the production of torrefied wood pellets on this scale. Moreover, even obtaining data on this production scale of white wood pellets appeared to be difficult, since the plant was to be sold and the data on any business area was prohibited from sharing with anyone. Obtaining the investment data was already very difficult. Despite the fact that Georgia Biomass is a wholly owned subsidiary of Innogy SE, which is a subsidiary of RWE. The data collection was furthermore hampered due to the confidentiality of data because of confidentiality agreements, business interests and contracts with other companies.

Another issue during the development of the torrefied wood pellet supply chain, was the fact that the torrefaction market is still an immature market. Which resulted in the fact that there is a lack of data on commercial scale working torrefaction plants. So the input of the model was based on the input from accessible data within Blackwood, RWE and Georgia Biomass and complemented with scientific literature or assumptions. These assumptions have, however, an impact on the final costs of the supply chain. Since the investment costs, electricity costs and feedstock input costs of the white wood pellets plant are based on the actual costs of Georgia Biomass, the main margin of error would be in the assumptions for torrefied wood pellet production.

Some of the cost components could have been more accurate, however due to the lack of detailed cost insights, the assumptions were conservative. The absence of concrete storage costs at the port of Savannah resulted in the fact that the storage and handling costs were set equal for white wood pellets and torrefied wood pellets. While the advantage in hydrophobicity of torrefied wood pellets would result in lower storage costs. The sensitivity analysis showed however, that the influence of this cost component on the total cost would be relatively small.

The cost component with the highest influence on the total cost is the feedstock input costs. For the feedstock however, applies that when the feedstock costs are decreased, this applies for both white wood pellets and torrefied wood pellets.

Some of the data input in the model comes from scientific literature, based on studies of several years old. Therefore this data is volatile to changes. However, the fact that for these components mostly long term contracts apply, the data can be justified.

In the sensitivity analysis, some of the cost components are set as a variable input. Although some of the components would influence the final cost of the pellet supply, they do not influence the difference between white wood pellets and torrefied wood pellets, because the increase or decrease would apply to both of the supply chains. For example, if the ocean transportation cost decrease, this applies to both the transportation of white wood pellets as torrefied wood pellets. The final cost of the transportation cost can be variable. Historic data from Argus Media (Appendix Figure 28) shows, the freight transport is sensitive to price fluctuations. Which is also emphasized by the fact that there have been cases where the transatlantic trade of pellets have been hampered due to price fluctuations of freight rates (Junginger et al., 2008). This is e.g. indicated by the fact that the market spot price (Figure 28) for ocean transportation from the US southeast to Rotterdam (CIF ARA region). Therefore, the ocean transportation cost could be assumed to increase. However, the sensitivity to price fluctuations can be eliminated by arranging long-term contracts with fixed freight transportation rates.

In the processing cost component, some investment cost assumptions were based on the structural advantages of torrefied wood pellets. The conveying infrastructure cost of torrefied wood pellets were set as 50% of the white wood pellet investments. The feasibility of this assumptions is however not technically examined. The assumptions comes from the fact that for torrefied pellets there is no necessity to be separated from the coal during the transportation and feeding in the boiler.

Currently, the focus of coal replacement is on white wood pellets. However, the disadvantage of wood is the fact that the costs are relatively high. For co-firing woody biomass, subsidies are required in order to make it profitable and interesting for companies. Since these subsidies are limited for a certain period, the goal is to look for feedstock alternatives beyond wood, so-called waste streams. The most preferred option would be to create a supply chain with waste streams, like e.g. bagasse, which is the fibrous matter that remains after the processing of sugar cane. The bagasse could be torrefied and pelletized. The use of waste streams could possibly further reduce the costs at which the biomass would be delivered and be a promising alternative for coal replacement if no subsidies are granted anymore. The co-firing effects of bagasse on e.g. the boiler need to be examined first however.

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Appendix

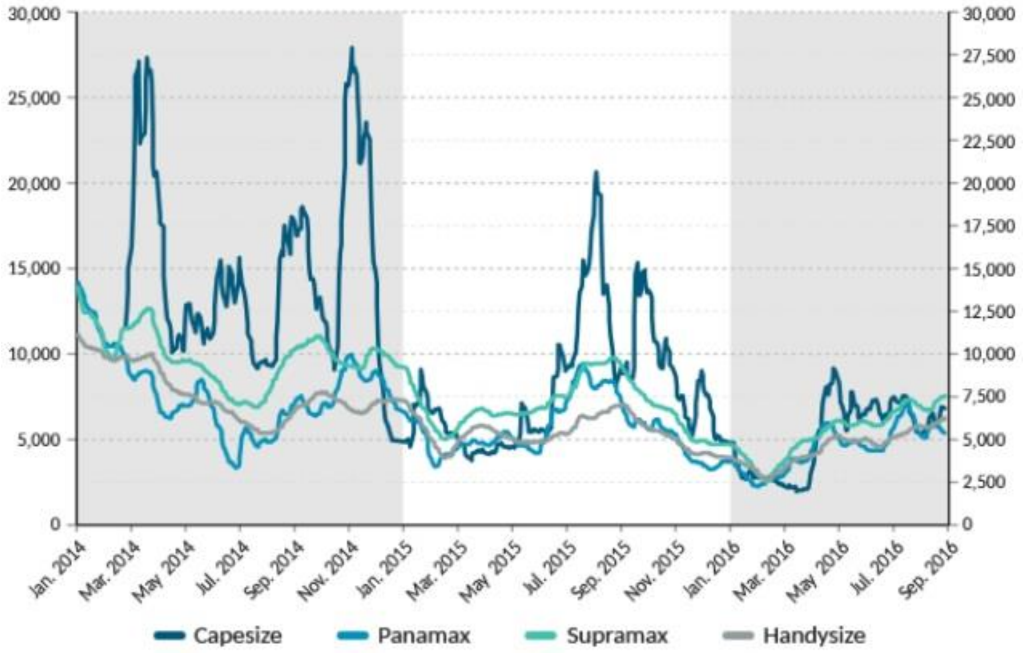

Figure 28. Baltic Exchange Dry Bulk Index in US $/day
(Source: BIMCO, Baltic Exchange and Clarkson)

Table 14. The exchange rate of US$ to Euro

	US to Euro
2000	0,92
2001	0,90
2002	0,95
2003	1,13
2004	1,24
2005	1,25
2006	1,26
2007	1,37
2008	1,47
2009	1,39
2010	1,33
2011	1,39
2012	1,29
2013	1,33
2014	1,33
2015	1,11
2016	1,11
2017	1,06

(Source: https://www.oanda.com/currency/average)