Co-firing white or torrefied wood pellets in the Netherlands?

An assessment of GHG emissions and emission savings

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Blackwood TECHNOLOGY

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DISCLAIMER

For this thesis data has been gathered from various industry actors. Some of the information used concerns confidential data and has been removed before publication. Therefore, certain paragraphs or data have been replaced by the words <*confidential*>.

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EXECUTIVE SUMMARY

In the Netherlands, the common pathway for achieving renewable energy targets is co-firing white wood pellets in existing coal power plants for electricity and heat production. However, it is uncertain if this pathway will be able to meet future greenhouse gas (GHG) emission savings criteria from the revised Renewable Energy Directive (RED II, proposal currently awaiting ratification). An opportunity in this respect could be the integration of torrefaction in the pellet supply chain. Previous research shows large ranges in emission savings of torrefied pellets (TOP) compared to white pellets (WP) or fossil fuels. Such uncertainty is a result from assumptions on e.g. feedstock type, drying fuel and torrefaction degree, as well as a lack of detailed data. Furthermore, previous TOP research is mostly based on pilot-phase data and not on commercial-scale pellet plants.

Therefore, this study presents a detailed GHG emission assessment of a specific supply chain case study. Following the RED II methodology and including multiple feedstocks in scenarios, the GHG emissions saving potential of WP and TOP co-firing in the Netherlands under future EU legislation is assessed. The case study regards wood feedstock supply and pretreatment in the Southeast US (SE US), and transportation to a co-firing plant in the Netherlands. Furthermore, industry data is combined with literature to decrease uncertainty in pellet production. For WP, data is obtained from a US Pellet Producer operating on commercial scale. For torrefied pellets similar data could not be obtained. Instead, estimations on the energy consumption and input requirements of a future TOP plant is obtained from a torrefaction technology supplier: Blackwood Technology, which has experience with a torrefaction demonstration plant. The sensitivity analysis investigates the effects of uncertainty in TOP production and several methodological assumptions on the final result.

The GHG emission results on a primary energy basis ($gCO_{2\text{-eq}}/MJ_{pellet}$) are shown in Figure E1.

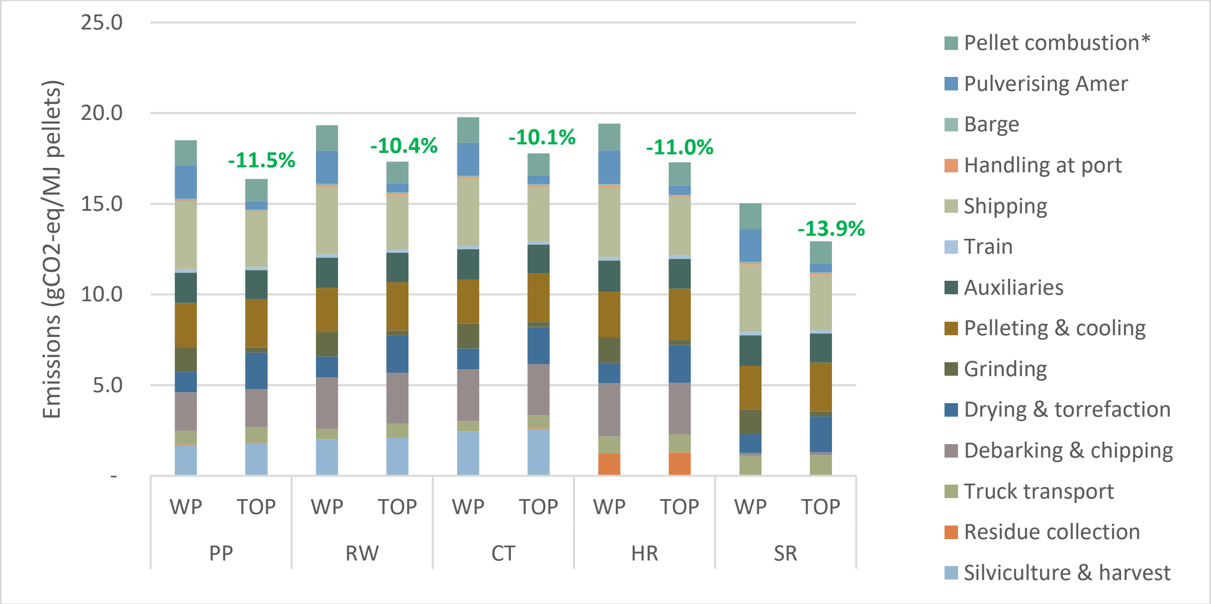

Figure E1. GHG emissions of white- (WP) and torrefied pellet (TOP) scenarios on a pellet energy basis. US Pellet Producer (PP), roundwood (RW), commercial thinnings (CT), harvest residues (HR), sawmill residues (SR). *CO_2 emissions from combustion excluded to account for forest carbon sequestration. Numbers above data columns are percental changes from switching from WP to TOP.

The results show that TOP lead to lower emissions than WP for all feedstock scenarios. The advantage of torrefaction is most apparent during intermodal transportation, because of the higher energy content of TOP compared to WP. Shipment of TOP offers an additional advantage over WP. The higher bulk density of TOP results in weight-limited instead of volume-limited shipment, leading to lower fuel requirements per shipment of pellets. Other processes where TOP induce lower emissions are grinding and pulverisation, as the brittleness of TOP makes these steps less energy-intensive, and at the combustion stage, as TOP induce a lower efficiency loss at the co-firing plant. Even though TOP production is associated with additional emissions in the feedstock supply step (due to higher feedstock requirements) and in the pelletisation step, the achieved GHG emission savings outweigh these additional emissions. Furthermore, it can be seen that, aside from evidently lower emissions in the sawmill residues scenario, differences between feedstock scenarios are relatively low. This suggests that even though harvest residues are usually considered a preferred feedstock over other plantation products, such preference is not supported by a GHG emissions perspective. It should be noted, however, that this research does not account for potential carbon debt and carbon stock changes. Research on this topics point out that harvest residues usually have low carbon debt payback times. Furthermore, uncertainty exists in the effect on carbon stocks when removing harvest residues from forest grounds.

Emission savings from final energy production are shown in Figure E2. Emission savings targets from the RED II are depicted with black striped and dotted lines.

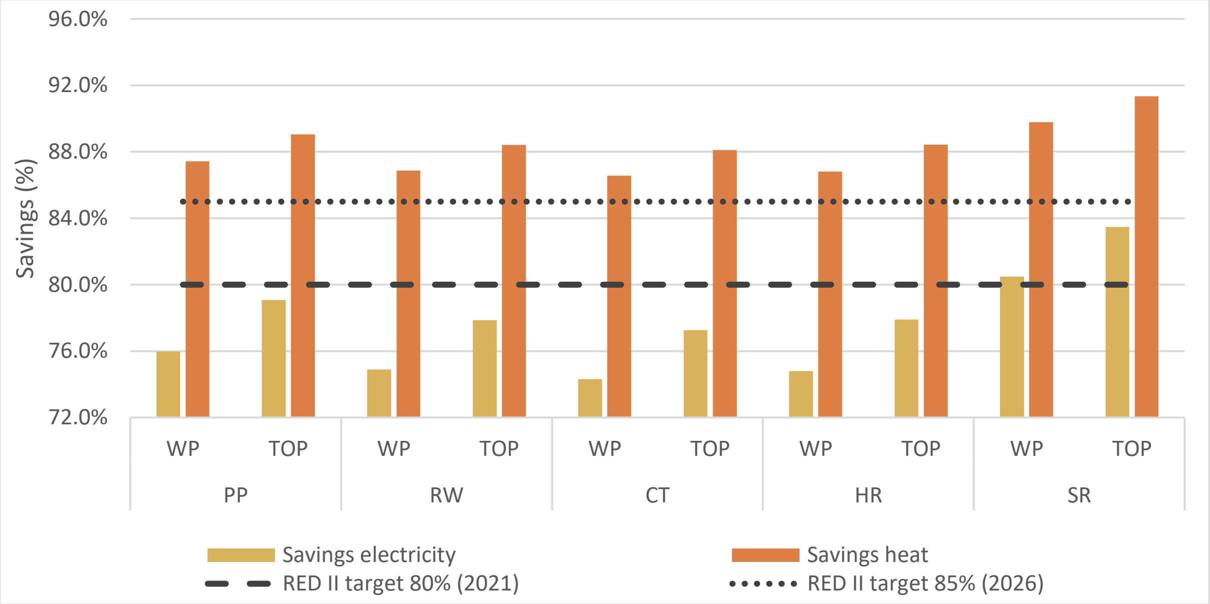

Figure E2. Final emission savings of WP and TOP scenarios compared to the RED II fossil fuel comparator. US Pellet Producer (PP), roundwood (RW), commercial thinnings (CT), harvest residues (HR), sawmill residues (SR).

Figure E2 shows higher emission savings for all TOP scenarios compared to their corresponding WP counterpart. TOP savings are on average 3 percent point higher for electricity production and 1.5 percent point higher for heat. Differences between electricity and heat production are a result from different reference fossil fuel comparators for electricity and heat, defined by the RED II. When the effect of the fossil fuel comparator was investigated by assuming the same coal emissions for electricity and heat, the results showed that the RED II overestimates savings from heat production and underestimates savings from electricity production. This is a way of the European Commission to favour certain supply chains over others. Currently, actors in the field argue for setting lower emission savings targets than currently stated in the RED II. Lower targets would be beneficial for the electricity producing scenarios in this research. Furthermore, actors argue for using local grid emission factor instead of the default fossil fuel comparator for grid electricity prescribed by the RED II. Sensitivity analysis showed that this is not beneficial for case studies with pellet facilities in the SE US, as this region has a larger grid emission factor than the default value.

The analysis in this research is based on actual measurements of commercial-scale WP production, whereas this was not possible for TOP. The TOP production phase is therefore associated with the highest uncertainty. The effect of this uncertainty is investigated in the sensitivity analysis. Input data for the sensitivity analysis was based on a different TOP process with other feedstock and pellet characteristics than assumed in this research, and could thus not be directly compared with the base case. However, it is used as estimation for different TOP production. In this analysis, the benefit of TOP over WP decreased, but remained significantly positive with 7.4-12.8%, increasing the robustness of the results. Nonetheless, TOP production remains the stage with the highest uncertainty. Therefore, it is recommended that the efforts made in this research are continued by including measurements from currently operating commercial-scale TOP facilities.

In conclusion, this research has decreased uncertainty in the GHG emission savings of a pellet supply chain common to the Netherlands. All investigated feedstock scenarios showed significant savings when a switch from WP to TOP is made. Even though no difference between WP and TOP with respect to meeting RED II targets was observed in this case study, differences could occur in other supply chains considering the significant benefit of TOP over WP. This research provides knowledge on the GHG emission savings potential of WP and TOP co-firing in the Netherlands. Since pellet co-firing is a controversial subject in the Dutch political landscape, this research can guide policy makers in their decision-making regarding pellets and their contribution towards renewable energy targets, in which still significant efforts need to be made.

ACRONYMS AND ABBREVIATIONS

a.r.	As received (wet based)
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
$CO_{2\text{-eq}}$	Carbon dioxide equivalent
CT	Feedstock scenario Commercial Thinnings
EC	European Commission
EU	European Union
FFC	Fossil Fuel Comparator
GHG	Greenhouse gas
HFO	Heavy Fuel Oil
HR	Feedstock scenario Harvest Residues
kWh	Kilowatthour
LCA	Life Cycle Assessment
LHV	Lower heating value, equal to net calorific value (NCV)
LULUCF	Land use, land use change and forestry (sector)
m.c.	Moisture content
N_2O	Nitrous oxide
NL	The Netherlands
o.d.	Oven-dry (wood), meaning no moisture (moisture content 0%)
PP	Feedstock scenario US Pellet Producer
RCO	Regenerative Catalytic Oxidizer
RED	Renewable Energy Directive
RED II	Revison proposal for the Renewable Energy Directive: COM(2016) 767 final/2.
RTO	Regenerative Thermal Oxidizer
RW	Feedstock scenario Roundwood
SE US	Southeast United States
SR	Feedstock scenario Sawmill Residues
t	See 'tonne'
tonne	Metric ton, measure of weight. All tonnes in this report are metric tons.
TOP	Torrefied pellet
WP	White pellet
wt%	Weight percentage

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1. INTRODUCTION

The Netherlands is lagging behind with their European targets for renewable energy generation (Proskurina et al., 2016). At present, biomass accounts for the largest share in renewable energy generation and this is expected to continue towards 2030, when a share of 60% is predicted (van Meijl et al., 2016). An common application for biomass utilisation in the Netherlands is co-firing wood pellets in existing power plants for electricity and heat production (Proskurina et al., 2016). Nevertheless, there is an increasingly strong lobby against using wood for combustion in the Netherlands. The current coalition agreement of the Dutch government mentions that current co-firing subsidies will conclude by 2024 and that all five coal power plants in the Netherlands should be closed by 2030 (Rutte et al., 2017). Despite these developments co-firing is expected to be a cost-effective option to meet Dutch emissions targets in the short-term (Ministry of Economic Affairs, 2015).

Biomass combustion in the Netherlands is regulated by the European Commission (EC) under the Renewable Energy Directive (2009). This directive was revised in November 2016 (RED II), and the proposal is currently awaiting ratification. At the time of writing, the revision includes a compulsory minimum level of greenhouse gas (GHG) emissions savings from using solid biomass instead of fossil fuels for the production of electricity and heat. GHGs must be reduced by 80% for solid biomass installations starting operation from 2021 onwards, and by 85%[1] for installations starting operation from 2026 onwards (EC, 2017). Previous studies have shown that the common practice in the Netherlands of co-firing wood pellets for electricity and heat production does not always meet these criteria (Dwivedi et al., 2014; Hanssen et al., 2017; Woytiuk et al., 2017).

An opportunity in this respect could be the integration of torrefaction in the pellet supply chain (Batidzirai et al., 2014; Kumar et al., 2016; Thrän et al., 2016). Torrefaction is the thermal pretreatment of biomass into a product with higher energy density (Batidzirai et al., 2013). Combining torrefaction with a compacting step such as pelletising enables the production of torrefied pellets (TOP). The higher energy density of TOP leads to lower transport emissions per unit of energy compared to non-torrefied, white pellets (WP). Additionally, TOP have chemical and physical properties closer to coal, which decreases the grinding energy needed at conversion plants (Obernberger & Thek, 2010; Repellin et al., 2010). However, since the torrefaction process requires additional energy input, net GHG emission savings are only achieved if the savings of GHG emissions in TOP supply chains are higher than the extra emissions occurring from pretreatment (Hansson & Hackl, 2016).

Previous research on torrefaction includes technology reviews (e.g. Acharya, Sule, & Dutta, 2012; Batidzirai et al., 2013; Chew & Doshi, 2011; Kumar et al., 2016; Nunes, Matias, & Catalão, 2014; Stelte et al., 2012; Tumuluru et al., 2011; Wild & Visser, in press) and economic analyses of TOP compared to WP (e.g. Agar, 2017; Batidzirai et al., 2013; Beets, 2017; Pirraglia et al., 2013, 2012). Several studies have also been conducted on the emission savings of TOP versus WP supply chains (Adams, Shirley, & McManus, 2015; Agar, 2017; Batidzirai et al., 2014; Hansson & Hackl, 2016; Kabir & Kumar, 2012; McNamee et al., 2016; Thrän et al., 2016; Tsalidis et al., 2014; Woytiuk et al., 2017). Most of these studies conclude that co-firing TOP supply chains lead to less GHG emissions and less fossil fuel consumption than WP supply chains. However, previous literature often indicates that emission savings are extremely dependent on the supply chain set-up and related assumptions. This translates into large variations in savings for switching from WP to TOP observed in previous research. For

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[1] Based on RED II version COM(2016) 767 final/2. The proposed targets are currently under intensive discussion. It is expected that targets in the final version of the RED II will not be higher than currently proposed.

example, research from McNamee et al. (2016) shows savings of 10-31%, research from Thrän et al. (2016) shows ranges of 25-50% savings, and Woytiuk et al. (2017) reports only 5% savings. Some studies even show an increase in emissions when switching from WP to TOP (Agar et al., 2015; Hansson & Hackl, 2016). Such uncertainty results from assumptions on the choice of feedstock, type of heat supply, torrefaction degree, and transport distance, as well as a lack of detailed data. Furthermore, all abovementioned research on GHG emissions from torrefaction is based on pilot-phase data and not commercial-scale plants, leading to uncertainty in energy consumption of commercial plants. These examples illustrate considerable ambiguity about the GHG emissions saving potential of TOP. In order to identify the GHG emission savings of co-firing TOP instead of WP in the Netherlands, a detailed assessment is needed. This research aims to provide such assessment.

The study presents a life cycle GHG emission assessment with multiple feedstock scenarios according to RED II guidelines, to investigate the emissions and emission savings of WP and TOP co-firing in the Netherlands under future EU legislation. To mitigate uncertainty regarding energy consumption of pellet production, industry data is gathered from a commercial-scale WP producer. For TOP, similar data could not be obtained. Instead, estimations on the energy consumption and input requirements of a future TOP plant is obtained from a torrefaction technology supplier that has experience with a TOP demonstration plant. The supply chain case study examines biomass harvested and pretreated in the Southeast United States region (SE US), and transported for co-firing at a coal power plant in the Netherlands. This supply chain is selected because the US is a key export country for the Netherlands (Miedema et al., 2017), and the southeast region accounts for the largest production within the US (EIA, 2018). By looking at a one specific case study, the supply chain is studied in great detail.

The results of this research add to the knowledge base by addressing the uncertainty surrounding emissions from commercial-scale pellet production with the use of industry data. Efforts are made to reduce ambiguity in savings achieved when integrating torrefaction in white pellet supply chains by investigating a supply chain case study in detail. Moreover, this research is societally relevant, as it can guide policy makers in the Netherlands in their decision-making regarding biomass and (torrefied) pellets. Since the future role of pellet co-firing in the Netherlands is uncertain, this research intends to provide knowledge on the possibilities of emission savings by pellet co-firing with different feedstocks. In this way, policy makers can determine if and how pellet co-firing can contribute to renewable energy targets, in which significant efforts still need to be made.

2. THEORETICAL BACKGROUND

This chapter explains the concepts underlying this research: the Life Cycle Assessment framework, the criteria of the revised Renewable Energy Directive and the general set-up of pellet supply chains.

2.1 LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) is a methodological framework used to assess the environmental impacts of a product or service throughout its life cycle (Baumann & Tillman, 2004). A complete cradle-to-grave LCA covers the entire life cycle: the extraction of raw materials and energy acquisition, production, manufacture, use, recycling and final disposal. Alternatively, LCA practitioners can execute partial LCA's, e.g. cradle-to-gate or gate-to-gate (Rebitzer et al., 2004). The International Standards Organisation (ISO) standards on LCA[2] distinguishes four phases, shown in Figure 1.

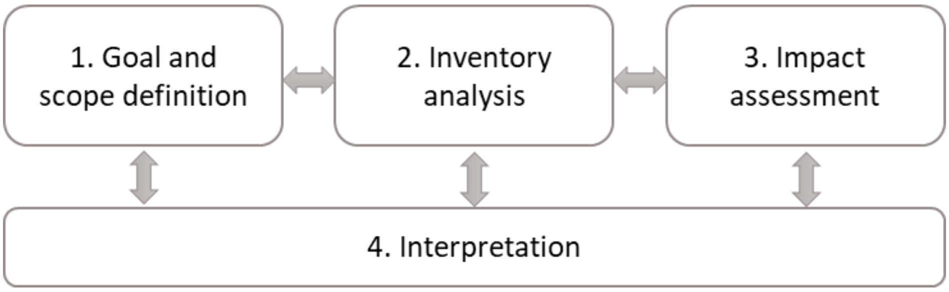

Figure 1. Phases in Life Cycle Assessment (LCA).

The first phase is *goal and scope definition*. In this phase the objective of the study and the scope are clearly defined. This includes defining the system under study, the functional unit, system boundaries including geographical and time boundaries, allocation procedures and impact categories. Allocation procedures are necessary when process with more than one output occur in the system under study. According to ISO guidelines, it is preferable to use system expansion when possible for dealing with allocation problems. In system expansion, the boundaries of the system are expanded by including the impacts of alternative production systems (Baumann & Tillman, 2004). Alternatively, allocation through partitioning could be used, in which emissions are divided among the different products of a processes, e.g. on the basis of physical relations, market value, energy or mass (Cherubini & Strømman, 2011). Furthermore, it is important to specify which environmental impacts are taken into account. Examples of impact categories are global warming potential, acidification potential, eutrophication potential, and human or eco-toxicity. If only one impact is studied, the analysis can be regarded as a single-impact LCA. All choices in the first phase determine which inventory data needs to be collected in the second phase, *inventory analysis* (Baumann & Tillman, 2004).

The *inventory analysis* phase entails identifying the in- and outflows of the processes within the system boundaries and data collection for these flows. The data should be aligned with the functional unit. In the third phase, *impact assessment,* the information from the inventory analysis is aggregated, sorted and evaluated. If multiple impacts are studied, characterisation and weighing should take place (Baumann & Tillman, 2004). This step is of less importance when a single-impact LCA is performed. In the last phase, *interpretation*, the results are analysed and compared with previous findings. Usually a sensitivity analysis is part of this phase. LCA is an iterative process (see Figure 1). For example, during impact assessment it may turn out that better data collection is required (Curran, 2013).

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[2] ISO 14040:2006, ISO 14041:2006, ISO 14042:2006, ISO 14043:2006

2.2 RENEWABLE ENERGY DIRECTIVE II

In regulatory frameworks or directives often choices are made concerning LCA methodology, in order to provide guidelines and improve uniformity. The revision proposal of the Renewable Energy Directive (RED II) is such an operationalisation of LCA methodology. The RED II is published in 2016 and revises the earlier Renewable Energy Directive (RED) from 2009, on the production and promotion of renewable energy in the European Union.[3] The RED II is currently awaiting ratification and it is possible that alterations will take place before a final version is adopted (EC, 2017). Future energy production from biomass is expected to be subjected to the revised legislation of the RED II, just like it was under the earlier RED legislation. This chapter explains the RED II with respect to solid biomass fuels.

During preparation of the RED II, external institutes conducted research on the sustainability and optimal use of biomass resource, which contributed to the formulation of *sustainability criteria*, *emission saving targets* and *GHG emission accounting methodology* for biomass fuels, such as pellets (EC, 2017; Giuntoli et al., 2017a). The *sustainable criteria* in the RED II relate primarily to sustainable harvesting of biomass resource. An important part of the sustainability criteria concerns requirements for biomass use to reduce risks of direct and indirect land use change emissions. These are based on the LULUCF proposal (2015), which is established to regulate emissions in the land use, land use change and forestry (LULUCF) sector. The sustainability requirements for forest biomass include: legal harvesting, forest regeneration and minimizing impacts on soil quality, biodiversity and long-term forest productivity. Furthermore, the origin region of the biomass must have legislation in place to preserve carbon stocks and to report GHG emissions. Contrary to the first RED, the *emission saving targets* in the RED II include targets for electricity and heat production from biomass fuels. These criteria only apply for installations with a minimum capacity of 20MW. Emission saving targets are currently set to 80% for installations starting operation from 2021 onwards, and 85% from operations starting 2026 onwards. It should be noted that at the time of writing, these targets were subject to discussion and it is possible that changes are made in the final version of the RED II. It is expected that targets in the final RED II will not be higher than currently proposed.

In order to ensure harmonised GHG accounting and consistency throughout EU member states, the RED II has specified *GHG emissions accounting methodology*. The scope defined in the RED II is summarised in Table 1 (EC, 2017).

Table 1. Summary life cycle assessment assumptions in the Renewable Energy Directive II.

LCA aspect	RED II
Functional unit	Biomass fuels: 1 MJ of biomass fuel Electricity and heating: 1 MJ of electricity or heat
System boundaries	Feedstock supply (extraction/cultivation of raw materials) Carbon stock changes by land use change Pretreatment/processing Transport/distribution Fuel in use Savings from soil carbon accumulation by improved agricultural management Savings from carbon capture and storage Savings from carbon capture and replacement
Allocation procedures	No upstream emissions allocation to residues Energy allocation for all co-products Exergy allocation for conversion to heat/electricity
Impact categories	GHG emissions (carbon dioxide, methane and nitrous oxide)

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[3] First version published November 2016. This research uses version COM(2016) 767 final/2, published February 2017.

Since the waste management phase is excluded from the system boundaries, the RED II is considered a partial LCA. Furthermore, allocation through partitioning on energy is prescribed. Even though ISO guidelines advocate system expansion, partitioning is deemed more suitable when products with the same functional unit are compared (Goedkoop et al., 2016). The RED II covers one impact category, GHG emissions, and is thus a single-impact analysis. The RED II includes the three most important GHG emissions: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).[4] The GHG emissions in the RED II have a time horizon of 100 years (Giuntoli et al., 2017a). Two functional units are described in the RED II. For the production of biomass fuels, the functional unit is 1 MJ of biomass fuel. For final energy production, the functional unit is 1 MJ of electricity (MJ_e) or heat (MJ_{th}) produced.

2.3 WOOD PELLET SUPPLY CHAINS

This chapter aims to provide a background of the general set-up of wood pellet supply chains. The set-up is dependent on the locations of feedstock and end users. There are two main end-use sectors for pellets: the industrial sector, in which pellets are used to generate electricity and heat in large scale plants, and the residential sector, where pellets are used in small scale heating units (Thrän et al., 2017). This research focuses on wood pellets for industrial end use in co-firing plants. Industrial wood pellet trade is dominated by the linear supply chain between the US and Europe (Thrän et al., 2017). Figure 2 shows an overview of such supply chains for pellet co-firing. The separate steps – feedstock supply, pretreatment, distribution and end use – are described in the following sections.

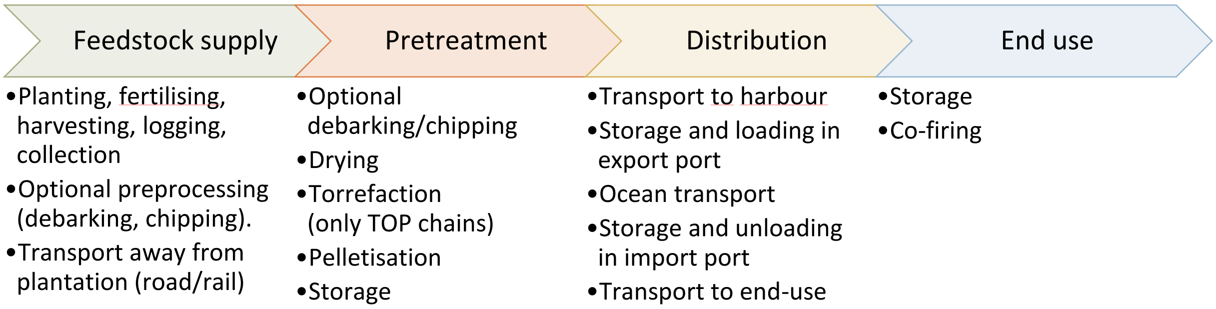

Figure 2. Overview wood pellet supply chains.

2.3.1 Feedstock supply

Different feedstocks for pellets are available. An overview is shown in Figure 3. Wood plantations generate several products. Saw wood and chip ‘n saw wood are the highest valued products, and too expensive for wood pellet feedstock (Hanssen et al., 2017). Via different wood processing pathways and consumers, this wood can reach pellet plants, usually in the form of wooden crates, pallets or other post-consumer wood (EIA, 2018). Additionally, residues from wood processing are used as pellet feedstock, most notably sawmill residues. Other wood plantation products for bioenergy are unmerchantable roundwood, thinnings and harvest residues. Unmerchantable roundwood concerns wood that is otherwise unsellable, e.g. diseased or rotten wood. Thinnings are a result of silviculture operation. During thinning processes trees are harvested in order to reduce tree density, which is practiced to advance the growth of the remaining trees (Dale et al., 2017). The definition of roundwood is a sensitive one. In this research roundwood concerns lower quality trees, not acceptable for saw wood or chip-n-saw wood purposes. Both thinnings and roundwood have sufficient quality to be used for the pulp and paper industry.

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[4] In LCA practice it is common to express GHG emissions as the Global Warming Potential, which is the increased heat absorption in the atmosphere caused by a substance relative to CO_2 (Baumann & Tillman, 2004). In this research, the term GHG emission is used instead of the Global Warming Potential.

Silviculture operations of wood plantations include soil preparation, planting, herbicide and fertilisation application, thinning, and a concluding clear-cut at the end of the rotation period (Jonker, Junginger, & Faaij, 2013). Thinning and final cut yields harvest residues that can be used as pellet feedstock: tops and branches or forestry wood chips (Hanssen et al., 2017). Feedstocks that are larger than sawdust or chips are usually chipped. Chipping can be done decentrally, immediately after collection in the forest by diesel powered chippers. Alternatively, chipping can take place centrally at the pretreatment facility. Central chipping is usually electrically powered and more efficient (Giuntoli et al., 2017a). Whole trees can optionally be debarked before chipping, which is mandatory if high quality pellets (type A1) are to be produced (Obernberger & Thek, 2010). Bark from debarking processes can be used as pellet feedstock, but only for low quality pellets, due to high ash contents.

Historically, sawmill residues were the most common and preferred feedstock for pellets (Obernberger & Thek, 2010; Röder, Whittaker, & Thornley, 2015). Sawmill residues are already reduced in size, often drier than other sources of woody feedstock, and easily collectible at point source. However, this has changed in recent years. For the world's largest pellet producing country, the US (Thrän et al., 2017), pellet production from other residues (other than from sawmills) and from roundwood is currently 3.5 and 1.4 times larger[5] respectively than pellet production from sawmill residues (EIA, 2018).

In most cases, feedstock is not located in the exact location of pretreatment facilities, and must therefore be transported, usually by truck (Hoefnagels, Searcy, et al., 2014). As a result of the low energy density and bulk density of raw biomass, truck transport to pellet plants is relatively expensive (Batidzirai et al., 2014). Therefore, transport distances are usually below 120 km (Dale et al., 2017). An overview of the feedstock supply step and possible woody feedstocks for pellets is shown in Figure 3.

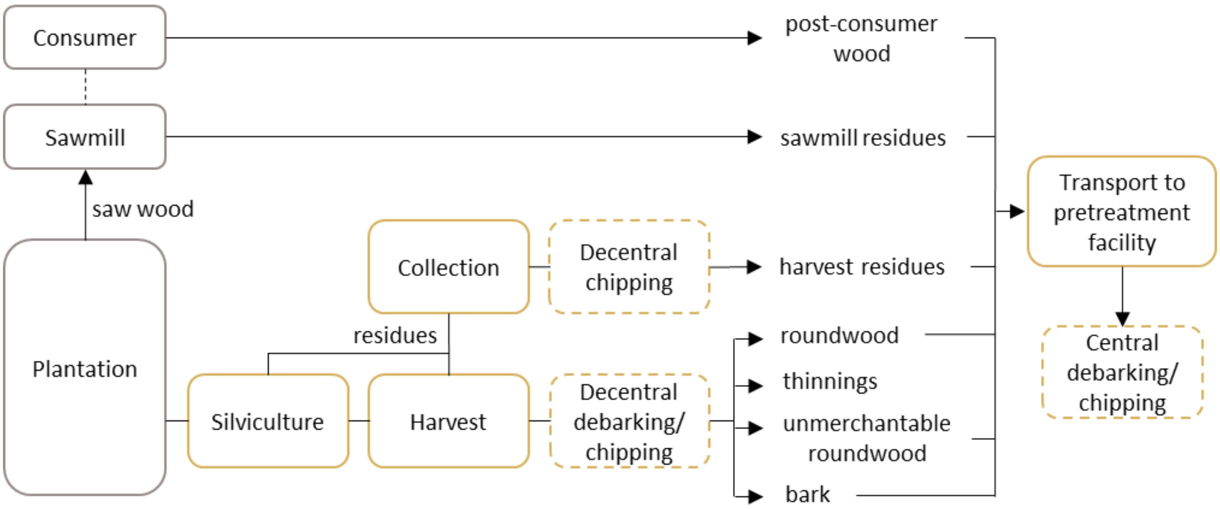

Figure 3. Possible woody feedstocks for pellets.
Based on Obernberger & Thek (2010), Hanssen et al. (2017) and EIA (2018). Chipping and optionally debarking is either done decentral in the forest or centrally at the pretreatment facility (indicated with dashed borders). After the sawmill, wood products reach consumers via different wood processing pathways (not shown).

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[5] Based on US pellet production in 2017 up to October (rest of the year not yet available). Pellet production from sawmill residues, roundwood and other residues is 1.5 Mt, 2.1 Mt and 5.2 Mt respectively. Of all US based pellet production, 83% is produced in the SE US region (EIA, 2018).

2.3.2 Pretreatment

The required process steps for pretreatment into pellets depend on the type of raw material used (Hoefnagels, Resch, et al., 2014). These steps are visualised in Figure 4.

White Pellets (WP)

To produce white pellets (left part of Figure 4), biomass must be reduced in size before it can be fed to the dryer. If debarking and chipping has not taken place decentrally at the forest ground, these processes take place at the pretreatment facility. After initial size reduction by chipping, the biomass needs to be coarse ground. Smaller feedstock types like wood shavings or sawdust need no initial size reduction steps (Obernberger & Thek, 2010). The drying stage reduces the moisture content of the feedstock to 7-14% (Thrän et al., 2016, US pellet producer, personal communication, November 14, 2017). Wood shavings and some types of sawdust are already low in moisture content and do not need to be dried. The heat required for drying must be delivered by a support fuel. This could be bark from debarked roundwood or another stream of biomass, fired in a biomass combustor, or it could be natural gas. After another (fine) grinding step, conditioning of the wood takes places. This involves the treatment of dry wood, usually with steam or water. Alternatively, biological additives (unaltered products from agriculture or forestry) can be used (Obernberger & Thek, 2010). For all pellet classes (A1, A2 and B), the amount of additives may not exceed 2$\%_{wt}$ of the pellets (EPC, 2015). Conditioning aids the binding process during pelletisation and enables the production of pellets with higher mechanical durability and better moisture resistance. Furthermore, conditioning leads to lower pelleting energy requirement (Kumar et al., 2016). The actual pelletisation of the biomass is performed by placing layers of biomass on a die and overrunning the layers with rollers. Increased pressure results in the desired densification. Lastly, the produced WP need to be cooled (Obernberger & Thek, 2010).

Torrefied Pellets (TOP)

In a torrefaction plant (right part of Figure 4), roundwood does not need debarking or coarse grinding, only chipping (T. Chopin – Blackwood Technology, personal communication, September 15, 2017). In size reduced biomass is dried first to a moisture content of about 10-20% before it is torrefied (Obernberger & Thek, 2010; T. Kleingeld - Blackwood Technology, personal communication, December 13, 2017). After drying, the biomass enters the torrefaction system, in which the biomass is exposed to temperatures between 200-300°C under atmospheric pressure in the absence of oxygen. The combination of this temperature and the time of exposure leads to a breakdown and devolatisation of the hemicellulose and cellulose in biomass (Koppejan et al., 2012; Tumuluru et al., 2011). This gradually increases the heating value of the product and makes the material brittle (Koppejan et al., 2012). After torrefaction typically 70% of the initial mass is preserved, containing 90% of the initial energy content. The by-product torrefaction gas (torgas) contains the remaining 30% mass and 10% energy content, and can be combusted to provide the required heat supply (Adams et al., 2015; Bergman, 2005). When the initial biomass enters the process at a moisture of approximately 35% or lower, the energy of the torgas produced is sufficient to provide heat for both the drying and the torrefaction stage. This is usually only the case when dry sawmill residues are used. For feedstock with moisture contents greater than 35%, a support fuel typically provides the additional heat required. In practice, support fuel is added in any case to ensure stable heat supply and to cope adequately with variations in feedstock moisture (T. Chopin – Blackwood Technology, personal communication, September 15, 2017). Cooling takes place immediately after torrefaction. The torrefied material is then finely ground. The brittleness of the torrefied biomass makes the grinding step less energy-intensive compared to WP. After pelletisation a second cooling step takes place (Obernberger & Thek, 2010).

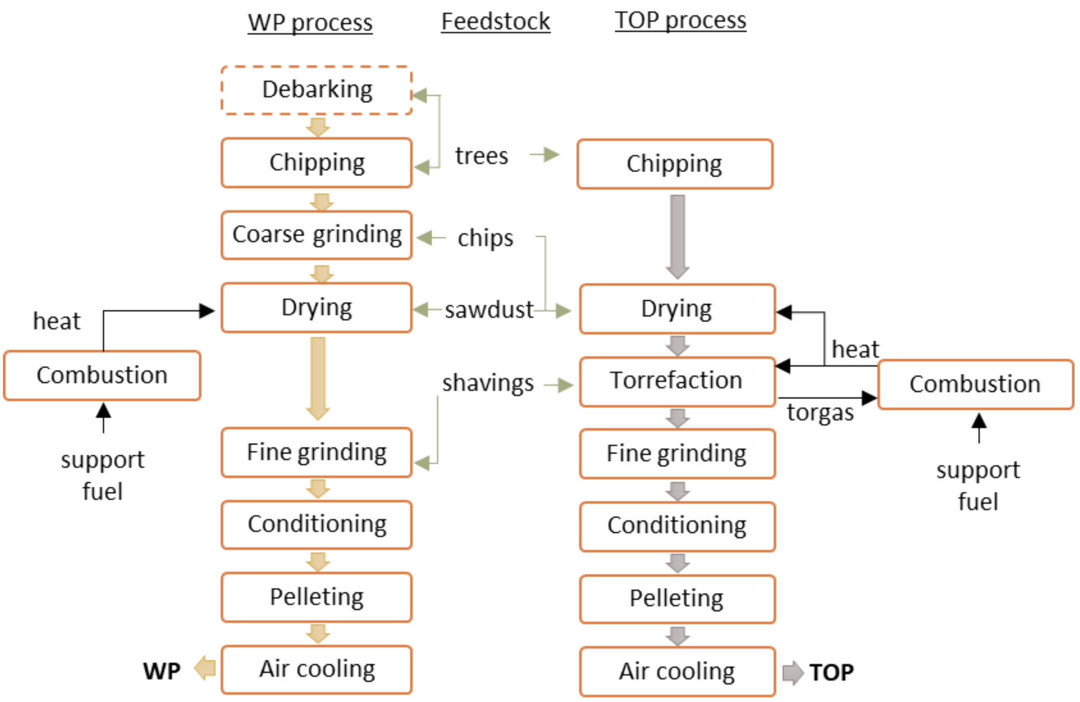

Figure 4. Pretreatment steps of white pellets (WP) and torrefied pellets (TOP).
Based on Cremers et al. (2015), Obernberger & Thek (2010), and T. Chopin - Blackwood Technology, personal communication, September 15, 2017. The need for debarking depends on pellet quality requirements (indicated with dashed border).

Table 2 shows properties of wood chips, WP, TOP and coal. As can be seen, TOP offer several advantages over WP. Besides decreased moisture content, increased heating value and better grindability, TOP show less biodegradation. The changes in the biomass' structure during torrefaction cause the material to largely lose its capacity to absorb water, becoming more hydrophobic instead of hydrophilic. As a result, TOP are less sensitive to moisture uptake and are therefore easier stored (Adams et al., 2015; Koppejan et al., 2012). Because of improved grindability and properties resembling coal, co-firing of TOP is easier and requires less modifications to coal plants than WP (Kumar et al., 2016; McNamee et al., 2016).

Table 2. Properties of wood chips, white pellets, torrefied pellets, and coal. Adapted from Thrän et al. (2016).

	Wood chips	White pellets	Torrefied pellets	Coal
Moisture content (%$_{wt}$)	30-55	7-10	1-10	10-15
Lower heating value (MJ/kg)	7-12	15-18.5	17-24	23-28
Volatile matter (%$_{o.d.}$)	70-84	75-84	55-80	15-30
Fixed carbon (%$_{o.d.}$)	16-25	16-25	22-35	50-55
Bulk density (kg/m^3)	200-300	550-650	550-800	800-850
Energy density (GJ/m^3)	1.4-3.6	8-11	12-19	18-24
Dust	average	limited	limited	limited
Hydroscopic properties	hydrophilic	hydrophilic	moderately hydrophobic	hydrophobic
Biological degradation	fast	fast	slow	none
Grindability	poor	poor	good	good
Milling requirements	special	special	standard	standard
Product consistency	low	high	high	high

Torrefaction technology

Multiple different torrefaction reactor technologies are currently available. Some of these technologies are reactors originally used for other applications, such as drying, and are modified to be suitable for torrefaction. These existing reactor designs include rotary drum dryers, multiple hearth furnaces, ovens and heated screw reactors. New reactor concepts specifically dedicated to torrefaction are also in use, most importantly the moving bed and fluidised bed concepts (Wild et al., 2016). An extensive overview of the various torrefaction concepts is available in Cremers et al. (2015).

All torrefaction reactors include some form of particle movement, because biomass particles need to be heated to the core in order to obtain a uniform torrefaction product. The temperature and the residence time in the reactor determine the degree of torrefaction. Higher torrefaction degrees are associated with higher energy density of the torrefied product, but also with a higher loss of energy to the torgas. Theoretically, torrefied biomass with an energy density equal to coal can be produced, but this requires relatively high production costs since much more feedstock is needed (Thrän et al., 2016). Multiple torrefaction initiatives are currently operating in different stages of development, see Table 3. Previously conducted research is mostly based on demonstration-, pilot- or laboratory- scale data, and not on commercial-scale data.

Table 3. Verified torrefaction initiatives in 2016. Adapted from Wild et al. (2016).

Production capacity	Developer (country)	Technology
Commercial (> 2 t/h)	Arigna Fuels (IR) Blackwood Technology (former Topell Energy), idle (NL) Clean Electricity Generation (UK) Horizon Bioenergy, dismantled (NL) Solvay (FR) / New Biomass Energy LLC (US) Torr-Coal (NL)	Screw conveyor Fluidised bed Oscillating belt Oscillating belt Screw reactor Rotary drum
Demonstration (0.5 – 2 t/h)	Airex (CAN) Andritz (AT) Andritz (DK) / ECN (NL) BioEndev/ETPC (SE) CMI-NESA (BE) Earth Care Products (US) Grupo Lantec (SP) Integro Earth Fuels LLC (US) Konza Renewable Fuels (US) LMK Energy (FR) River Basin Energy (NL/US) TSI (US)	Cyclonic bed Rotary drum Moving bed Screw reactor Multiple hearth Rotary drum Moving bed Multiple hearth Rotary drum Moving bed Fluidised bed Rotary drum
Pilot (500 kg/h)	Agri-tech producers (US) CENER (ES) Terra Green Energy (US) Wyssmont (US)	Screw conveyor Rotary drum Multiple hearth Multiple hearth
Laboratory	CEA (FR)	Multiple hearth
Unknown	Bio Energy Development & Production (CAN)	Fluidised bed

2.3.3 Distribution

From pretreatment facilities, WP or TOP are transported to end users. If end users are situated close to the pretreatment facility, it is common to use truck or train transport. For end users that are not located close to the pretreatment facility, a mix of transport types is used, called intermodal transportation (Hoefnagels, Searcy, et al., 2014). For intercontinental pellet trade, pellets are usually transported by truck or train to a harbour, from where the pellets are shipped (Obernberger & Thek, 2010). Deep-sea bulk carriers are classified in four categories: Handysize (30,000-35,000 DWT[6]), Handymax/Supramax (40,000-60,000 DWT), Panamax (60,000-75,000 DWT) and Capesize (170,000-180,000 DWT). Larger ships offer economies of scale and thus cost reductions, but can bring about issues with access to seaports (Hoefnagels, Searcy, et al., 2014). Upon arrival at the destination seaport, pellets are unloaded into storage or directly onto further transport equipment such as barges or rail cars. Afterwards, pellets are transported to the end-user's facility by barge ships, trains or trucks (Obernberger & Thek, 2010).

2.3.4 End use

After on-site storage at the end-user plant, pellets are combusted to produce heat and electricity. For WP, the most common method is direct co-firing, which avoids large modifications to the power plant. In this approach WP and coal are mixed together or separately, after which the mixture is fired. However, with this option co-firing ratios of only 3-5% by mass are usually achieved. Because of the different structure of biomass compared to coal (biomass is fibrous and elastic), higher co-firing ratios lead to problems such as plugging of bunkers, jamming of mills, fouling of burners, or corrosion of the boiler surface. If higher co-firing ratios are to be achieved, greater plant modifications are needed. For instance, some coal-fired power plants can be made suitable for indirect co-firing in which biomass is gasified before entering the boiler. Another option is retrofitting the coal plant for parallel co-firing in which dedicated biomass mills and burners are installed (Agbor, Zhang, & Kumar, 2014). TOP require less modifications to existing mills and can simply be premixed with coal in the existing infrastructure (Obernberger & Thek, 2010). Therefore, TOP can reach higher co-firing rates than WP. With TOP, even 100% TOP as fuel input can be achieved (Kumar et al., 2016). However, reaching the exact same energy output as with coal within an existing coal plant is not possible. Since TOP tend to have a lower energy density than coal, mass throughput has to be increased to deliver the same energy production. This means that the existing pulverizing mills in the coal plant have to be adapted to a higher throughput, or else more mills have to be installed if the same energy production as with coal needs to be achieved. This de-rating phenomenon also applies to WP.

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[6] DWT = dead weight tonnage, the total weight a ship can carry including the ship itself.

3. METHODOLOGY

The goal of this research is to decrease uncertainty in the GHG emissions saving potential of producing electricity and heat with TOP instead of WP or coal in the Netherlands. This is done by performing a life cycle GHG emissions analysis for a specific supply chain case study common to the Netherlands in detail. It is chosen to look at a supply chain from Southeast US (SE US) to the Netherlands, since this region accounts for the world's largest pellet production and most pellets imported in the Netherlands originate from this region (Miedema et al., 2017; Thrän et al., 2017). The GHG emissions analysis is done according to the calculation methodology set in the RED II. In this way, it is determined whether the investigated supply chain will meet RED II emission targets in the future. This chapter explains the system boundaries defined by the case study, other scope related assumptions, and the methodology of the GHG emission analysis and sensitivity analysis.

3.1 RESEARCH SCOPE

The system boundaries of the research are determined by the case study explained in chapter 3.1.1. This chapter explains the chosen case study in detail. The functional unit, allocation procedures and impact categories are defined by the RED II (see also chapter 2.2) and further explained in chapter 3.1.2.

3.1.1 Case study

It is chosen to include different feedstocks in scenarios to enable comparison between feedstock and the influence of feedstock choice on GHG emissions. The feedstock scenarios and characteristics are shown in Table 4. The Pellet Producer (PP) scenario consists of the feedstock mix of the *US Pellet Producer*, which was contacted for this research. The scenarios commercial thinnings (CT), harvest residues (HR), and sawmill residues (SR) represent the single-feedstock in the *US Pellet Producer's* mix. Lastly, a roundwood scenario (RW) is included, as pellet producers increasingly use roundwood as feedstock (EIA, 2018) and different emissions are associated with roundwood use. Roundwood is assumed to have the same feedstock characteristics as commercial thinnings. In all scenarios, wood is assumed to be pine softwood, as this is the dominant feedstock in the supply base of the *US Pellet Producer.* Table 4 shows that the heating value of harvest residues is considerably lower than for the other scenarios. The reason for this difference is not certain, but could be related to the fact that harvest residue feedstock contains branches and foliage, or possibly more sand and dirt than the other feedstocks. Feedstock is assumed to be transported by truck to the pretreatment facility. Data on emissions from feedstock production, collection and truck transport is obtained from literature.

Table 4. Characteristics feedstock scenarios investigated in this research.

		PP [a,c]	**RW**	**CT**	**HR**	**SR** [b,c]	**Source**
Average moisture content	%	44.7%	47.3%	47.3%	41.1%	38.0%	[1]
Average LHV dry	MJ/kg$_{o.d.}$	19.41	19.44	19.44	18.80	19.46	[1]
Average sourcing distance	km	79	60	60	100	129	[1]

Source: [1] US Pellet Producer, personal communication, November 14, 2017. Notes: a. Consisting of 70% commercial thinnings, 6% harvest residues, and 24% sawmill residues. b. Consisting of 54% green sawdust, 29% dry shavings and 17% sawmill chips. See for an overview of sawmill residues characteristics Appendix A. c. Average moisture content, heating value and sourcing distance calculated by mass share.

For WP production at the US Pellet Producer, commercial thinnings are centrally debarked, and centrally chipped to microchips. Harvest residues and sawmill residues are added to the chipper to ensure consistent feedstock size. Afterwards, biomass is first conveyed to the drying process and then into hammer mills for fine grinding. Lastly, pelletisation and cooling takes place. During pellet production, biomass hog fuel consisting of bark, harvest residues and sawmill bark is used in a conventional moving grate boiler. These steps are used for the PP feedstock scenario. For the other scenarios, it is assumed that only required pretreatment steps are included (see Figure 4).

For TOP production, data is obtained from Blackwood Technology. Data from Blackwood Technology is based on installed capacity of Blackwood's idle torrefaction plant in the Netherlands, and on a technological feasibility study for a future plant in South Africa. It should be noted that TOP data from Blackwood Technology does not represent actual measurements, whereas WP data from the US Pellet Producer does. The difference between data quality for WP and TOP is taken into account in the sensitivity analysis.

For the TOP facility the same location as for the WP facility is assumed. Debarking is excluded, as this is not required for TOP. Chipping and drying is assumed to be similar to WP production. After drying, biomass enters Blackwood's torrefaction system. This system is based on the fluidised toroidal bed reactor. Biomass enters a toroidal shaped reactor from the top. The reactor has angled blades at the bottom, through which a hot gas is blown with a high velocity of 50-80 m/s. This creates toroidal swirls and a high turbulence within the reactor, leading to rapid heating of the biomass particles (Koppejan et al., 2012). Afterwards, the torrefied biomass is grinded and pelletised. Similar to the WP process, the assumption is made that only required pretreatment steps are included for the feedstock scenarios (see Figure 4). The capacity of the Blackwood system is 87,600 t/year, which can be scaled by placing modular systems (T. Chopin – Blackwood Technology, personal communication, September 15, 2017). It is assumed that the TOP system can be scaled to the same output of the WP system of the US Pellet Producer without efficiency gains or losses.

Pellets are distributed by intermodal transportation to the Netherlands, for which energy consumption of transportation is obtained from literature. First, pellets are transported by train to the Port of Savannah. Then, pellets are shipped in Handysize ships over a 7300 km distance to the Port of Rotterdam in the Netherlands. Lastly, pellets are shipped by river barges of type Europe II/IIa/II-long over a distance of 50 km to the end user: the Amer combined heat and power plant (CHP) in Geertruidenberg (W. Timmermans – RWE, personal communication, November 28, 2017).

The Amer CHP is a retrofitted coal power plant owned by RWE Generation Netherlands. This company accounts for 80% of the co-firing volume in the Netherlands (Thrän et al., 2016), and plans to increase co-firing rates at the Amer CHP to 50% in 2018 and 80% by 2019 (RWE, 2017). The plant provides mainly electricity, but also heat for residential heating. At the Amer CHP, pellets are pulverized and directly co-fired with coal. A co-firing rate of 50% is assumed for this research. This co-firing rate is possible at the Amer CHP as half of the coal mills have been modified to biomass mills. Data for electricity and heat production and for co-firing WP are obtained from RWE Generation Netherlands. Data on co-firing TOP was not available, and is obtained from literature.

An overview of the supply chain and scenarios included in this research is shown in Figure 5.

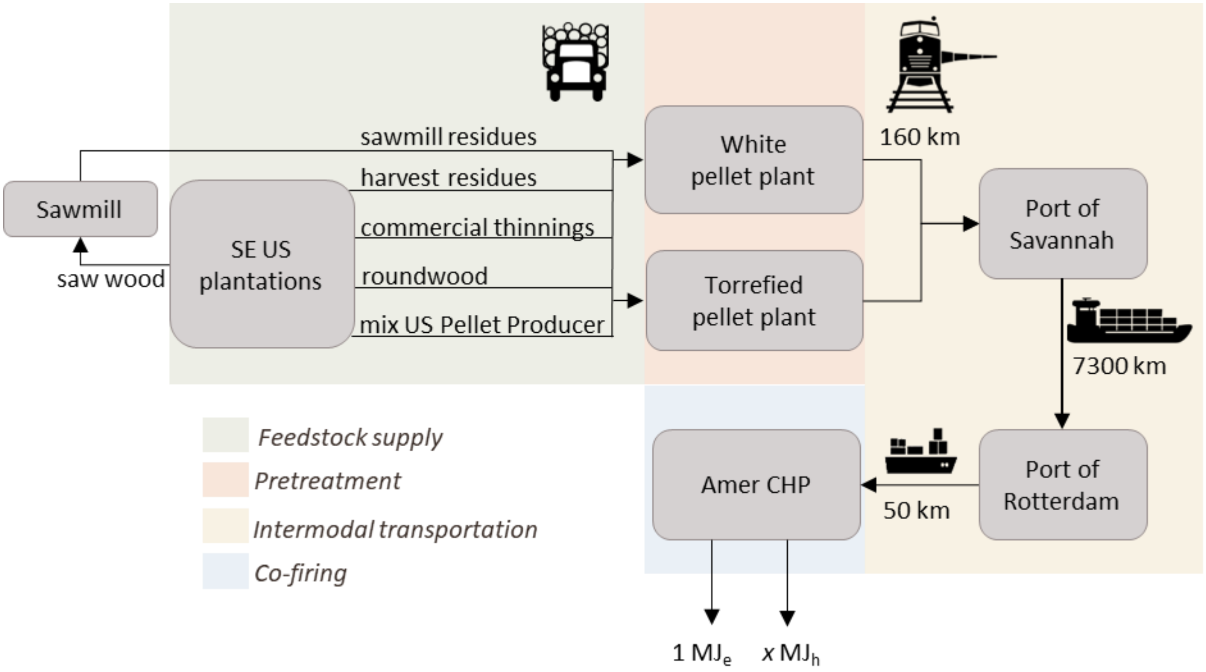

Figure 5. Overview case study and scenarios investigated in this research

3.1.2 Functional unit, boundaries, allocation, and impacts

The RED II specifies choices on the functional unit, system boundaries, allocation procedures and impact categories that should be used (see chapter 2.2). These choices are adapted to suit the case study investigated. The research scope is summarised in Table 5.

For the processes required to include in the system boundaries, several adjustments are made. Carbon stock changes due to land use change are excluded, since the plantations in the case study are long-established and have not experienced land-use change recently (SBP, 2016). Savings from improved agricultural management, carbon capture and storage, and carbon capture and replacement are discarded as these processes do not take place in this case study. Furthermore it is assumed that the sustainability criteria from the RED II on sustainable and legal plantation management are met within the case study, since the plantations in the case study regenerate more forest and grow more carbon stock than is being harvested, and strong legal systems are present in the region (SBP, 2016).

Furthermore, allocation need to be considered. Allocation is relevant for the silviculture and harvest emissions at wood plantations in the feedstock supply step. The RED II prescribes to use energy allocation and to not allocate emissions to residues up until the point of collection. Therefore, no feedstock supply emissions are allocated to the sawmill residues and harvest residues scenarios. For wood plantations, energy allocation is considered similar to mass allocation, because the different wood products of pine plantations have similar heating values. Data on differences in heating values of the different plantation products was not available, thus it is decided to use mass allocation. For the combustion of pellets at the co-firing plant, exergy allocation is used, as prescribed by the RED II.

Table 5. Summary research scope.

LCA aspect	Research scope
Functional unit	Pellets: 1 MJ of pellets Electricity and heating: 1 MJ of electricity or heat
System boundaries	*Defined by investigated case study* Feedstock supply (extraction/cultivation of raw materials) Pretreatment/processing Transport/distribution Fuel in use
Allocation procedures	No upstream emissions allocation to residues Mass allocation for plantation products Exergy allocation for conversion to heat/electricity
Impact categories	GHG emissions (carbon dioxide, methane and nitrous oxide)

3.2 GHG EMISSION ANALYSIS

The next step is determining the carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) emissions for each process within the system boundaries. As specified by the RED II, emissions from the supply of chemicals and fuels are included, and indirect emissions associated with manufacture of machinery and equipment are excluded. For electricity requirements, grid electricity is assumed. The RED II specifically states that instead of local grid emission factors, the fossil fuel comparator set out in the directive must be used (EC, 2017). In the sensitivity analysis, the difference with using the local grid emission factor is looked at. Forest carbon sequestration in the feedstock supply step is accounted for by excluding biogenic CO_2 emissions from combustion of biomass and pellets. Note that this only applies to CO_2 and that the N_2O and CH_4 emissions of biomass and pellet combustion are included. The data inventory for each step is given in chapter 4.

Emissions are converted to carbon dioxide equivalent ($CO_{2\text{-eq}}$) by the following conversion factors: 1 N_2O = 298 $CO_{2\text{-eq}}$ and 1 CH_4 = 25 $CO_{2\text{-eq}}$ (EC, 2017). All emissions are aligned with the functional unit 1 MJ pellets. This first step is described by equation 1.

$$\mathbf{E = e_{fs} + e_p + e_{td} + e_u} \qquad \textbf{[Eq. 1]}$$

where:

E = total emissions of pellets ($gCO_{2\text{-eq}}/MJ_{pellet}$)
e_{ec} = emissions from feedstock supply (extraction or cultivation of raw materials)
e_p = emissions from pretreatment/processing
e_{td} = emissions from transport and distribution
e_u = emissions from the fuel in use

The second step is conversion into final energy (heat and electricity in a CHP). This is done by equation 2 and 3 (EC, 2017).

$$\boldsymbol{E_{el} = \frac{E}{\eta_{el}}\left(\frac{C_{el}*\eta_{el}}{C_{el}*\eta_{el}+C_h*\eta_h}\right)} \qquad \textbf{[Eq. 2]} \qquad \boldsymbol{E_h = \frac{E}{\eta_h}\left(\frac{C_h*\eta_h}{C_{el}*\eta_{el}+C_h*\eta_h}\right)} \qquad \textbf{[Eq. 3]}$$

where:

E_{el} , E_h = Final energy emissions (electricity and heat, respectively
η_{el} , η_h = electrical efficiency and heat efficiency, respectively
C_{el} = fraction of exergy in the electricity
C_h = fraction of exergy in the useful heat, equal to the carnot efficiency.

Equations 2 and 3 represent exergy allocation, but with a small alteration in the fraction of exergy in useful heat (C_h). In the RED II, carnot efficiencies for useful temperatures below 150°C are set equal to the carnot efficiency at 150°C (0.3546), when in fact, the carnot efficiency would be lower. In the Amer CHP, useful heat is supplied at 120°C (Obernberger & Thek, 2010), leading to a carnot efficiency of 0.3053. This is a small difference and has the same influence on WP as on TOP, so it is decided to use the RED II methodology.

Lastly, the emission savings of electricity and heat production with pellets are calculated by equation 4 and 5 (EC, 2017).

$$\boldsymbol{Savings_{el}} = \frac{\boldsymbol{E_{el} - E_{FFC,el}}}{\boldsymbol{E_{FFC,el}}} \quad \textbf{[Eq. 4]} \qquad \boldsymbol{Savings_{h}} = \frac{\boldsymbol{E_{h} - E_{FFC,h}}}{\boldsymbol{E_{FFC,h}}} \quad \textbf{[Eq. 5]}$$

where $E_{FFC,el}$ and $E_{FFC,h}$ are the fossil fuel comparators for respectively electricity and heat. The fossil fuel comparators are based on expected emissions from fossil fuel electricity and heat production in Europe by 2030. For electricity production, the fossil fuel comparator is 183 $gCO_{2\text{-}eq}/MJ_e$. For heat production, the RED II states two fossil fuel comparators: 80 $gCO_{2\text{-}eq}/MJ_{th}$ for fossil fuel substitution in general, and 124 $gCO_{2\text{-}eq}/MJ_{th}$ if a direct substitution of coal is demonstrated (EC, 2017). As pellets in the Amer CHP substitute coal, the latter fossil fuel comparator is assumed.

3.3 SENSITIVITY ANALYSIS

A sensitivity analysis is conducted to assess the robustness of the results and investigate alternative cases. The sensitivity analysis consists of two parts. For the first part, uncertainty within the input data is assessed. The second part investigates two cases of changes in methodological assumptions.

3.3.1 Part I: uncertainty in TOP production

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3.3.2 Part II: sensitivity cases

The second part of the sensitivity analysis investigates two cases of changing methodological assumptions: the High Growth case and the Alternative Fossil Fuel Comparator case. With these two cases, the sensitivity of the results to the methodology is tested.

The High Growth case assesses the situation for a higher demand for pellets and a consequent switch to more intensive plantation management. The base case is based on the current, relatively small wood pellet demand. However, demand for bioenergy is expected to increase (van Meijl et al., 2016). Therefore, this second part of the sensitivity analysis looks into a higher demand for the investigated supply chain. Several adaptations to the base case were made:

- Switch to more intensive plantation management. When demand for pellets increases, it is likely that plantations will be more intensively managed to produce more yield.
- Switch to Supramax ocean carriers. With a larger pellet demand, larger volumes of pellets need to be shipped, and it is likely that pellets will be transported in larger ocean carriers.
- Larger truck transport distance. When demand for pellets and thus demand for biomass feedstock increases, it is likely that truck transport distances will get higher, because feedstocks need to be sourced from further away.
- Higher co-firing ratio. Lastly, a higher co-fire ratio in the power plant is assumed.

The Alternative Fossil Fuel Comparator (Alternative FFC) case concerns the fossil fuel comparator used in the RED II methodology. The fossil fuel comparator is currently under debate and some actors in the field disagree with the use of the fossil fuel comparator as local grid emission factor and reference coal emissions. In this sensitivity analysis, the emissions and emissions savings are calculated without the fossil fuel comparator. The following changes are made:

- Using local grid emission factors instead of the fossil fuel comparator.
- The emissions of the pellet supply chains are compared to emissions of average emissions from coal combustion in the Amer CHP.

4. DATA INVENTORY

This chapter shows the emission factors used in this research (impact assessment), data collection of the processes within the system boundaries per supply chain step, and data input to the sensitivity analysis.

4.1 EMISSION FACTORS

Table 6. shows the emission factors used within this research. Factors for fuels and chemicals include the emissions related to the supply of the fuel or the chemical. Conversion factors to obtain carbon dioxide equivalent factors are: 1 N_2O = 298 $CO_{2\text{-eq}}$ and 1 CH_4 = 25 $CO_{2\text{-eq}}$ (EC, 2017)

Table 6. Emission factors.

	CO_2	N_2O	CH_4	$CO_{2\text{-eq}}$	Sources & notes
Fuels	g/MJ	g/MJ	g/MJ	g/MJ	
Diesel	92.9	-	0.09	95.1	[1]
Gasoline	N/A	N/A	N/A	93.3	[1]
HFO	92.8	-	0.05	94.2	[1]
MDO	92.8	-	0.05	94.2	[1]
Hard coal – Europe	102.6	2.5E-04	0.39	112.4	[1]
Biomass and biomass fuels	g/kg	g/kg	g/kg	g/kg	
Biomass/pellets oven dry	-	20.78		20.78	a, b
Torgas	-	28.64		28.64	a, b
Grid electricity	g/MJ	g/MJ	g/MJ	g/MJ	
SE US	N/A	N/A	N/A	183.0	[1]
Netherlands	N/A	N/A	N/A	183.0	[1]
RED II Fossil Fuel Comparator (FFC)					
Electricity production	N/A	N/A	N/A	183	[2]
Heat production	N/A	N/A	N/A	124	[2]
Chemicals	g/kg	g/kg	g/kg	g/kg	
N-fertiliser	3,876.5	2.2	2.2	4,571.5	[1]
P_2O_5-fertiliser	N/A	N/A	N/A	547.1	[1]
K_2O-fertiliser	N/A	N/A	N/A	416.7	[1]
Pesticides/herbicides	11,209.6	1.7	12.0	12,009.7	[1]

Sources: [1] Giuntoli et al. (2017b, 2017a). [2] EC (2017). Notes: N/A = not available. a. CO_2 emissions from combustion are excluded to account for forest carbon sequestration. b. According to Hanssen et al. (2017), 98.45% of GHG emissions of biomass or pellet combustion are due to CO_2, and the remaining 1.55% to N_2O and CH_4. Value calculated as [44/12] kgCO_2 released per kg carbon. Carbon content of oven dry feedstock and pellets is assumed to be 50% (Hanssen et al., 2017) and of torgas 36% (T. Kleingeld – Blackwood Technology, December 13, 2017).

4.2 FEEDSTOCK SUPPLY

Diesel, fertiliser and herbicide use for silviculture operation are shown in Table 7. In the SE US, plantations are usually divided in low, mid and high intensity plantations. Plantations in which trees are only planted and harvested are called low intensity, whereas at high intensity plantations fertilisation, herbicide application and thinning are included to increase yield. Mid intensity plantation are moderately fertilised plantations including thinning (Jonker et al., 2013). Plantations in the supply base of the US Pellet Producer are characterised by thinning during mid-rotation, chemical and mechanical site preparation, and usually no fertiliser application or other chemical treatment. High intensity plantations represent only a very small percentage of the supply base (SBP, 2016). The plantations of the case study investigated in this research are thus best characterised by the mid-intensity variant, adjusted by excluding fertiliser application and including chemical site preparation. The values highlighted in red in Table 7 are included in this study for plantations in the supply base of the US Pellet Producer.

Table 7. Plantation emissions for low, mid and high intensity plantations in SE US. Highlighted values are included in this study.

	Unit	year l/m/h[a]	Low	Mid	High	Sources & notes
Raking and spot piling (diesel fuel)	L/ha	0/0/0	43.0	43.0	43.0	[1]
Bedding (diesel fuel)	L/ha	-/0/0	-	53.0	53.0	
Herbicide (velpar ULW)	kg/ha	-/-/0	-	-	3.4	
Planting (diesel fuel)	L/ha	0/0/0	28.0	28.0	28.0	
Herbicide (glyphosate)	kg/ha	-/-/0	-	-	11.2	
Fertilisation (DAP) [b]	kg/ha	-/-/0	-	-	224.0	
Fertiliser application (gasoline fuel) [c]	L/ha	-/-/0	-	-	9.0	
Herbicide (glyphosate)	kg/ha	-/-/1	-	-	11.2	
Fertilisation (DAP) [b]	kg/ha	-/3/5	-	224.0	140.0	
Fertilisation (urea)	kg/ha	-/-/5	-	-	431.0	
Fertiliser application (gasoline fuel) [c]	L/ha	-/3/5	-	9.0	9.0	
Thinning (diesel fuel)	L/ha	-/15/12	-	616.0	616.0	
Fertilisation (urea)	kg/ha	-/15/12	-	358.0	431.0	
Fertilisation (DAP) [b]	kg/ha	-/-/12	-	-	140.0	
Fertiliser application (gasoline fuel) [c]	L/ha	-/15/12	-	9.0	9.0	
Clear-cut harvest (diesel fuel)	L/ha	25/25/20	616.0	616.0	616.0	
Yield total	$T_{o.d.}$/ha	25/25/20	101	140	194	[1], d
Yield thinning	$T_{o.d.}$/ha	-/15/12	-	40	55	[1], d
Yield clear-cut	$T_{o.d.}$/ha	25/25/20	101	100	139	[1], d

Source: [1] Jonker et al. (2013). Notes: a. Values given as year for low/medium/high intensity. b. Based on phosphorus fertiliser production. c. Fertiliser is assumed to be applied by helicopter running on gasoline (Jonker et al., 2013; Markewitz, 2006). d. It is assumed that every third row is removed by thinning (Jonker et al., 2013), and that thinning leads to 50% enhanced growth of the remaining trees (Hanssen et al., 2017).

The fuels and chemicals shown in Table 7 are mass-allocated over the harvested thinnings and clear-cut roundwood. Emissions up to thinning are allocated equally to both thinning yield and roundwood yield. For thinning practice, it is assumed that every third row of the plantation is harvested (Jonker et al., 2013), and that enhanced growth of the remaining trees is 50% (Hanssen et al., 2017). Therefore, emissions from thinning practice are allocated for 2/3 to thinning yield and for 1/3 to clear-cut roundwood yield. Emissions after thinning are allocated to clear-cut yield only. The result of this allocation can be seen in Table 8. Emissions at the plantations in the case study are lower than medium intensity plantations, as chemical and fertiliser treatment is not commonly practiced.

Table 8. Emissions per wood product and plantation intensity.

	Unit	Low	Mid	High	Case study
Commercial thinnings	$kgCO_{2-eq}/t_{o.d}$	-	39.28	40.65	38.47
Roundwood	$kgCO_{2-eq}/t_{o.d}$	23.29	48.92	50.57	31.44

Chipping is assumed to take place at the pretreatment facility, so after feedstock production and collection, biomass is transported by truck to the WP plant. The transport distance is equal to the average sourcing distance given in Table 4. Empty returns of the trucks are included. Input data for the feedstock supply step is shown in Table 9.

Table 9. Input data feedstock supply.

		Unit	Value	Sources & notes
Feedstock supply	Roundwood emissions	$kgCO_{2\text{-}eq}/t_{o.d}$	33.36	a
	Commercial thinnings emissions	$kgCO_{2\text{-}eq}/t_{o.d}$	40.39	a
Truck transport	Diesel consumption full	MJ/km	13	[1]
	Diesel consumption empty	MJ/km	8	[1]
	Max cargo load (weight)	t	26	[2]
	Loaded trips of total trips	%	50%	[2]
	Diesel use loading to truck	L/load	4.7	[3]
	Diesel use unloading truck	L/load	1.7	[3]
Losses	Total losses feedstock supply	$\%_{wt}$	3%	[4]

Sources: [1] Hoefnagels, Searcy, et al. (2014). [2] US Pellet Producer, personal communication, November 14, 2017. [3] Lindholm, Berg, & Hansson (2010). [4] Sikkema et al. (2010). Notes: a. See Table 8.

4.3 PRETREATMENT

Input data for the pretreatment step is divided into characteristics of pellets produced, mass balances, electricity requirements and fossil fuel requirements.

4.3.1 Produced pellets

The produced WP and TOP have different characteristics. This is shown in Table 11. Differences in heating value are a result of different LHVs of incoming feedstock, and in case of TOP because of differences in torrefaction degree, which is optimized for each scenario (T. Kleingeld – Blackwood Technology, personal communication, January 8, 2018).

Table 10. Characteristics produced pellets.

		Unit	WP	Sources & notes	TOP	Sources & notes
Pellet moisture content		%	6%	[1]	7%	[3]
Pellet bulk density		kg/m^3	680	[2]	750	[3]
Pellet heating value	PP	$MJ/kg_{a.r.}$	18.17	[1], a	20.59	[3], a
	RW	$MJ/kg_{a.r}$	18.20		20.63	
	CT	$MJ/kg_{a.r}$	18.20		20.63	
	HR	$MJ/kg_{a.r}$	17.60		19.51	
	SR	$MJ/kg_{a.r}$	18.22		20.40	
Wood moisture content at dryer outlet		%	13.6%	[1]	10%	[3]

Sources: [1] US Pellet Producer, personal communication, November 14, 2017. [2] US Pellet Producer, personal communication, December 22, 2017. [3] T. Kleingeld – Blackwood Technology, personal communication, December 13, 2017. Notes: a. Calculated from mass balances (WP: Appendix B, TOP: Appendix C).

4.3.2 Mass balances

For WP and TOP scenarios, mass balances are composed by means of the incoming feedstock characteristics (see Table 4) and the moisture content at the dryer outlet (see Table 10). The complete mass balances can be found in Appendix B for WP and Appendix C for TOP. Besides mass loss due to moisture loss, a 1% mass loss for pelletising (Sikkema et al., 2010) and a 3.1% mass loss for cleaning incoming feedstock from sand and metals (T. Kleingeld – Blackwood Technology, November 8, 2017) are included for both WP and TOP. With the mass balances, the amount of raw material required to produce 1 tonne pellets is determined.

Besides biomass feedstock for producing pellets, biomass is needed to fuel the combustor that supplies heat to the drying process, and in case of TOP also to the torrefaction unit. For this purpose, the US Pellet Producer uses hog fuel, composed of bark, sawmill bark and harvest residues, shown in Table 11. This composition is used for the Pellet Producer feedstock scenario.

Table 11. Support fuel requirements white pellet (WP) production US Pellet Producer.

		Bark	Sawmill bark	Harvest residues	Sources & notes
Consumption	t wet/year	153,676	4,964	39,183	[1]
Moisture content	%	36.2%	36.2%	41.2%	[1]
Lower heating value wet	MJ/kg_{wet}	11.89	11.89	10.18	[1], a

Source: [1] US Pellet Producer, personal communication, November 14, 2017. Note: a. Heating value for sawmill bark not available, assumed equal to bark.

For the other WP and all TOP feedstock scenarios, different compositions of hog fuel are assumed according to availability of bark and sawmill bark in the scenario. An overview of feedstock requirements and support fuel needed is given in Table 113.

Table 12. Feedstock requirements (in $t/t_{pellets}$) white pellet (WP) and torrefied pellet (TOP) production.

	PP		RW		CT		HR		SR		Notes
all values in $t/t_{pellets}$	WP	TOP	WP	TOP	WP	TOP	WP	TOP	WP	TOP	
Conversion factor excluding support fuel	1.78	2.35	1.81	2.46	1.81	2.46	1.62	2.13	1.58	2.01	a
Support fuel – bark	0.21	N/A	0.30	N/A	0.30	N/A	N/A	N/A	N/A	N/A	b, c
Support fuel – sawmill bark	0.01	0.01	N/A	N/A	N/A	N/A	N/A	N/A	-	0.02	b
Support fuel – harvest resid.	0.05	0.04	-	0.09	-	0.09	0.25	0.04	0.18	-	b
Torgas combustion	N/A	0.31	N/A	0.31	N/A	0.31	N/A	0.27	N/A	0.26	d
Conversion factor including support fuel	2.04	2.40	2.16	2.56	2.16	2.56	1.92	2.17	1.77	2.04	e

Notes: N/A = not available in scenario. a. Calculated from mass balances in Appendix B (WP) and Appendix C (TOP). b. Support fuel requirements for PP WP scenario obtained from personal communication US Pellet Producer, November 14, 2017. For the other WP scenarios and for the TOP scenarios, the same availability of support fuel is assumed. See appendices for more information. c. Bark is not available in TOP scenarios because no debarking takes place. d. Obtained from T. Kleingeld – Blackwood Technology, personal communication, December 13, 2017. e. Calculated from table values.

TOP scenarios require less biomass support fuel than WP scenarios as heat requirements are mainly delivered by torgas. For the different scenarios, 20% of heat supply provision by external biomass fuel is assumed (T. Kleingeld - Blackwood Technology, personal communication, January 8, 2018).

4.3.3 Electricity consumption

Electricity consumption of the WP production process is obtained from the US Pellet Producer, and for TP production from Blackwood Technology. Data obtained from both suppliers is shown in Table 13.

Table 13. Electricity consumption obtained from the US Pellet Producer and Blackwood Technology.

Process	Unit	US Pellet Producer	Blackwood Technology
Debarking	$kWh/t_{pellets}$	-	N/A
Chipping	$kWh/t_{pellets}$	-	-
Drying	$kWh/t_{pellets}$	-	29.68
Torrefaction	$kWh/t_{pellets}$	N/A	20.79
Grinding	$kWh/t_{pellets}$	-	8.40

Pelleting & cooling	kWh/t$_{pellets}$	-	80.75
Auxiliaries	kWh/t$_{pellets}$	-	15.52
Total	kWh/t$_{pellets}$	192.71	-

N/A = not applicable

As can be seen from the table, WP data was given as an aggregated value and chipping electricity requirements were not available in both WP and TOP data. Therefore, other sources are qualitatively analysed to add to the available data and in order to place the numbers above into context. Literature results are shown in Table 14. From literature, values from pilot experiments are excluded, as they are considered not applicable to commercial-scale pellet production. For WP, a *fitted value* column is added representing literature values best applicable to the case study. These values are used to subdivide the total electricity consumption reported by the US Pellet Producer (Table 13) to separate processes. For debarking, it is assumed that energy consumption is 2.8% of chipping requirements (Olszewski et al., 2017). Chipping and drying is based on the electricity consumption of a different US pellet producer. For drying, an average from the table values is used. For grinding, it is chosen to use an average of 30-40 kWh/t, as this was specifically stated to be valid for grinding microchips, which corresponds to the case study. For pelleting and cooling, most sources reported energy use between 50 and 70 kWh/t$_{pellets}$, so a nominal value of 60 kWh/t$_{pellets}$ is chosen. Electricity requirement for auxiliaries is chosen equal to the TOP case (see Table 13).

Table 14. Literature sources on electricity requirements WP and TOP production.

		WP						TOP		
		[1]	[2]	[3]	[4]	[5]	Fitted value	[6]	[7]	[8]
Debarking	kWh/t$_{pellets}$	-	-	-	-	-	1.4	-	-	-
Chipping	kWh/t$_{pellets}$	38.8	-	-	48.8	-	48.8	-	-	-
Drying	kWh/t$_{pellets}$	N/A	23.9	31.9	10	-	23.9	10	N/A	
Torrefaction	kWh/t$_{pellets}$	-	-	-	-	-	-	57		
Grinding	kWh/t$_{pellets}$	21.3	18.8	40.7	N/A	30-40	35	37	15	6.1-18.7
Pelleting, cooling	kWh/t$_{pellets}$	60.2	53.2	101.9	63.5	50-70	60	58	80	123.3
Auxiliaries	kWh/t$_{pellets}$	8.5	18.4	21.3	Incl.		15.5	Incl.		

Sources: [1] Sikkema et al. (2010). [2] Obernberger & Thek (2010). [3] Uasuf & Becker (2011). [4] Values correspond to a different US pellet producer, obtained through personal communication. This plant had periods with high overall energy consumption due to engineering issues. Values are chosen from a period in which total electricity consumption resembled the US Pellet Producer considered in this study the most. [5] Employee Kahl Group, personal communication, January 12, 2018. [6] Mobini et al. (2014). [7] McNamee et al. (2016). [8] Kumar et al. (2016). Notes: N/A = not available. Incl. = included in values above.

Input data on electricity consumption is summarised in Table 15. Total electricity consumption reported by the US Pellet Producer is 4.4% higher than the total from the column *fitted value*. Therefore, 4.4% was added to the *fitted values* to obtain input data for the WP production process. For TOP, values from Blackwood Technology were complemented with chipping consumption per tonne of incoming feedstock equal to WP. To obtain values per tonne of TOP produced, the WP values are corrected for the larger amount of incoming feedstock required.

Table 15. Input data electricity for white pellet (WP) and torrefied pellet (TOP) production.

		Unit	Input WP	Input TOP
Debarking	Electricity	kWh/$t_{pellets}$	1.4	N/A
Chipping	Electricity	kWh/$t_{pellets}$	49.9	57.2
Dryer	Electricity	kWh/$t_{pellets}$	28.5	29.7
Torrefaction & cooling	Electricity	kWh/$t_{pellets}$	N/A	20.8
Grinding	Electricity	kWh/$t_{pellets}$	35.8	8.4
Pelletising & cooling	Electricity	kWh/$t_{pellets}$	61.3	80.1
Auxiliaries	Electricity	kWh/$t_{pellets}$	15.8	15.5

N/A = not applicable.

4.3.4 Fossil fuel consumption

Besides electricity, fossil fuels are used during pretreatment. At the US Pellet Producer, diesel oil is used for raw material handling. Furthermore, natural gas is used for volatile organic compounds (VOCs) removal from exhaust air. VOC emissions are generated during drying, hammer milling and pelletising. These emissions are regulated by law and need to be destroyed in regenerative thermal and catalytic oxidizers (RTOs and RCOs), running on natural gas. Table 16 shows input data for WP, obtained from the US Pellet Producer.

For TOP, diesel oil use per tonne of incoming feedstock is assumed to be equal to WP. Natural gas use for VOC removal can theoretically be lower, because the system can be designed such that less VOCs are generated during drying and relatively more during torrefaction. VOCs generated during torrefaction can then be led to the combustor together with torgas, leading to lower natural gas requirements for RTOs and RCOs (T. Kleingeld – Blackwood Technology, personal communication, January 8, 2018). However, data on VOC generation per process is not available, thus natural gas consumption per tonne of incoming feedstock is considered equal to the WP case (see Table 16).

Table 16. Input data fossil fuel consumption for white pellet (WP) and torrefied pellet (TOP) production.

Process	Energy carrier	Unit	Input WP	Input TOP
RCOs & RTOs	Natural gas	MJ/$t_{pellets}$	282.4	331.2
Raw material handling	Diesel oil	L/$t_{pellets}$	0.8	1.0

4.4 DISTRIBUTION

Input data for the distribution phase is given in Table 17. Fuel consumption for shipping is calculated according to the methodology set in Giuntoli et al. (2017b). Besides the characteristics of the Handysize ocean carrier assumed in the case study, values for a larger Supramax carrier are shown for comparison. The Supramax values are used in the sensitivity analysis.

Table 17. Input data intermodal transportation.

		Unit	Value	Sources & notes
Train transport	Fuel	-	Diesel	[1]
	Max load (weight)	t	1,820	[1]
	Max load (volume)	m^3	4,550	[1]
	Fuel consumption empty	MJ/km	207	[1]
	Fuel consumption full	MJ/km	20	[1]
	Emptry trips	%	50%	[2]
	Distance	km	*<confidential>*	[2]
Handling at export port	Diesel use	L/$t_{pellets}$	0.048	[2], a
	Electricity use	kWh/$t_{pellets}$	0.791	[2], a
	Losses	$\%_{wt}$	1%	[3]

Shipment			Handysize	Supramax	
	DWT	t	28,000	57,000	[4]
	LWT	t	8,000	13,000	[4]
	Fuel, crew, water, storage	t	2,000	3,000	[4], b
	Stowage factor	t/m^3	0.75	0.75	[5]
	Max load (weight)	t	26,000	54,000	[4]
	Max load (volume)	m^3	34,667	72,000	[4]
	Min load (ballast)	t	7,000	14,250	[4], c
	Fuel consumption	g/tkm	1.67	1.09	[4]
	Empty trips	%	30%	30%	[5]
	Losses	$\%_{wt}$	2%	2%	[3]
	Distance	km	7300	7300	[6]
Handling at import port	Diesel use	$L/t_{pellets}$	0.048		d
	Electricity use	$kWh/t_{pellets}$	0.791		d
	Losses	$\%_{wt}$	Negligible		[3]
Barge transport	Fuel type	-	MDO		[1]
	Load (weight)	t	2,842		[7]
	Load (volume)	m^3	4,874		[7]
	Fuel consumption empty	MJ/km	435		[1], e
	Fuel consumption full	MJ/km	480		[1], e
	Empty trips	%	50%		[8]
	Distance	km	50		[6]

Sources: [1] Hoefnagels, Searcy, et al. (2014). [2] US Pellet Producer, personal communication, November 14, 2017. [3] Sikkema et al. (2010). [4] Giuntoli et al. (2017b). [5] Giuntoli et al. (2017a). [6] https://sea-distances.org/ [7] Rijkswaterstaat (2002). [8] M. Bouwmeester – RWE, personal communication, November 28, 2017. Notes: a. Assumed to be equal for WP and TOP. b. Value valid for full load journey. During empty returns, 80% of this value is assumed (Giuntoli et al., 2017b). c. Assumed to be 25% of DWT (Giuntoli et al., 2017b). d. Assumed to be equal to handling requirements in the US and assumed to be equal for WP and TOP. e. Fuel consumption is linear interpolated by weight from values in Hoefnagels, Searcy, et al. (2014), in order to obtain values corresponding to Europe II barges (see Appendix A, Table A2).

4.4 END USE

Within this last supply chain step, energy is consumed due to grinding of the pellets before feed to the pulverised coal boiler. TOP offer advantages in comminution because the brittleness of the pellets leads to lower grinding energy requirements (Agar, 2017). Next to emissions within the power plant and pellet combustion emissions, conversion efficiency has to be taken into account. The ratio between electricity and heat produced in the Amer CHP depends on demand. It is assumed that the electrical capacity of the boiler is fully utilized. A co-firing percentage of 50% on an energy input basis is assumed. Using WP instead of coal leads to small efficiency losses. This loss is caused by increased air flow requirements to transport the larger wood particles through pulverizing mills. Because of safety concerns, this air needs to be cooled. The increased air flow leads to increased cooling requirements and thus a small efficiency loss (M. Bouwmeester – RWE, personal communication, December 18, 2017). Hence, efficiency loss is a result from the larger particles of pulverized pellets than coal. Pulverized TOP are characterized by smaller particles than pulverized WP due to their coal-like characteristics and brittleness (Tumuluru et al., 2011), leading to a smaller efficiency loss than for WP. Losses in efficiency are allocated to pellet produced electricity and heat only (not to coal conversion). Input data for the co-firing step is shown in Table 19.

Table 18. Input data co-firing pellets in Amer CHP.

	Unit	Value	Sources & notes
Energy use pulverising WP	kWh/t pellets	50	[1]
Energy use pulverising TOP	kWh/t pellets	15	[1]
Nominal electric capacity power plant	kW_{el}	625,000	[2]
Nominal thermal capacity power plant	kW_{th}	55,000	[2]
Electric efficiency at 100% coal firing	%	41.8%	[2]
Thermal efficiency at 100% coal firing	%	3.7%	a
Feed temperature district heating network	°C	120	[3]
Fraction exergy in electricity	-	1	[4]
Fraction exergy in heat (Carnot efficiency heat at T<150°)	-	0.3546	[4]
Co-firing percentage	%	50%	assumed
Efficiency loss WP at 50% co-firing	%	0.50%	[5]
Efficiency loss TOP at 50% co-firing	%	0.17%	b

Sources: [1] Agar (2017). [2] M. Bouwmeester - RWE, personal communication, November 28, 2017. [3] Obernberger & Thek (2010). [4] EC (2017). [5] M. Bouwmeester – RWE, personal communication, December 18, 2017. Notes: a. Calculated from electric efficiency and output. b. Phanphanich & Mani (2011) found that the geometric mean diameter of different white and torrefied biomass is on average 0.73 mm and 0.40 mm respectively. Assuming a geometric mean diameter of 0.23 mm for coal (Saastamoinen et al., 2010) and a linear relation between air flow requirements and particle size, the efficiency loss for TOP is estimated to be 0.17%.

4.6 SENSITIVITY ANALYSIS

4.6.1 Part I: uncertainty in TOP production

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4.6.2 Part II: sensitivity cases

For part II of the sensitivity analysis parameters are changed according to the parameters of the High Growth case and the Alternative Fossil Fuel Comparator case. The two sensitivity analyses cover the results including conversion to electricity. An overview of the parameters changed in the sensitivity analysis is shown in Table 21.

Table 19. Changed parameters sensitivity analysis part II. Highlighted values remain equal to the base case.

	Unit	Base Case	High Growth	Alternative FFC	Notes
Plantation emissions – roundwood	$kgCO_{2\text{-}eq}/t_{o.d}$	31.44	50.57	31.44	a
Plantation emissions – thinnings	$kgCO_{2\text{-}eq}/t_{o.d}$	38.47	40.65	38.47	a
Ocean carrier fuel consumption	gHFO/tkm	1.67	1.09	1.67	b
Truck distance RW/CT	km	60	120	60	c
Truck distance HR	km	100	120	100	c
Truck distance PP	km	79	120	79	c
Truck distance SR	km	129	129	129	d
Efficiency loss co-firing	%	0.50%	1.20%	0.50%	e
Grid emission factor US	$gCO_{2\text{-}eq}/MJ_e$	183.0	183.0	202.5	f
Grid emission factor NL	$gCO_{2\text{-}eq}/MJ_e$	183.0	183.0	146.7	g
Emissions reference coal plant	$gCO_{2\text{-}eq}/MJ$	183.0	183.0	260.84 (elec.) 92.49 (heat)	h

Notes: a. See Table 8. b. See Table 17. c. The maximum sourcing distance is usually 120 km (Dale et al., 2017). d. Sawmill residues are already sourced from the maximum distance. e. Efficiency loss at 80% co-firing is 1.2% (M. Bouwmeester – RWE, personal communication, December 18, 2017). f. Jonker et al. (2013). g. BioGrace II (2015). h. Supply and combustion of coal in Europe is on average 112.4 $gCO_{2\text{-}eq}/MJ_{LHV}$ (see Table 6). Combined with the electrical efficiency of 41.8% and heat efficiency of 3.7% (see Table 19), gives the emission factors displayed.

5. RESULTS

This section shows the results. First, the emissions results of the supply chain on a mass basis and primary energy basis of the pellets are given. These results include all supply chain emissions until conversion in the power plant. Next, emissions on a final energy basis are presented, which include the conversion into useful heat and power. Also, the emission savings compared to the fossil fuel comparator are given. Lastly, the results of the sensitivity analysis are presented.

5.1 PELLET EMISSIONS

It is common to present emissions of pellets on a mass basis ($kgCO_{2\text{-eq}}/t_{pellet}$). Figure 6 shows these results. It shows that total emissions are comparable for WP and TOP. For the *harvest residues* and *sawmill residues* scenarios, TOP have lower total emissions.

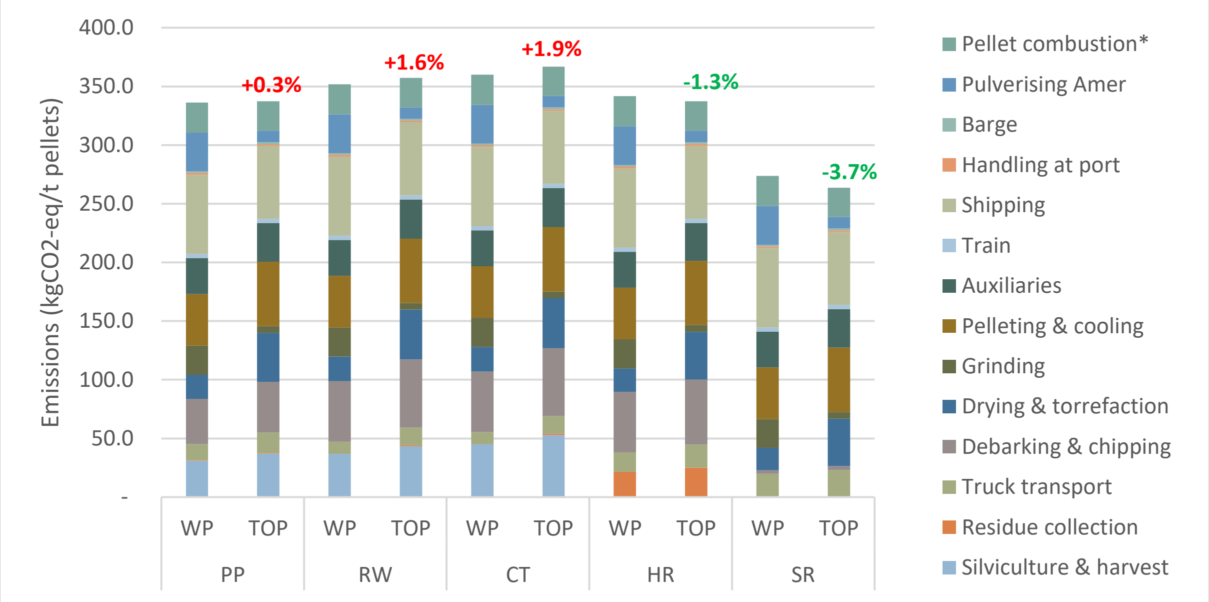

Figure 6. GHG emissions of white- (WP) and torrefied pellet (TOP) scenarios on a pellet mass basis.
US Pellet Producer (PP), roundwood (RW), commercial thinnings (CT), harvest residues (HR), sawmill residues (SR). Numbers above data columns are percentage changes from switching from WP to TOP.
* CO_2 emissions from combustion are excluded to account for forest carbon sequestration.

However, comparing white and torrefied pellets on a mass basis gives a distorted image, as the TOP production process delivers pellets with a higher energy content. It is thus more insightful to look at the emissions per energy content of the pellets ($gCO_{2\text{-eq}}/MJ_{pellet}$), which are achieved by dividing the mass based emissions by the pellet energy content). These results are shown in Figure 7.

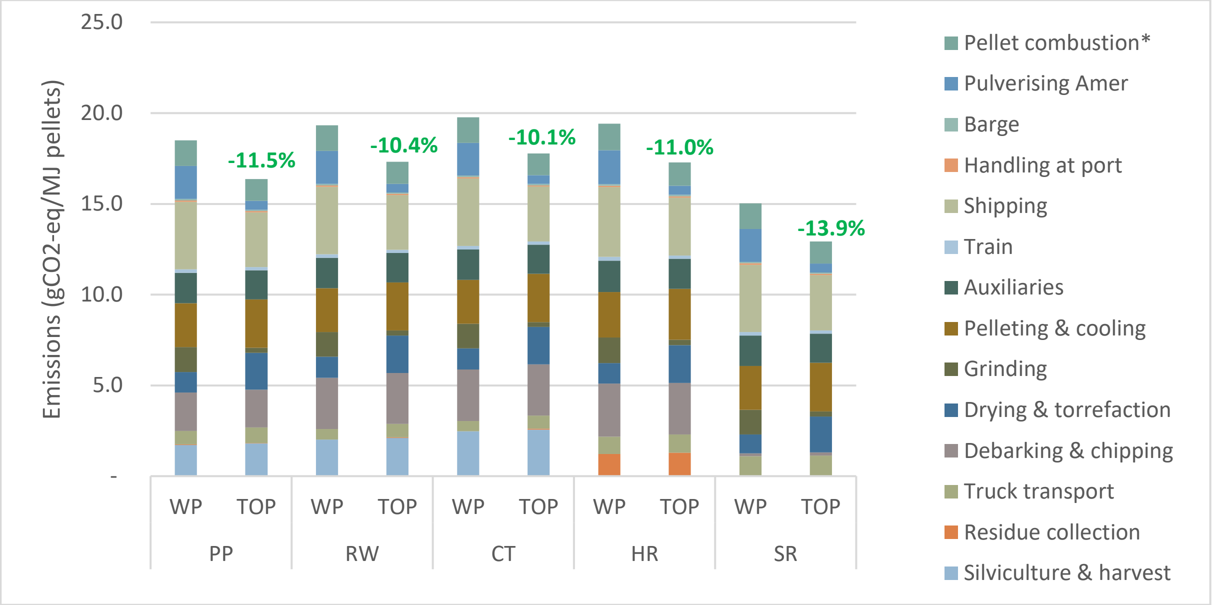

Figure 7. GHG emissions of white- (WP) and torrefied pellet (TOP) scenarios on a pellet energy basis. US Pellet Producer (PP), roundwood (RW), commercial thinnings (CT), harvest residues (HR), sawmill residues (SR). Numbers above data columns are percentage changes from switching from WP to TOP.
* CO_2 emissions from combustion are excluded to account for forest carbon sequestration.

The results of emissions on an energy content basis show significantly lower emissions for all TOP scenarios compared to the corresponding WP scenarios. The largest reductions are seen in all processes occurring after the production of pellets, mostly during intermodal transportation (16.2-18.0%). For train and barge transport, this is a direct result from the higher calorific value of TOP. Oceanic transport offers an additional advantage for TOP. The higher bulk density of TOP compared to WP leads to a shift of volume limited cargo to weight limited cargo in bulk carriers. This means that the ship can be loaded to its maximum cargo weight and the available room for cargo is optimally used in the case of TOP. Other reductions in emissions between TOP and WP are seen in lower energy requirements for grinding during pretreatment and pulverisation at the coal power plant, as torrefied material is easier to comminute than non-torrefied material. Also, lower emissions are seen at the pellet combustion stage, as TOP combustion has a higher efficiency than WP combustion.

Higher emissions of TOP scenarios compared to the corresponding WP scenarios are seen in feedstock supply, because slightly more feedstock is needed for TOP on a MJ pellet basis. This leads to higher emissions for silviculture and truck transport. Furthermore, more emissions are seen in the pelleting and cooling step, because pelletisation of torrefied material requires more electricity than pelletisation of non-torrefied biomass. However, the total GHG emission savings are higher than additional emissions occurring in these steps, leading to net savings of 10.1-13.9%.

Between feedstock scenarios, the highest savings are seen within the *sawmill residues* scenario, due to no silviculture and collection, and no chipping emissions. The lowest emission savings when moving from WP to TOP are seen in the *roundwood* and *commercial thinnings* scenarios. This can be explained by relative high emissions associated with silviculture and harvest.

5.2 FINAL ENERGY EMISSIONS

The previous results did not include the conversion into useful heat and power. Table 20 shows the emissions of the different scenarios including conversion and savings of TOP compared to WP. As can be seen in the table, emissions savings from switching from WP to TOP on a produced electricity and heat basis are a little higher compared to savings on a MJ pellet basis.

Table 20. Emissions WP and TOP scenarios including conversion into electricity and heat.

		PP		**RW**		**CT**		**HR**		**SR**	
		WP	TOP	WP	TOP	WP	TOP	WP	TOP	WP	TOP
Emissions electricity	$gCO_{2\text{-eq}}/MJ_e$	44.0	38.3	45.9	40.5	47.0	41.6	46.1	40.4	35.7	30.3
Emissions heat	$gCO_{2\text{-eq}}/MJ_{th}$	15.6	13.6	16.3	14.4	16.7	14.8	16.4	14.3	12.7	10.7
Change on a MJ_e or MJ_{th} basis		**-12.9%**		**-11.8%**		**-11.5%**		**-12.4%**		**-15.3%**	

To obtain savings of the scenarios compared to coal these emission factors are compared with the fossil fuel comparators from the RED II: 183 $gCO_{2\text{-eq}}/MJ_e$ for electricity and 124 $gCO_{2\text{-eq}}/MJ_{th}$ for heat replacing coal. This leads to the savings visualized in Figure 8. The future GHG emission saving criteria from the RED II are depicted with black striped or dotted lines.

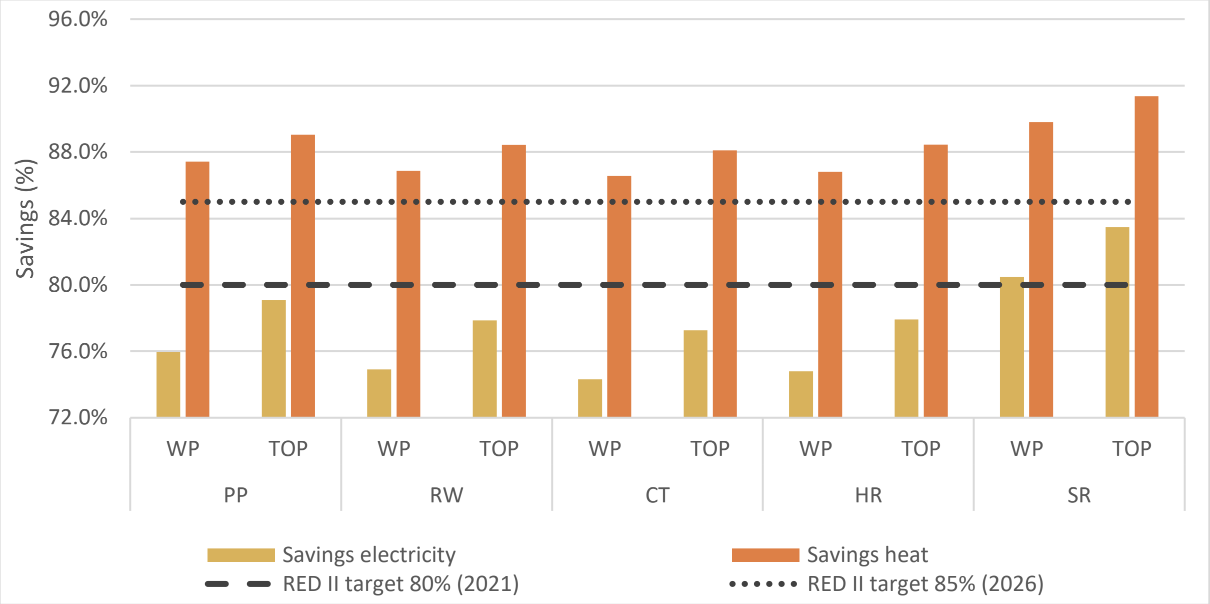

Figure 8. Final emission savings of WP and TOP scenarios compared to the RED II fossil fuel comparator. US Pellet Producer (PP), roundwood (RW), commercial thinnings (CT), harvest residues (HR), sawmill residues (SR).

The figure shows significantly better emission savings of TOP scenarios compared to their corresponding WP counterpart. The TOP scenarios are on average 3.0-3.1 percent point better when electricity production is concerned, and 1.5-1.6 percent point better for heat production. All TOP scenarios perform similarly better, indicating that switching from WP to TOP is beneficial from a GHG emission perspective for each feedstock scenario in the investigated case study. Even though the figure does not show differences between WP and TOP in reaching RED II targets, this could be different for other supply chains, especially for supply chains with larger transport distances. Another observation is that electricity production is associated with lower savings than heat production. This can be due to the choice of reference fossil fuel comparator prescribed by the RED II. The effect of this choice and other methodological choices is evaluated in the sensitivity analysis in the next chapter, as well as the uncertainty in TOP production data.

5.3 SENSITIVITY ANALYSIS

5.3.1 Part I: uncertainty in TOP production

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5.3.1 Part II: sensitivity cases

The second part of the sensitivity analysis investigates changes in methodological assumptions in a High Growth case and an Alternative FFC case (see chapter 3.3.2). The combined effect of changing parameters in these cases for electricity production with the US Pellet Producer feedstock scenario is shown in Figure 9.

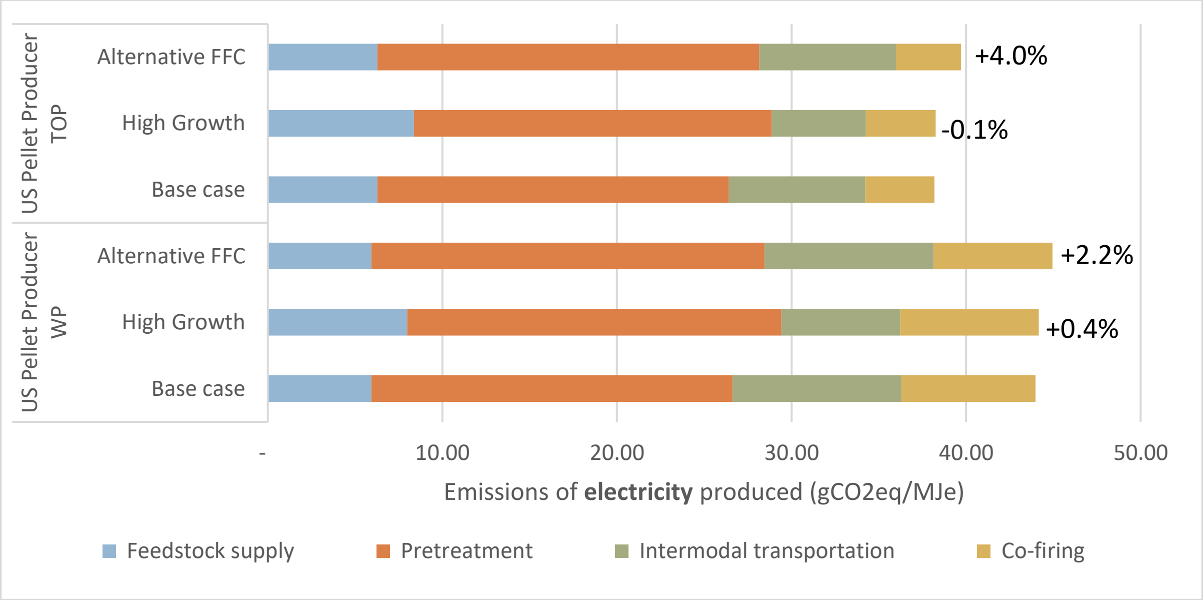

Figure 9. Sensitivity cases for electricity production in the US Pellet Producer feedstock scenario.

The High growth case leads to more emissions in both the WP and TOP cases. Increases are seen in the *Feedstock supply* step, due to higher plantation emissions and increased sourcing distance, and in the *Co-firing* step, due to increased co-firing losses. A decrease is seen in the *Intermodal transportation* step, due to more efficient ocean carriers. The effect of switching to Supramax ships shows a stronger decrease in total emissions for WP (-7.1%) than for TOP (-6.5%). The benefit of TOP during transportation decreases when transportation becomes more efficient. The increased co-fire loss has a higher influence on WP (+3.6%) than on TOP (+1.8%), because TOP is associated with a lower co-firing loss in general. For an increase to high intensity plantation management and an increased sourcing distance, emissions increase slightly more for TOP than for WP, as TOP need slightly more feedstock. The increase occurring from a switch to high intensity plantation management is small, since thinnings are associated with high emissions in both mid- and high intensity situations. The figure shows that the larger effect of increased co-fire loss for WP is the strongest, as WP emissions increase slightly more (3.0%) than TOP (+2.9%).

The Alternative FFC analysis also shows increased emissions for both WP and TOP. An increase is seen in the *Pretreatment* phase, as the Southeast US has a higher grid emission factor than the fossil fuel comparator. A small decrease is seen at the *Co-firing* stage, as the Netherlands has a lower grid emission factor than the fossil fuel comparator. The effect is stronger on TOP than on WP, as TOP use more grid electricity during *Pretreatment*.

Emission savings of the High Growth and Alternative FFC cases are visualised in Figure 12 for electricity and Figure 11 for heat. Note that the savings in the Alternative FFC case are equal for electricity and heat, because coal emissions before conversion are equal.

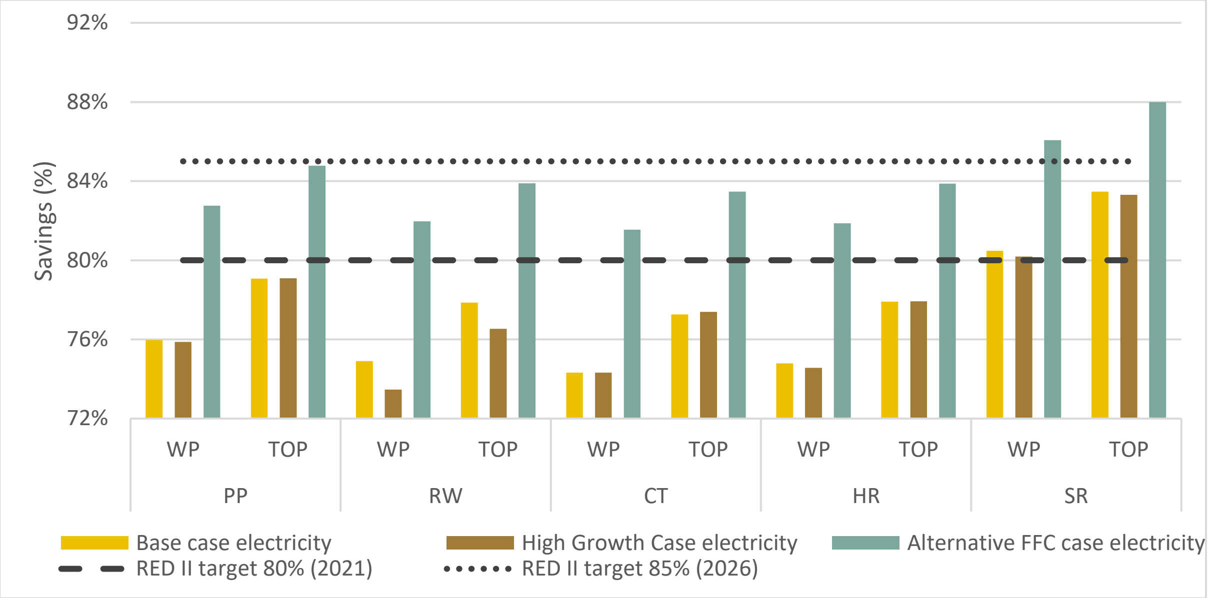

Figure 10. Emission savings electricity for the base case and sensitivity cases.

The figure shows that emission savings in the High Growth case do not differ much from the base case. Only for roundwood the savings are considerately lower. This is due to the switch to high intensity plantation management, which is related with a relatively high emissions increase per tonne yield for roundwood, and only a small increase in emissions for thinnings (see Table 8). For the Alternative FFC case, savings are 5-7 percent point higher than in the base case. So even though supply chain emissions are higher in the Alternative FFC case, the difference between the fossil fuel emission factors is even higher. In the Alternative FFC case, all scenarios reach the 2021 target of 80% where most scenarios did not in the base case. WP and TOP from sawmill residues even reach the 2026 target of 85%.

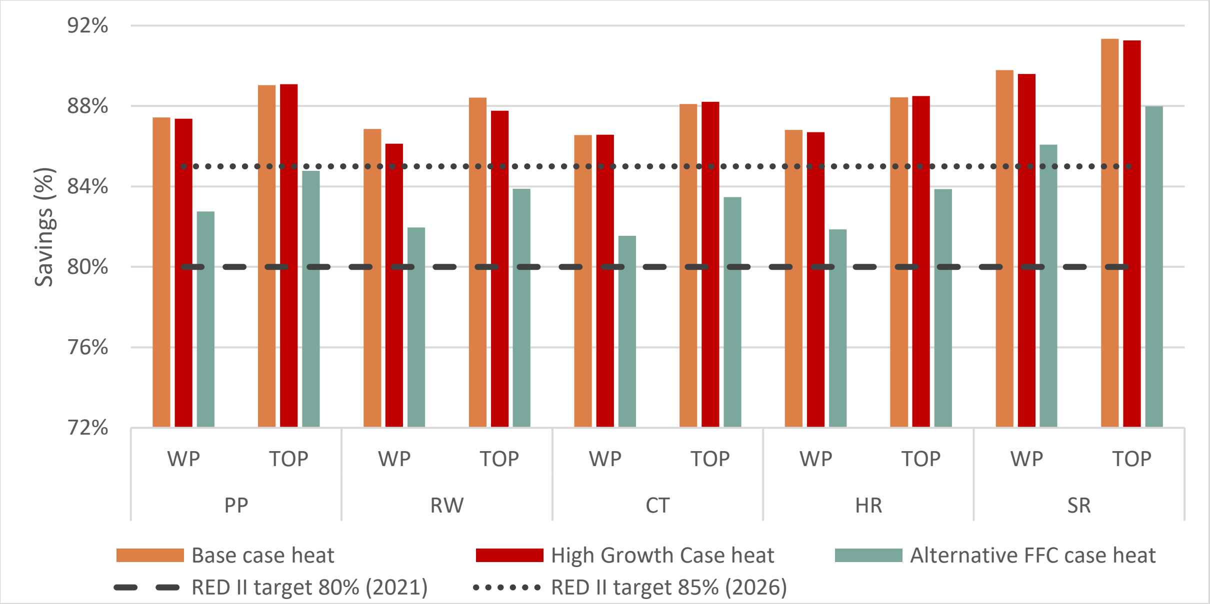

Figure 11. Emission savings heat for the base case and sensitivity cases.

When looking at heat production, the same trend as for electricity production is visible in the High Growth case: small decreases in savings, most notably in the roundwood feedstock scenario. Alternative FFC savings are 3-5 percent point lower compared to the base case, while they were higher for electricity production. This shows that the fossil fuel comparators used in the RED II methodology of the base case tend to underestimate electricity emission savings and overestimate heat emission savings. Furthermore, it can be seen that in the Alternative FFC case the 2026 target of 85% is not reached anymore for all feedstocks except sawmill residues.

For switching from WP to TOP, the savings achieved are shown in Table 21.

Table 21. Change in electricity/heat emissions of switching from WP to TOP.

	PP	RW	CT	HR	SR
Base case	**-12.9%**	**-11.8%**	**-11.5%**	**-12.4%**	**-15.3%**
High growth case	**-13.3%**	**-11.5%**	**-11.9%**	**-13.2%**	**-15.7%**
Alternative FFC case	**-11.7%**	**-10.7%**	**-10.4%**	**-11.1%**	**-13.8%**

From this table it becomes clear that for an increased demand for pellets and thus increased production in the High Growth case, the benefit of TOP in terms of GHG emissions increases for all feedstock scenarios except *roundwood.* This is due to the fact that roundwood from high intensity plantations is associated with a larger increase in emissions and TOP requires more feedstock. The increase in plantation emissions is for commercial thinnings much smaller. For the Alternative FFC case it can be seen that the difference between TOP scenarios and their corresponding WP scenarios has become smaller. The higher grid electricity emission factor in the US is unfavourable for TOP since TOP requires more electrical energy during pretreatment than WP. All in all, TOP remain better in terms of GHG emissions than WP for all scenarios.

6. DISCUSSION

This research compares the GHG emissions of a white pellet (WP) and torrefied pellet (TOP) supply chain and includes different woody feedstock scenarios to assess the potential of TOP in the Netherlands. Before finishing with the conclusion in the next chapter, the limitations and implications of the analysis are discussed, as well as the addition of this research to existing literature.

6.1 METHODOLOGICAL CONSIDERATIONS

For the feedstock supply step, several remarks need to be made. Firstly, it is prescribed by the RED II to not allocate upstream emissions to residues. However, there is no consensus about the correctness of this assumption in the scientific community and some authors do allocate upstream emissions to residues (see Hanssen et al., 2017; Morrison & Golden, 2016; Röder et al., 2015; Whittaker et al., 2011). In Hanssen et al. (2017), upstream emissions from plantation management, thinning and sawmill operation (the latter only for sawmill residues) are 29% of total emissions for sawmill residues and 16% for harvest residues. When these upstream emissions would have been assigned in this research, a rough calculation shows a lower GHG emission saving potential of switching from WP to TOP: 9.1% instead of 12.4% for harvest residues and 10.7% instead of 15.3% for sawmill residues. This effect results from TOP requiring more feedstock than WP. The decrease is stronger for sawmill residues, as both plantation management and sawmill operation emissions are assigned. It can be seen that allocating upstream emissions decreases the clear advantage of sawmill residues over the other feedstock scenarios found in this research. Still, TOP remain better than WP.

Secondly, effects of changes in forest carbon and soil carbon stock are not included in this research. The plantations of the case study investigated in the SE US rarely apply fertilisation (SBP, 2016). The effects of in- or excluding fertilisation on soil carbon stocks and soil quality differ amongst studies because they are site-specific (Jandl et al., 2006; Shryock et al., 2014) and time horizon specific (Vogel et al., 2011). A study by Rifai, Markewitz, & Borders (2010) investigated the long-term effects of fertilisation and herbicide application on pine plantations in the SE US. The study shows that levels of soil carbon and nitrogen increase during long-term fertilisation and decrease during long-term herbicide application, although the effects of nitrogen were not significant. This indicates that the current practice of the wood suppliers of the US Pellet Producer leads to lower levels of soil carbon, and thus increased levels of atmospheric carbon. The absence of fertilisation could also lead to a decrease in soil nutrient availability (Vogel et al., 2011).

Thirdly, the carbon debt debate – soil carbon stock changes and the loss of carbon sequestration potential of a land area due to initial harvest – is left out of the RED II. In the Netherlands, sustainability certification including carbon debt criteria is currently implemented under the Dutch Energy Agreement (for an overview fo the criteria, see Netherlands Enterprice Agency, 2017). When this happens, biomass supply chains to the Netherlands have to comply with these carbon debt criteria. For the case study investigated in this research, it could be argued that carbon debt is not applicable to roundwood or thinnings as the plantations studied are long-established. In any case, carbon debt should be evaluated when this legislation comes into force. Furthermore, the removal of harvest residues from the forest ground could also lead to carbon debt. When harvest residues are used for bioenergy production, the carbon content in residues is released immediately instead of over time, which happens when they are left in the field to decompose (Repo et al., 2015). The size of this effect is dependent on the time horizon: it is largest when harvest residues are removed for the first time, and decreases during continuous removal towards a new equilibrium (Repo, Tuomi, & Liski, 2011). A meta-analysis conducted by Achat (2015) found that removing branches and foliage from the forest ground leads to an average reduction of 10.3% in forest floor carbon stock over a period of 33 years. Since the initial carbon stock of the plantations in the case study was unknown, the effect of this reduction could not be estimated. It is important to acknowledge that even though these effects are difficult to take into account in research without detailed plantation analysis, they attribute to the GHG emission saving potential of pellet supply chains.

For truck transport, this research assumes the same sourcing distance for WP and TOP, but it is likely that these are different. Since TOP requires slightly more feedstock, sourcing distance for the TOP facility is likely to be larger than for the WP facility. On the other hand, sourcing distance for the TOP facility could decrease because TOP production has lower feedstock quality requirements (Proskurina et al., 2017). In this research, sourcing distance is kept equal due to a lack of data on feedstock availability in the Waycross area. In any case, impacts are expected to be marginal.

Total emissions for feedstock supply determined in this research were in the same range as existing studies (Agar et al., 2015; Hanssen et al., 2015; Hansson & Hackl, 2016, McNamee et al., 2016). Small differences observed can be due to assumptions on plantation intensity, such as fertiliser and herbicide application. Fuel consumption for truck transport to the pellet facility used in this research is consistent with other studies (Blok & Nieuwlaar, 2016; Giuntoli et al., 2017a).

For the pretreatment step, data for the WP production process at the US Pellet Producer is based on real life measured data, whereas data for the TOP production process is not. Even though the TOP process is simulated as close to a commercial operating facility as possible, data quality is lower for the TOP process. This is accounted for in a sensitivity analysis, performed with input data from another TOP supplier. The analysis reduced the benefit of TOP over WP to 6%. Still, TOP remained better than WP in all feedstock scenarios. Furthermore, to calculate pretreatment requirements for the feedstock scenarios, the electricity consumption at the US Pellet Producer is subdivided over the different plant processes by using percent shares of average values for these processes. In this way, the electricity consumption of the separate processes is not directly measured data. Especially with the share of chipping to total energy requirements significant uncertainty exists. Literature on the electricity consumption for efficient central debarking and chipping for pellet production was difficult to obtain, and requirements are dependent on the chipping process, feedstock, and quality requirements (van Belle, 2006). Future research could make use of process-specific measured data from a commercial pellet facility.

For intermodal transportation, fuel consumption is consistent with other literature (Dwivedi et al., 2016; Miedema et al., 2017; Sikkema et al., 2010). In contrast to other studies, this study takes into account that shipping fuel consumption is different for volume-limited cargo compared to weight limited cargo, in line with Giuntoli et al. (2017b). Volume-limited cargo has lower fuel consumption than weight-limited cargo per shipment, and not including this effect leads to a slight amplification of the advantage of TOP during shipment. The method followed in this research is therefore considered more appropriate and detailed to assess differences between WP and TOP supply chains.

6.2 IMPLICATIONS

For this research one specific supply chain was studied in great detail. By making a more thorough and more in-depth analysis than previous studies, this research adds to existing knowledge on GHG emissions of pellet supply chains. Furthermore, by using commercial-scale data measured from real life operation (WP) or demonstrated technology (TOP), the results of this research are a closer representation of reality than previous research, which is mostly based on pilot or demonstration phase data. The results are valid for this specific supply chain and demonstrate the emission savings for similar supply chains from Southeast US to Europe. Results cannot be generalised to other supply chains with different process configurations, feedstock or transport distances, since previous research has shown that results differ widely with supply chain set-up. Nevertheless, the methodology of this research could be adopted to assess supply chains with deviating conditions.

When looking at different feedstock scenarios, the highest emissions are associated with the use of commercial thinnings (19.8 and 17.9 $gCO_{2\text{-}eq}/MJ_{pellet}$ for WP and TOP respectively) or roundwood (19.3 and 17.3 $gCO_{2\text{-}eq}/MJ_{pellet}$). Surprisingly, harvest residues did also lead to relatively high emissions (19.4 and 17.3 $gCO_{2\text{-}eq}/MJ_{pellet}$). Even though no emissions are allocated until the point of collection and thus no silviculture or harvest emissions are assigned, this is compensated by emissions associated with collection and lower heating values of harvest residues compared to other feedstock scenarios. These results showed that even though harvest residues are normally preferred as feedstock for bioenergy over other plantation products (Obernberger & Thek, 2010), emissions are quite similar. However, it should be noted that this research did not look into carbon debt and alternative scenarios for feedstock. In studies on this topic, harvest residues have low carbon debt payback times because they are alternatively left to decompose in the field if not used as for bioenergy (Hanssen et al., 2017). The lowest emissions are achieved by sawmill residues as feedstock (15.0 and 12.9 $gCO_{2\text{-}eq}/MJ_{pellet}$).

With respect to the emission savings compared to the RED II fossil fuel comparators, electricity production led to 74-80% savings for WP and 77-83% savings for TOP. This shows that the 2026 target of 85% is not possible to reach with the supply chain investigated. For heat production, emission savings ranged from 87-90% for WP and 88-91% for TOP. In contrary to electricity, heat production with pellets reached all RED II targets. The results showed that TOP perform on average 1-3 percent point better than WP. The benefit of TOP could increase for other supply chain set-ups, especially if large transport distances are taken into account. Even though not the case in this research, the significant benefit of TOP over WP could make a difference in achieving the targets from the RED II when other supply chains are considered. Furthermore, the results showed that heat production leads to more savings than electricity production. These differences are largely due to the fossil fuel comparator reference values chosen in the RED II, as the fossil fuel comparator for heat production from coal is relatively large. In the sensitivity analysis the effect of fossil fuel comparator choices is analysed by using the same coal combustion emissions for both heat and electricity. This analysis showed that the choice for fossil fuel comparators in the RED II overestimates savings from heat production and underestimates savings from electricity production. In this way, the RED II can favour certain supply chains over others. The RED II aims to stimulate low transport distances and highly efficient conversion technologies (EC, 2017).

Currently, there is a lot of discussion on the emission savings targets in the RED II, and actors in the field argue for setting lower targets, e.g. at 75% maximum (Ryckmans, 2017). Lower targets would be beneficial for all WP and TOP feedstock scenarios producing electricity in this research, especially for the TOP scenarios. A 75% target for example, would be difficult to achieve for WP feedstock scenarios roundwood, commercial thinnings and harvest residues, whereas they are easily reached with TOP in the same scenarios. This example shows the additional potential of TOP over WP in meeting emission targets. Furthermore, actors in the field argue to change the rule that the fossil fuel comparator should be used for grid electricity emissions, and to use local grid emission factors instead (Giuntoli et al., 2017a; Murray, 2017). This research has investigated the effect of this change in the sensitivity analysis. Using local grid emission factors would not be beneficial for the case study investigated, as grid electricity in the SE US has a higher grid emission factor than the fossil fuel comparator. Emissions increased with 2.3% for WP and 4.0% for TOP in the US Pellet Producer feedstock scenario (PP).

For comparing WP with TOP, this study has shown that even when supply chain emissions are adapted to a higher demand for pellets, TOP scenarios will lead to lower GHG emissions than WP. The savings of electricity and heat production from TOP instead of WP in the base case are 11.5-15.3% depending on the type of feedstock. Even though results comply with previous research stating the advantage of torrefaction, savings of TOP over WP are smaller than in most previous studies (see Batidzirai et al., 2014; Kabir & Kumar, 2012; McNamee et al., 2016; Thrän et al., 2016). This shows that it is essential to study supply chains in detail and that it is difficult to generalise about the advantage of torrefaction, since GHG emission savings are extremely dependent on supply chain set-up.

This research has tried to reduce uncertainty in emissions occurring during pretreatment. For WP, actual data measurements are taken into account, but for TOP this was not possible. Data has been obtained from two commercial-scale TOP producers, but these did not represent actual measurements. Therefore, the highest uncertainty in the GHG emission saving potential of TOP versus WP and coal supply chains remains in the pretreatment phase. Future research could continue the efforts started in this research by including measurements from currently operating TOP facilities. Furthermore, the differences between the various torrefaction technologies available could be assessed. For these purposes, it is recommended that currently operating TOP producers become transparent about their processes and energy requirements.

For the Netherlands, this research showed that for the investigated supply chain, it would be better to co-fire TOP than WP from a GHG emissions perspective. These results are important to take into account by policy makers. Nonetheless, uncertainty on actual energy consumption of TOP production still exists and the results found in this research are only valid for supply chains from Southeast US to the Netherlands. Furthermore, other indicators are relevant for assessing the potential of TOP co-firing in the Netherlands, such as costs and public opinion. It is not a foregone conclusion that TOP are always the better choice for co-firing in the Netherlands, but this research showed that GHG emissions savings are possible.

7. CONCLUSION

This research presents a life cycle GHG emissions assessment with multiple feedstock scenarios in order to investigate the emissions and emission savings of white pellet (WP) and torrefied pellet (TOP) co-firing in the Netherlands. By using the methodology set in the proposed revision of the Renewable Energy Directive (RED II), it is assessed whether WP and TOP co-firing in the Netherlands will comply with future EU legislation. Feedstock is sourced and pretreated in the Southeast United States (SE US). After WP or TOP production the pellets are shipped to the Netherlands for co-firing in the Amer CHP plant. Literature is combined with industry data of commercial-scale WP and TOP suppliers to reduce uncertainty in the emissions occurring at the pretreatment stage.

Results on emissions per tonne pellet show similar values for all TOP scenarios compared to their WP counterpart. However, when adjusted to the higher energy density of torrefied material, all TOP scenarios have lower values. Emissions for TOP scenarios are 10.1-13.9% lower than WP emissions on a primary energy basis. Even though TOP scenarios have higher emissions than WP in the pretreatment stage, the reduction in emissions in the transport and co-firing stages is larger. These results are in line with previous research, but show lower variation than previous studies. The results demonstrate the importance of detailed analyses when pellet supply chains are concerned. When a high growth of pellet demand and production is assumed, the savings of TOP over WP even increase. Furthermore, this research has reduced uncertainty in the pellet production phase by including actual measurements from commercial-scale WP production. Unfortunately, this was not possible for TOP. Therefore, uncertainty in TOP production remains high. It is recommended that the efforts made in this research are continued by investigating actual energy consumption from commercial-scale TOP production.

Results of achieved emission savings show that all scenarios comply with future RED II emission saving targets for heat production. For electricity production, none of the feedstock scenarios reached the 2026 target of 85% savings, and only pellets from sawmill residues – both WP and TOP – reached the 2021 targets of 80% savings. Even though no difference with respect to the targets between WP and TOP scenarios were observed in this case study, the significant benefit of TOP over WP indicated the GHG emissions saving potential for other supply chains. Between the different feedstocks considered, the *sawmill residues* scenario lead to the lowest emissions and highest emission savings, as expected, since no emissions are allocated until the point of collection. The highest emissions are induced by the *commercial thinnings* scenario, followed by the *roundwood* and *harvest residues* scenarios. The emissions of these three scenarios did not differ much.

For the Netherlands, this research showed that significant emission savings are possible by co-firing both WP and TOP. Even though economic, social or other environmental indicators have not been assessed, the research shows potential for cofiring TOP in the Netherlands to reduce GHG emissions and to count towards renewable energy generation targets.

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APPENDICES

APPENDIX A. ADDITIONAL DATA

Table A1. Characteristics sawmill residues.

	sawdust	shavings	chips	Sources & notes
Share of total	54%	29%	17%	[1]
Moisture content	48.9%	12.4%	47.3%	[1]
Lower heating value (LHV), dry based	19.45	19.48	19.47	[1], a
Sourcing distance	150.00	125.00	65.00	[1]

Sources: [1] US Pellet Producer, personal communication, November 14, 2018. Notes: a. LHV of sawmill chips not available. Therefore, the average of sawdust and shavings is assumed.

Table A2. Interpolation fuel consumption Europe II, Europe IIa and Europe II-long barges.

	Weight (t)	Full (MJ/km)	Empty (MJ/km)	Source
Class II	550	220	177	[1]
Class III	950	314	272	[1]
Class IV/Class V	2,500	470	425	[1]
Europa II, IIa & II-long barge	2,842	480	435	calc.
Class VI	10,800	717	661	[1]

[1] Hoefnagels, Searcy, et al. (2014).

APPENDIX B. MASS BALANCES WHITE PELLETS (WP)

<confidential>

Appendix C. Mass balances Torrefied Pellets (TOP)

Table C1. Torrefied pellet (TOP) mass balance US Pellet Producer feedstock scenario.

		Fds in	Cleaning	Clean fds	Dryer	Dried fds	FlashTor	Torr fds	FT cooling	Torr fds	Grinding	Torr fds	Pelletising	TOP
Mix US Pellet Producer														
Moisture content	%	44.7%		44.7%		10.0%		0.0%		5.0%		7.0%		7.0%
Massflow oven dry	t/hr	12.98		12.58		12.56		9.39		9.39		9.39		9.30
Massflow as received	t/hr	23.47		22.75		13.95		9.39		9.89		10.10		10.0
LHV as received	MJ/kg	9.71		9.71		17.24		22.32		21.09		20.59		20.59
Support fuel harvest residues														
Consumption	kg/hr				408.82									
Moisture content	%				41%									
LHV as received	MJ/kg				10.13									
Support fuel sawmill bark														
Consumption	kg/hr				89.87									
Moisture content	%				36.2%									
LHV as received	MJ/kg				11.89									
Losses														
Biomass loss	kg/hr		727.66										101.01	
Moisture content	%		44.7%										7.0%	
LHV as received	MJ/kg		9.71										20.59	

Table C2. Torrefied pellet (TOP) mass balance roundwood/commercial thinnings scenario.

		Fds in	Cleaning	Clean fds	Dryer	Dried fds	FlashTor	Torr fds	FT cooling	Torr fds	Grinding	Torr fds	Pelletising	TOP
Roundwood/thinnings														
Moisture content	%	47.3%		47.3%		10.0%		0.0%		5.0%		5.0%		7.0%
Massflow oven dry	t/hr	12.98		12.58		12.56		9.39		9.39		9.39		9.30
Massflow as received	t/hr	24.63		23.87		13.95		9.39		9.89		10.10		10.00
LHV as received	MJ/kg	9.16		9.16		17.27		22.36		21.12		20.63		20.36

Support fuel harvest residues														
Consumption	kg/hr				869.64									
Moisture content	%				41%									
LHV as received	MJ/kg				10.13									
Losses														
Biomass loss	kg/hr		763.56										101.01	
Moisture content	%		47.3%										7.0%	
LHV as received	MJ/kg		9.16										20.63	

Table C3. Torrefied pellet (TOP) mass balance harvest residue scenario.

		Fds in	**Cleaning**	**Clean fds**	**Dryer**	**Dried fds**	**FlashTor**	**Torr fds**	**FT cooling**	**Torr fds**	**Grinding**	**Torr fds**	**Pelletising**	**TOP**
Harvest residues														
Moisture content	%	41.1%		41.1%		10.0%		0.0%		5.0%		7.0%		7.0%
Massflow oven dry	t/hr	12.56		12.17		12.15		9.39		9.39		9.39		9.30
Massflow as received	t/hr	21.33		20.67		13.50		9.39		9.89		10.10		10.0
LHV as received	MJ/kg	10.13		10.13		16.69		21.15		19.98		19.51		19.51
Support fuel harvest residues														
Consumption	kg/hr				389.00									
Moisture content	%				41.1%									
LHV as received	MJ/kg				10.13									
Losses														
Biomass loss	kg/hr		661.24										101.01	
Moisture content	%		41.1%										7.0%	
LHV as received	MJ/kg		10.13										19.51	

Table C4. Torrefied pellet (TOP) mass balance sawmill residues scenario.

		Fds in	Cleaning	Clean fds	Dryer	Dried fds	FlashTor	Torr fds	FT cooling	Torr fds	Grinding	Torr fds	Pelletising	TOP
Sawmill residues														
Moisture content	%	38.0%		38.0%		10.0%		0.0%		5.0%		7.0%		7.0%
Massflow oven dry	t/hr	12.48		12.10		12.08		9.39		9.39		9.39		9.30
Massflow as received	t/hr	20.13		19.51		13.42		9.39		9.89		10.10		10.00
LHV as received	MJ/kg	11.19		11.19		17.28		22.11		20.89		20.40		20.40
Support fuel sawmill bark														
Consumption	kg/hr				244.40									
Moisture content	%				36.2%									
LHV as received	MJ/kg				11.89									
Losses														
Biomass loss	kg/hr		624.17										101.01	
Moisture content	%		38%										7.0%	
LHV as received	MJ/kg		11.19										20.40	