A future for pellets?

An assessment of the economic and
carbon impacts of lignocellulosic
pellet supply

Lotte Visser

This work was part of the BioLogikNL project, which aimed to develop knowledge of the logistics chains of biomass from abroad to the Netherlands. It was made possible by the financial support from the 'Subsidieregeling Energie en Innovatie Biobased Economy: Kostprijsreductie Elektriciteit-en Warmteproductie.' (Grant No.TEBE213008) by the Dutch Ministry of Economic Affairs.

Lay-out:	Publiss – www.publiss.nl
Printed by:	Ridderprint – www.ridderprint.nl
ISBN:	978-90-8672-092-7

© 2020, Lotte Visser, the Netherlands

All rights reserved. No part of this thesis may be produced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage or retrieval system, without prior written permission from the author.

A future for pellets?

An assessment of the economic and carbon impacts
of lignocellulosic pellet supply

Een toekomst voor pellets?

Een analyse van economische en koolstofeffecten
van aanvoerketens van pellets uit houtige biomassa

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de
Universiteit Utrecht
op gezag van de
rector magnificus, prof.dr. H.R.B.M. Kummeling,
ingevolge het besluit van het college voor promoties
in het openbaar te verdedigen op

vrijdag 20 november 2020 des ochtends te 11.00 uur

door

Lotte Visser

geboren op 9 januari 1988

te Hoorn

Promotor:

Prof. dr. H.M. Junginger

Co-promotor:

dr. R. Hoefnagels

CONTENTS

Chapter 1	Introduction	7
Chapter 2	Wood pellet supply chain costs – A review and cost optimization analysis	35
Chapter 3	Sourcing overseas biomass for EU ambitions; Assessing net sustainable export potential from various countries	73
Chapter 4	The potential contribution of imported biomass to renewable energy targets in the EU – the trade-off between ambitious greenhouse gas emission reduction targets and cost thresholds	115
Chapter 5	Exploring the limits to sustainable pellet production for international markets – The impact of increasing pellet production in the US Southeast on feedstock use and carbon sequestration in forest areas	151
Chapter 6	Synthesis and conclusion	195
	References	227
	Appendices	252
	Nederlandse samenvatting	301
	Acknowledgements	339
	About the author	343

Introduction

CHAPTER 1

1.1. THE ROLE OF BIOMASS IN REDUCING GREENHOUSE GAS EMISSIONS

The energy transition from a fossil-fuel dominated towards a carbon neutral energy sector is necessary to limit global average temperature increase, as agreed in the Paris Agreement (IPCC, 2014; United Nations Framework Convention on Climate Change, 2015). At the current level of greenhouse gas (GHG) emissions, the remaining carbon budget that will limit global warming to 1.5 °C could be spent within one or two decades¹ (IPCC, 2018b). Reducing net carbon emissions at the necessary pace requires extreme growth of all renewable energy technologies, including wind, solar and biobased energy (bioenergy) (Edenhofer et al., 2011; Vuuren et al., 2018; Zappa, Junginger, Broek, & Cover, 2019; Zuijlen, Zappa, Turkenburg, & Schrier, 2019). Large scale deployment of intermittent renewables such as wind and PV however also create challenges to the energy system as dispatchable generation capacity decreases (Zappa et al., 2019). Replacing fossil fuels with bioenergy can contribute towards reducing emissions while providing a dispatchable source of energy. Biomass can also be used to replace fossil fuels in sectors less suitable for electrification such as the process industry or heavy-duty, marine or air transport. The combustion of biomass results in carbon emissions, just as is the case with fossil fuel use. The difference between these two sources is that biogenic carbon emissions can be re-sequestered through new tree growth, thereby only resulting in a temporary and not a permanent increase in carbon emissions. This does require careful selection of sustainable feedstock sources and careful management of forest areas to ensure replanting and regrowth of trees after harvesting. The overall greenhouse gas reduction potential of biomass depends on biogenic emissions from changes in carbon stock, emissions from the biomass supply chain as well as the type of fuel replaced. Developments in the use of carbon storage or utilization technologies could result in significant reductions in carbon emissions. Combined with the use of biomass for production of energy or materials, atmospheric carbon removal (i.e. negative emissions) could be achieved through carbon utilization or geological storage, which

¹ 66% probability, medium confidence. Remaining budgets of 420 GtCO₂ using global mean surface air temperature as measure method and 570 GtCO₂ using global mean surface temperature. Current rate of depletion is 42 ± 3 GtCO₂ per year (high confidence)(IPCC, 2018a).

are considered necessary to reach long-term carbon reduction targets. Taking these aspects into account, studies have shown that biomass has an important role to play in reaching climate goals and can form a significant contribution to future energy supply (Clarke et al., 2014; Daioglou, 2016; Mendes Souza et al., 2017; Rogelj et al., 2018; Scarlat, Dallemand, Monforti-ferrario, & Banja, 2015; Vuuren et al., 2018).

Use of biomass is relatively versatile: It can be used for production of electricity, heat, biofuels and chemicals, and is, compared to other types of renewable energy, relatively easy to store and transport over long distances. Globally, bioenergy is an important source of renewable energy, constituting 70% of renewable primary energy supply (World Bioenergy Association, 2018). Most of this is supplied in the form of heat, more than 80% of global biomass supply is used for heating and cooking, predominantly in Africa and Asia, using traditional biofuels such as wood fuel or wood chips (World Bioenergy Association, 2018). When considering the contribution to renewable electricity generation, biomass forms a much smaller share, constituting 9%, compared to larger contributions of hydropower (68%) and wind energy (16%). In the EU, bioenergy and renewable waste makes up by far the largest share of renewable energy supply, largely in the form of bioheat and largely produced from solid biomass, as can be seen in Figure 1.1. The use of biomass is an important contributor to reaching renewable energy targets in certain sectors. In the transport sector, for instance, the contribution of biofuels is much larger than other renewable alternatives such as electric transport (IEA, 2019).

Figure 1.1 – Role of bioenergy in the EU28 in 2016, data taken from (Bioenergy Europe, 2018)

The Economic Modelling Forum (EMF) has demonstrated that biomass is likely to play a key role in GHG mitigation scenarios (Daioglou, Doelman, Wicke, Faaij, & Vuuren, 2019). However, the contribution of biomass depends strongly on the mitigation scenarios and Shared Socioeconomic Pathways (SSPs) assumed. In the baseline scenario, contribution of biobased energy and chemicals to the global primary energy supply ranges between 8% and 19% in 2100 for the different SSPs, mainly in the form of liquid and solid fuels (Daioglou et al., 2019). In the most ambitious mitigation scenario, aiming at long term radiative forcing targets of 1.9 W/m², this share increases to 50% in the SSP1 scenario and 32% in the SSP2 scenario in 2100 (Daioglou et al., 2019). In a long-term vision for a climate neutral economy in the EU,

biomass is expected to be utilized mainly for the production of aviation fuel, industrial process heating and biomaterials (European Commission, 2018). The projected increase in demand for bioenergy and biomaterials, combined with an uneven distribution of biomass resources and mobilization opportunities as well as significant differences in cost factors between world regions, will likely result in increased global trade of solid biomass and liquid biofuels. For the EU specifically, this is for instance shown in Mandley et al. (Mandley, Daioglou, Junginger, Vuuren, & Wicke, 2020), projecting an increase in demand for bioenergy and materials, unlikely to be met by intra-EU production of biomass. The projected increase in global biomass trade also follows from several studies using Integrated Assessment Modelling (IAM). For instance, a study by Matzenberger et al., analysing bioenergy demand, production and trade using the models GFPM, TIMER and POLES, results in a positive trade balance for Russia and the former USSR, the Middle East and North Africa, Brazil and Canada (Matzenberger et al., 2015). Daioglou et al. (Daioglou et al., 2019) have assessed supply and demand of biomass in different world regions, including agricultural and forestry residues and energy crops, using the IMAGE 3.0 model. Depending on the SSPs assumed, this work shows increasing importance of Latin America and the Former Soviet Union, alongside continued importance of Asia and the OECD countries.

Today, biofuels used in the transport sector and for the production of biomaterials are predominantly based on agricultural crops and to a very small extent on municipal waste and agricultural residues (Bioenergy Europe, 2019b; Phillips, Flach, Lieberz, & Bolla, 2019). Electricity and heat production are on the other hand still predominantly based on the consumption of forestry biomass (Bioenergy Europe, 2019a), which means there are largely separated markets for the different end uses. The development of advanced biofuels and chemicals could shift the demand market for woody biomass from just electricity production to a new range of applications including industry and heavy transport. Moreover, baseload electricity production may become increasingly uneconomical, and electricity production may shift to peak load coverage (Zappa et al., 2019). Developments in biorefining could result in the co-production of electricity and biofuels or chemicals,

thereby potentially further integrating the different demand sectors (Vera & Hoefnagels, 2019). Sustainably sourced lignocellulosic biomass is therefore a viable option for electricity production as well as the production of transport fuels and biomaterials.

Traditional solid biomass however has some clear disadvantages when compared to fossil fuels, including a high moisture content and low energy density. This makes long distance transport costly, limiting the use to regions with sufficient availability. Furthermore, the heterogeneity in quality makes trade of traditional biomass impossible other than direct sales between a seller and buyer. A way to reduce these barriers is the pelletization of woody biomass. Pre-treatment in the supply chain, close to the biomass source, results in a solid biofuel with a much higher energy density than traditional wood fuel, increasing the efficiency of downstream logistics, thereby enabling sourcing and trade across larger distances. This is supported by, for instance, Bryngemark (2019), using a partial equilibrium model to show the impact of increased penetration of bio-LNG in Sweden. Results of this study show that at low levels of penetration, sawdust is the predominant feedstock used for the production of bio-LNG. At higher levels, pellets become the dominant feedstock type, benefitting from lower transport costs. Pelletization also allows for the creation of a much more homogeneous fuel, defined in international standards, which allows pellets to turn into a commodity and be more easily traded, nationally and internationally (Thrän et al., 2017). Consistent quality also increases the suitability for use in different applications, ranging from very small pellet stoves to industrial scale electricity plants (Obernberger & Thek, 2010). The production and trade of wood pellets has been growing at a much faster rate in recent years than other bioenergy carriers produced from lignocellulosic biomass, such as pyrolysis oil or bio-LNG. The well developed technology and existence of supply chains gives pellets an advantage for increased use in the short-term future. The growing importance of traded biomass in reaching renewable energy and carbon reduction targets makes it necessary to assess the potential role and limitations of international wood pellet trade.

1.2. DEVELOPMENTS IN PELLET PRODUCTION AND TRADE

Toda, only 4% of the gross inland bioenergy consumption in the EU is generated using imported biomass (World Bioenergy Association, 2018). The development of densified biomass, such as pellets, reduces the economic and sustainability restrictions to long distance trade of biomass, and for wood pellets a significantly higher share of inland consumption in the EU is supplied by imported pellets. The EU is the largest global consumer of pellets as well as the largest importer, supplementing 17 Mt of production with 10 Mt of imported pellets (Bioenergy Europe, 2019c). Worldwide production of wood pellets has increased from 5 Mt in 2005 to over 55 Mt in 2018, largely produced in China (36%) and the EU (30%) (Bioenergy Europe, 2019c). The data for China is based on estimations and not on official data, and is therefore relatively uncertain compared to other regions (Bioenergy Europe, 2019c). Pellets produced in China are used within the country and not traded to other countries, and the exact production statistics therefore have very little implications for international wood pellet trade (Bioenergy Europe, 2019c).

In the EU, wood pellets are largely used in the residential market (10.3 Mt) and for electricity production (9.3 Mt), followed by commercial use (3.6 Mt) and use in CHPs (2.9 Mt). Within Europe, pellets are used for heat production in large quantities, ranging between 3.3 and 1.6 Mt, in Italy, Denmark, Germany, Sweden and France. In all of these countries, residential heating is the main application, except for Denmark, in which the share of CHP heat production is the largest. Industrial wood pellet consumption, mainly for the production of electricity, is especially large in the UK, with 7.8 Mt yearly consumption. Besides the UK, industrial pellet consumption is relatively large in Denmark and Belgium, with 2.1 and 1.1 Mt pellets respectively, followed by Sweden and the Netherlands, consuming 0.6 and 0.4 Mt pellets for industrial use respectively (Bioenergy Europe, 2019c).

Imported wood pellets are mainly intended for industrial use, with increased imports being the result of the development of efficient long-distance supply chains. This enables wood pellet trade from areas with different supply and

demand characteristics and cost factors, resulting in relatively low supply chain costs. Imports into the EU28 consist largely of wood pellets imported from the US, 7 Mt in 2018, and to a smaller extent of pellets imported from other European countries, 2.1 Mt (Bioenergy Europe, 2019c; USDA Foreign Agricultural Service, 2020) See Figure 1.2 for an overview of recent global trade of wood pellets between the main trade partners. Further increasing demand of wood pellets is expected to result in even more trade of pellets from areas with large resource availability to countries with limited forest area and extensive renewable energy targets and aims (Daioglou et al., 2019; Matzenberger et al., 2015). This is for instance reflected in projections for pellet production and export from the Southeast of the US (US SE). As shown by Fingerman et al., who based their work on a review of (Duscha et al., 2014; U. Fritsche & Iriarte, 2014; Galik & Abt, 2016; Hoefnagels, Junginger, & Resch, 2015; Lamers, Hoefnagels, Junginger, Hamelinck, & Faaij, 2015; Lechner & Carlsson, 2014; Southern Environmental Law Center, 2015), these exports could range between 0 – 28 Mt pellets in 2030 (Fingerman et al., 2017). As biomass use for energy or materials increases, and biomass is traded across increasingly large distances, it will become even more important to focus on the supply chain design of biomass supply.

Figure 1.2 – Global, international trade of wood pellets, of trade flows exceeding 0.5 Mt pellets traded per year between specific countries/regions. Based on data from FutureMetrics (n.d.).

1.3. INCREASED WOOD PELLET CONSUMPTION IS LIMITED BY SUPPLY CHAIN COSTS AND SUSTAINABILITY CONSTRAINTS

Supply chain optimization is necessary to limit costs and emissions of internationally traded wood pellets. Through ensuring cost-efficient and sustainable supply of biomass, the contribution of bioenergy to the reaching of climate targets can be increased. The market price of pellets is still significantly higher than fossil fuels, requiring either the availability of subsidies or a substantially higher level of carbon pricing to achieve comparable costs of electricity production (Argus, 2018; K. Hansen, 2019; U.S. Energy Information Administration, 2019c). To establish competitive prices compared to coal and natural gas, a CO₂ allowance level of about 60 US\$/t CO₂ is required (U. Fritsche et al., 2019). This requires a doubling of the highest ever CO₂ allowance price observed so far (IETA & PwC, 2019), which could be feasible on the long term, but is not likely to happen in the near future according to price forecasts until 2030 (Schøjlset, 2014). Pellet consumption is furthermore in competition with other renewable energy sources such as solar and wind energy. Costs of electricity production of biomass, solar PV and onshore wind energy are currently comparable, but especially wind and PV are still undergoing significant cost reductions, with costs of new, best-practice, installations outperforming bioenergy (K. Hansen, 2019; IRENA, 2015; U.S. Energy Information Administration, 2019c). The increased competition with other renewable energy technologies as well as fossil fuels negatively impacts market prospects of wood pellets, especially for electricity production. Future developments of supply and demand of renewable energy technologies are uncertain, as is the case for carbon price developments in the European Emission Trading System. Still, understanding the challenge of increasing the competitiveness of wood pellets, a scenario of increased wood pellet demand only seems likely if prices of wood pellets decrease or at least remain stable compared to current levels of spot prices or contract prices.

High market prices of wood pellets are largely the result of high supply chain costs of pellet production. Profit margins for pellet producers are relatively

small, leaving little room to lower market prices (U. Fritsche et al., 2019; Lechner & Carlsson, 2014). One way to lower market prices is therefore to lower supply chain costs, for instance by optimizing supply chain design. Another potential way to lower costs is to invest in new supply chains in regions with favourable conditions such as affordable biomass. There are more options to increase the competitiveness of wood pellets, which will not be discussed in detail in this thesis. The use of pellets in higher value markets, such as the production of advanced biofuels and biochemicals (possibly with the inclusion of CCS), could result in more viable import opportunities (Vera & Hoefnagels, 2019). Further development of pellet consumption in sectors beyond bioenergy production² will add to the total pellet demand and imports (Ioannis Dafnomilis et al., 2017). For these end-uses also, analysing supply chain costs, and investing in supply chain optimization, will result in improved business cases and more favourable conditions of pellet use.

As much as costs are a limitation to biomass use, so are sustainability aspects such as supply chain emissions. While investing in increasingly reliable and cost-effective supply chains, the sustainability of wood pellet-based bioenergy production should be safeguarded as well. The generic sustainability of forestry biomass is difficult to assess since this depends strongly on locational factors such as the type of forest, the climate and the forest management system (Van der Hilst, 2018). When assessing the impact of forestry operations, results depend strongly on methodological choices such as the temporal and spatial scope or the choice of counterfactual scenario (Berndes et al., 2016). In the European Union, minimum sustainability criteria were established for all bioenergy sectors in the revised Renewable Energy Directive (RED II) to address the most urgent risks of bioenergy production. These binding criteria cover a number of sustainability issues, including biodiversity, carbon stock and supply chain GHG emissions. For instance, what is agreed upon by the European Commission is that forestry biomass used for energy can only come from forestry plantations and managed forests that comply with sustainable harvesting criteria, and not from land converted from natural forests or from areas with high carbon stock or biodiversity (European Parliament, 2018). An increase in global pellet

² In this thesis, the term "bioenergy production" refers to the conversion of primary biomass to secondary energy such as electricity or heat.

production therefore depends on the availability of sufficient feedstock in areas with growing forest stocks.

For some of the RED II criteria, there are no quantifiable indicators to measure compliance and progress (European Parliament, 2018). For instance, for the protection of biodiversity, forest harvesting must be done in accordance with principles of sustainable forest management. Furthermore, energy from biomass must not be made from material sourced from land with a high biodiversity value such as primary forests and land identified as being highly biodiverse by relevant authorities (European Parliament, 2018). Still the extent of biodiversity in a particular area is difficult to address and measure with generally applicable criteria and indicators. Other criteria, such as the minimum level of GHG savings over the supply chain, are very clearly defined. A clear standardized methodology is provided of how to calculate potential GHG savings, apart from the impact of market mediated effects such as indirect land use change (ILUC) and biogenic carbon accounting, for which it is difficult to assign emissions to specific supply chains. Minimum GHG savings thresholds differ per end-use type. For installations with a rated thermal input >20 MW, the GHG savings threshold starts at 70% compared to a pre-defined fossil fuel comparator for installations starting operation from 1 January 2021. Efforts to make supply chains more efficient shouldn't stop here, since this threshold will increase to 80% for installations starting operation from 1 January 2026. The adoption of measures to ensure compliance with RED II criteria is complicated since there are trade-offs between different sustainability aspects. As an example, maximizing biodiversity in forestry areas comes at the expense of reduced biomass yields per area as e.g. use of fertilizers or pesticides is not possible. Strengthening of the GHG reduction criteria will increase the GHG emission savings per unit of biomass but could result in a decreased quantity of utilized biomass for energy and materials, thereby reducing overall GHG emissions savings.

1.4. RESEARCH NEEDS/KNOWLEDGE GAPS

1.4.1. Impact of supply chain design on costs and emissions

Insights in supply chain cost components is necessary for the optimization of existing supply chains and the development of new supply chains. Uncertainty and variation in cost components needs to be understood in order to increase the usefulness of studies utilizing pellet cost assumptions. Policy makers can furthermore benefit from better knowledge to determine appropriate levels of wood pellet subsidies and other support schemes. Whereas the costs of specific pellet supply chains have been analysed in great detail by many authors, not enough efforts have been made to explicate the differences between results of seemingly very similar supply chains.

Both costs and emissions of wood pellets are determined to a large extent by the supply chain design. Increased production and trade of wood pellets could be an opportunity to implement supply chain optimizations. Larger trade volumes could allow for economies of scale, producing pellets in larger pellet mills and utilizing larger ships. New feedstock supply chains could furthermore benefit from technological advances or increased knowledge and understanding. Assessing the potential contribution of wood pellets to renewable energy targets, based on production potentials and costs, must include the uncertainty in costs and the impact of supply chain design. A distinction must be made between several causes of cost differences. Firstly, there is significant uncertainty on the costs of several supply chain components, caused by a lack of transparency on supply chain costs. Secondly, aside from the uncertainty, differences in supply chain design will have an impact on cost components. Thirdly, several cost factors will change naturally throughout time, such as fuel costs or shipping charter costs. What needs to be understood is the impact of these different sources of cost variation and uncertainty, especially the impact of design variables on total costs and the trade-offs and synergies between specific components.

Variation in cost components can partially be explained by accounting for differences in supply chain design, such as the impact of larger transport

distance on logistics costs and the price differences between various feedstock types. Still, even in case of seemingly similar supply chain design, uncertainty in cost estimates of wood pellet supply chains becomes apparent when comparing costs of different components in literature studies. For instance, Pirraglia et al. (Pirraglia, Gonzalez, & Saloni, 2010) assume personnel costs of 49 US\$/t, for the operation of a 75 kt/y pellet mill in the US. For an equally large pellet mill, also in the US, Qian & McDow (Qian & McDow, 2013) report personnel costs of 10 US\$/t. A smaller but still significant difference can be found in feedstock prices. Peng et al. (Peng et al., 2010) have assumed feedstock cost of 17 CA\$, compared to 28 CA\$ used in Mobini et al., both for sawmill residues (Mobini et al., 2014). Cost differences in literature studies are even larger when accounting for differences in supply chain design variables. For instance, costs for raw material for pellet production in selected literatures studies, when considering all different feedstock types in different countries, vary between 11 €/t pellets (Bergman, 2005) and 93 €/t pellets (Trømborg et al., 2013). For each cost component, there are several design aspects determining the costs. Transport of pellets from pellet mills to export ports for instance depends on the transport distance, the mode of transportation as well as assumptions on a number of aspects such as fuel costs, truck costs, hourly wages and driving speed. In examined literature studies this specific component varies from 4 €/t pellets (Bergman, 2005) to 28 €/t pellets (Mobini, Sowlati, & Sokhansanj, 2013). Variation between studies with similar supply chain design can partly be explained by considering macro-economic factors, causing for instance regional and temporal variation in prices of feedstock, fuel or electricity. A good example of this is the historical development in shipping charter rates in response to supply and demand dynamics, with the Baltic Dry Index varying a factor 40 in the period between 2003 and 2017 (Fulp, 2017). Analysing the impact of macro-economic factors on cost components can help explicate cost differences between studies.

In several studies, the impact of changing one or more variables on total costs is compared. For instance, Trømborg et al. (Trømborg et al., 2013) compare pellet production costs in the US and several European countries, varying factors such as energy, personnel and feedstock costs but using similar assumptions on pellet production requirement and costs. Thek &

Obernberger (Thek & Obernberger, 2004) compare supply chains in Austria and Sweden and furthermore have analysed the impact of supply chain variables focussing on pellet mill design and operational assumptions. In other studies, different case studies are compared with completely different supply chain setups tailored to different regional circumstances, including different assumptions on production size, type of feedstock and processing requirements (Ehrig, Behrendt, Wörgetter, & Strasser, 2014; Sikkema, Junginger, Pichler, Hayes, & Faaij, 2010). Whereas these studies have resulted in insights on potential cost optimization strategies, the scope is too limited to fully understand the impact of (especially long distance, intercontinental) supply chain design variables and data uncertainty on general wood pellet supply chain costs.

For a large part, optimisation of supply chains results in savings of both costs and emissions. Densification of biomass, for instance in the form of pelletization or a combination of torrefaction and pelletization, results in savings in downstream logistics both in terms of costs and emissions (Wild & Visser, 2018). The trade-off between additional investments and upstream costs with downstream cost savings must be analysed for specific supply chain designs. Improved knowledge on the technical challenges of torrefaction and the impacts on specific supply chain designs could result in the realization of lowered total costs and emissions. Reducing transport distances of feedstock or pellets will likewise have a positive impact on both aspects. On the other hand, the contribution of supply chain components to total costs and emissions is not the same, making it necessary to analyse potential savings in costs and emissions separately to understand the impact of future developments on both aspects. Pellet demand will be impacted by market restrictions such as the price of wood pellets compared to alternatives. Pellet supply on the other hand will be restricted by legislative restrictions such as the sustainability criteria included in the RED II, national legislation and voluntary certification systems. An analysis of supply chain costs and emissions of spatially explicit pellet production will increase understanding of the potential contribution of wood pellets to the decarbonisation of the European economy.

Creating a better understanding of current supply chain costs and the impact of supply chain design, will help to better predict potential future costs and prices of wood pellets. Future supply chain costs are assumed to differ from current costs. Feedstock costs for instance are expected to respond to regional supply and demand developments. Several underlying cost factors, such as fuel costs and shipping costs, are impacted by macroeconomic developments. Understanding the impact of cost factors and components on total pellet costs will contribute to improved insights on current and future cost developments and uncertainties and will allow for better modelling of the potential contribution of biomass to renewable energy and materials.

1.4.2. Impact of changing international trade patterns on wood pellet costs and GHG emissions

Part of the uncertainty of future cost developments is the question of how supply chain designs will change. An important aspect is the geographical location of pellet production, since this affects multiple cost components such as feedstock costs, pelletizing costs and transport costs. Changed supply and demand patterns could shift pellet production to new areas, thereby affecting supply chain costs. Current worldwide pellet production predominantly takes place in China, the EU28 and North America, representing a combined 86% of total production (Bioenergy Europe, 2019c). At the same time, research into future bioenergy trade shows significant production in other world regions (Daioglou et al., 2019; Matzenberger et al., 2015). Existing estimates of wood pellet production costs are largely based on the countries that have long been the dominant producers of pellets for the export market such as Canada and the US. As pellet demand increases, new production areas are expected to emerge, both as a result of limited potential feedstock availability in existing production regions and as a result of local opportunities and developments in emerging regions. In light of the uncertainty of future pellet production and trade routes, the impact of cost differences and logistics requirements in several potential world regions must be analysed.

Pellet imports from emerging regions is only possible if supply chain costs and emissions are within bounds. Efficient design of supply chains therefore becomes an important challenge when shifting to new sourcing and production areas. The potential for pellet production in potentially emerging production countries can only be assessed by including local cost and GHG emission components. There are studies exploring wood pellet production costs in emerging countries. Uasuf & Becker (Uasuf & Becker, 2011) for instance, have calculated costs of pellets in Northeast Argentina using country specific estimates for raw material costs, labour costs and energy costs. Still, the investment costs for pelletizing equipment is taken from existing studies on pellet production costs in European and North American countries. Nabavi et al. (Nabavi, Azizi, Tarmian, & David, 2019) have analysed the availability and quality of biomass feedstock and the production costs of wood pellets. In this study as well, some components, costs of biomass, labour and energy, are based on Iranian data. This study concludes that production costs are low compared to established pellet production countries, but also that the availability of affordable residues is uncertain and that raw wood processing industries operate seasonally and do not have suitable access roads (Nabavi et al., 2019). Pellet production costs in Mexico were analysed by Tauro et al., based on equipment costs of European and Chinese manufacturers, using Mexican data on labour and energy costs. Logistics costs are analysed specifically for the Mexican situation, whereas it is unclear what feedstock costs were based on. Overall, however, there is little research done on potential pellet costs from emerging countries. Furthermore, the studies mentioned above were based on single supply chains. Assessing potential cost changes when shifting to new regions or countries needs to be done by comparing different countries on the basis of similar assumptions while varying relevant costs factors. This will allow for the analysis of specifically the impact of geographical scope on pellet costs.

The low value and low energy density of biomass limits transport distances, necessitating the availability of biomass locally, close to production locations. Availability of low-cost biomass is potentially large in areas where there is no large existing pellet industry yet, where biomass sources such as residues are currently underutilized and wasted. Welfle et al. (Welfle,

2017) for instance have analysed the potential availability of biomass in Brazil, concluding that the potential to mobilize a large amount of biomass resources makes the country well placed to be a dominant exporter. From a sustainability perspective, biomass should however be used locally in case there is demand for these resources. These researchers have found that the adoption of more ambitious energy strategies in Brazil could result in a significantly lower availability of feedstock for export (Welfle, 2017).

The spatial limits to pellet production and trade, as a result of the impact of increased transport distance on costs and emissions, limits the total pellet production potential. Supply chain optimizations increase the potential sourcing area of feedstock and potential production regions of pellets. The production of wood pellets results in optimized logistics, unlocking new potential sourcing regions when compared to the trade of raw biomass such as wood fuel or wood chips. Faced with increased demand for biomass and increasingly stringent criteria of total costs and greenhouse gas emissions, the question is how much can be realized by further optimizing wood pellet supply chains, and what could be the potential advantage of more advanced chains such as the production of torrefied pellets.

1.4.3. Availability of feedstock for pellet production

The basis of every pellet production supply chain is the feedstock used to produce pellets from, and the type of feedstock used has implications for total supply chain costs and emissions. Besides costs and GHG emissions, other aspects such as local demand, mobilization opportunities and the existence of pre-treatment capacity determine potential levels of pellet production. An aspect which is generally overlooked is the logistics required to mobilize large quantities of biomass. Spatial shifts in feedstock availability and allocation will result in changed logistics, especially in the case of pellets produced for export markets that need to be exported through seaside ports.

Costs of feedstock is one of the largest components of total wood pellet supply chain costs (Boukherroub, LeBel, & Lemieux, 2017; Obernberger & Thek, 2010; Qian & McDow, 2013; Thek & Obernberger, 2004; Trømborg et al., 2013). Furthermore, cost of biomass is an ongoing expense for pellet

producers and very sensitive to changes in supply and demand, unlike for instance investment costs in pelletizing equipment. The availability and costs of feedstock determines the viability of wood pellet business cases. Pellet production is generally based on forestry biomass, either in the form of low quality/ small diameter pulpwood, harvested from forest areas, or in the form of residues from other industries such as wood chips, sawdust or shavings (Bioenergy Europe, 2019c; Canadian Biomass, 2017; U.S. Energy Information Administration, 2019d). The use of pulpwood from forests requires forest management operations such as harvesting and collection as well as transport from forest areas to pellet plants. In pellet plants, roundwood feedstock requires several drying and grinding steps to prepare the feedstock for pelletization. The use of industry residues could result in much lower supply chain emissions. In case these feedstocks are a waste product, emissions from harvesting are not allocated to the residues. If a pellet plant is built strategically next to a large source of residues, transport distances are furthermore low. A residue type such as sawdust is already ground and dried, thereby eliminating further energy consumption at pellet plants. The type of feedstock used for pellet production, and how this could change if pellet consumption increases, must therefore be considered when analysing the costs and sustainability impact of wood pellet use. Existing supply chains are presumably based on an optimization of transport and feedstock costs, utilizing feedstock availability relatively close to export ports suitable for long distance shipping. Limited feedstock availability could force new supply chains to move to new, more inland, areas or to use different types of feedstocks such as increased use of pulplogs instead of sawmill residues. This could negatively impact costs of pellet production and transport.

When assessing the availability of feedstock, it is, however, not sufficient to only account for costs and GHG emissions in determining which share of potential feedstock supply can be imported within certain thresholds. From a sustainability perspective, additional feedstock use could result in overexploitation of natural resources, eventually reducing ecosystem services such as biodiversity and nutrient recycling (European Commission, 2017; Pelkmans et al., 2017). Increased demand for bioenergy, especially when promoted through subsidies or support systems, may also drive up prices and limit feedstock availability for local markets (European Commission, 2017).

On the longer term, additional demand could result in additional feedstock production. This thesis however focusses on the relatively short term and on the existing potentials that could be mobilized within the next decade. Distortion of local markets is undesirable from a social perspective, reducing the opportunities of local feedstock consumption in favour of feedstock which is exported to satisfy demand in other countries. From a systems perspective, local market displacement could result in increased costs and emissions of the entire wood based products system, as new trade routes and supply systems result in increased distance between feedstock supply and demand markets.

1.4.4. Interaction between wood-based industries

To analyse the impact of increased feedstock demand for pellet production, the relationship between pellet production and other sectors such as timber, pulp and paper manufacturing must be considered. The interaction between feedstock availability and supply chain costs and GHG emissions is complex. For instance, optimizing for pellet mill location could be complicated in case larger feedstock availability inland needs to be balanced with increasing transport distances to export ports. This becomes even more difficult when accounting for the continuously changing market of feedstock availability and competing demand. Impacts of pellet demand therefore cannot be analysed in isolation, but instead must be considered within a systems perspective of the entire wood products industry.

Different potential feedstock types can also be used by other industries such as the timber, pulp and paper industries. Some studies imply that other industries are able to pay more for feedstock than the pellet industry, having higher profit margins and therefore a higher paying capacity (Lechner & Carlsson, 2014). Pellet production is therefore currently often making use of underutilized feedstock either from areas where regional supply of forestry biomass exceeds demand or from areas where large timber industries are producing significant quantities of unused residues (Dale, Kline, et al., 2017; E. Hansen, Panwar, & Vlosky, 2013; Wood Resources International LLC, 2017). Still, pellet production adds to the total feedstock demand and affects regional interaction between different demand and supply markets. Larger

overlap with sourcing areas of industries with similar feedstock requirements will impact the business case of manufacturing facilities and could result in a larger share of pulpwood used for pellet production. An increasing demand for pellets combined with stable or increasing demand for other wood-based products could result in more competition for feedstock, resulting in higher prices for several industries and increased harvesting of roundwood. Increased competition with industries with higher paying capacities could shift pellet production to other regions, for instance more inland regions further away from export ports. Feedstock availability therefore not only impacts the associated costs and emissions of feedstock itself, but also of other components such as transport of feedstock and pellets.

Whereas some industries, such as the pulp and paper industry, can be in competition with pellet mills for similar feedstock, the proximity of other forest industries offers benefits. For instance, there is synergy between pellet plants and industries producing residues such as the timber industry. The impact of pellet production therefore depends on demand developments in other sectors. Increased demand for pellets can easily be covered in an area where demand for certain other forest products is declining, as was the case in the US in the period between 2010 and 2014 when newsprint and paper production continued to decline while the improving housing market resulted in increased availability of sawmill residues (Forest2Market, 2015).

Jonsson and Rinaldi (Jonsson & Rinaldi, 2017) have used an equilibrium model for the forest sector to analyse the impact of increasing wood pellet consumption in the EU on global forest product markets. Their findings first of all point at the importance of considering all the inter-dependencies between different forest products. Increased production of wood pellets is modelled to result in increased production of timber and decreased production of wood-based panels and pulp & paper products in areas where wood pellet production is projected to increase. This in turn results in increased harvesting of sawlogs but decreased harvesting of pulplogs. What is missing in these studies is the combination of a system analysis of the entire wood-based products market with a detailed supply side allocation of forestry and mill feedstock. Furthermore, an analysis of different levels of future pellet production and expansion of manufacturing locations is needed

to analyse specifically the impact in terms of pellet production within the system dynamics of the forestry system.

1.4.5. Impact of feedstock availability and consumption for pellet production on landscape carbon

As explained in previous sections, there are factors limiting the pellet production potential from a supply-side perspective, such as local demand and the availability of mobilization and pre-treatment infrastructure. Other aspects determine the feasibility of importing wood pellets, such as supply chain costs and GHG emissions. The potential contribution of pellets to a reduction of greenhouse gas emissions however not only depends on supply chain emissions, as are included in GHG emission reduction targets, but also on biogenic CO₂ emissions, including emissions from combustion and carbon absorption during plant regrowth (European Commission, 2016a). Reported carbon savings of bioenergy production often assume carbon-neutrality of biomass, assuming that CO₂ emitted at combustion will be compensated by CO₂ captured during regrowth of trees. In case of slow growing systems, such as forest biomass, there can be a delay between harvesting and regrowth of up to a few decades (European Commission, 2016a). This factor is especially important as feedstock consumption shifts from the use of industry and harvest residues to the increased use of pulpwood, potentially resulting in increased harvesting. Additional pellet production in an area, or changing feedstock demand in general, potentially impacts levels of wood harvesting and growth, thereby impacting total carbon emissions to the atmosphere. Only by including this aspect, can the sustainable limits of pellet production and trade be explored. The type of feedstock used for pellet production and the impact of pellet production on the entire wood-based products industry has implications for total levels of harvesting and regrowth in forest areas. Therefore, feedstock demand not only impacts supply chain GHG emissions, but also affects biogenic carbon emissions. The availability and use of different feedstock types has significant impacts on the sustainability of wood pellets. Apart from efficient supply chain design, the interaction between pellet production and carbon storage on a landscape scale needs to be considered in order to assess the sustainability of pellet use (Berndes, Cowie, Englund, Simmons, & Thiffault, 2019b).

There are several existing studies that have analysed the impact of feedstock demand on feedstock allocation, harvest levels and resulting land-use change, mainly covering the US and Europe. Duden et al. (Duden et al., 2017) have analysed the impact of additional pellet demand on forest dynamics and land use in the US SE, showing that increased demand result in a large increase in pine plantation area and a net growth in timberland area. Galik and Abt (Galik & Abt, 2016) used a regional timber supply model to show that increased pellet demand in the US SE has a small impact on biomass prices and removals and forest inventories. This small impact however does result in significant land-use changes at regional levels, showing an increase in total forest area and planted pine in particular. Latta et al. (Latta, Baker, & Ohrel, 2018) have analysed demand for forestry products in the US South until 2030, including for instance the demand for timber, pulp, paper and biopower, using a resource allocation model. Their results show an increase in clear cut harvests, thinnings and utilization of residues to meet increased demand levels, especially in the US South, where most of the demand increases are absorbed. Carbon sequestration levels in the US South initially decrease quickly driven by rapidly growing demand for lumber and biopower, converting the region from emission sink to source between 2014 and 2017. Supply-side responses, such as increased regrowth of regenerated forests, result in the US South shifting back to an emissions sink between 2019 and 2035. At the end of the modelling period, sequestration rates in the US South slowly start to decline again, explained by continuous demand increases while the extent of forest area is assumed to be fixed. Research by Henderson et al. (Henderson, Joshi, Parajuli, & Hubbard, 2017) has shown that mill residues in the US South are cost-effective and readily available, but also for the largest part already utilized. Results from this study show that increased demand for wood pellets will result in increased harvesting in the US. An analysis based on growth-to-drain ratios furthermore shows that harvest levels for increased pellet production do not exceed sustainable limits.

Given the interlinkages between the pellet industry and other wood products industries, and the complex impact of increased pellet demand on feedstock consumption, the aspect of biogenic emissions could be best

analysed on a landscape level (Berndes et al., 2019b). Instead of focussing on emissions and sequestration of a single tree, changes in carbon flow should be considered at the level of forested areas supplying feedstock to the wood products industry. These impacts on landscape level can furthermore only be analysed while accounting for competition and synergies with other sectors as explained above. Focussing on the entire wood based products sector allows to account for industry interactions, including displacement of feedstock use between sectors as a result of increased pellet production. Ultimately, what needs to be analysed is whether increased pellet production in specific region results in changes in the forestry sector on a landscape scale, and how this impacts the balance between carbon storage and emissions. At the same time, some authors emphasize that a sustained yield in a forest landscape managed for bioenergy production does not equal carbon neutrality of biomass for bioenergy, since carbon neutrality can only be assessed in comparison to a reference scenario involving no harvest for bioenergy (Ter-mikaelian, Colombo, & Chen, 2015).

The methodology to calculate wood pellet supply chain emissions as laid out in the RED II includes the impact of carbon stock changes due to land-use change but does not include carbon stock changes within forested areas as a result of changes in management such as harvest intensity (European Parliament, 2018). Carbon stock changes do however need to be included on a national level, following RED II methodology. For countries party to the Paris agreement or with a submitted national contribution to the United Nations Framework Convention on Climate Change this is included by accounting and reporting of land-use, land-use change and forestry emissions. For countries not meeting the above criteria, laws or management systems need to be in place to ensure that carbon stock and sink levels are maintained or increased (European Parliament, 2018). Only by analysing both supply chain emissions, as well as landscape emissions, can pellet production be optimized for minimal impact on the environment and can sustainable limits to pellet production be assessed.

1.5. Research objective and research questions

The objective of this thesis is to analyse the potential current and future impact of increased wood pellet production and international long distance trade on costs and emissions. Variation in supply chain costs is analysed by accounting for regional and temporal differences in cost factors, by including the impact of supply chain design and by analysing the uncertainty of available data on cost components. The impact of supply chain design on both costs and emissions is especially considered for different production regions, by including structural differences in cost factors and by accounting for spatially explicit feedstock availability resulting in different logistics requirements. The spatially explicit availability and allocation of feedstock for pellet production is furthermore assessed in relation to the competition and synergies with other wood-based products industries. The availability and use of feedstock has several impacts. On the one hand, cost and emission thresholds limit the type of feedstock used for pellet production and the total sourcing areas and production potential. On the other hand, increased pellet production impacts total feedstock demand, impacting the supply chain design, costs and emissions as well as the balance between carbon emission and sequestration in forest areas. The following research questions are addressed:

1. What are the factors that determine the cost and GHG emissions of long distance international woody biomass feedstock supply chains and how can supply chains be optimized, including the pre-treatment options pelletization and torrefaction?
2. How do economic support policies and supply chain GHG emission constraints affect supply potentials of imported woody biomass and what is the impact on long distance international trade?
3. If export supply potentials would be exploited in the future, what could be local impacts on costs, GHG emissions and carbon fluxes in forest areas, when considering the interaction with non-energy markets?

Table 1.1 – Overview of research questions covered in each chapter

	RQ 1	RQ 2	RQ 3
Chapter 2	✓		
Chapter 3	✓	✓	✓
Chapter 4	✓	✓	✓
Chapter 5			✓

Chapter 2 of this thesis examines the uncertainty of wood pellet supply chain costs in existing literature, focusing on the impact of supply chain design variables in explicating cost differences. This article focusses on individual design components, such as the type of feedstock used, the pellet plant size or the production country, combined with an analysis of the impact on total costs. In the first part, the largest cost components in pellet production and trade are identified, as well as the components which are most uncertain in literature. In the second part, a techno-economic assessment is used to analyse the impact of cost optimization strategies on total supply chain costs, focussing on potential trade-offs or synergies between various components. The insights obtained through the literature review are used to calculate best estimate costs for two different supply chain designs, varying the type of feedstock and the production size.

Chapter 3 covers the potential for sustainable wood and agricultural pellet exports from Brazil, Colombia, Indonesia, Kenya, Ukraine and the United States. A consistent methodology is applied to all case study countries in order to contrast and compare results. Export potentials are calculated based on the technical availability of feedstock. In each country a different combination of feedstocks is included, based on local availability. From this total, several portions are subtracted, based on a collection of sustainability criteria, the extent of local demand, which is prioritized over export, and the availability of pellet production capacity. For these different limitations, estimates are made of future developments until 2030, in a business as usual scenario and a scenario favouring higher export quantities. This chapter furthermore examines the likeliness of trade of pellets from the different regions to Western Europe by including supply chain costs and GHG emission curves. This work shows potential total pellet imports when adopting certain total cost and emission criteria.

Chapter 4 expands on the impact of supply chain design and country differences on costs and emissions as covered in chapters 2 and 3, by explicitly focussing on feedstock availability and logistics costs. Furthermore, this chapter analyses the addition of torrefaction to the pelletization process as a potential supply chain design optimization strategy. This chapter addresses supply chain costs and GHG emissions of wood pellets and torrefied pellets from Brazil, Canada, Estonia, Latvia, Lithuania, Russia and the US, transported to Western Europe. The total production and export potential from these countries is analysed in detail on the basis of spatially explicit incremental growth of forestry feedstock, combined with transportation requirements using existing infrastructure. Transport distances on road networks are included, as well as differences in sea shipping distance and country specific costs and GHG factors to generate supply curves for the seven countries included in this chapter. The impact of sustainability criteria and cost limitations on the total production potential is analysed by including a number of different costs and emissions thresholds.

Chapter 5 aims to show the impact of increased wood pellet production for the export market in the Southeast of the United States on feedstock use, carbon emissions and costs. This analysis considers pellet production within the existing forest products system by allocating available forestry feedstock and mill residues to the total demand of all sectors using a lowest cost optimization of the entire system. In this chapter, both supply and demand are analysed spatially explicit, based on existing locations of forestry plots and forestry product mills and potential new locations of pellet mills. Demand and supply are changed yearly, following macroeconomic trends and expected forestry growth in existing forest areas, until 2030. The impact of sustainability guidelines is included through the use of different scenarios, analysing the expansion of new pellet mills based on total carbon flux in surrounding forest areas and analysing the impact of increased utilization of logging residues. Different scenarios of total export pellet production are used to show the impact of additional demand, with the focus on spatial availability and allocation of feedstock types, carbon flux in forest areas and supply chain costs.

ABBREVIATIONS

AEO	Annual Energy Outlook	LHV	Lower Heating Value
ARA	Ports of Amsterdam – Rotterdam – Antwerp	LURA	Land Use and Resource Allocation model
BAU	Business as Usual	NE	Northeast
BECCS	Bio-Energy with Carbon Capture and Storage	MC	Moisture content
BIT-UU	Biomass Intermodal Transport model	OECD	Organisation for Economic Co-operation and Development
CCS	Carbon Capture and Storage	PoR	Port of Rotterdam
CIF	Cost Insurance Freight	PV	Photovoltaic
CHP	Combined Heat and Power	RED I	Renewable Energy Directive
EC	European Commission	RED II	Renewable Energy Directive (revised)
ETS	Emissions Trading System	RPR	Residue to Product Ratio
EU	European Union	SE	Southeast
FAO	Food and Agriculture Organization of the United Nations	SOC	Soil Organic Carbon
FIA	Forest Inventory and Analysis of the US Forest Service	SRF	Sustainable Recovery Factor
GHG	Greenhouse gas	SSP	Shared Socioeconomic Pathways
GIS	Geographic Information System	SSS	Short Sea Ship
HE	High Export	SW	Softwood
HW	Hardwood	SW US	Southwest United States
IAM	Integrated Assessment Modelling	TOP	Torrefied pellets
ILUC	Indirect land use change	UK	United Kingdom
IPCC	Intergovernmental Panel on Climate Change	US	United States
LD	Local Demand	US EIA	United States Energy Information Administration
		US SE	Southeast of the United States
		WP	White pellets (regular pellets)

Wood pellet supply chain costs – A review and cost optimization analysis

Published in: Renewable and Sustainable Energy Reviews 118 (2020) 109506

L. Visser, R. Hoefnagels, M. Junginger

2.1, INTRODUCTION

Moving towards a low carbon future while maintaining economic growth requires the use of solid biomass for energy purposes. Co-firing of wood pellets in coal fired power plants can help provide a greener, less carbon-intensive, future while maintaining sufficient electricity generation capacity. One of the barriers to co-firing wood pellets is the significant price gap between coal and wood pellets, varying between 16 and 22 €/MWh³, resulting with in many business cases relying on subsidies (Biomass Magazine, 2018; Ehrig et al., 2014). At the price level of the second quarter of 2018, the required EU ETS price to break even would be 69 €/tonne⁴ (Argus, 2018; IPCC, 2007). To lower supply chain costs, the impact of supply chain design variables, and underlying cost factors must be understood. There is little merit in focusing on lowering the costs of single supply chain components. All components react differently to changes, and optimization of some could have an opposite effect in others. Optimizations should be analyzed across the entire chain and for different conditions.

Various previous studies have explored wood pellet supply costs under different scenarios or conditions. The work by Obernberger and Thek (2010) analyzed in great detail the costs of supply chain components and the total costs of producing pellets in Austria. Ehrig et al. (2014) have analyzed the differences between pellet supply chain costs for pellets produced in three different countries and transported to Northwestern Europe, including use of different feedstock and different production scales. More recently, Boukherroub et al. (2017) calculated the return on investment for pellet production and transport scenarios with various operating scales, level of government support, harvesting costs and sales price of pellets. Existing studies have resulted in more knowledge on specific case studies and supply chains. At the same time, existing studies show a large variation in results for several cost components. For instance, costs of biomass for pellet production varies almost a factor 4 in some examined literature studies. Costs

³ Pellet spot prices ranged from 6.3 to 9.3 €/GJ, between 2009 and 2018, based on 17.5 GJ/tonne pellets (FutureMetrics, 2018; OFX, 2019). Coal prices ranged from 1.9 €/GJ to 3.2 €/GJ between 2008 and 2018, based on 29.3 GJ/tonne coal (BP, 2018; OFX, 2019).

⁴ In the second quarter of 2018, the price difference between pellets and coal, as given by Argus Media, is 19 €/MWh (Argus, 2018). When assuming a conversion efficiency of 48%, associated avoided CO₂ emission of 710 gCO₂/kWh and pellet supply chain GHG savings of 80% compared to coal, the required EU ETS price would be 69 €/ton (IPCC, 2007).

of pelletizing, including capital and operational expenditures, varies more than a factor 5⁵. These large cost ranges result in an uncertainty that hinders the use of literature studies for an assessment of wood pellet cost optimization strategies. What needs to be analyzed is whether these cost differences can be partly or fully explained by differences in the supply chain design, such as the type of feedstock used or the geographical scope. Increased knowledge on the impact of supply chain design factors on cost components will enable more realistic cost estimates for specific supply chains.

The objective of this study is first to improve understanding of the cost structure of inter-continental wood pellet supply chains and second to assess potential cost savings of individual components as well as the entire chain. The specific focus on inter-continental traded pellets is in line with the expectation that growing bioenergy consumption, combined with spatial distribution of biomass demand and supply, will result in increased trade of solid biomass (Matzenberger et al., 2015). In this study, the uncertainties of cost ranges in existing literature studies are analyzed, increasing the understanding of the source of variation. An explication of the impact of supply chain design variables on cost variation will increase knowledge and certainty on total supply chain costs of wood pellets. The first part of this work consists of an analysis of literature on total cost variation, assumptions made about supply chain design and the type of data used. This will highlight the costliest parts of the supply chain, which will be focused on in the second part of this study. In the second part, cost optimization strategies are analyzed, exploring the impact of supply chain variables on cost components. This study will pay particular attention to trade-offs or synergies between various cost components. Cost optimization must be analyzed from a supply chain perspective since supply chain design changes can have an opposite effect on different cost factors.

Researchers will benefit from the data analyzed in this study as it provides a good starting point for further research into supply chain optimization and provides insight into cost uncertainties and the impact of supply chain design on total costs. This article is supplemented by a harmonized and up-

⁵ Feedstock costs are 27 €/t of pellets for a mixture of sawdust and shavings in Mobini et al. (2013), and 114 \$/t pellets for roundwood in McKechnie et al. (2016). Total costs of pelletizing in Agar (2017) is 25 €/t pellets, compared to 136 €/t in Pirraglia et al. (Pirraglia et al., 2010)

to-date dataset of supply chain costs of different components, to be used by the scientific community in future work. Furthermore, this research will be especially relevant for policy support. The quantification of the total costs of producing and transporting pellets can be used to determine required subsidy levels to support the replacement of fossil fuels for wood pellets.

2.2. METHODOLOGY

This article consists of a literature review of studies that have researched wood pellet supply chain costs, focused on explicating the difference between costs in literature. Input data as well as supply chain design assumptions were compiled in an excel database, which is made available with this article. This literature review was used, combined with additional data, as input for a techno-economic assessment of the impact of supply chain design and cost optimization strategies.

2.2.1. Supply chain scope

The supply chain considered in this article is the typical chain of wood pellets used to replace solid fossil fuels in large scale utilities. This chain includes large scale production of pellets, with international and intermodal transport to import regions. Pellet production from agricultural feedstocks is not considered. The few large-scale power plants in Western Europe that consume pellets are currently only using forestry-based pellets, which are considered technically superior and easier to combust in existing boilers (Liu, Quek, & Balasubramanian, 2014). The different supply chain components included in this study are shown in figure 2.1, together with the most important considerations and assumptions.

Figure 2.1 – Supply chain components included in this study

2.2.2. Geographical scope

Literature analyzed in this study is based on a geographical scope of production of pellets in various world regions and consumption in Western Europe, imported through the ARA ports (Amsterdam-Rotterdam-Antwerp). The impact of supply chain design will be analyzed and calculated in more detail, applied to a specific supply chain of pellet production in the southeastern part of the United States (US SE) and consumption in the Netherlands. The United States pellet market is the most developed in the world, with pellets for export being produced mainly in the southeast. The trade between the US SE and Europe totaled 6.7 Mt in 2017, making it the largest wood pellet trade flow in the world (Thrän et al., 2017) (Bioenergy Europe, 2018).

2.2.3. Difference between cost and price

The difference between the definitions of cost and price is whether a profit margin is included. Literature studies referenced in this study generally use the phrase “cost”, even for components in which profit seems to be included such as logistics cost based on price quotes of logistical companies. The difference between cost and price also depends on the perspective of actors within the chain. For instance, the price of feedstock includes profit for land owners, but is at the same time a cost expense for pellet producers. Literature studies often use different approaches, mixing cost and price data. In most cases it is not clear whether sources refer to costs or prices, or what profit margins are included. Cost data from literature used in various parts of this paper are used as such, without adding or removing profit margins for certain components.

For the calculations made in this study, profit margins are excluded as much as possible to calculate the lowest possible supply chain costs. This is specifically the case for calculated pellet production and road transport costs. Data limitations result in the use of price data for some calculated components, such as the use of charter rates in the calculation of rail transport costs and shipping costs, and the use of data on feedstock prices paid by pellet producers.

2.2.4. Supply chain variables and components

The impact of supply chain design variables and context factors will be analyzed separately. The remainder of this article will focus on the impact of four different supply chain design variables: Production country, site location, pellet plant size and feedstock type. The methodology and results of the impact of context factors can be found in Appendix A.1. Context variables analyzed are shipping charter rates and fuel costs and the differences in exchange rates and inflation. For all combinations of supply chain design variables and factors, an evaluation was made of the impact on cost components. This evaluation was based on a first screening of literature and an initial assessment rooted in previous work and experience. The different supply chain components analyzed in this research are:

- Feedstock cost, delivered to pellet plant
- Pelletizing cost
- Costs of transport to export port
- Handling & storage costs at export port
- International transport costs (usually shipping cost)
- Costs of handling & storage at import port

The focus will be on combinations of variables and components with the strongest impacts, as shown in table 2.1.

The uncertainty in pelletizing costs is analyzed in more detail by assessing the variability within three different types of pellet production expenses. Building a pellet plant requires upfront capital costs, usually secured in the form of outside investments or loans. Amortization of this capital results in expenses during the operation of the pellet plant. Capital costs are divided into two categories, which are expected to respond differently to supply chain design: Capital costs related to equipment for pellet production and storage, and capital costs for peripheral equipment, infrastructure, planning, installation and construction. The third category is the operating costs required to produce pellets with the installed equipment, consisting of costs of feedstock transported to pellet plants, labor costs and costs for heat and electricity.

Table 2.1 – Impact of supply chain design variables on cost components, dark blue = strong impact, light blue= weak impact. White = no/very little impact and therefore excluded from the analysis.

Variables	Feedstock		Feedstock transport		CAPEX		OPEX				Transport to port		Shipping		
	Feedstock costs	Feedstock transport distance	Specific transport costs	Required equipment	Specific equipment costs	Required labor	Specific labor costs	Required processing energy	Utilities costs	Pellets transport distance	Availability of rail infrastructure	Shipping distance	Availability of ship sizes	Specific shipping costs	
Feedstock															
Country															
Site location															
Scale															

Since most studies do not specify the energy content of pellets, costs are given per tonne of produced pellets instead. If supply chain components were not included in specific literatures studies, the average of all other data points were used. Costs were first accounted for inflation until 2017, according to equation 2.1. and subsequently converted to euro values where necessary (Eurostat, 2017a; OANDA, 2017). For literature sources that did not explicitly include a reference year for costs data, the submission year, or else the publication year was used to calculate the inflation adjusted values.

$$\text{Adjusted value} = \left(\frac{\text{Literature Value}}{\text{Consumer Price Index}} \right) \cdot 100 \quad \text{Eq. 2.1}$$

2.2.5. Input data

2.2.5.1. Selection of literature

The basis for the selection of literature in this work was a focused search in Scopus and ScienceDirect for all the articles between 2007 and 2017 containing the words (wood) pellet(s) and any term related to supply chain costs⁶. After an initial screening of titles and abstracts, 57 studies were assessed for suitability based on three criteria, starting with the type of feedstock used to produce pellets. There are considerable differences between pelletizing forestry residues and agricultural residues, both in terms of feedstock costs and pelletizing process (Sultana & Kumar, 2012). The size of a pellet plant has an impact on the supply chain design. The second criterium was the size of analyzed pellet plants. Pellet plants producing for the export market in the US SE range between production sizes of 12 kt/a to 825 kt/a (Biomass Magazine, 2017b). In this research, only studies on pellet plants >12 kt/a were included. In case the pellet plant size was not explicitly mentioned in a literature study, an assumption was made based on the available costs data. For instance, studies that include costs for long distance feedstock sourcing or intermodal pellet transportation were assumed to be based on larger scale pellet plants and were included in the analyses. Explicit information on costs parameters is required to compare studies with different scopes and assumptions. Only studies that provide information on different costs components or parameters were considered suitable to include in the analysis. The final criterium was data availability. Only studies that explicitly include data on the calculation of supply chain costs, for a minimum of three cost components, were considered suitable input to conduct a techno-economic analysis. Additional literature was identified by consulting the bibliographies of already included studies.

The final list of included literature was used to analyze the type of cost data used and the variation of cost results. The results of this analysis consist of a general description of the literature, including the geographical scope, type of feedstock used, production size, publication year and included costs components. The type of input data used in the different literature studies was analyzed qualitatively. Distinct types of data sources were identified:

⁶ supply chain / supply chain costs / costs / net present value / cash flow / rate of return / value chain / economics / economic assessment / economic analysis / financial analysis

- Expert judgment,
- Industry data
- Market data (publicly available data)
- Literature sources
- Unknown sources
- Self-citation

Literature sources were further divided into categories to show the age of cited literature, ranging from *literature before 2000*, to *literature before 2020*. between the included studies are shown explicitly by analyzing the citations between the include group of studies.

2.2.5.2. Calculation of transport costs

Road and rail transport costs were calculated using a GIS-based transport model which was developed for this analysis. The model was based on existing infrastructure networks in the United States. Transport distances were calculated based on Railroads maps and OpenStreetMap, as made available by Esri (ArcGIS, 2019) and Geofabrik (Geofabrik, 2019). Costs were calculated using the parameters given in table A.1 in Appendix A.2. The assumption was made that truck drivers are generally paid per twelve-hour shift, making as many deliveries as possible within this time period. Unused paid hours were added to the trip costs. On short distances, truck transport is the cheapest and most flexible, benefitting from low capital costs. The much larger capacity of rail transport results in lower variable costs, ensuring lower overall costs for long distance transport, but requires proximity of railways. Rail transport is included as a feasible option for pellet plants within 20 km of existing railroads. Freight is not transferred from road to rail infrastructure or between different railroad companies. Transport costs were calculated to a few selected ports currently exporting wood pellets from the US SE⁷, from which the cheapest option was selected (Southern Environmental Law Center, 2015).

⁷ Baton Rouge, Mobile, Norfolk, Panama City, Savannah

Shipping costs were calculated between the ports of Savannah and Rotterdam as consisting of two components, time-related charter costs and fuel consumption costs, for Handysize and Supramax ships. Costs were analyzed for a longer time period to analyze the impact of cost fluctuations, using yearly average charter costs and fuel costs (Clarkson Research Services Limited, 2018). For the period in which data on maritime fuel costs was not available, before 2009, costs were modelled after the crude oil price (Bunker Index, 2018; Index mundi, 2018). Detailed methodology on the calculation of shipping costs can be found in Appendix A.2.

2.2.6. Supply chain design variables

2.2.6.1. Feedstock type

Wood pellets can be produced from several types of forestry feedstocks such as industry residues, forestry management residues or pulp- or timber grade pulpwood⁸. Large scale pellet production will often be designed based on a mixture of various feedstocks, depending on local availability and costs. Besides potential price differences between feedstock types, pelletizing costs are affected as well. The necessity of including various size reduction and moisture reduction steps in the pelletizing process depends on the raw material used, as indicated in figure 2.2.

Variation in literature of feedstock costs and pelletizing costs for different feedstocks was quantified through a Monte Carlo analysis. It was not considered possible to assess the likelihood of individual data points from literature, instead trendlines, choosing between linear, power, exponential and logarithmic functions, were fitted to literature values using Microsoft Excel. The trend line with the best fit, with the highest R-squared value, was used to model probability distributions for each feedstock category. These distributions, confined between the lowest and highest literature data points, were used as input for Monte Carlo simulations. After 100,000 simulations, the resulting probability distributions were used to calculate average values as well as 50% likelihood values for each specific feedstock.

⁸ Pulpwood refers to trees or parts of trees from plantation forests that are of too low quality to produce lumber. This category consists of low grade roundwood (for instance damaged or crooked trees), treetops left as by-product of sawtimber harvest as well as commercial thinnings.

The uncertainty of probability distributions depends strongly on the number of data points available as input. Monte Carlo analysis was only considered suitable for feedstock costs, and not for other cost components, because of the relatively large availability of data in included literature. Only the feedstock categories for which there was enough data, from at least five different studies, were separately included. This resulted in the categories *Pulpwood*, *Sawdust* and the combination of *Sawdust/shavings*. In this analysis, both the variation in feedstock costs and the pelletizing costs for different feedstocks were included.

Feedstock costs are verified with market data from the United States (U.S. Energy Information Administration, 2018c). Costs for respectively pulpwood and sawmill residuals were taken from the United States Energy Information Administration (US EIA). The US EIA requires all pellet producers in the US to report information on the type of feedstock used and the price paid. The feedstock categories used by the US EIA only partially match feedstock assumptions from literature studies. For this study, US EIA data on Roundwood/pulpwood was used for pulpwood calculations, data on Sawmill residuals was used for sawdust calculations. US EIA data and the average exchange rates used can be found in Appendix A.3. Other feedstock categories could not be assessed. US EIA cost data is only available for raw material, without information on the moisture content of feedstock types. Conversion factors were calculated as in equation 2.2., using assumptions for moisture content of feedstock (MC_{in}) and pellets (MC_{out}), energy efficiency of a chips boiler (η_{cb}), processing energy required to evaporate a tonne of water (ER) and the net calorific value of feedstock (NCV), as indicated in figure 2.2.

$$\text{Conversion factor} = \frac{(1-MC_{out})}{(1-MC_{in})} + \frac{(MC_{in}-MC_{out}) \cdot ER}{\eta_{cb}} \times \frac{1}{NCV} \quad \text{Eq. 2.2}$$

i. Moisture content based on several include literature studies, as shown in Appendix A.4. Net calorific value based on (Forest Research, 2018). Feedstock is assumed to be dried to 8% before pelletization. The energy requirement per t of evaporated water, ER, was assumed to be 1200 kWh/t (Oberberger & Thek, 2010), produced in a chips boiler with efficiency, cb, of 85% (European Commission, 2015).

Figure 2.2 – Overview of pelletization steps, for different feedstock types

2.2.6.2. Production country

Several cost factors are expected to vary between different pellet production countries, such as feedstock costs, labor costs, fuel costs and availability of infrastructure. The analysis of country impact will focus on factors explicitly included in several literature studies, namely feedstock costs and shipping costs. Cost variation of feedstock in several countries was analyzed in the same way as the different feedstock types. A Monte Carlo analysis was done for the countries for which enough data was available, which were *the United States* and *Canada*. There were not enough data points to use Monte Carlo analyses for the other cost components analyzed for country related cost differences.

Shipping costs are directly affected by the geographical scope since the distance between production and consumption country largely determines shipping costs. To analyze the impact of shipping distance, costs from literature were normalized by assuming a linear cost increase per distance. Shipping

distance was taken directly from literature studies when explicitly mentioned. In case this information was not included, distances were assumed based on the general geographical scope⁹. The impact of geographical scope on utility costs is assumed to be significant. Factors such as local taxes, and subsidies, as well as costs for labor, fuel and electricity all depend on the country and specific region of production. However, because of the complexity of these factors, combined with time and resource limitations, the impact of the pellet production country on utility costs was not included in the final analysis.

2.2.6.3. Wood pellet plant site selection

One of the most important factors in choosing a suitable pellet production site is the availability of feedstock. This aspect not only impacts the price of feedstock but also the costs of transporting feedstock to the pellet plant. Since transparent data on regional price variations of feedstock is not available, the focus of this article will be on the impact of supply of biomass on feedstock transportation costs. This was analyzed by calculating feedstock transport costs for pellet plants of the same size, on different locations. To produce more results as realistic as possible, the location of existing pellet plants in the US SE were used in this analysis. A list of the pellet plants in the US SE producing pellets for the export market at the time of this analysis can be found in Appendix A.5. These plants are presumably located in fiber baskets with enough biomass to support a pellet plant. Feedstock supply areas were calculated based on local biomass availability on county level in the US SE, taken from Fingerman et al. (2017), calculating transport costs from weighted centers of counties. Biomass was allocated starting from the county and pellet plant combination with the lowest transport costs, allowing for partial allocation in any case where supply exceeded remaining demand of a pellet plant. By following this method, the impact of competing pellet plants on regional feedstock availability is included. The allocation model was explicitly designed to optimize for single feedstock deliveries as opposed to a system optimization of lowest costs to all pellet plants. Optimizing for the entire system is considered less realistic since most pellet plants operate independently and will compete for feedstock with neighboring plants. A pellet plant's location will also impact transportation of pellets to export

⁹ Assumed distance to the ARA region: West Canada – 16500 km; East Canada – 5000 km; Ontario, Canada – 6500 km; St. Petersburg, Russia – 2900 km; Cape town, South Africa – 13500 km.

terminals, since site selection will determine the transportation distance to the nearest suitable port. This was analyzed by comparing the transportation costs from pellet plants to the export ports included in this study (Southern Environmental Law Center, 2015).

2.2.6.4. Pellet plant size

Different supply chain components react different to scale increases. Feedstock costs are assumed to be relatively constant with increasing scale, provided that sufficient feedstock is available. Feedstock supply areas, and therefore feedstock transportation costs, will presumably increase with increased pellet plant size. To illustrate this, the impact of pellet plant size on transportation costs was calculated. To explore the impact of pellet plant size, the aforementioned transportation model was run three times, once for the actual size of existing pellet plants and for a small and large pellet plant with assumed sizes of 50 and 500 kt/a production size.

Rail transport requires the transportation of a minimum quantity of pellets. Using train transport is considerably more cost effective when using a unit train, consisting of 40 – 120 railcars, delivering according to a contracted schedule (Gonzales, Searcy, & Ekşioğlu, 2013). According to Obernberger and Thek (2010), storage silos at pellet plants generally hold about 8 days of production. The assumption was made that pellets need to be distributed from pellet plants once a week, during 90% of the year, resulting in a minimum of 168 kt/a for a 40-year car train. The same rational was applied to ship size, assuming pellets need to be shipped out once a month. Cost-effective shipping depends on carrying as much load as possible, therefore the assumption was made that larger ships will only be used if the amount of cargo approaches the maximum tonnage. Twelve shipments of a fully loaded Supramax ship would result in the transportation of 580 kt/a (J. Giuntoli, Agostini, Edwards, & Marelli, 2017). Based on these calculations the assumption was made that rail transport and the use of Supramax ships are viable options for the large pellet plant but not for the small pellet plant.

Pelletizing capital and operational expenditures are expected to decrease with increasing size. Wood pellets are produced in modular designed pellet mills with several parallel production lines. For example, a pellet

plants producing 600 kt/a could consist of four parallel production lines, with five pellet mills per line (Abbott, 2017; Mobini et al., 2013). Although this modular design limits the scale up of equipment, buyers of pellet equipment expect volume discount when buying multiple equipment units, resulting in decreased equipment costs (T. Chopin (Blackwood Technology), 2019). With increasing pellet production capacity, the required processing labor per unit of output is assumed to decrease to a large extent. Pellet production is a highly automated process, the number of production workers to monitor processes will not increase linearly with production capacity. Furthermore, administrative personnel requirements will not change considerably with larger production output.

A general economies of scale factor of 0.85 was used in consultation with pellet production experts. Scaling factors assumed in literature vary between 0.7 (Hoefnagels, Junginger, & Faaij, 2014; Pirraglia et al., 2010; Rentizelas & Li, 2016; Uslu, Faaij, & Bergman, 2008) and 0.82 (Obernberger & Thek, 2010). The labor component of OPEX costs are considered to scale much more significantly, with an assumed scale factor of 0.25 (Patel et al., 2006). Other operational expenditures, such as the costs of electricity and heat are not considered to scale at all. Capital expenditures and operational expenditures of different sized pellet plants were analyzed by applying a scale factor to costs from literature. For the reference pellet plant, 50 kt/a production was assumed. The literature studies on pellet plants with sizes below 100 kt/a were considered representative. Average costs from these studies were used for assumptions on capital expenditures, labor costs and other operational expenditures. Costs were indexed based on the pellet plant size, using the same economies of scale factors.

2.2.7. Total supply chain costs

Based on the analyses in this study, the total supply chain costs for two different types of pellet plants were calculated. The first type of pellet plant assumed is a small, 50 kt/a plant using sawmill residues. The second is a larger, 500 kt/a pellet plant using pulpwood and having access to rail infrastructure. Furthermore, the assumption was made that the small plant will use Handysize ships to transport pellets overseas, whereas the large

pellet plant uses Supramax ships. Besides the difference in feedstock costs, the additional equipment required for drying and grinding of pulpwood compared to sawmill residues is also included in the total cost overview. This is analyzed by either fully including or excluding the costs of grinding and drying equipment, based on investment cost data as given in some of the included literature studies (Mani, Tabil, & Sokhansanj, 2006; Mobini et al., 2013; Obernberger & Thek, 2010; Pirraglia et al., 2010; Uasuf & Becker, 2011; Urbanowski, 2005). These costs were amortized assuming a debt repayment period of 10 years and a cost of debt of 7% (Thek & Obernberger, 2004). The differences in electricity and heat requirement were not assessed in detail but would contribute to slightly higher operating costs for using pulpwood instead of residues.

2.3. RESULTS

2.3.1. Literature review

2.3.1.1. Selection of literature

Applying the selection criteria resulted in the selection of 23 studies for further analysis. Details on scope and design can be found in table 2.2. Some of the included studies are aimed at analyzing costs of bagged pellets, torrefied wood pellets, chips or other forestry biomass. These studies were considered to provide useful data on some supply chain components that match the scope of this study, such as the costs of forestry feedstock collection and transport.

Table 2.2 – Overview of literature sources included in this study

Source ⁱ	Production region	Consumption region	International transport	Feedstock type	Size (kt/a)	Product type
1	AT/SE	AT/SE	No	4	24/80	1
2	ZA	EUR	Yes	1, 4	56/ 80	1,2
3	CA	EUR	Yes	4, 5	32	1
4	CA	-	No	4	45	1
5	CA	NL/SE	Yes	4	100	1
6	AT	AT	No	4	40	1
7	US	US	No	1	75	1
8	CA	NL/SE	Yes	-	180	1,2
9	US	NL	Yes	4, 5	150	1
10	CA	EUR	Yes	1, 4, 5	-	1
11	AR	-	No	4, 5	24	1
12	CA	EUR/CA	Yes	4, 5	160	1
13	US	US	No	1	100	2
14	US	NL/BE	Yes	1	75	1
15	SE	SE	No	1	200	2
16	FI/DE/NO/ SE/US	EUR	Yes	1, 4, 5	120	1
17	CA/AU/RU	NL	Yes	1, 4, 5	40/120	1
18	CA	EUR/CA	Yes	4, 5	160	2
19	US	US	No	1	-	1
20	CA	CA	No	1	150	1,2
21	CA	NL	Yes	2	-	1,3
22	CA	NL	yes	2, 3	50/100/150	1
23	No specific country ²	Yes	-	64/80	1,2	

i. Literature reference numbers can be found in Appendix A.6.

ii. Cost data corresponds to market rates in the Netherlands, a port-to-port shipping distance is included, roughly the distance from South-Africa to the Netherlands or Brazil to Finland (Agar, 2017).

The data set is comprised of a few early publications, five in total, from the years 2004-2006. In 2010, corresponding to a sharp increase in pellet production in the United States for export to Europe, the topic appears to be under renewed interest (Lang & Copley, 2016). Eleven studies published in the years 2010 – 2013 are included. In the more recent studies, from 2014-2017, there is slightly more focus on additional pre-treatment technologies, such as the production of torrefied pellets (Agar, 2017; Bergman, 2005; Mckechnie, Saville, & Maclean, 2016; Mobini et al., 2014; Peng et al., 2010; Pirraglia, Gonzalez, Saloni, & Denig, 2013; Svanberg, Olofsson, Flodén, & Nordin, 2013), and on use of alternative feedstock such as damaged pulpwood and thinnings (Barrette et al., 2017; Boukherroub et al., 2017). The size of pellet

plants assumed in the different literature studies varies between 24 and 200 kt/a of pellet production. The assumed size of pellet plants was smaller in the studies published until 2010 than in later years, as shown in figure 2.3 (Bioenergy International, 2005, 2017). This is still significantly smaller than some of the actual pellet plants in the US, especially the plants producing pellets for the export market which average at 389 kt/a (Biomass Magazine, 2017b). In the United States, the total production capacity in 2000 measured 460 kt/a, produced in small scale production units below 50 kt/a capacity (Lamers, Junginger, Hamelinck, & Faaij, 2012). From 2008 onwards, several significantly larger pellet plants with annual output of >500 kt/a have started to produce pellets in the Southeast region of the US (Southern Environmental Law Center, 2015; Thrän et al., 2017). The misrepresentation of pellet plant size in literature could impact the certainty of cost estimates.

Figure 2.3 –Pellet plant sizes assumed in analyzed literature and actual size ranges of existing pellet plants in different countries in 2005 and 2019 (Bioenergy International, 2019)(Bioenergy International, 2005).

As shown in figure 2.4, all studies at least include the costs of feedstock. In some cases, the feedstock costs are given as delivered to the pellet plant whereas in other studies a distinction is made between transport costs and purchasing costs of feedstock from the perspective of a pellet producer. A few authors, such as Svanberg et al. (2013), Lu et al. (2015) and Boukherroub

et al. (Boukherroub et al., 2017) include further details on timber harvesting operations, such as harvesting costs, collection costs and stumpage fees. With the exception of the studies by Pirraglia et al. (2013) and Svanberg et al. (2013), all studies include pelletizing costs. Some studies include a large level of detail such as Thek & Obernberger (2004), Obernberger & Thek (2010) and Mobini et al. (2013) whereas other studies only give the total costs of pelletizing (Levin, Krigstin, Wetzel, & Levin, 2011; Lu et al., 2015; Peng et al., 2010). Transport to export ports and shipping costs are covered in more than half of the studies while handling & storage costs in export and imports ports are covered in about a third of the studies. Some studies include regional distribution of pellets, analyzing pellet production and consumption within the same country (McKechnie et al., 2016; Obernberger & Thek, 2010; Thek & Obernberger, 2004). Considering the differences between regional distribution and long-distance bulk transport, these costs estimates are left out of this review. Transport in import countries is included in five studies, four of which analyze transport costs in the Netherlands and one of which analyses costs in the United Kingdom (Agar, 2017; Bergman, 2005; Ehrig et al., 2014; Qian & McDow, 2013; Sikkema et al., 2010).

Figure 2.4 – Type of data referenced in the analyzed literature

There are considerable differences between the type of input data used in the literature studies under review. Some studies make use of industry data such as data from pellet plants or logistical companies. This is most notable in Bergman (2005), Mobini et al. (2013), Mobini et al. (2014) and Boukherroub et al. (2017). This use of data based on operational information could increase the data reliability of these studies. On the other hand, this data is often used without providing further details on the supply chain design or assumptions associated with this data. This increases the uncertainty and limits the replicability of these studies. Besides the use of data from industry partners, several studies make use of assessments of experts, such as Hoque et al. (2006) and Mobini et al. (2014). A few studies make statements on supply chain costs components without further clarification or have an incomplete bibliography. This makes it very difficult to assess the usefulness and reliability of data from these sources.

A issues with the included literature sources is that similar values are often the result of having used the same data source, as illustrated in figure 2.5. A group of original sources from 2004-2006 are used as input in most of the literature in later years. Articles written between 2010 and 2013 are partially based on those first few studies. At the same time these articles are used as input for a third group of papers, written between 2013 and 2017. Indirectly, some of the newest studies refer to data which stems from the earliest articles. These secondary citations hide potential issues with the original data and often do not account for the specific framing of data in the original studies. Just three studies of the included literature sources are largely unrelated to the other studies.

The problem with re-use of data is twofold. First of all there is the issue of uncertainty. In case of similar costs values, a conclusion is easily made that there is a strong consensus in literature, whereas this could be the result of repeating use of the same input data. Another issue is the fact that studies from 2004 – 2006 most likely contain outdated information. For instance, the costs of shipping, handling and storage in Mobini et al. (2014) are taken from a combination of sources, among which a source from 2002. Cost data on wood pellet production, and several transport and handling steps in Agar (2017), was taken from a source dated back to 2005. This data appears to be

used without price level accounting to adjust for inflation. As was explained in section 2.2.4, the data in this study was adjusted to 2017 euros. For several cost factors, such as pelletizing and shipping costs, the use of outdated data could result in a misrepresentation of the actual situation, even if inflation is accounted for. Shipping costs have fluctuated strongly with changing market conditions since the first published study in 2004. The pellet market has changed drastically in this period, for instance when considering the size of pellet plants or the type of feedstock used, transitioning from the use of excess mill residues to predominant use of softwood pulpwood (Karen Lee Abt, Abt, Galik, & Skog, 2014). These changes will have had an impact on cost factors of pellet production.

Figure 2.5 – Data linkages between the included literature studies. Numbers refer to literature reference numbers, as referred to in table 2.2, and given in Appendix A.6.

2.3.2. Variation in cost components

The total supply chain costs in the included literature range between 88 €/t and 279 €/t with an average of 163 €/t and median value of 153 €/t (Figure 2.6). These total values include averages for supply chain components not included in the individual studies, which are left out of figure 2.6¹⁰. The variation for individual cost components is large, as can be seen in figure 2.7. The costs of transporting pellets to export harbors range between 1 €/t and 29 €/t. The variation is also large for the costs of pelletizing (factor 10 difference), delivered feedstock to pellet plants (factor 9 difference), for handling and storage in export ports (factor 8 difference) and for shipping (factor 6 difference). When comparing the different components of pelletizing costs, the operating costs stand out. This component makes up the largest, and most uncertain, part of the pelletizing costs. Pellet equipment is produced and traded globally, and economies of scale impact equipment cost to a lesser extent compared to some operating cost factors such as labor cost. Some of the components in operating cost, such as the cost of feedstock or transport, are likely impacted to a large extent by supply chain design. It must be noted that the sum of the capital and operating costs differs from the total pelletizing costs shown in figure 2.7. This is because total costs are based on a larger set of data points, including also the studies that only provide data on total pelletizing costs and not on cost components.

¹⁰ Feedstock, delivered to pellet plant – 50 €/t, Pelletizing – 46 €/t, Transport to port – 13 €/t, Handling & storage, export – 9 €/t, Ocean transport – 35 €/t, Handling & storage, import – 9 €/t

Figure 2.6 – Costs for selected wood pellet supply chain components as given in literature.

Figure 2.7 – Boxplot of cost values of different supply chain components in analysed literature, including minimum, median and maximum values and cost ranges between the 1st and 3rd quantile. Blue dots represent outlier data points.

2.3.3. Supply chain design variables

2.3.3.2. Feedstock type

In the analyzed literature, the average feedstock costs of a combination of sawdust and shavings is the least expensive, followed by sawdust. The use of pulpwood results in the highest supply chain costs, as can be seen in table 2.3. Pelletizing cost for sawdust/shavings are also lower than pelletizing cost for the pulpwood combination. Running the Monte Carlo analysis results in average total supply chain costs of 124 €/t pellets for sawdust/shavings pellets, followed by sawdust, with an average of 137 €/t pellets, as shown in figure 2.8. Pulpwood pellets are the most, averaging at 153 €/t pellets respectively. When comparing the 50% likelihood ranges, the total costs for pellets from sawdust/shavings are clearly below the values for the pulpwood-based pellets. Costs of sawdust/shavings pellets overlap with the two other categories. The additional capital required at a large-scale pellet plant for the processing of pulpwood adds 2.7 €/t. This is most likely an underestimation since this does not include installation of equipment or operational expenditures such as personnel and maintenance costs.

Figure 2.8 – Pellet supply chain costs likelihood of pellets produced from different types of feedstock, based on a Monte Carlo analysis of cost data from literature.

Table 2.3 – Feedstock and pelletizing cost for different feedstock types, in €2017/t pellets, as calculated based on a Monte Carlo analysis of cost data from literature.

		Average		50% likelihood
	Feedstock cost	Pelletizing cost	Total	Total
Sawdust/shavings	23.3	32.0	124.1	111 – 138
Sawdust	27.8	39.7	136.6	115 – 158
Pulpwood	37.4	46.0	152.5	129 – 175

Data on feedstock prices paid by pellet producers in the United States shows a smaller difference between pulpwood and sawmill residues. When comparing the costs as given, in \$/t feedstock, over 2017 and 2018 there is no difference between the two feedstock types, both averaging at 29 \$/t. The impact of variation exchange rates in the respective months introduces a small difference, with pulpwood being slightly cheaper at 26 €/t feedstock compared to 27 €/t feedstock for sawmill residues. Applying the different conversion efficiencies based different assumed moisture contents, the costs of sawmill residues amount to 46 €/t pellets, compared to 54 €/t for pulpwood. This conversion relies heavily on the assumed moisture content of feedstock. The impact of these assumptions is shortly discussed in section 2.3.4. The moisture contents assumed in the literature studies also vary to a considerable extent, even for similar feedstock types.

2.3.3.3. Production country

For the two different countries included in the Monte Carlo analysis, the United States and Canada, there is a small difference in the feedstock cost in literature, as shown in figure 2.9 and table 2.4. Feedstock cost in the United States are somewhat higher than in Canada, at 43 compared to 37 €/t pellets. The Monte Carlo simulations of total pelletizing cost, including different pelletizing cost data, results in the lowest supply chain costs for Canadian pellets, at 155 €/t pellets, followed by the United States with total costs of 162 €/t. The 50%-likelihood values overlap for the largest part.

Figure 2.9 - Pellet supply chain costs likelihood of pellets produced in different countries, based on a Monte Carlo analysis of cost data from literature.

Table 2.4 – Feedstock cost for different countries, in €2017/t pellets, as calculated based on a Monte Carlo analysis of cost data from literature.

	Feedstock cost	Pelletizing cost	Total	50% likelihood
United States	43.0	49.7	155.0	138-185
Canada	37.4	48.5	161.7	129-181

Shipping cost differ considerably in the literature, varying a factor 6.0 between 11 €/t and 66 €/t of delivered pellets. To understand the country impact, shipping costs were normalized for distance. The resulting variation remains however equally large, varying a factor 6.4, between 0.15 €/t.km and 0.93 €/t.km. This large uncertainty range can largely be attributed to one outlier. Without this one data point, normalized costs vary a factor 3.5, between 0.15 and 0.51 €/t.km.

2.3.3.4. Site selection

Calculated transport costs of feedstock to pellet plants vary between 0.7 €/t pellets, for a 12 kt/a pellet plant, and 23 €/t, for a 400 kt/a pellet plant. When correcting for different pellet plant sizes, the cost range remains large. When assuming 50 kt/a per year production for all pellet plant locations, transport costs range between 0.3 and 10 €/t pellets, with an average of 4 €/t. The lowest calculated transportation cost of pellets to ports are 3 €/t pellets, for a transportation distance of 42 km. The highest costs amount to 43 €/t, for

pellets transported across 729 km. There is a clear link between distance and costs. This relation is not entirely linear because of differences in accessibility of rail infrastructure. The largest transportation distance among the set of pellet plants and ports is 839 km, for which the calculated transportation costs are 35 €/t pellets.

2.3.3.5. Pellet plant size

Pelletizing costs for the small pellet plant, 50 kt per year, exceed the pelletizing costs for large pellet plants, including the additional costs of 2.7 €/t pellets required for pulpwood processing (see table 2.5). For the assumed production size of 500 kt per year, additional average costs for feedstock transportation amount to 9 €/t pellets on average. From the different pellet plant locations, the pellet transport costs when assumed road transport only, for small pellet plants, is 7 €/t pellets more expensive. Using rail transport results in lowered costs for 23 out of 41 pellet mills. These rail transport costs do not include additional cost investments in rail infrastructure that might be needed at some locations. Rail infrastructure costs are difficult to estimate since these depend on factors such as the type of track, the specific contractor, local regulations and the total length of track required. An indication of total costs of new rail track is given in (Deloitte, 2008), amounting to about €2 million per kilometer of new track. Calculated shipping costs vary between 10 – 31 €/t pellets for Handysize ships between 2007 and 2018, and between 7 – 26 €/t pellets for Supramax ships in the same period. On average, cost savings of using a larger ship are 4 €/t. Costs savings are largely, for 61%, the result of lower fuel consumption. The fluctuation of fuel costs is relatively small, varying a factor 3. The charter rates in the analyzed period fluctuated with a factor 11 for Handysize ships, and a factor 31 for Supramax ships (see Appendix A.1). The trade-offs between cost components for small and large pellet plants are discussed in more detail in section 2.4.2.

Table 2.5 – Calculated cost components for small (50 kt/a) and large (500 kt/a) pellet plants, in €2017/t pellets

	Small	Small	Large	Large
	Rangeⁱ	Averageⁱ	Rangeⁱ	Averageⁱ
Feedstock		46.4		55.6
Feedstock transport	0.3-10.2	3.9	4.4-34.4	13.1
Pelletizing		53.0		41.5
Pellet transport	3.3-48.8	18.8	3.3-28.8	11.7
Shipping	11.8-33.5	20.9	7.1-20.3	12.7

i. Cost of feedstock transport and pellet transport were calculated for specific pellet plant locations. The other cost factors were calculated without accounting for any supply chain differences other than size.

2.3.4. Comparison to market prices

Long-term price contracts are aimed at being mutually beneficial, providing both pellet plants and power plants with sufficient margin to sustain operations (FutureMetrics, 2018). The prices of pellets traded on the spot market respond to supply and demand imbalances, generally resulting in higher prices in case of excess demand and lower prices in case of excess supply (FutureMetrics, 2018). The large difference between contract prices and spot prices, peaking around the end of 2016, can be attributed to an oversupply of pellet production. The narrowing of the gap between contract prices and spot prices in 2017 indicates a balancing of supply and demand. After 2017, demand for pellets for both the electricity as well as the heat market have increased, further improving the position of pellet producers and narrowing the difference between spot and contract prices (FutureMetrics, 2018).

Supply chain costs as calculated were compared with contract and spot prices in recent years (FutureMetrics, 2018). CIF ARA spot price varied between 107 €/t and 137 €/t pellets, as shown in figure 2.10. Total supply chain costs in the analyzed literature, calculated with averages for missing cost components, exceed these prices for respectively 22 and 16 out of 23 studies for the lower and higher points of this range. Most of the pellets exchanged between the United States and Europe are traded under long-term price contracts instead of spot prices. Comparing costs to the contract prices in figure 2.10, which varied between 131 and 182 €/t pellets, could therefore offer a more realistic

insight. This resulted in literature results exceeding prices for respectively 18 and 8 studies. The total supply chain costs as calculated in this paper amount to 136 – 142 €/t pellets for assumed sizes of 50 and 500 kt/a. These costs are more in line with actual pellet prices.

Negative price differences between pellet costs in literature and reported prices could be the result of negative profit margins during the period of oversupply of pellets. In periods of low demand and low pellet prices, it could be beneficial for a pellet plant to temporarily reschedule or postpone debt payments to lower costs. A construction in which capital costs are temporarily lowered could eventually result in higher returns on debt or investment. The annualized capital investment on average contributes about 10% to the supply chain costs. By eliminating this cost component, the average marginal costs in literature reduce to 139 €/t pellets, ranging between 79 and 193 €/t pellets.

Figure 2.10 – Wood pellet contract prices, spot prices and the differences between contract and spot prices for Canada and the United States (FutureMetrics, 2018)

2.3.5. Total supply chain costs

Based on the work in this study, an overview of the most likely supply chain costs was created. These results were as much as possible calculated based

on market data, supplemented with results from the literature review. Costs for feedstock were based on the US EIA data, resulting in a cost saving for the small plant using sawmill residues, see figure 2.11. Feedstock transport was also calculated to be cheaper for the small plant, adding up to increased costs of 18 €/t pellets for the large pellet plant for delivered feedstock. Pelletizing costs were calculated to be higher for the small pellet plant compared to the large pellet plant, resulting in lowered costs of 12 €/t pellets for the large pellet plant. Transport of pellets is more cost efficient for large pellet plants, based on the assumption that large pellets can utilize rail transport and larger ships, resulting in savings of 7 €/t pellets. Across the entire supply chain, the costs calculated for the small-scale pellet plant amount to 143 €/t pellets, which is 6% higher than the 135 €/t pellets for the large-scale pellet plant. These impacts are highly site specific, varying with feedstock availability and transport distance to end users. The results for the locations of existing pellets plants show an impact ranging between a cost saving of 38 €/t and a cost increase of 31 €/t for a large compared to a small plant. Whereas increasing the size of pellet plants could save pelletizing costs it would also result in increased feedstock supply areas and feedstock transport costs.

Certain cost components are quite sensitive to supply chain design assumptions. As can be seen in figure 2.12, the lowest and highest values for transport costs of feedstock and pellets for all pellet plant locations analysed in this study create a large uncertainty. The costs for feedstock for individual pellet plants are highly dependent on local opportunities. Feedstock cost data used in this study is considered to be a reliable source of average costs. The assumptions on moisture content however introduce some uncertainty. Costs of pulpwood vary between 48 - 61 €/t pellets for assumed moisture contents between 45% - 55%. Costs of sawdust for pellet production range between 38 - 57 €/t pellets for moisture contents between 30% - 50%. Shipping costs are expected to vary over time with changing market conditions. For the data period assessed in this article, from 2006 to 2018, calculated shipping costs vary almost a factor 3.

Table 2.5 – Average calculated costs for small-scale and large-scale pellet plants at existing pellet plant locations in the United States, in €2017/t pellets

	Small	Large
Feedstock	46.4	55.6
Feedstock transport	3.9	13.1
Pelletizing	53.0	41.5
Pellet transport	18.8	11.7
Shipping	20.9	12.7

Figure 2.11 – Low and High costs for small-scale and large-scale pellet plants at existing pellet plant locations in the United States, in €2017/t pellets

2.4. DISCUSSION

2.4.1. Uncertainty in literature studies

As shown in this article, the range of uncertainty in literature on wood pellet supply chain costs is significant, with total costs ranging between 88 €/t pellets and 279 €/t pellets. An implication of this factor 3.2 difference is that literature data is of limited use when predicting or calculating supply chain costs of actual supply chains. The uncertainty of individual costs components, notably the feedstock costs, pelletizing costs and shipping costs is larger still than the overall uncertainty.

Part of the cost variation can be understood by normalizing for differences between geographical scope or for differences in supply chain design. There is a significant difference in literature between the costs of distinct types of feedstock, affecting the total supply chain costs. Data on prices paid for feedstock in the US SE shows a smaller difference between prices of pulpwood and sawdust residues. Pellet production is a low margin business, with limited possibilities to compensate for higher expenses. Therefore, pellet plant business cases will have to be based on affordable feedstock. The type of feedstock used depends on local feedstock supply and opportunities as well as local competition. Differences between feedstock costs in different countries, according to literature, are much smaller and are of minor impact on the total supply chain costs.

The uncertainty in pelletizing costs is largest for operational expenses, varying a factor 8.4. This factor responds strongly to regional differences in aspects such as labor cost and electricity cost. The uncertainty in capital costs is smaller, varying a factor 4.8. This uncertainty is still large considering that the market for pellet equipment is well developed and equipment is traded globally. Within this category especially the cost of grinding equipment is uncertain, this could be related to the feedstock used in different case studies, and the significant differences in grinding requirements for different feedstocks. Uncertainty in shipping costs is large, ranging a factor 5.8 between lowest and highest costs. When accounting for transport distance, this uncertainty does not reduce. When also accounting for varying charter rates and fuel costs throughout time, the uncertainty does reduce slightly, however remains large at a factor 3.5.

As this study shows, variation of costs factors in literature is significant. A large part of the variation cannot be attributed to differences in scope, context or supply chain design. Data availability remains an issue. The confidential nature of commercial production of wood pellets also hinders the comparison of specific feedstock, production and transportation costs of various pellet plants.

2.4.2. Impact of supply chain optimization

The impact of different cost reduction strategies when reviewed as stand-alone measures seems very substantial. Lowered feedstock costs in Canada compared to other countries contributes to a cost saving of 6 €/t pellets. The use of sawmill residues could result in 10 €/t lower costs compared to the use of pulpwood. Cost savings because of site selection could amount to 10 €/t for the transport of feedstock to pellet plants and 40 €/t for the transport of pellets to export ports. Economies of scale result in 14 €/t lower pelletizing costs for a large pellet plant compared to a small pellet plant. Shipping costs of pellet transport in larger, Supramax, ships are 5 €/t lower than transport costs using smaller, Handysize ships. As explained in section 2.2.6.4. using Supramax ships is only cost effective for large pellet plants. The combined supply chain savings resulting from optimization strategies are significantly smaller because of various trade-offs in cost components. The impact of pellet plant size on total costs is relatively small, with total costs of 143 €/t for a small pellet plant and 136 €/t for a large pellet plant. This is the result of a combination of cost reductions and increases for separate components. A large pellet plant would benefit from cost savings of 7 €/t on pellet transport, excluding additional investments needed to connect to existing rail infrastructure, and 8 €/t on shipping compared to a small one. This is completely offset by the 9 €/t increased costs of feedstock transport. Economies of scale result in a pelletizing cost reduction of 12 €/t for a large pellet plant. On the other hand, larger plants are more likely to require the use of relatively expensive feedstock such as pulpwood, resulting in a feedstock cost increase of 9 €/t. Trade-offs between various cost components show the complexity of supply chain cost optimizations. Appendix A.7 shows the results of cost calculations for small and large pellet plants for the locations of existing pellet plants. The differences between the pellet plants are only the result of different transport costs of feedstock and pellets, pelletizing and feedstock costs were kept constant for all pellet plants. These results show that the large variation in impact for individual pellet plants.

2.4.3. Feedstock market trends

In the US SE, forests are predominantly privately owned. The average land owner has a relatively small piece of land, with tree plantations sometimes considered an insurance or safety deposit instead of a source of continuous cashflow. Pellet mills will usually procure feedstock through short-term contracts, effectively continuously trading on the regional wood market. Market prices of feedstock depend on demand and supply, not only of pellets but also of the wood and paper market in general. Removals for pellet consumption make up a modest percentage of the wood market, 3% of total pine pulpwood removals in 2014 in the Atlantic and Gulf region, 15% of hardwood removals in the Atlantic region and negligible amounts of hardwood in the Gulf region (Forest2Market, 2015). Added demand for pellet consumption has had an assumed impact on the wood market and has contributed to regional increased pulpwood prices. Still, feedstock price changes in the US SE region are thought to be driven more by weather events, supply restrictions and the demand of non-pellet consumers (Forest2Market, 2015). The main driver of lumber prices in the US SE has historically been the US housing market, with new housing starts driving lumber requirements (Forest2Market, 2018).

Regional or local timber feedstock costs are likely impacted by changing demand patterns. The availability of feedstock directly impacts the costs of feedstock, transport and processing, and should therefore be a very important criterium in site selection processes. The strong economic growth in the US in recent years is expected to result in increased domestic demand for timber, for instance for housing starts and wood products. At the same time, the pellet demand in Europe and other world regions is increasing (Canadian Biomass, 2019). This increased demand for wood resources from the United States could result in increased feedstock costs. Should pellet production increase significantly, supply chain conditions are likely to change. In the United States, pellet plants producing for the export market are currently located close to export ports. Increased pellet production is expected to result in more competition for feedstock and increased feedstock prices. Additional feedstock demand could shift pellet production to more inland regions, resulting in increased costs of pellet transport. Future research

should focus on analysing the impact of increased pellet production on regional production shifts, and the effects this has on supply chain costs and sustainability implications.

Increased timber production could benefit pellet production. Pellets are often produced from lower cost feedstock such as sawdust, shavings or chips. Increased lumber production will result in higher availability of residues, which could result in lower prices for pellet feedstock. A growing pellet market creates other cost saving opportunities. Increased and more continuous production would enable the use of large bulk carriers such as Panamax sized vessels. If increased pellet production results in commoditization, this would allow for more cost-efficient bulk transport through hub-and-spoke based terminals.

2.5. CONCLUSION

Supply chains cost components in literature vary considerably, even for similar design assumptions such as the production country and type of feedstock used. Optimization strategies analysed in this paper result in trade-offs between cost components and impacts vary strongly depending on the pellet plant location. Costs of feedstock transportation to pellet plants varies between 9 and 54 €/t pellets depending on the locations. Calculations based on actual prices paid for feedstock by US pellet plants, for roundwood/pulpwood and sawmill residuals, result in 8 €/t pellets higher costs for pulpwood. Using residues instead of pulpwood furthermore could save an additional 3 €/t pellets in reduced capital costs for grinding and drying equipment as well as an unquantified amount of operational expenditures. Averaged over all locations analysed in the US SE, the calculated impact of economies of scale vary between a cost penalty of 46 €/t and a cost saving of 22 €/t pellets for larger pellets plant. Generalizing results based on similar supply chain design will likely introduce large errors. Cost optimization strategies must be tailored to specific pellet supply chains.

Analysed supply chain costs generally exceed spot prices and contract prices as paid by pellet consumers in recent years. The increasing pellet production in the Southeast United States, however, indicates that the industry

is generating enough revenue to remain a good business opportunity, suggesting an overestimation of costs in literature. This could be caused by the use of unrealistic input data from outdated sources or because of a misrepresentation of pellet market developments, such as the focus on small pellet plants. This study has incorporated recent market data for cost components where possible, resulting in a more realistic cost overview.

Sourcing overseas biomass for EU ambitions; Assessing net sustainable export potential from various countries

Published in Biofuel, Bioproducts & Biorefining

DOI: 10.1002/bbb.1853; Biofuels, Bioprod. Bioref. (2018)

Thuy Mai-Moulin, Lotte Visser, Kevin R. Fingerman, Wolter Elbersen, Berien Elbersen, Gert-Jan Nabuurs, Uwe R. Fritsche, Inés Del Campo Colmenar, Dominik Rutz, Rocio A. Diaz-Chavez, Axel Roozen, Mathijs Weck, Leire Iriarte, Luc Pelkmans, David Sanchez Gonzalez, Rainer Janssen, Martin Junginger

Copernicus Institute of Sustainable Development, University of Utrecht, Vening Meinesz Building A, Princetonlaan 8a, 3508 TA Utrecht, The Netherlands

International Institute for Sustainability Analysis and Strategy, Darmstadt, Germany and Humboldt State University, Arcata, California, USA

Wageningen University and Research, Wageningen, The Netherlands

International Institute for Sustainability Analysis and Strategy, Heidelberger Str. 129 1/2. D-64285 Darmstadt, Germany
CENER – National Renewable Energy Centre, Sarriguren (Navarra), Spain

International Institute for Sustainability Analysis and Strategy, Darmstadt, Germany

CHAPTER 3

3.1. INTRODUCTION

In recent years, many countries have made efforts to reduce greenhouse gas (GHG) emissions and to become less dependent on fossil energy supply through increasing renewable energy supply (European Commission, 2014; IRENA, 2015). One means of achieving those efforts is to increase the share of bioenergy, and as a result the role of biomass and bioenergy has become increasingly apparent in the energy mix in most EU countries and other developed regions in the last decade. In December 2015, 196 nations agreed to introduce measures and policies to globally reduce GHG emissions and to decarbonise the global economy in the Paris Climate Agreement. As of today, 152 countries have ratified the Agreement in which developing renewable energy sources, including biomass and energy efficiency, will play a key role (United Nations Framework Convention on Climate Change, 2015).

At present, many countries of the world are increasingly deploying and implementing renewable energy options, including bioenergy (REN21, 2016). The European Union (EU) has set a target to collectively reach a share of 20% renewables in the final energy mix in 2020 and at least 27% by 2030. Japan, the largest importer of biomass outside the EU, has set a 22-24% renewables target share for 2030 (Ministry of Economy Trade and Industry, 2016) whilst Republic of Korea, the second largest importer of biomass outside the EU, aims for an 11% share of renewable energy in the overall energy mix by 2035 (MOTTIE, 2015). Globally, biomass is the largest renewable energy source, and will continue to play a significant role in decarbonising the energy system (International Energy Agency (IEA), 2016). Wood pellets, e.g. pre-processed products from various lignocellulosic biomass feedstocks, are increasingly used for power generation in many countries in recent decades, and can provide a stable source of low-carbon electricity. Biomass used for heat has grown more slowly due to limited policy support. Renewable energy in the EU in general, will be increasingly market-oriented and untapped potentials need to be exploited (European Commission, 2014, 2016c; IRENA, 2015; Korean Ministry of Environment, 2014; Ministry of Economy Trade and Industry, 2016).

To safeguard sustainable production and use of solid biomass for bioenergy as identified in various national and regional renewable energy targets, (Ministry of Economy Trade and Industry, 2016; MOTTIE, 2015; REN21, 2016) sustainability requirements are to be applied. Within the EU, the European Commission (EC) issued a proposal for the new Renewable Energy Directive in 2016 to reinforce the existing EU sustainability criteria for bioenergy by extending their scope to cover biomass and biogas for heating, cooling, and electricity generation (European Commission, 2016c). Sustainability requirements of lignocellulosic biomass used for heat and power production are already implemented in a number of Member States such as Belgium, Denmark, the Netherlands, and the UK, the main importers of lignocellulosic biomass in the EU.

The EU is currently the largest producer and net importer of wood pellets (Eurostat, 2017b; Pelkmans et al., 2012). In 2015, 20.3 Mt wood pellets were consumed of which 7.2 Mt were imported. By 2020, EU wood pellet imports from third countries are expected to be in the range of 15–30 Mt (Pelkmans et al., 2012). The EU import of wood pellets from non-EU countries in 2014 mainly came from the United States (US, 59%), Canada (20%), and Eastern European countries (19%) (Granath, 2015). In most scenarios with ambitious climate change mitigation targets, lignocellulosic biomass use in the next decades is expected to increase (International Energy Agency (IEA), 2016; Lamers, Jacobson, & Wright, 2014; Matzenberger et al., 2015; Rose et al., 2014). These scenarios show that by 2030, the main exporting regions will likely be the same as today: US, Canada, and Russia. By 2040, top-down models indicate a broadening of main exporting regions, with an increasing role for Latin America, Oceania, and Africa (Lamers et al., 2014; Matzenberger et al., 2015).

With increasing demand for wood pellets and other lignocellulosic biomass in the EU but also in other parts of the world such as Japan, Republic of Korea, and India, additional domestic and imported resources will be needed. Focusing on domestic but also on new non-EU import regions is rational since this could reduce the energy dependence of the EU on some particular regions, and could help to mobilise unused, sustainably sourced,

and residual resources. This article focuses on sustainable lignocellulosic biomass potentials, particularly residual biomass sources, in non-EU regions that have so far not contributed to the lignocellulosic biomass exports already in place. It follows a bottom-up approach and takes into account sustainability constraints, current alternative local use of biomass, and other local barriers.

Main objective

The main objective of this paper is to investigate six selected prospective international sourcing regions with promising sustainable biomass potentials that may be mobilised and exported to the EU between 2020 and 2030. This investigation includes the following tasks:

- Assessment of sustainable export potentials: an initial review of lignocellulosic biomass potentials in various countries revealed that a number of countries have high potentials of agricultural and/ or forestry residues and land availability for bioenergy crops. Six different case study regions were selected based on data availability and local contact; high expected biomass potentials; promising logistic infrastructure and intercontinental transport; variation of socio-economic and environmental constraints. The six case studies, on 5 different continents, are Kenya, Indonesia, Colombia, Brazil, the US, and Ukraine.
- Analysis of the cost and GHG emissions along the supply chain: Cost supply curves and GHG emission supply curves were generated for wood pellets produced in the six case study regions and transported to the port of Rotterdam, the Netherlands.

3.2. METHODOLOGY

The potentials assessed in this analysis include the technical potentials of lignocellulosic biomass, the sustainable potentials, calculated by including sustainability criteria, the sustainable surplus potentials which takes into account domestic demand in sourcing countries, and the export potentials which are the amount of sustainable biomass that could be available for export to other world regions such as the EU (see Figure 3.1). A general and

comparable assessment approach for potentials was applied in all case study regions, allowing for a comparison of sustainable export potentials, based on similar criteria (Fingerman et al., 2017; U. R. Fritsche & Iriarte, 2018).

To qualify the lignocellulosic biomass that can be mobilised for exports, a number of pre-requisites were formulated (Pelkmans et al., 2017):

- **Sustainable sourcing** is a precondition for all exported lignocellulosic biomass, and for all domestically sourced biomass, the sustainability principles and criteria that are already implemented in the EU are considered.
- **Local demand for both energy and material purposes gets priority over export.** Thus, domestic demand of biomass should be satisfied first before exploring exporting options. In this way it avoids distortion of local markets.
- **Emissions from the entire supply chains of biomass** should lead to substantial chain reduction in comparison to the fossil fuel equivalence.
- **Performance-based sustainability requirements** need to be applied on the entire value chains (including production and logistics) up until the import harbour.

The following section briefly discusses the applied methodology to calculate the potentials, supply chain costs and supply chain GHG emissions (U. R. Fritsche & Iriarte, 2018).

3.2.1. Methodology to calculate potentials

In view of limited time and resources, the first methodological step was the selection of the case study regions with the highest biomass potentials within different countries, and the potential mix of biomass resources to be analysed per region (see Figure 3.1 and Appendix B.1 for more details).

Figure 3.1 - Methodology to calculate the different potentials

In the six case studies, different feedstocks were included, following local opportunities (see Table 3.1). Primary agricultural residues are residues generated in the field during harvesting processes, whereas secondary residues are generated at the processing stage. Primary forestry residues are residues originating from harvesting or forest management practices, such as logging and thinning, typically left behind in either natural or plantation forests. Secondary forestry residues originate from the processing of forest products, and include for instance saw mill residues. Dedicated energy biomass is the production of either energy crops such as switchgrass or miscanthus, or forestry biomass, dedicated to the production of (lignocellulosic) biofuels (B. Batidzirai, Smeets, & Faaij, 2012).

Kenya was the first case study in which the methodology was applied, including an investigation of all types of biomass, agricultural residues, energy crops, and forest residues. This case study however showed very limited potentials from energy crops and forest residues, after which it was concluded that the remaining case studies would focus on the most promising potentials in the respective regions. For the Brazil case study, the availability of agricultural and forestry statistics allowed for the inclusion of both these feedstock types. In Indonesia, more than 50% of the land is covered by natural forests, which are for biodiversity reasons protected. Considering the sustainability risks in Indonesia, only residues from certified palm plantation areas or land under governmental support were included (Facts and Details, 2015). In Colombia, although more than half the land is

covered by forests, the potential for forestry biomass is assumed to be low since most of the forests are biodiversity rich, and protected areas. For this reason, the Colombian case study focused solely on agricultural residues (Elbersen, Diaz-Chavez, & Elbersen, 2016). For the case of the Ukraine, there was access to detailed data on the potential for energy crops (Van der Hilst, Verstegen, Zheliezna, Drozdova, & Faaij, 2014). For other case studies this data was not available. In the US case study, the calculated potential was based on existing practices. By far the largest share of pellets produced in the case study region in the US is produced from forestry residues and forestry products such as roundwood. Therefore the US case study will focus on these residues (Biomass Magazine, 2017a).

Table 3.1 – Feedstocks included in case study countries

		Brazil	Colombia	Indonesia	Kenya	United States	Ukraine
Agri-cultural residues:	Primary	X	X	X	X		X
	Secondary		X	X	X		
Forestry residues:	Primary	X				X	X
	Secondary	X					X
Dedicated energy biomass:	Agriculture						X
	Forestry					X	

In the second step, the technical potential was calculated, which follows the definition of potentials in the Biomass Energy Europe project (Torén et al., 1994), and is defined as the terrestrial biomass considered available under the current techno-structural framework conditions with current technological possibilities (such as harvesting technologies, infrastructure and accessibility, and processing technologies), while also taking into account spatial confinements due to other land uses (such as food, feed and

fibre production, nature reserves). The technical potential (PT) in the different case study regions were calculated using equation 3.1 based on production statistics of agricultural and forestry products combined with residue-to-product ratios (RPR), or from literature on the production of lignocellulosic biomass or residues per hectare.

$$P_T = A_i \times Y_i \times RPR \times E_i \quad \text{Eq. 3.1}$$

where A_i is the crop area of crop i in the case study region, Y_i represents the yield of crop i in the case study region, RPR is the residue to product ratio and E_i is the energy content of crop i in the case study region (LHV).

The sustainable potentials (PS), defined as the share of the technical potentials which meet environmental, economic and social sustainability criteria (Torén et al., 1994), was calculated in the third step. An assessment was made per region and feedstock, based on literature and local expert opinions, of the sustainable land availability and sustainable recovery factor (SRF) of residues and energy crops. By applying restrictions on the harvestable area and removable biomass shares, the sustainable potentials were calculated using equation 3.2. The basic sustainability requirements included in all case studies are closely aligned with the requirements of the Renewable Energy Directive (RED I) (European Parliament, 2013). Additional requirements were included in some case studies based on data availability and relevant local sustainability criteria. The residue to product ratio, energy content per feedstock and sustainable recovery factors used per case study country and feedstock are presented in Appendix B.2.

$$P_S = P_T \times (1 - L_S) \times SRF_i \quad \text{Eq. 3.2}$$

where L_S is the fraction of land excluded because of sustainability criteria (such as high biodiversity areas), and SRF_i represents the Sustainable Recovery Factor of crop i in the case study region, the factor of residues that can be extracted while meeting sustainability criteria.

The surplus potentials (PSS) were calculated in the fourth step. These were defined as the potentials which could be available for export to other regions, after subtracting current and expected future local demand for biomass for

material and energy applications, covering industrial and residential utilization. Based on local expert opinions, the percentage of primary and secondary residues used locally was subtracted from the sustainable potentials to form the sustainable surplus potentials. The local demand in the different case studies is presented in Appendix B.3.

$$P_{SS} = P_S - LD_i \quad \text{Eq. 3.3}$$

where LD_i represents the local demand of crop i in the case study region.

In the fifth step, the export potentials (PE) were calculated, defined as the potentials which could be exported, taking into account requirements such as the availability of transport infrastructure and pre-treatment plants. Lignocellulosic biomass needs to be pre-treated and densified before it can be transported across long distances. This is, amongst others, done to reduce safety risks related to self-heating and microbial hazards, but also to improve handling properties, and reduce the cost and energy requirements of transport. As default pre-treatment technology, pelletization of woody and agricultural biomass was assumed since this is the pre-treatment technology most commonly used for lignocellulosic biomass (European Biomass Association (AEBIOM), 2016). The future pelletization capacity was estimated by analysing current capacities (if any) and growth curves of production capacity in the respective countries and by considering potential capacity growth rates. Acknowledging this requirement, the availability of pellet production facilities was taken into account as limiting factor to calculate the export potential.

$$P_E = \text{MIN}(P_{SS}, CY_P) \quad \text{Eq. 3.4}$$

where CYP is the pelletising capacity in the case study region.

In the final step, to calculate the costs and GHG emissions of exported lignocellulosic biomass, transport routes from case study regions to the EU were designed and calculated. The port of Rotterdam was chosen as import point, because of its central location in the EU and the good port facilities, making it an interesting potential import hub for lignocellulosic biomass energy carriers. Based on the export potentials, the costs of delivering

lignocellulosic biomass to the port of Rotterdam, as well as the emitted GHG emissions were calculated, including feedstock cultivation, pellet production, inland transport and transport to Rotterdam. Cost supply curves and GHG emission supply curves were generated to account for differences between different supply regions and feedstocks.

3.2.2. Supply chain cost calculation

Supply chain costs were calculated using equation 3.5 by taking several components along the chain into account, while combining country specific data and uniform cost assumptions.

$$C_D = C_P + C_{Tdf} + C_{Pt} + C_{Tdp} + C_{Ti} + C_H \quad \text{Eq. 3.5}$$

where C_D is the total production cost of biomass, C_P is the cost of feedstock production, C_{Tdf} is the cost of domestic transport from the fields to pre-treatment facilities, C_{Pt} represents the cost of pre-treatment, C_{Tdp} is the cost of domestic transport from pre-treatment facilities to export location, C_{Ti} is the cost of international transport from export locations to the port of Rotterdam, and C_H represents the cost of handling and storage.

Most of these cost parameters were taken from literature. In some cases, field research and interviews with experts provided country specific parameters. The cost factors used in the different case study countries can be found in Appendix B.4.

Transport cost to the pre-treatment facilities (C_{Tdf}) was calculated by including road transport over 50 km. The production cost of pellets (C_{Pt}) was based on Ehrig et al. (Ehrig et al., 2014) Cost of some consumables such as spare parts were included based on Pirraglia et al. (Pirraglia et al., 2010) The cost structure of pre-treatment is assumed to be similar in the different case studies. In most of the case study countries, there is no large-scale pellet production yet; making it difficult to assess potential cost, therefore, the decision was made to base the cost for all countries on the same data sources. A number of country specific cost factors are included in all case studies, such as the cost for electricity, labour, and feedstock. In case of the Colombian case study, data limitations prevented the calculation of cost

based on country specific factors. Instead, total pelletization costs were assumed based on the other case studies.

Cost of transporting pellets to export ports was calculated by taking the distance from weighted centres of regions to export ports. For most case study regions, this was done based on a first-level administrative division (typically state-level); for the US, this was done on a second-level basis (i.e. county level). Road transport was assumed in most of the case studies, since rail networks are often not or very poorly developed. For the Ukraine and the US, rail transport is a viable option for some locations. For these two countries, it was possible to calculate the transport cost in more detail by making use of the existing BIT-UU model (Hoefnagels, Resch, Junginger, & Faaij, 2014). The BIT-UU model is a GIS-based biomass transport model with an intermodal network structure of road, rail, inland waterways, short sea shipping in Europe, and ocean shipping. The model combines linear optimization of the allocation between supply and demand nodes with global input data on cost for transport of lignocellulosic biomass. The cost of international transport (CTi) was calculated by making use of the BIT-UU model where possible. For countries that are not included in this model, these costs were calculated through a web-based sea freight calculator (See Freight Calculator, n.d.).

3.2.3. Supply chain greenhouse gas emissions calculation

To determine GHG emissions for each stage of the supply chain, global warming potentials were estimated from electricity, fuels, and materials use. The calculation of GHG emissions closely followed the EC approach (European Commission, 2014). When actual data were not available, default values provided by the EC and other references were applied (European Commission, 2014; Jacopo Giuntoli, Agostini, Edwards, & Marelli, 2015).

The GHG emissions were calculated according to equation 3.6

$$E = E_{ec} + E_s + E_p + E_{at} + E_{it} \quad \text{Eq. 3.6}$$

where E_{ec} is the emissions from cultivation (applied only for energy crops), E_s represents the emissions from nutrient replacement (including

emissions from production and use of fertilizer to compensate for biomass removal, which leads to the emissions of GHGs via chemicals use), E_p is the emissions from pre-treatment (including chipping, drying and pelletization), E_{dt} is the emissions from domestic transport, and E_{it} is the emissions from intercontinental transport to the Port of Rotterdam.

Analysis of potential GHG emission savings was made by comparing emission avoidance in relation to production of electricity and heat from fossil resources. In order to compare the GHG emission savings with fossil fuel alternatives, the RED I was used. Where forest or agriculture residues are considered, the required GHG emission savings in the EC are, in principle at least 70% compared to fossil fuel alternatives. However, lower savings can occur for short-rotation coppices (e.g. eucalyptus in tropical countries), in case of low fertiliser use in agriculture, and when natural gas is used for drying pellets (Jacopo Giuntoli et al., 2015). It is therefore considered to be good practice for existing bioenergy installations to achieve GHG emission savings of at least 70% compared to the fossil fuels comparators. This equates to lifecycle emissions of less than or equal to 12.8 g CO₂eq./MJel for electricity, and 34.1g CO₂eq./MJel for generated heat. In the more ambitious EC pathway, the GHG emission savings should be 80% lower, equal to 10.6 gCO₂eq./MJel for electricity and 28.4g CO₂eq./MJel for generated heat in a combined heat and power plant (CHP) (Biograce II, 2015; Jacopo Giuntoli et al., 2015).

3.2.4. Scenario development

One of the key aims of the analysis presented in this paper was to investigate future markets and opportunities for sustainable lignocellulosic biomass feedstocks. This depends on aspects such as technological and economic developments and changes in climate, energy, agricultural and business policies. To anticipate the possible changes in biomass trade, and market developments, two scenarios were designed for 2020 and 2030.

The Business As Usual (BAU) scenario was based on a continuation of historic and current trends. The BAU scenario was built on current and expected policies in climate and environmental policies in the sourcing regions. Historic feedstock production trends in most countries show an increase in production area and yield. These trends were assumed to continue in the BAU scenario.

The sustainable potential calculations were based on current feedstock extraction rates, taking into account existing sustainability restrictions. The domestic demand for different feedstocks was estimated using statistics where possible, and in consultation with local field experts otherwise. The BAU scenario took into account trends in local use, for instance local use of residues for bioenergy production. Continuation of pellet production capacity growth trends was applied in the BAU scenario where possible. In case the growth of production capacity was unclear, growth of pellet plant capacity was based on worldwide growth estimates.

The High Export (HE) scenario explored options under which larger volumes of sustainably produced biomass might become available for export. These may include an assessment of possibilities to increase the yields of biomass production, of additional land availability for biomass production and of reduced local demand for biomass. Agricultural and forestry production was assumed to follow optimistic growth trends, including improved yields as a result of better management practices and higher fertilizer use.

For the calculation of the surplus potential, the lower ranges of expert assessment of local demand of feedstock were used. The growth rates for pellet plant capacity were assumed to be higher in the HE scenario. As a maximum growth rate, the recent historic growth rates in the US were taken, which showed a very high increase from 160 ktonne in 2006 to 4,800 ktonne in 2013 (Southern Environmental Law Center, 2015). The growth rates in specific case study countries were modelled to the US growth rates starting from the period with similar total production volume.

3.2.5. Case study assumptions and specific adaptations

The calculation of potentials in each case study was largely determined by availability of statistical data, literature, and access to local experts. Assumptions were made based on literature and expert consultations. In some case studies, it was necessary to diverge from the general methodology due to data limitations or case specific situations that justified an adapted, more suitable approach. The most important case specific adaptations to the general methodology will be discussed below.

In Brazil, the technical potential was restricted by land suitability, consisting of technical and non-technical constraints, according to Verstegen, Van der Hilst & Woltjer (Verstegen et al., 2016). This entailed that certain restrictions were already partially included in the additional technical potential towards 2030. This restriction had a larger effect in the HE scenario considering the assumptions of larger increases in yields and agricultural areas.

In Colombia, the calculation of the sustainable potential fully excluded oil palm trunks and leaves, as experts deemed collection as prohibitively costly. This could limit the sustainable potential by more than just the residue fraction needed to cover sustainability criteria. Furthermore, since reliable information about pellet production capacity was not available, pellet plant capacity was not considered as a limiting factor (Elbersen et al., 2016). For this reason, the only results shown for Colombia were the surplus potentials, and not the export potentials. Cost supply curves were calculated based on the surplus potentials.

In Indonesia, the yield of agricultural crops in the HE scenario was assumed to be higher than in BAU, and increased over time until 2030. At the same time, the rate of residue removal was supposed to increase, since fewer residues are needed for soil protection and to maintain soil organic carbon levels as a result of improved crop management (Boer et al., 2012).

In Kenya, just as in the Colombia case study, pellet production capacity was not considered as a limiting factor since data about pellet production was not available. Similarly, cost supply curves were calculated based on surplus potentials.

In Ukraine, agricultural production has varied strongly in the past years. Future investments in the agricultural sector in Ukraine were uncertain due to the difficult political and economic situation resulting from the Ukrainian Revolution of February 2014. The assumption was made that the total agricultural production volume remains unchanged both in the BAU and the HE scenario. The amount of residues needed to maintain SOC levels was modelled by applying the Rothamsted Carbon model to calculate the soil carbon balance (Coleman et al., 1997; Farina, Coleman, & Whitmore, 2013; Jenkinson & Coleman, 2008). The model input was taken from the MITERRA-

EUROPE model. The database used in this model is on NUTS 2 level and includes relevant data such as land use, crop type, soil type, and topography (Velthof, Oudendag, & Oenema, 2007). Data on soil organic carbon levels was retrieved from the European Soil Database (European Soil Data Centre, 2013). In the HE scenario, the assumption was made that the residue removal rate increases gradually until 2030 as a result of improved management practices and the application of fertilizer, except for those regions in which the removal rate is 0% (Gelten, 2010; Smeets & Faaij, 2010; Van der Hilst et al., 2014). In Ukraine, a significant potential for dedicated energy crops was assumed, based on a study of Van der Hilst et al. (Van der Hilst et al., 2014). This study analysed the bioenergy production potential in Ukraine as well as related GHG emission balances of land-use change. In this study, the demand for food and feed was calculated in a BAU and progressive scenario, in 2020 and 2030, as well as the land required to meet this demand. The bioenergy potential was calculated based on the production of switchgrass on land still available after accounting for this existing demand.

In the US, the focus is on the South East, which is the most important pellet exporting region within the US (Hoefnagels, Searcy, et al., 2014). Pellet production was based on forestry feedstocks, among which logging residues, mill residues, and pulp logs, making up only a small percentage of the total wood market (Fletcher, 2015). By applying sustainability criteria only for wood used for energy purposes, the risk of leakage exists; wood sources meeting the criteria can be (re-)allocated to biomass purposes, whereas non sustainable sources could be used for other purposes not covered by sustainability schemes (Fingerman et al., 2017). This effect is to be avoided in order to ensure overall sustainable harvest practices. Therefore, a slightly different approach was used in the US case study. In the calculation of the sustainable potentials, only the biomass used for pellets was limited by the sustainability criteria. In the calculation of the surplus potential however, the assumption was made that the entire domestic demand for biomass, that was the existing wood market, must also meet the sustainability criteria (Fingerman et al., 2017). The availability of pellet equipment was not included in the calculation of the export potentials. The pellet market in the US was well developed; large historic growth rates have shown that the industry was capable to respond quickly to market developments. Therefore, the

pellet plant capacity was considered to develop in response to market developments, and was not included as a limiting factor in the calculation of export potentials (Fingerman et al., 2017).

3.2.6. Data collection

Data for the calculation of the different potential was gathered from a combination of sources. Statistical data on agricultural and forestry production was combined with data from literature, for instance on sustainable restriction. As much as possible regionally specific data was used to calculate the different potentials. Data from literature was, where possible, supplemented by assessment from experts in the case study regions.

The technical potentials in all case studies were based on production statistics on a state level, or higher resolution. The sustainable potentials were in some cases based on regionally specific input, such as in the Ukraine and US case studies. In other case studies, such as in the Brazil study, data availability made it necessary to use default values for the entire case study. Data on the domestic demand of different crops was largely based on personal communications with local experts, and was assumed to be similar for all regions.

3.2.7. Sensitivity analysis

The calculation of potentials, costs, and GHG emissions in the different case studies involved the making of several assumptions and the use of uncertain data. The two different scenarios reflect the uncertainty in the future development of biomass potentials, costs, and GHG emissions. To furthermore analyse the impacts of data uncertainty, sensitivity analyses were carried out for the supply potentials, supply costs, and supply GHG emissions by varying several factors that strongly impacted the calculations.

The preferred method of obtaining minimum and maximum values for selected parameters was considered from available literature. In case no data could be found in literature, a three tier uncertainty system was applied with low, medium and high levels of uncertainty reflected in different uncertainty ranges of 10%, 25%, and 50% for export potentials and costs; and

of 5%, 10%, and 20% for GHG emissions. The uncertainty for GHG emissions were assumed lower because in practice, there is less fluctuation in the three impacting factors used for GHG emission calculation (nutrient substitution, local transport and electricity use). In order to assess the level of uncertainty, interviews with experts, where possible from the specific case study regions, were used.

3.3. RESULTS

First, to show the results of applying the different methodological steps to calculate the export potential, the results from one case study are highlighted in section 3.3.1. To this end, the case study of Brazil was considered to be a good example for several reasons. Most importantly, the availability of locally collected data allowed for the application of all the steps of the general methodology. Furthermore, the domestic use of biomass, specifically for bioenergy production, was increasing in this country. This results in clear differences between the scenarios and timelines as the domestic demand were increased. The situation in Brazil therefore evidently shows the effect of applying different constraints, while varying these constraints in different scenarios.

In section 3.3.2, an analysis of the overall results of all the six case studies are shown, focusing on the differing export potentials under different timelines and scenarios, as well as the respective cost supply curves and the greenhouse gas supply curves.

3.3.1. Results from Brazil case study

The technical potentials of agricultural and forestry residues show the importance of sugarcane residues, especially from São Paulo state, accounting for 43% of the total technical potentials (see Appendix B.5 for a map of all included states). The sustainable potentials were calculated by applying a sustainable recovery factor (SRF); see equation 3.2. SRF values for Brazil were obtained from literature research, and for sugarcane, cross-checked through interviews with local experts (Roozen A, personal communication) (AEBIOM, 2014; Briggs, 1994; Carvalho et al., 2017; de Paula Protásio et al., 2013; Gavrilescu, 2004; Graham, Nelson, Sheehan, Perlack, &

Wright, 2005; Lindstrom, 1986; Papendick & Moldenhauer, 1995). The SRFs obtained from literature were derived from field experiments investigating the effects of residue removal on soil nutrient balance, soil erosion rates, and soil organic carbon percentages. The chosen SRFs represent a removal rate at which these sustainability indicators are not negatively impacted. The SRFs are impacted by local conditions, such as soil type, slope and climate, there was however no data available on geographically specific SRF factors. To overcome this problem, a default SRF was used for the entire case study region, drawing from literature on sustainable residue removal in Brazil (Carvalho et al., 2017) This default can be considered conservative, case studies on the removal of rice, soybean and corn residues in Brazil showed removal rates that are higher than the default removal rates used in this study (Denadai, Guerra, Bueno, & Lancas, 2013; Leitão, Perez, Trentin, Sisti, & Nunes, 2012; Mansur, 2014).

The residue recovery limitation did not apply to processing residues such as bagasse, rice- and coffee husks, and orange peels, which can be 100% utilized. The sustainable recovery factors of the different feedstocks can be found in Appendix B.2 since the use of sugarcane bagasse is not restricted by sustainability criteria. The relative contribution of sugarcane to the sustainable potentials was even larger, with sugarcane bagasse accounting for 56% of the total potentials (see Figure 3.2).

Figure 3.2 shows the sustainable and sustainable surplus potential of the different residues in Brazil. Sugarcane bagasse is predominantly used already for the production of local electricity and heat. Currently 90% of the bagasse is used locally to provide electricity and heat to sugarcane mills, and excess electricity to the power grid (A.Roozen, personal communication). The demand for local residues used to produce electricity was expected to increase significantly based on expected increased contribution of bioelectricity to Brazil's energy needs from 3% to 18% (UNICA, n.d.).

Considering this strong pull towards local use of sugarcane bagasse, the assumption was made that the remaining residues that can technically be harvested will, in the future, be used locally as well. The additional assumption was made that residues that do not meet the quality standard required for local production of electricity or heat, will neither meet the criteria required

to produce pellets, and are therefore considered unavailable. Therefore the local use of sugarcane bagasse was assumed to increase to 100% in the BAU 2030 scenario.

In the past, sugarcane straw has predominantly been burned in the field. In recent years, federal governments, with São Paulo being the first, have banned this practice to limit damage to the environment and surrounding villages (SugarCane, n.d.). The common practice changed to piling up the sugarcane stalks in the field. Partial straw removal from the field for additional electricity production has begun to take place. These trends, as considered by local experts, will likely result in increased local use of residues towards 2030 (Cervi, Lamparelli, Seabra, Junginger, & Van der Hilst, 2019). To account for the uncertainty in these developments, the domestic demand was considered varying: demand was assumed to increase from 0% in the current situation towards 50% in the BAU scenario, and 25% in the HE scenario in 2030. After considering the domestic demand for residues, the total sustainable surplus potential was reduced to just 17% of the sustainable potential in 2030 in the BAU scenario, and 31% in the HE 2030 scenario.

The last limitation applied was the availability of pellet plant capacity needed to densify the residues. The current potentials were calculated based on the capacity of existing plants (Bioenergy International, 2014). The capacity in the case study regions was, at the time of investigation, 630 ktonnes per year. A capacity factor of 80% was used to calculate the actual pellet producing capacity. This is considered optimistic, since in reality, pellet plants often run at lower capacity because of supply limitations (Wood Pellet Association of Canada, n.d.).

As data about expected growth rates of pellet production capacity was not available, estimation about future capacity in the BAU scenario was based on world-wide pellet capacity developments expected between 2015 and 2023 (KMEC Engineering, n.d.). This growth was expected to continue until 2030. For the HE scenario, the assumption was made that the pellet plant capacity increases with growth rates modelled after historical pellet capacity growth in the US (Southern Environmental Law Center, 2015). This results in an annual export potential of 71 PJ in the BAU scenario, and 411 PJ in the HE scenario in 2030.

The newly added pellet capacity was assumed to be divided according to the surplus potential in each state. Until 2020, pellets were assumed to be produced from forestry residues; the sustainable surplus forestry potential exceeds the pellet plant capacity. After 2020, agricultural residues were assumed to make up a share of 30% of the additional pellet production capacity, increasing in some states where there is a limited supply of forestry residues.

Figure 3.2 - Technical potentials of current scenario, per feedstock and region; technical, sustainable and sustainable surplus potentials of current scenario in Brazil

3.3.2. Limiting factors

The extent to which specific constraints limit the various potentials varies between case studies, reflecting amongst others differences in sustainability concerns, domestic uses of biomass, and the maturity of wood pellet production markets. In this section, the main limiting factors per case study country are discussed.

In Brazil, the potentials were limited by the local use of sugarcane residues for the generation of heat and electricity, corn stover, and cassava straw for cattle feed, rice, and coffee husk for chicken bedding, and oranges peel for citrus pulp pellets (A. Roozen, personal communication) (Citrosuco, 2015; Da Silva & Chandel, 2014; Empresa de Pesquisa Energética, 2014; Ferreira-Leitão et al., 2010; Mayer, Salbego, Almeida, & Hoffmann, 2015; Missagia, 2011). A lack of railway infrastructure increases the cost of pellet export and the export potentials were limited by the lack of pre-treatment technology, the existing pellet capacity was very small in Brazil and the focus was on ethanol instead of pellets (Bioenergy International, 2014).

In Colombia the potentials were reduced by the use of palm residues for compost production and the use of sugarcane bagasse for co-generation to generate process energy in sugar and ethanol mills. Poor infrastructure limits the mobilization of field residues, increasing the cost of transporting pellets from inland areas. High mineral and moisture content of residues limits the production of pellets. A lack of pellet plant capacity limits the export potentials in general, no pellet plants exist in Colombia as of yet and data on pellet capacity development was lacking (Elbersen et al., n.d.).

The potentials from Indonesia were limited by the local use of palm residues for electricity production at palm oil mills and the use of palm fronds as fertilizer at palm plantation sites. Sustainability concerns of expanding palm plantation areas, especially at areas not under governmental support, results in excluding these areas from the sustainable potentials. No pellet plants existed in the investigated regions in Indonesia, limiting the export potentials. At the same time, capacity was assumed to grow at a fast pace, considering the possibility to integrate pellet production in existing and growing oil mills (Boer et al., 2012).

In Kenya, avoiding soil erosion and nutrient depletion is an important issue, resulting in a low SRF. The use of agricultural residues for cattle feed, and forest residues for cooking, reduces the surplus potentials. Large distances from production regions to the Mombasa port, and poor quality of infrastructure, increases the cost of exporting pellets. No pellet plants existed in Kenya, and no data was available on pellet capacity development, limiting the export potentials (Bothwell Batidzirai, 2013a; Kenya Sugar Board, 2013; Kibulo, 2007).

In some regions in Ukraine, the SRF factor is low. In many regions, 100% of the maize straw can be removed, with stubbles, chaff and belowground carbon being sufficient to maintain SOC levels. Removal levels for barley straw are however generally low, below 45%. Levels for rapeseed, sunflower and wheat vary between 0% and 100% per region. Historic growth rates of pre-treatment capacity were low, therefore pellet capacity was assumed to remain a strong limiting factor (Bioenergy, 2014).

In the US, sustainability requirements were considered to apply to the entire US wood market, forming the main limiting factor. This in order to avoid nutrient depletion and biodiversity loss, and to avoid unsustainable shifts in harvest practices (Fingerman et al., 2017).

3.3.3. Combined case study results

Results show a very large technical potentials of lignocellulosic biomass supply in 2030, especially in the form of energy crops from Ukraine and agricultural residues from Brazil, as seen in Figure 3.3. Due to several restrictions applied in this study, the sustainable surplus and export potentials were considerably smaller. In the BAU scenarios, the local demand for biomass formed the largest restricting factor, with the pre-treatment capacity being an important limitation as well. In the HE export, the limited increase over time of pre-treatment capacity formed the main limitation.

The overall export potentials increase strongly in the HE scenario towards 2030, due to the high assumed annual growth rates of pellet production capacity. In 2030 in the HE scenario, Brazil contributes 27% to the total potentials, Indonesia and the US each 30%, and Ukraine 13%. Since the export potentials could not be assessed in the case studies of Colombia and Kenya, these countries are left out of consideration.

Figure 3.3 - Technical, sustainable, sustainable surplus, and export potentials in the different case study countries - BAU 2030 and HE 2030

3.3.4. Cost Supply Curves

When looking at the cost supply curves (Figures 3.4 and 3.5), there is a large difference between the case studies. The least expensive lignocellulosic biomass can be imported from the Ukraine, the cheapest residues being 6.4 €/GJ. Delivery cost from Indonesia (from 11.8 €/GJ) and Brazil (from 10.8 €/GJ) are significantly higher. The cost of lignocellulosic biomass from the US in the HE scenario starts off reasonably low at 7.8 €/GJ and stays under 15 €/GJ for 400 PJ (about 90% of the total export potential) (Fingerman et al., 2017). The steep increase in costs towards the end of the US cost supply curve is the result of the modelling of cost of forest thinning from areas with poor or no road access. Increased "distance to road" results in very expensive biomass, which in reality would not likely be harvested, but is still available for use (Fingerman et al., 2017; Perlack & B.J.Stokes, 2011). The US case study furthermore includes incremental costs for additional feedstock supply, resulting in a sharp increase in feedstock cost towards the maximum supply potential as identified in this case study.

Figure 3.4 - Cost supply curves of export potentials (Brazil, Kenya, Ukraine - solid lines) and sustainable surplus potentials (Colombia, Kenya - dashed lines) delivered to the Port of Rotterdam in the BAU 2030 scenario

Figure 3.5 - Cost supply curves of export potential (Brazil, Kenya, Ukraine, United State - solid lines) and sustainable surplus potential (Colombia, Kenya - dashed lines) delivered to the Port of Rotterdam in the HE 2030 scenario

3.3.5. Greenhouse gas emission curves

The calculations of GHG emissions show that average emissions from the US are the lowest, emissions from Kenya, Ukraine, Brazil, and Colombia are higher but the highest values are for Indonesia (Figure 3.6). In the Colombia case study, the emissions of pre-treatment were assumed to be zero since residues were considered to be used for the production of energy for plant operation and maintenance activities, which resulted in no GHG emissions. In practice, there are still emissions due to diesel use for machinery and the use of electricity from the national grid in the pre-treatment plants. In order to easily compare the results with other case studies, a GHG emission factor from electricity production was taken into account in Colombia, following the BioGrace II default values (Biograce II, 2015).

Figure 3.6 - Average greenhouse gas emissions of lignocellulosic biomass supply chains in different case study countries

With shorter intercontinental transport routes to the import harbour of Rotterdam, Ukraine has the lowest international transport emissions. Indonesia has the highest transport emissions, due to the long transport distance to the EU. The emissions of local transport are highest in Kenya and Brazil. In both countries, the state of infrastructure was poor, and the distance

between sourcing regions to the export harbours was large. Emissions from pre-treatment plants are highest in the US and Ukraine, mainly due to the high electricity emission coefficients in those countries. Emissions from nutrient substitution are highest in Indonesia and Ukraine due to higher fertilizer use to substitute the removed residues for soil organic carbon. The US is the only country where cultivation and harvesting are taken into account, since the collection of forest residues is a well-regulated activity in which emitted GHG emissions are recorded.

In both BAU 2030 and HE 2030, the potential supply from all the case studies meets the current 70% and proposed 80% cut-off reference for heat as set by the current and revised RED (34.1 and 28.4 kg CO₂/GJ respectively in co-firing heat and power plants). When using the current 70 cut-off reference for electricity (12.8 CO₂/GJ), as defined in the current RED (European Commission, 2016c), all potentials from Indonesia and most potentials from Kenya, Brazil are above the limit of GHG emission reduction for heat production, as can be seen in Figure 3.7. When using the proposed 80% reference for electricity (10.7 CO₂/GJ) in the revised RED, 80% of total potentials are not qualified to be exported to the EU. The share of the potentials which does not meet this threshold will not likely be mobilised to the EU in the future if strict GHG emission reductions are applied.

Figure 3.7 - Greenhouse gas supply curves of export potential (Brazil, Kenya, Ukraine, United State - solid lines) and sustainable surplus potential (Colombia, Kenya - dashed lines) delivered to the Port of Rotterdam – BAU 2030 (left) & HE 2030 (right)

3.3.6. Sensitivity analysis

Sustainable surplus potentials

The uncertainty analysis was based on the sustainable surplus potentials, since this was assessed for all the countries. The export potentials as calculated in this study depend solely on the pelletization capacity as limiting factor and would therefore not show the impact of varying parameters. The three factors that have the highest impact on the sustainable surplus potential, the RPR, the SRF, and the LD were varied in this sensitivity analysis.

For the Ukraine case study, the RPR was varied with the highest and lowest value within Europe (European Commission, 2016b), resulting in a variation between 81-137%. For the SRF, a lower value was used based on a EC report, resulting in potentials of 91% of the reference potentials (European Commission, 2016b). For the LD, as lower end of the range, the reference value was used combined with the assumption that residues are traded across regions. The higher end of the range uses an alternative estimate from the EC of 14.5% instead of 31%, resulting in a variation between 87-133% (European Commission, 2016b).

The RPR variation in Brazil for all crops was modelled after data of the range of Cassava availability, between 144 and 257% of the product (Ferreira-Leitão et al., 2010). The SRF in Brazil was highly uncertain, as referenced by a variation of corn stover removal in literature between 20% and 100% (Regis et al., 2013; Wilhelm, Johnson, Hatfield, Voorhees, & Linden, 2004). Alternative sources also provided data on sugarcane tops and straw SRF values of 65% of the reference value and soybean straw SRF values of 144% of the reference values (Portugal-Pereira, Soria, Rathmann, Schaeffer, & Szklo, 2015). To reflect this large uncertainty, a variation of 50% for non-process residues was used. The availability of residues varied with 35% based on assumption used by Portugal-Pereira et al. (Portugal-Pereira et al., 2015).

For the US case study, it was not possible to assess the data uncertainty in literature, since the parameters were the result of several overlapping, spatially explicit datasets. It was not possible to use literature to assess the data uncertainty on this detailed spatial level. Since the pellet production industry is well established in the US, the uncertainty of residue availability as well as the demand for paper, paperboard and panels is considered low. Therefore the RPR and LD were varied with 10%. The SRF was considered somewhat more uncertain, considering the difficulties of determining local sustainability concerns based on a high-level spatial analyses. As a result, the SRF was varied with 25%.

In Colombia, the RPR and SRF values of palm and sugar cane residues were undetermined as residues were estimated based on the total quantity per ha in Colombia. Those values were considered based mainly on the studies of palm residues in Indonesia and Malaysia, with ranges of 82-127% and 74-112% respectively. Local demand was estimated based on the project field interviews with a range of 86-114% (Elbersen et al., n.d.).

In Kenya, interviews with representatives of Ministries of Agriculture and Energy as well as meetings with farmers in various regions of the country have resulted in an average RPR range of 82-127%; LD range of 77-136% (Mai-Moulin, Dardamanis, & Junginger, 2016). Regarding the SRF, no data was available for the Kenyan case study. However, SRF references were taken into considerations from Mozambique and South African data with similar

local conditions of agricultural cultivation and harvesting (Bothwell Batidzirai, 2013a; Kenya Sugar Board, 2013; Van der Hilst, Versteegen, Karssenberg, & Faaij, 2012).

For the Indonesian case study, the average RPR was estimated based on studies of palm oil residue potentials for both Indonesia and Malaysia (of similar climate and agricultural conditions) (Kheang, Subramaniam, & Ngatiman, 2012; Paltseva, Searle, & Malins, 2016), resulting in a variation between 80-124%. Regarding the SRF value, a range of 74-112% was applied based on the studies on palm oil residues used in both Indonesia and Central Kalimantan (Paltseva et al., 2016; Suharno, Dehen, Barbara, & Ottay, 2013). Based on studies on Malaysian local use of palm residues, the LD was varied between 94% and 115% (Abdullah & Sulaim, 2013).

The combined effect of varying the parameters on the potentials in the BAU 2030 and HE 2030 scenarios is shown in Figure 3.8.

Figure 3.8 - Total surplus potential uncertainty ranges of the six case studies – based on the BAU 2030 potentials (left) and HE 2030 potentials (right)

Costs

There were large degrees of uncertainty in the use of different cost factors. It was not possible to assess the cost factors through detailed field research in the different case studies or literature review. To show the impact of cost assumption, 5 varying parameters were considered: electricity cost,

transport cost (from pre-treatment facilities to import ports), pre-processing cost (including cost of feedstock, collection and transport to pre-treatment facilities), pellet plant capital cost, and labour cost. The cost of electricity was considered relatively less uncertain, and was varied with only 10%. Capital cost of pellet plants was considered the most uncertain, as mentioned in expert interviews, and was varied with 50%. The other factors were varied with 25%.

Figure 3.9 - Sensitivity of 5 case studies (excluding Colombia) for different cost parameters

The combined effect of varying different parameters (varied with respectively 10%, 25%, and 50% as explained above) is shown as a cost supply curve uncertainty range for the BAU 2030 scenario in Figure 3.10, and for the HE 2030 scenario in Figure 3.11.

Figure 3.10 - Uncertainty ranges cost supply curves - BAU 2030

Figure 3.11 - Uncertainty ranges cost supply curves - HE 2030

GHG emissions

The three key factors impacting the GHG emissions that strongly depend on local conditions are nutrient substitution, transport emissions and electricity production emissions (Da Silva & Chandel, 2014; Kheang et al., 2012; Missagia, 2011; Paltseva et al., 2016; Southern Environmental Law Center, 2017; Suharno et al., 2013; Verstegen et al., 2016). Research and consultation with stakeholders were also carried out to investigate to what extent ranges of these factors reflect changes in GHG emissions. The study then considered that in Ukraine, Indonesia, Kenya, Brazil, and Colombia, variation of nutrient substitution and local transport was $\pm 20\%$ (low: -20% and high: $+20\%$). This can be explained by using nutrients to boost crop yields; and a low quality of infrastructure which results in high GHG emissions per kilometre. Electricity use has a range of $\pm 10\%$ (low: -10% and high: $+10\%$), which reflected changes in electricity use in the sourcing regions. With a similar consideration for local transport in the US, transport emissions were also set at $\pm 20\%$. However nutrient substitution is currently not applied for the use of forest biomass in the US, also electricity emission factor is less uncertain, therefore they were set at 5% for comparison and uncertainty analysis.

The results of sensitivity analysis of the different case study countries can be found in Appendix B.9. The combined effects of GHG emissions presented in Figures 3.12, 3.13 and 3.14 show the ranges of total GHG emission uncertainty for the five case studies in the BAU 2030 (no export potentials available for the US under this timeline) and for the six case studies in the HE 2030. In the current situation, the largest part of the export potentials from the sourcing countries meet the EU 80% GHG emission reduction for heat production and 70% GHG emission reduction for electricity production, as can be seen in Figures 3.12, 3.13 and 3.14. Most potentials would be eliminated under the strictest EU GHG emissions limit if three impacting factors are all included (except for some parts from Ukraine, the US and Colombia). Figure 3.14 also indicates that if lower nutrients, less fossil fuels, and grid electricity are used in the local supply chains, a higher quantity of biomass are qualified for export from the Ukraine, the US, and Colombia.

Figure 3.12 - Sensitivity of 6 case studies for different GHG emission parameters

Figure 3.13 - Uncertainty ranges GHG emission curves - BAU 2030

Figure 3.14 - Uncertainty ranges GHG emission curves – HE 2030

3.4. DISCUSSION AND CONCLUSIONS

3.4.1. Discussion

Future export perspective

In the US, given the interlinkages between the pellet industry and the conventional (in particular sawmilling) wood industry, the pellet industry can only flourish if the traditional industry flourishes (Wear & Greis, 2013). The pellet industry is expected to expand significantly if the conventional forest products use increases, as this would lead to increasing levels of low quality round-wood and residues becoming available. However, these dynamics are not explicitly accounted for in the present analysis. Domestic demand, together with EU sustainability constraints, also plays an important role in determining whether export potentials will be available from the US. In the BAU 2030 case, due to higher local demand and stricter application of sustainability requirements for sustainable biomass exported to the EU,

export potentials are equal to zero. In the HE 2030 scenario there is high availability of biomass for export. In order to reach these export quantities, pelletization capacity needs to be expanded, requiring trust by the industry that demand (in the US, the EU or other export markets) will steadily increase.

In Ukraine, forest residues are not included in the potential estimation as in practice they are not mobilized and there are no incentives to change this situation. The quality of the road networks in Ukraine limits accessibility to certain areas, especially during certain weather conditions. This is included in the calculation of cost supply curves in the form of high transport cost per kilometre, but is not included as limiting factor for the calculation of potentials. The lack of pellet plant capacity in the Ukraine strongly limits the export potential. Investments in the bioenergy sector in Ukraine, as a result of increased demand for lignocellulosic biofuels in Europe, could reduce this barrier. However, the current political situation may hinder investments.

In Brazil, potentials increase from the current situation towards 2030. Current agricultural practices of leaving high amount of residues in the field, if positively changed by collecting part of those residues, could add to the surplus potential over time. If the bioenergy sector in Brazil develops, it could make significant contributions to socio-economic developments in Brazil as well as strengthen the renewable energy sector both in Brazil as well as in the EU.

In Colombia, the investigation indicated that more investments in the bioenergy sector would be needed. Calculated potentials are lower than actual potentials as a result of excluding inland regions where transport costs are too high. Investments in accessible infrastructure would increase the potential for lignocellulosic biomass mobilization both for local and export uses. In Indonesia, palm residues such as fronds or empty fruit bunches are currently largely left as waste in the fields and at oil mills. Palm residues are currently free of charge, in the future, feedstock cost might be added once palm residues become commercialised. Costs might also be higher in case the certification of the Roundtable on Sustainable Palm Oil would be implemented to provide sustainability compliance of palm plantation. It was difficult to predict local consumption of palm residues in Indonesia. It is

considered likely that palm residues will be largely attributed to export due to the established supply chains of the palm industry. Local households could mobilise other local alternative energy carriers such as rice straw and husk and corn stover.

In Kenya, aggregate biomass potentials decrease over time as food demand, woody biomass deficit, and livestock nutritional needs are projected to increase towards 2030. Some agricultural yields in Sub-Saharan Africa are projected to decrease, caused predominantly by lack of water, soil loss, and land degradation (Kenya National Bureau of Statistics, 2015). Proper farming practices could help to boost agricultural production and thereby also result in more residue production. Kenya is not considered a suitable country for energy crop cultivation as many attempts failed to boost biofuel production in the country. There is resistance from local NGOs; there are conflicts between locals, and governmental corruption is an issue. Overall, Kenya does not seem to be a suitable export country until these issues are resolved. This could differ for other Sub Saharan countries. For example, in another study van der Hilst and Batidzirai find substantial biomass export potentials for Mozambique while applying a similar (B. Batidzirai et al., 2012; Van der Hilst et al., 2012).

This study found that, in certain regions, the poor state of infrastructure, logistic conditions and pre-treatment capacity limits the availability of lignocellulosic biomass to be mobilised for export. These barriers furthermore result in high costs and high GHG emissions in some regions. If these challenges are to be overcome, costs and GHG emissions will be reduced and access to feedstocks in remote regions could be achieved, leading to higher export potentials available, with more competitive costs and lower GHG emissions.

If sustainability requirements, are being implemented or established in certain countries, the market price and global trade of lignocellulosic biomass might change from one country to the other. Countries with no or loose sustainability requirements will more likely import certain shares of biomass compared to countries with strict sustainability requirements. More research is necessary to more accurately predict future global trade of lignocellulosic biomass for the bioenergy sectors in different countries.

Differences in local demand for biomass feedstock, sustainability criteria and different levels of market maturity result in different levels of feedstock availability for export. For easy comparison of costs and GHG emissions, the assumption was made that most feedstocks are suitable for pelletization. In reality, agricultural residues may require additional pre-treatment compared to biomass originating from forestry (e.g. washing to remove corrosive elements) or may require pre-treatment through pyrolysis or torrefaction. Those assumptions may also lead to lower or higher biomass availability for export, as well as changed cost supply curves and emissions supply curves.

As a result of limited data availability and difficulties in consulting local stakeholders regarding national policy focus and local markets, results need to be interpreted with a large degree of uncertainty. Market prices for biomass used for bioenergy production were not stable in the last two years and it is difficult to predict market trends in the future.

Other global demand for biomass

So far, this paper implicitly assumed that all export potentials are available to the EU. However, the demand for lignocellulosic biomass for bioenergy is predicted to also increase elsewhere until 2030 (International Energy Agency (IEA), 2016; Lamers et al., 2014). Matzenberger et al. (Matzenberger et al., 2015) have studied three global integrated assessment models, GFPM, TIMER and POLES, and assessed the (implicit) global biomass trade streams in these models. This study shows that Europe will still be the main importing region of bioenergy by 2030. At the same time there are emerging countries competing for lignocellulosic biomass resources with the EU, notably India, Japan, and Republic of Korea. The latter two have recently started to import biomass for energy. Simply based on the geographic vicinity, it is possible that the Indonesian resource potentials will be used in East Asia rather than be exported to the EU.

While this study has focused on the six case studies, initial investigations of potentials have indicated that countries such as Canada, Russia, Mozambique, Argentina, Vietnam, India and China also have high potentials of lignocellulosic biomass for both local use and export. Canada produces 48 PJ of wood pellets/ year and 90% of this quantity is currently

exported (Murray, 2016, 2017). Canada also implements sustainable forest management, aiming to meet environmental, socio-economic requirements for lignocellulosic biomass, and is currently a leader in third party certified forests (Murray, 2017). Russia is an exporting country of wood pellet and has a high potential resulting from its large forest industry (Matzenberger et al., 2015; Rose et al., 2014), although the current political situation has limited its export capacity. According to van der Hilst et al. and Batidzirai et al. (B. Batidzirai et al., 2012; Van der Hilst et al., 2012). Mozambique has potentials of up to 2.7 PJ of combined agricultural and forestry residues as well as potentials of 1.6-7.0 EJ from energy crops. Although local use of food and feed have not been carefully investigated in this study, still Mozambique probably has the potential to export biomass (B. Batidzirai et al., 2012; Bothwell Batidzirai, 2013a; Van der Hilst et al., 2012). Vietnam is currently the leading export of wood pellets to Republic of Korea and Japan with more than 18 PJ of wood pellets exported in the last three years (Murray, 2016), and is currently the highest exporting country of lignocellulosic biomass in Asia.

From this perspective, further investigation in these countries together with this study will provide a more comprehensive overview of potential global trade of lignocellulosic biomass. Given the existence of additional demand for biomass in other world regions and potential additional exporters to the EU not included in this paper, the projected biomass import potentials in this study should be seen as examples to illustrate the order of magnitude and conditions for import, not as lignocellulosic projections.

3.4.2. Conclusions

Results for the six case studies have shown that the sustainable export potential of lignocellulosic biomass is currently limited. However, depending on specific country conditions, the study also shows that sustainable export potentials may increase in the future in most countries, particularly in the HE scenario.

Ukraine, Indonesia and Brazil may become promising sourcing countries in the future as potentials increase from 18, 0 and 9 PJ in the current situation to 203, 356 and 411 PJ respectively in the HE 2030 scenario. On the other hand,

potentials in the US decrease to almost zero in 2030 in the BAU scenario when sustainability criteria are applied to the whole forest sector instead of just the pellet sector. Such assumptions were not made in the other case studies. When sustainability criteria are only applied to the pellet sector, the export potentials from the south-east US may become the largest of all case studies, increasing to 452 PJ in the HE 2030 scenario. Potentials in Kenya and Colombia increase only moderately compared to other countries from 20 and 29 PJ in the current situation to 68 and 93 PJ respectively in the HE 2030 scenario.

The feasibility of importing lignocellulosic biomass to the EU is limited by costs. When comparing the estimated costs of lignocellulosic biomass export from the different sourcing countries with the global average market prices in the last five years, it can be seen that this is a main limiting factor. The costs of lignocellulosic biomass from Ukraine are relatively low, ranging from 6.4 €/GJ to 11.8 €/GJ. This can mainly be explained by the shorter transport distance from Ukraine to the port of Rotterdam. Interestingly, Colombia is three times farther from the Netherlands than Ukraine but costs from Colombia are calculated to be between 6.5 and 9.2 €/GJ as a result of cheap feedstock and low pellet production cost. In the US, the costs range between 7.4 €/GJ to 35.0 €/GJ, the high end of the range is the result of increased cost of collecting residues when approaching the maximum potential, resulting in 90% of the potential ranging between 7.4 €/GJ and 15.0 €/GJ and the other 10% ranging between 15 €/GJ to 35.0 €/GJ. As a result of long-distance intercontinental transport, as well as expensive inland transport, Brazil and Indonesia bear higher cost ranges, from 10.8 €/GJ to 15.3 €/GJ and 11.6 €/GJ to 16.2 €/GJ.

The market price of wood pellets in the Netherlands between 2009 and 2016 ranged between 6.3 €/GJ to 8.0 €/GJ, which is considered representative for the international wood pellet market value (Biomass Magazine, 2016). It can be seen that lignocellulosic biofuels from the six case study countries are not likely to be exported under the low-end of this price range. Under the high end price, a small potential of 15.7 PJ in the BAU 2030 or 94.4 PJ in the HE 2030 could be exported. In both scenarios this can be attributed to potentials from Ukraine. In all other case studies, calculated supply cost exceed 8.0

€/GJ. If the market price were to increase to 10 €/GJ, the import potential meeting this threshold would increase to 34.2 PJ in the BAU 2030 scenario and 308 PJ in the HE 2030 scenario.

This study also shows that GHG emissions are currently not a critical issue in the investigated countries for biomass to be qualified for export to the EU. The entire potentials from all the six investigated countries comply with the GHG reduction requirements of 70% reduction compared to fossil fuel based electricity production, as defined in the proposed RED (European Commission, 2015). This can be explained by the fact that the largest part of the potentials is mobilized from agricultural and forest residues where emissions from cultivation are exempted. In addition, pre-treatment plants partly use lignocellulosic biomass to produce electricity for their operations. Therefore, pre-treatment emissions are also partly exempted.

If the requirements of GHG emissions are strengthened up to an 80% reduction, as identified in the proposed RED (European Commission, 2016c), only the potentials in the US, Ukraine and Colombia, and part of the potentials in Kenya and Brazil, meet the sustainability requirements for heat production. The potentials are particularly limited regarding biomass used for heat production, in this case only part of the potentials from the US, Ukraine and Brazil meet the reduction criterion. This is mainly due to intercontinental and local transport which accounts for a large share of the GHG emissions, especially from countries far away from the European Union. In Indonesia, Ukraine and Kenya, high amounts of fertilisers need to be used for nutrient substitution, which also causes higher total emissions.

Despite all these constraints, it can be concluded that substantial sustainable biomass export potentials currently exist, and one of the biggest constraints is currently to mobilise these potentials. The results presented in this study were used in the BioSustain study, research at EU level to analyse potential future intra-EU and extra-EU biomass supply scenarios. The BioSustain results show that the potential from the case studies included in the Biotrade2020+ study could cover 32% of the extra-EU demand for biomass in 2020 and 69% in 2030 (BioSustain, n.d.).

The potential contribution of imported biomass to renewable energy targets in the EU—the trade-off between ambitious greenhouse gas emission reduction targets and cost thresholds

Published in *Energies* 2020 13(7) 1761

Lotte Visser, Ric Hoefnagels, Martin Junginger

4.1. INTRODUCTION

In the European Union (EU), the energy transition is largely shaped by the renewable energy targets set for 2020 in the 2009 Renewable Energy Directive (RED I) and for the period 2020-2030 in its recast (RED II) (European Parliament, 2018). In several EU countries, increased utilization of woody biomass for electricity and heat is a means to reaching renewable energy targets (Roni et al., 2017). In their long-term vision for a prosperous climate-neutral economy, the European Commission foresees an important role to be played by biomass, especially in sectors which are more difficult to decarbonize such as industry and (heavy) transport, by using biomass for the production of aviation fuel, industrial process heating and bio-based materials and chemicals (European Commission, 2018). These different applications can all be covered by the utilization of sustainably sourced lignocellulosic biomass. A limiting factor in this is the availability of sustainable and affordable feedstock. Discrepancies between supply and demand in different countries have resulted in an emerging trade in fuel wood, wood chips and especially wood pellets between countries and world regions (Proskurina, Junginger, Heinimö, Tekinel, & Vakkilainen, 2018; Thrän et al., 2018). In 2018, the EU supplemented 17 Mt of wood pellet production with the importation of 8 Mt from the US and 2 Mt from other European countries (Bioenergy Europe, 2019c). Increased demand for biobased energy and materials will likely result in further increases in the international wood pellet trade (Matzenberger et al., 2015).

With the introduction of RED II, binding sustainability criteria were established for all bioenergy sectors to ensure sustainable production. These criteria relate to aspects such as supply chain GHG emissions, the risk of indirect land use change and the protection of land with high biodiversity or carbon stock. In contrast to for example indirect land use change (ILUC) criteria, indicators for GHG savings criteria are relatively well defined and quantifiable. Minimum thresholds per end-use type have been defined. The calculation method is standardized including pre-defined fossil fuel comparators and calculation rules (European Parliament, 2018). For installations with a rated thermal input >20 MW, the standard is 70% savings after January 2021, compared to a predetermined fossil fuel comparator, increasing to 80% after 2026. Besides

the imposed threshold on supply chain GHG emissions, there are market constraints for total supply chain costs. The fact that wood pellet utilization is in competition with fossil energy such as coal and natural gas as well as other renewable energy technologies limits maximum supply chain costs.

As shown in previous studies, the cost and GHG performance of solid biomass depends to a large extent on supply chain design such as the type of feedstock used and transport distances. The US currently is globally the largest exporter of wood pellets, mainly to western Europe (Bioenergy Europe, 2019c; Thrän et al., 2017). With increasing demand, the question is whether new trade routes will emerge, utilizing unused fiber baskets in other world regions. Existing literature studies have concluded that an increase of wood pellet consumption in the EU may result in increased imports from, amongst others, Russia, Canada, Brazil and the US (Johnston & Van Kooten, 2016; Jonsson & Rinaldi, 2017; Pelkmans et al., 2012). What these studies however did not take into account is the detailed spatially explicit availability of feedstock and how this impacts supply chain costs and emissions. Emerging trade routes and import potentials can only be assessed by considering detailed mobilization and trade potentials at different cost and emission levels, and by comparing this to market and legislative constraints.

Supply chain costs and emissions could potentially be optimized by introducing additional pre-treatment technologies, such as thermochemical treatment to produce torrefied pellets (TOP). Combustion of pellets is more challenging than coal, introducing issues such as mechanical degradation during storage, efficiency loss resulting from lower energy density and increased ash deposition in boilers (Roni et al., 2017). Using TOP instead of white pellets (WP) could reduce some of these issues. TOP have increased grindability and hydrophobicity and a higher energy density, resulting in lower transport costs and emissions (Wild & Visser, 2018). On the other hand, the production of TOP increases processing costs and introduces an additional, energy consuming, processing step. Whether a transition towards using TOP instead of WP results in optimized costs and emissions of bioenergy production depends on the design of specific supply chains. This research will analyze and quantify the potential role for TOP in meeting current and future GHG and cost criteria. This analysis will show whether there are favorable

conditions for TOP production and trade, as well as whether production of TOP unlocks increased production areas.

Policy making in the context of climate change can be based on integrated assessment modelling of the impact of different pathways or specific policies on carbon emissions or global warming. European energy system models, such as the Price-Induced Market Equilibrium System (PRIMES) (E3MLab, 2015), the JRC-EU-TIMES model (Simoes et al., 2013) and global integrated assessment models such as IIASA's Global Biosphere Management Model (GLOBIOM) (Forsell et al., 2016), the IMAGE model framework (Stehfest et al., 2014) and the Global Forest Products Model (GFPM) (Buongiorno, 2015) are generally based on default biofuel supply chains, not accounting for supply shifts resulting from increased demand. Whereas these models do account for regional variation in costs of labor, land or capital, the impact of spatial feedstock availability and logistics on biomass costs is not included. The role of biobased energy and materials production in the energy transition can only be understood by incorporating a detailed characterization of logistics required to mobilize large quantities of biomass. The large impact of supply chain design on costs and emissions of bioenergy necessitates the inclusion of spatial impacts in global energy modelling. Sustainable import potential of pellets from different world regions to the Netherlands were analyzed in Chapter 3, however not including the spatial availability of feedstock and the impact of transport networks and distances in detail.

This article is based on the premise that a sharp worldwide reduction in GHG emissions will be pursued and realized, and that biobased energy and materials have an important role to play to achieve the required emission reductions. Within this article, the focus will be on solid biomass in the form of wood pellets, produced from forestry biomass in the US, Canada, Brazil, Russia and the Baltic States and imported to Western Europe. In this study, a spatially explicit assessment is made of import potentials, based on the growing stock of forestry biomass, limited by an exclusion of protected and high-biodiverse land as well as local use for energy and non-energy purposes. These potentials are combined with an explicit assessment of wood pellet supply chain costs and emissions, including the transport requirements from inland locations to export ports. Costs and GHG emission thresholds are

applied to calculate potential import quantities to western Europe as well as maximum potential sourcing areas in the different countries for pellets and torrefied pellets.

4.2. METHODOLOGY

This work consists of a few different components, see Figure 4.1. Firstly, supply chain design costs and emissions were calculated for discrete supply chains from selected sourcing countries (United States, Canada, Brazil, Estonia, Latvia, Lithuania, Russia). Certain supply chain design characteristics were varied to analyse the impact on total costs and emissions, specifically the choice between pulpwood and sawmill residues, and the distinction between wood pellets and torrefied pellets. The impact of inland transport distance was also calculated. See Figure 4.2 for the impact of design variables on the included cost components. Secondly, pellet production potentials were calculated in the different countries based on feedstock availability in forests. These two parts were combined to generate costs and GHG supply curves, including the impact of inland transport. By applying different cost and emission criteria, the total potential availability of pellets under different circumstances was analysed.

Figure 4.1 – General research framework.

Figure 4.2 – Typical wood pellet supply chain, including the country factors varied in this study as well as the impact of two different variables, the choice of feedstock between sawmill residues or roundwood and the choice of pelletization technology between pellets or torrefied pellets (TOP).

When using "wood pellets" or "pellets" in the remainder of this article, this is always in reference to regular pellets from forestry biomass. The selection of sourcing countries was based on current pellet production and consumption and on the potential for future production increases (Bioenergy Europe, 2018; Matzenberger et al., 2015; Proskurina et al., 2018; Welfle, 2017). Supply chain costs and GHG supply curves of potential pellet production and trade were constructed based on the locations of export ports suitable for pellet export, within the including sourcing countries. Results from costs and emission analyses were used in the calculation of maximum supply areas and the total potential pellet production that can be supplied from these areas. This potential was calculated based on incremental growth of forestry biomass in spatially explicit forestry areas. Areas assumed high in biodiversity were subtracted from the total area, including protected areas and areas previously untouched by human exploration, considered a good estimation of the extent of primary forests. Of the incremental growth, a share of 90% was assumed to be reserved for existing local energy and material use. The GHG emission thresholds used were the 70% and 80% included in the RED II standards, as well as 85% in reflection of further tightening of emission criteria. Calculations were based on the fossil fuel comparator for electricity and heat production as outlined by the Joint Research Centre (JRC) (J. Giuntoli et al., 2017). These comparators represent typical or default GHG emissions of fossil electricity and heat production, and are based on a marginal mix of present and perspective power production and feedstocks (J. Giuntoli et al., 2017).

For the calculation within cost limits, a few criteria were included. A limit of 150 €/t pellets CIF ARA (costs, insurance and freight at the Amsterdam-Rotterdam-Antwerp ports), was used as reference, based on contract prices of pellets from Canada and the US fluctuating around this price level between 2012–2017 (FutureMetrics, 2018). As a lower limit, total costs of 125 €/t pellets were assumed, reflective of a situation in which there are fewer subsidy schemes supporting the use of wood pellets, and prices need to be more competitive. On the other end of the spectrum, cost limits of 175 and 200 €/t pellets were used. These higher costs represent scenarios in which the use of wood pellets is increasingly subsidized, or in which the use of fossil fuels has become considerably more expensive. The maximum costs for torrefied pellets were assumed to be equal to regular wood pellets on an

energy basis, and therefore 114% higher per tonne of pellets. Shipping costs and emissions were calculated to the Port of Rotterdam and are considered representative for the entire Amsterdam–Rotterdam–Antwerp (ARA) region. The expected price difference between all ports in western Europe is very small based on the small difference in shipping distance. Therefore, these results can also be considered a very close representative for other import regions in for instance the UK, Belgium or Denmark.

Supply chain components included in the cost and emission analyses can be seen in Figure 4.2. For each component, assumptions were made on the specific supply chain design, as explained in Section 2.1. These design choices impact the total costs and emissions and therefore have an impact on total calculated production potentials as well. For certain components, such as shipping, costs vary only with the type of ship used and the shipping distance. For other components, country differences were included, for instance in the form of differences in fuel, electricity and labour costs.

4.2.1. Supply chain costs and emissions

The RED II GHG calculation methodology for biofuels prescribes that total emissions need to be calculated as the sum of emissions from raw material extraction/cultivation, emissions from processing, transport and distribution, emissions from fuel combustion and annualized emissions from carbon stock changes, minus emission savings from carbon storage through improved forest management and CO₂ capture and geological storage or replacement (European Parliament, 2018). This methodology was applied to the calculation of emissions in this research, with the exception of both positive and negative carbon stock changes caused by land-use change or improved management. Whereas changes in carbon stock can add significantly to total emission savings or losses, it could not be assessed within the limited scope of this paper. Production of energy from biofuels was not assumed to be combined with carbon storage or replacement, since this technology is currently not widely used and is not considered an available option for most bio-based power plants. This yields the following Equation (1) for total emissions (E), adapted from the RED II methodology (European Parliament, 2018):

$$E = e_{ec} + e_p + e_{td} + e_c \quad \text{Eq. 4.1}$$

Where (e_{ec}) is the emissions from extraction or cultivation of raw materials, in this case forestry residues, (e_p) are the processing emissions from the production of pellets, emissions from transport and distribution (e_{td}) is a combination of the transport of raw material and transport of pellets in the production country and internationally, until delivery at energy companies located in the Port of Rotterdam. This category also includes loading and unloading at the various supply chain locations. Following RED II methodology, emissions from combustion of biomass to fuel processes (e_c) only includes non- CO_2 GHG. The emission factors for pellets of CH_4 and N_2O were taken from (Jacopo Giuntoli et al., 2015) and were converted to $\text{CO}_{2\text{-eq}}$ by using the global warming potential values for a 100-year time horizon from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Myhre et al., 2013).

Savings (S) were calculated compared to RED II fossil fuel comparators for electricity (F_{el}) and heat (F_h) of respectively 183 and 80 $\text{gCO}_{2\text{-eq}}/\text{MJ}_{th}$. Efficiencies of energy generation were assumed to be 40% for electricity and 89% for heat, based on pellet-based electricity or heat production, following Equation (2) (Croezen, Vroonhof, & Rooijers, 2006; European Parliament, 2018).

$$S = \frac{F_{(el/h)} - E}{F_{(el/h)}} \quad \text{Eq. 4.2}$$

4.2.1.1. Market prices and costs

There is a difference between supply chain costs and prices, depending on whether profit margins are included for the different components. In this research, wherever possible, calculations were based on costs, excluding profit margins for supply chain actors. This was considered to yield more robust results since profit margins can vary significantly between different supply chain actors and will vary over time as a response to market dynamics. An exception to this is the costs of feedstock. Calculating the biomass costs based on stumpage fees and harvesting and collection costs was not feasible for all countries since data on these components is lacking. Therefore, the choice was made to use biomass prices available at roadside

instead of biomass costs to achieve homogeneous results across all regions. In the remainder of this article, the term cost will be used for all supply chain components, in the case of feedstock this refers to the biomass prices paid by pellet producers. The development of feedstock prices is uncertain and depends on many factors such as demand developments, competition for feedstock, improvements in infrastructure or technological innovations and productivity of forest areas. Especially in new markets, without large pellet sectors, the impact of increased feedstock demand for pellet production on feedstock prices is uncertain. Potential market developments and changes in feedstock prices lie beyond the scope of this article and could not be assessed. The assumption was made that current costs of feedstock are stable and will remain constant when demand increases.

4.2.1.2. Extraction and cultivation

The different forestry feedstocks modelled are pulpwood, logging residues and sawmill residues, with assumed moisture contents of 50% for pulpwood, 55% for logging residues and 30% for sawmill residues (Clark & Daniels, 2000). Pulpwood is defined, following the definitions used by the U.S. Forest Service, as wood that does not meet the quality standards for sawlogs, including a diameter at breast height over 23 cm for softwood and over 28 cm for hardwood, but does contain a minimum of 50% sound wood fiber by volume (U.S. Forest Service, 2019; Waddell, 2010). Definitions of pulplogs and sawlogs could be different in other countries. Country specific data on prices of pulplogs, as will be discussed in Section 2.1.3, were used as such, without adjusting for differences in definitions. In case data was available for different diameter classes, the specific diameter class assumed will be specified. The volume of a tree meeting sawlog standards furthermore only includes the part of the trunk from a 1-foot stump to a 15 cm diameter top (softwood) or 20 cm diameter top (hardwood) (Waddell, 2010). A felled tree can therefore yield sawlog as well as pulplog timber, with tops and branches being classified as logging residues. Pulplogs are too small and of too low quality to be used by sawmills but can be used by other forest product industries such as pulp and paper companies and pellet mills. Logging residues are generated during harvesting activities and consist of damaged or degraded trees that cannot be utilized by industries requiring premium timber, as well as tops and

branches of harvested trees. Sawmill residues consist of residues generated during sawtimber production processes that are available for use by other industries. This consists of a mixture of sawdust, shavings and chips. Per RED II prescribed methodology, feedstock supply emissions are only allocated to pulpwood and not to residues. Allocation was done on mass basis for reasons of simplicity, instead of energy basis which would be more realistic (Derks, 2018). See Table 4.1 for fuel input during forestry management. This data is based on medium productive forest plantations. Not all forestry production in the included countries will be based on cultivated forestry feedstock, and while this study excludes biomass from primary forests, other types of forests, such as natural or semi-natural forests are included in accordance with RED II methodology (European Parliament, 2018). Still this data is considered a good assumption since pellet production is facing relatively strict sustainability criteria, favouring the use of feedstocks from forestry plantations as opposed to feedstock from more natural forests. Furthermore, an increase in feedstock demand for pellet production is expected to result in increased management of forests (Jan Gerrit Geurt Jonker, Junginger, & Faaij, 2014).

Table 4.1 – Assumptions on forestry management and required fuel and fertilizer inputs, adapted from (Jan Gerrit Geurt Jonker et al., 2014). Forestry plantation management was assumed to include mid-rotation thinning, chemical and mechanical site preparation and some application of fertilizers during growth (Jan Gerrit Geurt Jonker et al., 2014).

Activity	Quantity	Unit
Raking and spot piling (diesel fuel)	43	L/ha
Bedding (diesel fuel)	53	L/ha
Planting (diesel fuel)	28	L/ha
Fertilization (DAP)	224	L/ha
Fertilizer application (heli fuel)	9	L/ha
Thinning (diesel fuel)	616	L/ha
Fertilizer use (urea)	358	L/ha
Aerial fertilizer application (jet fuel)	9	L/ha
Clear-cut harvest (diesel fuel)	616	L/ha
Residue collection (diesel fuel) ⁱ	2.2	L/t residues
Pulpwood yield thinnings ⁱⁱ	40	T _{o.d.} /ha
Pulpwood yield clear-cut	100	T _{o.d.} /ha
Yield total	140	T _{o.d.} /ha

i. Based on Lindholm et al. (Lindholm, 2010).

ii. Assuming every third row is removed by thinning and thinning results in 50% enhanced growth (Jan Gerrit Geurt Jonker et al., 2014; U.S. Energy Information Administration, 2018c).

4.2.1.3. Feedstock price

The costs of harvesting were not explicitly calculated, since prices for biomass were reported on the basis of roadside costs, including the costs for forestry management, harvesting and collection. This study relies largely on country specific prices of forestry fibers, thereby not considering regional differences. An exception is made for the US where a distinction was made between the Southeast (SE) and Northeast (NE), and Canada where a distinction was made between the Southeast and Southwest (SW). The United States Energy Information Agency (US EIA) publishes monthly data on the average feedstock prices paid by pellet producers (U.S. Energy Information Administration, 2018c). This is considered a good approximation to use for the Southeast, since pellet capacity in the US SE makes up 70% of the capacity in the entire country. The average price of 2018 was used, calculated from monthly data on average prices and production quantities.

US EIA data is given for different feedstock types, among which roundwood/pulpwood and sawmill residuals. There is no significant difference in prices between the different feedstock types reported by the US EIA (U.S. Energy Information Administration, 2018c). Therefore, the assumption was made that prices for raw material are equal for all feedstock types in the US SE, at least on a wet basis.

Prices in Canada, US and Brazil were calculated relative to the US EIA data. Forest2Market reported on prices of hardwood and softwood in Brazil, the US SE and US NE and SE Canada and SW Canada in 2017 (Stuber & Forest2Market, 2017). From this data, an average value of softwood and hardwood prices was calculated for these regions. This value was converted to the level of US EIA feedstock prices using the ratio between the US EIA and Forest2Market prices for the US SE. Feedstock prices in the Baltic States and Russia were taken from a variety of sources. Data was available for pulplogs or sawlogs, sometimes of specific specified species and tree size categories. Feedstock prices in Estonia were based on pulpwood biomass from state forests and were first averaged for softwood and hardwood species using data on the distribution of fellings (Teder & Raudsaar, 2017). Latvian data, for the second quarter of 2018, taken from the central statistics bureau, distinguished between different species and diameters. Softwood prices are 65–95% higher than hardwood prices and are reported in different size categories. Considering this large price difference, the assumption was made that in the case of Latvia pellet production would be based on the more affordable hardwood species. Pulplog prices were based on average costs of hardwood trees < 24 cm diameter. Lithuanian data was given as the average price of pulpwood sold from state forests in 2018, per cubic meter (Baltpool, n.d.). Russian feedstock prices were based on price data for pulpwood, averaged for softwood and hardwood species (Indufor, 2018). For the various countries, data on residue prices could not be found. Therefore, just as in the US case, prices of harvest and sawmill residues were assumed equal to the price of pulpwood, at roadside or the mill gate where residues are produced, on a wet basis.

4.2.1.4. Processing

In the case of pulpwood use, pelletization of forest biomass starts with debarking, and course grinding to obtain similar particle size. All feedstock types then require drying and fine grinding in a hammer mill, pelletization, cooling and storage (Chapter 2). Cultivation and transport emissions of feedstock consumed for drying purposes were allocated to pelletizing emissions. Energy consumption for the different pelletizing components was taken from several literature studies, with the average of multiple values being used (Ehrig et al., 2014; Mobini et al., 2014; Obernberger & Thek, 2010; Pirraglia et al., 2010; Sikkema et al., 2010; Thek & Obernberger, 2004; Uasuf & Becker, 2011). During pelletization, a loss of 1% feedstock was assumed. The produced pellets were assumed to have an energy content of 17.5 GJ/t and bulk density of 0.65 m³/t. For the generation of electricity and heat, pellet mills were assumed to generate heat in a boiler fuelled with biomass, assuming an efficiency of 85%, with the additional use of grid electricity (J. Giuntoli et al., 2017). All assumptions on energy requirements and efficiencies are included in Table C.6 of Appendix C.2.

Pelletizing costs are difficult to determine, as discussed in (Chapter 2). Using the data laid out in this article, three different values were assumed for pelletizing costs, the median value of costs from literature was used as the baseline, medium cost value. The first and third quartile values were used as a low and high scenario for the calculation of pellet production potentials. Part of the variation of literature costs can be explained by supply chain design differences. In this study, a distinction was made between capital costs, maintenance costs, labour costs and costs for electricity and heat production. Capital costs are kept constant for all feedstock types, with the exception of costs for grinding equipment, which is not required when using sawmill residues. It must be noted that in practice many pellet mills will use a mixture of feedstock types and will therefore also require grinding equipment. The option of exclusively sawmill residues-based pellet production is however considered feasible in case of close proximity to and collaboration with lumber mills. For this reason, this study includes a cost analysis of pellet production based only on sawmill residues, using some adapted cost factors as explained in this section. Maintenance costs are assumed to be constant

for all feedstock types and sizes, and were based on Pirraglia et al. (Pirraglia et al., 2010). The base labour costs were based on the United States. Costs in other country were calculated by applying a cost factor based on hourly wages compared to the US, as given in Appendix C.1. Labour requirements and costs were assumed to be equal for all feedstock types.

Emissions of torrefied pellets were calculated using the same assumptions and data as for wood pellets. During torrefaction, biomass is heated to 200–300 °C in the absence of oxygen, resulting in the devolatilization of hemicellulose and cellulose (Bergman, 2005; Tumuluru, Sokhansanj, Hess, Wright, & Boardman, 2011). Pellets from torrefied material have improved characteristics such as a higher energy and bulk density, 20 GJ/t and 0.75 m³/t respectively, increased brittleness and improved hydrophobicity. During the torrefaction process, roughly 30% of the input mass is turned into several volatile components (Bergman, 2005). The torrefaction gas emitted through this process can be combusted to provide the heat required for the torrefaction process as well as drying of the biomass prior to torrefaction. Total processing heat demand and the heat supply generated by the combustion of torrefaction gas was calculated based on Mobini et al. (Mobini et al., 2014). The main cost factors and electricity and heat requirement of pellet production used in this study can be found in Table 4.2.

Table 4.2 – Base cost factors and electricity and heat requirement of CAPEX and OPEX costs for the United States, in €/t pellets, for a 500 kt/y pellet plant, based on data from (Chapter 2).

Component	Pellet type	Unit	Pulpwood	Logging residues	Sawmill residues
CAPEX	WP	€/t pellets	7.9	7.9	6.1
	TOP	€/t pellets	10.2	10.2	9.3
Maintenance	WP/TOP	€/t pellets	5.0	5.0	5.0
Labour	WP/TOP	€/t pellets	7.4	7.4	7.4
Electricity	WP	kWh/t pellets	183	163	163
Electricity	TOP	kWh/t pellets	189	169	169
Heat	WP	kWh/t pellets	1080	1333	429
Heat	TOP	kWh/t pellets	1764	2093	917

4.2.1.5. Transport and distribution

Feedstock is assumed to be transported by truck to pellet plants. Weight limits vary for different feedstock types, as can be seen in Table 4.3. Fuel consumption was based on a load of 26 tonne/truck, which was adapted to other weight limits, based on an assumed linear relation between weight and fuel consumption (International Energy Agency (IEA), 2017). Costs were calculated using different diesel prices, of May 2019, in the respective countries. Road transport includes costs for labour, against country specific labour prices. Fuel and labour costs for the different countries included in this study are given in Appendix C.1. To any trip, 50% of the total duration was added for loading/unloading, driver breaks and delays. Trucks were assumed to work at 100% capacity for the trip from forests to pellet plants. Transported feedstock was assumed to contain some contaminants in the form of sand or metals, measuring up to 3% of the total mass.

For transport of pellets, both road and rail transport were considered viable theoretical options. Road transport is calculated in the same way as feedstock transport but based on an assumed load limit of 25 t/truck (Jacopo Giuntoli et al., 2015), using heavy diesel trains. Since separate data on fuel consumption was available for the United States, Canada and the EU, the distinction was made between these geographical regions. For all other regions, the emissions of the United States were assumed. Costs of rail transport were based on a fixed price and a distance dependent price of the railway company CSX Transportation (CSXT) in the United States, as given in Gonzales et al. (Gonzales et al., 2013). Return trips on both road and rail are assumed to be empty, with emissions and costs being fully allocated to feedstock transport based on the empty weight of trucks and rail cars (EcoTransIT World Initiative (EWI), 2014). Detailed information on transport cost calculations can be found in Chapter 2. General cost calculations to compare the different countries were based on a feedstock transport distance of 50 km and a transport distance from pellet plants to export ports of 500 km, via road transport.

Table 4.3 – Data used for calculation of costs and emissions of truck transport of forestry feedstock.

Activity	Quantity	Unit	Source
Load limit road			
Weight load limit – pulpwood/thinnings	26.0	t/ruck	(Conrad, 2018; Dowling, Bolding, Aust, Fox, & Dowling, 2010)
Weight load limit – chips	28.5	t/truck	(Thompson, Klepac, & Sprinkle, 2012)
Volume load limit - sawdust	19.7	t/truck	(Thompson et al., 2012)
Weight load limit – pellets	25.0	t/truck	(Jacopo Giuntoli et al., 2015)
Fuel consumption road (diesel)			
Pulpwood/thinnings/pellets	0.45	L/km	(International Energy Agency (IEA), 2017)
Chips	0.47	L/km	(International Energy Agency (IEA), 2017)
Sawdust	0.41	L/km	(International Energy Agency (IEA), 2017)
Empty truck	0.28	L/km	(International Energy Agency (IEA), 2017)
Load limit rail			
Payload	1820	t/trip	(Hoefnagels, Searcy, et al., 2014)
Fuel consumption rail (diesel)			
United States	12.1	L/km	(EcoTransIT World Initiative (EWI), 2014)
Canada	11.1	L/km	(EcoTransIT World Initiative (EWI), 2014)
EU (heavy)	9.6	L/km	(EcoTransIT World Initiative (EWI), 2014)

4.2.1.6. Shipping and port operations

Shipping fuel consumption was calculated as in Chapter 2, largely following the methodology as given in (Jacopo Giuntoli et al., 2015). Fuel consumption and emissions were calculated for four different ship types: short sea ship (SSS), Handysize, Handymax and Supramax. Fuel consumption was taken from the International Maritime Organisation and shipping distances between two ports were taken from online calculation tools (I. Dafnomilis, Lodewijks, Junginger, & Schott, 2018; Ports.com, 2018). Pellet transport from the Baltic countries and Russia was assumed to be done in an SSS vessel with a

deadweight capacity of 10 kt. The other ports were assumed to be able to utilize the three larger ship types, which were varied in different scenarios, with a Handymax ship used as the reference case. Shipping costs were calculated using data on fuel costs and charter costs, both of which fluctuate over time and are therefore uncertain. Both fuel costs and charter costs were varied in a low, medium and high option, as can be seen in Table A5.

Emissions from engine use during berth, anchorage and manoeuvring operations were included during the period of loading and unloading, and vary per ship size (International Maritime Organisation, 2015). The maximum unloading capacity was based on the Port of Rotterdam, and was set at 10,000 t/day (I. Dafnomilis et al., 2018). This unloading rate does not include potential delays caused by bad weather or scheduling difficulties. The assumption was made that loading emissions equal the unloading emissions. Additional terminal operations were also included, including the emissions from ship unloading and conveying of pellets (Günthner, Tilke, & Rakitsch, 2010). These operations are based on the Rotterdam terminal as well, assuming pneumatic ship unloading and conveying across 1500 m (I. Dafnomilis et al., 2018). Costs of port operations were based on the above methodology, calculated using country specific costs of electricity. Labour costs were left out of this equation since these depend largely on the degree of automation and form a small part of total costs compared to, for instance the daily charter costs.

4.2.2. Techno-economic and GHG supply potential

4.2.2.1. Feedstock availability

The impact of maximum supply areas was calculated by totalling the feedstock availability within supply areas in the different export countries. The availability of mill residues was excluded since this availability is inherently limited by the existence and proximity of other industries, and reliable spatial data on the extent of timber and paper industries in all included countries was not available. Logging residues were also excluded from total availability. Although this source of feedstock could be utilized for pellet production, mobilizing these residues requires significant effort and is usually not cost efficient compared to pulpwood (Fulvio, Forsell, Lindroos, Korosuo, & Gusti,

2016). Increased use of logging residues instead of pulpwood presumably requires the existence of specific policies or support schemes. Furthermore, the extent of logging residue availability depends on the type and size of trees as well as the minimum merchantable diameters specified locally and is therefore difficult to estimate spatially explicit (X. Wang, Bi, Ximenes, Ramos, & Li, 2017). The total potentials calculated in this study can be considered indicative of the differences between various production regions but are not considered to represent accurate estimates of pellet production potential. The potential availability of forestry feedstock was analysed spatially explicit, based on raster maps of forested areas in the different countries. Detailed information on the data used for all different countries can be found in Appendix C.3. All data given in volume was converted to weight based on a value of 990 kg/m³ green wood, taken from (Forest Research, 2018), calculated as the average between softwood and hardwood at 50% moisture content (MC) on a wet basis. Per tonne of pellets, 2.1 tonne of pulpwood feedstock is required. Calculated using the MC of 50% and a MC of dried feedstock of 8%, an efficiency of heat production of 85% and heat requirement for drying of 1200 kWh/t of evaporated water (Sikkema et al., 2010; Thek & Obernberger, 2004).

4.2.2.2. Sustainability restrictions

To ensure that use of bioenergy results in carbon savings, the total forestry stock should not decrease, as required in the RED II. For this reason, total availability of forestry resources in this study was based on current annual incremental growth as opposed to total growing stock. Annual growth varies per tree and forest type, forest management intensity, climate and other factors. Whereas spatial data on annual growth was available for some countries, for other countries estimates had to be made on available data and additional literature. Appendix C.3 shows the method used in the different countries to calculate feedstock availability. This includes additional sustainability criteria such as the protection of land with high biodiversity value. Although it was not considered feasible to do a detailed analysis of biodiversity and species richness, this concern was included through the exclusion of untouched forest areas and areas marked as protected areas from total forest areas. In the case of Brazil also areas inhabited by indigenous people were excluded. In the case of the Baltic States, availability was taken

from wood production maps, as analysed by the European Forest Institute. These maps already include several locational factors such as protected areas, and the resulting maps were used as such (BioSustain, n.d.; Verkerk et al., 2015). To avoid distortion of local markets and displacement of emissions, pellet production should not use feedstock already used locally for production of other forest products (BioSustain, n.d.). The existing demand for forestry feedstock could not be assessed sufficiently detailed for the different countries. Instead a fixed percentage of incremental growth was assumed to be available for pellet production. In the US SE, in 2014, forest harvest removals for pellet production represented < 3% of removals in the entire region (Dale, Kline, et al., 2017). Since then, pellet production in the US SE has doubled roughly, resulting undoubtedly in more removals. As upper limit in this study a value of 10% of the total annual increment was assumed. This forestry feedstock availability was assumed to be in the form of pulplogs, excluding harvest residues such as tops and branches. The collection and processing of residues requires several additional processing steps, necessitating the development of new procedures while the biomass is of relatively low energetic and monetary value. For this reason, the assumption was made that pellets will be produced from pulpwood and not from harvest residues. Other factors, such as the amount of biomass that needs to remain in forest areas to satisfy biodiversity and soil quality standards were not included (Chapter 3).

4.2.2.3. Mobilization

Pellets can only be produced and exported cost efficiently if feedstock can be transported across roads and is located close enough to export ports. To analyse this, the availability was calculated in relation to distance from the main export ports, in 100 km tranches based on the use of road networks, until a maximum of 2000 km. Distances from export ports that exceeded 100 km were assumed to be covered by transport of pellets and not feedstock. Transport distances were calculated based on Railroads maps and OpenStreetMap, as made available by Esri (ArcGIS, 2019) and Geofabrik (Geofabrik, 2019). Assumed speed limits were varied for motorways (80 km/h), primary and secondary roads (60 km/h) and tertiary and residential roads (40 km/h). In the Baltic states even smaller, unpaved roads were included (20

km/h), unlocking additional forested areas. In the case of the US, where road networks are very extensive, all roads smaller than secondary roads were excluded. Transport across road with an assumed speed limit <80 km/h was factored according to the additional costs per distance, depending on the balance between fixed and variable costs. Service areas were calculated in ArcGIS using the Network Analyst Service Area tool (ArcGIS 10.7, Esri, Redlands, CA, USA). In calculating the availability within limits of maximum costs and GHG emissions, the maximum distance of each service area was used, e.g. the costs of pellets from a service area between 0–100 km were calculated using 100 km as transport distance value. In case of overlapping service areas, as is the case with several export ports in close proximity, the potentials were allocated based on lowest costs and emissions to a single export port. Figure 4.3 shows an example of the exclusion of forested areas based on biodiversity concerns or transport distance to export ports in Brazil.

Figure 4.3 – (a) Example of forestry feedstock availability calculation for Brazil, based on total area classified as forest vegetation by the Instituto Brasileiro de Geografia e Estatística (Instituto Brasileiro de Geografia e Estatística (IBGE), 2016); (b) Protected areas (green) and areas inhabited by indigenous people (orange), were based on data from (Fundação Nacional do Índio, n.d.; Ministério do Meio Ambiente, n.d.; Potapov et al., 2008); (c) Forestry feedstock availability minus protected areas as shown in (b); (d) Only the areas within 2000 km from selected export ports were considered feasible for mobilization; (e) The resulting remaining potential areas for pellet production; (f) As the final step, OpenStreetMap road infrastructure, adapted from (Geofabrik, 2019), was used to calculate transport costs.

4.3. RESULTS

4.3.1. Supply chain GHG emission CIF ARA

As shown in Figure 4.4, the largest component of total greenhouse gas emissions is pelletizing, although this depends strongly on the emission factor of electricity production in the different countries. Pelletizing emissions constitute 16% of total emissions for pellets produced in Brazil, compared to 54% in the case of Latvia. Emissions of silviculture and harvest and feedstock transport are also significant, contributing a combined 26–60% of total emissions. Shipping emissions vary with transport distance and are almost a factor 5 higher for western Canada than for Lithuania. In all countries, emissions of torrefied pellets are lower than emissions of pellets, the difference between the two increases with increasing transport emissions. Supply chain emissions for pellets from pulpwood are 46–91% higher than emissions for sawmill pellets. This is largely the result of no allocation of silviculture and harvest emissions to sawmill residues, which is in line with the RED II methodology followed in this article (European Parliament, 2018). Furthermore, the emissions of feedstock transport and pelletizing are lower because of the lower moisture content of sawmill residues compared to pulpwood. Supply chain emissions of TOP are consistently lower than wood pellets, including the pelletizing and torrefaction energy requirements. As a result of the combustion of torrefaction gas, energy requirements are lower per unit of energy delivered. The largest reduction was calculated to be for pellets from pulpwood, ranging between 12–24% GHG savings. Results for TOP produced from sawmill residues, show a 2–10% GHG saving. Calculations show that emissions for silviculture, harvest and feedstock transport are slightly higher for torrefied pellets, explained by the fact that the production of TOP requires more feedstock input. This is however more than compensated for by the fact that TOP have a larger energy density than WP, resulting in reduced transportation requirements per unit of energy delivered.

Figure 4.4 – Supply chain greenhouse gas emissions for wood pellets and torrefied pellets made from pulpwood (solid) and sawmill residues (striped), for all analysed countries. Total emissions were based on feedstock transport distance of 50 km and pellet transport distance of 500 km. As a sensitivity, minimum and maximum values are shown based on transport distance of pellets between 0–2000 km. Maximum transport distance in the Baltic States remains 500 km, which is the maximum distance possible in these smaller countries. Shipping transport was calculated for Handymax ships, except for the Baltic States in which case the use of a short sea ship (SSS) was assumed.

4.3.2. Supply chain Costs CIF ARA

The total costs of delivered pellets vary between 6.8 €/GJ pellets for pellets from Brazil and 12.7 €/GJ for pellets from Lithuania, shown in Figure 4.5. The largest share of pellet costs is the price of feedstock, contributing between 33–61% of total costs, which is the predominant cause for cost differences between the various countries. Transport costs also vary in the selected countries, most of all the shipping costs. Because of the different ship types assumed for the pellets transported across the Baltic Sea, costs for Latvia, Lithuania, Estonia and Russia are comparable to shipping costs from the other regions regardless of the much smaller transport distance. Supply chain costs of sawmill residue pellets, varying between 6.1–10.6 €/GJ pellets, are consistently lower than that of pulpwood pellets, ranging between 2–27% cost savings. Costs of torrefied pellets are generally comparable or slightly higher on a mass basis, but lower on an energy basis. Per GJ of delivered pellets, torrefied pellets from pulpwood are up to 15% cheaper,

in the case of Russia. An exception to this is Brazil. High costs for electricity production cause significantly higher pelletizing costs for TOP, resulting in an 8% increase in total costs. Torrefied pellets made from sawmill residues are generally slightly more expensive than wood pellets. The lower feedstock drying requirements for sawmill residues reduce the benefit of combustion of torrefaction costs.

Figure 4.5 – Supply chain costs for wood pellets and torrefied pellets made from pulpwood (solid) and sawmill residues (striped), for all analysed countries. Total costs were based on feedstock transport distance of 50 km and pellet transport distance of 500 km. As a sensitivity, minimum and maximum values are shown based on transport distance of pellets between 0–2000 km. Maximum transport distance in the Baltic States remains 500 km, which is the maximum distance possible in these smaller countries. Shipping transport was calculated for Handymax ships, except for the Baltic States in which case the use of a short sea ship was assumed.

4.3.3. Combined supply curves

Supply curves were generated based on the production potential of pellets in each region, sorted for lowest costs and combined in intervals of 2 Mt production potential. The average costs and emission values for each interval was used to construct the line charts shown in Figure 4.6.

Figure 4.6 – Cost supply curves of wood pellets made from pulpwood with corresponding GHG emissions. Assumed transport on road, across 50 km for feedstock. Shipping transport per Handymax, and SSS ship in the case of transport across the Baltic Sea. – Sorted for lowest costs of wood pellets.

The lowest and highest GHG value within each 5 Mt production potential intervals was also included to show the large variation within each range. There is a small correlation between costs and emissions. A defining factor in total emissions is the grid electricity emission factor. The countries in this study with affordable feedstock, Brazil, Canada, Estonia and the US, also have low emission factors. The most expensive part of the supply chain consists of pellets produced in regions far away from export ports and in regions with large shipping distances such as western Canada, resulting in increased costs as well as emissions. Still, the range of lowest and highest emissions is significant at most parts of the curve. Just optimizing for lowest costs could therefore result in suboptimal GHG emissions. The supply chain costs and greenhouse gas emission results for the different export regions, used to construct the combined supply curves as shown in Figure 4.6, are shown in more detail in Appendix C.4 and Appendix C.5 respectively.

4.3.4. Maximum supply areas

The differences in feedstock, pelletizing and shipping costs result in variations in the maximum transport distance across which feedstock and pellets can be transported while staying within the predetermined costs and emissions thresholds. In Figure 4.7, the difference between WP and TOP is shown, when assuming total maximum supply chain costs of €150/t WP, or the equivalent €171/t TOP.

Figure 4.7 – Maximum supply area of pellets made from sawmill residues and pulpwood when applying thresholds of: (a) 70% GHG emissions savings; (b) 80% GHG emission savings; (c),(d) €150 /t pellets CIF ARA for wood pellets, corresponding to €171 t/pellets CIF ARA for torrefied pellets, in proportion to the higher energy density.

This cost criterium excludes pellet production of WP made from pulpwood in Western Canada and large parts of Eastern Canada and the United States. The maximum supply area for sawmill residue pellets is larger, specifically in the case of WP for which a larger inland area of the US SE would be available for pellet production. A GHG emission reduction of 70% results in very large supply areas, in all countries, exceeding the 2000 km used as practical limitation for pellet transport. The reduction limit of 80% also results in relatively large potential supply areas compared to the cost limit of €150/t pellets. The difference between 70% and 80% is however already significant, impacting the maximum production areas in Brazil, SW Canada and Russia. When using pellet costs as a limiting factor, the difference between WP and TOP is relatively small in Brazil. This because the costs are dominated by other factors such as transport costs, and feedstock and pelletizing costs form a smaller part of the total supply chain costs than in other countries. In Latvia and Lithuania, high feedstock prices limit the production of regular and torrefied pellets from pulpwood in the entire country and only allow production in a small area when using sawmill residues. In Estonia, there is not much difference between the maximum supply area for the different feedstock and pellet types. In Russia, on the other hand, the difference

between pellets produced from pulpwood and sawmill residues is large, pellets from sawmill residues can cost effectively be produced in a large part of Russia. GHG emissions in the Baltic states and Russia are much less of a limiting factor.

4.3.5. Pellet production potential

The potential production of pellets in the different countries is limited by the availability of feedstock as well as costs and emissions of pellet production and transport. Figure 4.8 shows the techno-economic pellet production potential of pellets made from roundwood in the different countries analysed. The potential as limited by supply chain costs, is largest in Brazil and the US. An assumed cost limit of 200 €/t pellets gives a total potential of almost 60 million tonnes of pellets, of which 50% is sourced from Brazil and 39% from the US. Total availability of forestry feedstock in the Baltic countries is small and prices of feedstock are high, resulting in a very low potential. Feedstock prices are more competitive in Canada and Russia. However, the main forestry potential in these regions is located more inland, at large transport distance from export regions, limiting the available feedstock for pelletization. The total potential from all countries is significantly impacted by supply chain costs limits. At the other end of the range, at an assumed cost limit of 125 €/t pellets, the total potential varies between 3–28 million tonnes in the different scenarios. Since the difference in costs between WP and TOP is very small, results are also very similar. Overall for TOP, the potential from Brazil is slightly lower and the potential from the US slightly higher. The total potential of torrefied pellet production and import falls within 95–103% of the wood pellet potential.

Figure 4.8 – Techno-economic pellet production and net import potentials, CIF ARA, limited by supply chain costs – for wood pellets (WP) and torrefied pellets (TOP) – calculated using different assumptions on the development of pelletizing costs and shipping fuel and charter costs in a Low, Medium and High scenario.

The production potential limited by high GHG emission thresholds is lower, as can be seen in Figure 4.9. At a 70% reduction target, almost the entire pellet production potential is available, 61 Mt in the case of electricity production from pellets, of a maximum of 65 Mt. This reduction target does not form a limitation for pellets from Estonia, Latvia and Lithuania. The potential from these regions however remains small compared to the US and Brazil because of the lower availability of forestry feedstock. An 80% reduction threshold reduces the total potential significantly from 61 to 16 Mt pellets in the case of electricity production and 13 Mt in the case of heat production. Going to the 85% threshold, the potential for electricity or heat production reduces to just 1 Mt pellets. Especially in case of the 80% threshold, the production of torrefied pellets would increase the total potential significantly, with 23 Mt pellets to almost 40 Mt in the case of electricity production and 36 Mt in the case of heat production. Especially in Brazil and the US, the production of torrefied pellets could allow for the import of larger amounts of pellets within the limits of certain GHG reduction standards. The potential availability of other feedstocks, such as harvest or industrial residues, was not considered in this analysis. This could significantly impact the production potentials, especially when limited by GHG emissions considering the relatively large reduction in supply chain emissions as shown in Figure 4.9 These potentials therefore

do not represent an upper limit but should be viewed as an indication of the impact of stricter GHG thresholds.

Figure 4.9 – Techno-economic pellet production and net import potentials, CIF ARA, limited by supply chain GHG emissions – for wood pellets (WP) and torrefied pellets (TOP) produced from pulpwood.

4.4. DISCUSSION

4.4.1. Uncertainty factors in feedstock availability

Some of the supply areas analysed in this study might not be readily accessible due to natural barriers such as steep slopes or waterways. Furthermore, although some sustainability constraints such as supply chain emissions and forest stock were included, other limiting factors such as biodiversity or soil quality were not accounted for. Calculated potentials therefore do not reflect sustainable potentials but rather import potentials under a few selected (sustainability) criteria. The potential production totals calculated in this study were based on the availability of pulpwood in forests. This approach may have resulted in an underestimation of total feedstock availability since availability of industry residues, or residues from forestry operations such as tops and branches, was not included. In Latvia and Lithuania feedstock is relatively expensive and calculations in this study have shown that pellet production is only cost effective when using sawmill residues. At the same

time, current pellet production in these countries is largely based on the use of sawmill residues, making up about 80% of the total feedstock consumption for pellets [6]. The calculated combined potential in Canada, Russia and the Baltic states is 6.9 Mt in the GHG reduction scenario for torrefied pellets, the least strict criteria for these countries. Current production statistics show that the 2018 production in these countries combined also totalled 6.9 Mt (Bioenergy Europe, 2019c). This is an indication that the estimation of potentials in this study is on the conservative side. The availability of sawmill residues is however inherently limited to the production capacity of wood processing industries. Solely relying on increased use of residues for growing pellet production is considered uncertain and risky.

The use of other feedstock types, such as agricultural residues, was not considered. In a country like Brazil it could be feasible to produce pellets from residues of sugarcane production, such as bagasse and straw. Research into alternative feedstocks can show whether there is potential for cost or emission reductions, and whether this would result in a significantly larger total production potential. Even without including agricultural residues, Brazil could become an important new supplier of pellets based on the low costs and emissions. Pellet production capacity in Brazil is currently very small. In 2018, total pellet production in Brazil totalled just 0.4 Mt (Bioenergy Europe, 2019c). A potential limitation to feedstock availability in Brazil is the prominent and growing pulp and paper market in Brazil, which could pull available feedstock away from pellet production (Forest2Market, 2017a). Local demand for other industries was assumed to be 90% of the incremental growth. If local demand, for instance for wood or paper products or local wood based generation of biofuels or bioenergy, exceeds this number, or even exceeds the incremental growth totals, there could be no pulpwood available for pellet production. Abt et al. (Karen L. Abt, Abt, & Galik, 2012) have modelled the impact of increased bioenergy production on softwood and hardwood removals, inventory and prices in Alabama, Florida and Georgia. Their results show that increased bioenergy consumption impacts the forestry sector, for instance resulting in an initial increase in prices of sawtimber. The impact on prices on the longer term, as well as the impact on forest area, inventory, removals and carbon stock strongly depends on the modelled supply and demand response as well as assumptions on utilization of logging residues

and plantation growth increases. Kim et al. (Kim, Baker, Sohngen, & Shell, 2018) have modelled impacts of global demand projections for bioenergy. Their results show that increased bioenergy demand will result in increased prices of pulpwood, while price changes of sawlogs are marginal. This work furthermore shows that overall levels of biomass, pulpwood and sawtimber harvesting will increase, achieved through a combination of timber substitution, increases in forest area and increases in forest management intensity. Especially the production of other wood-using industries, and the interaction with pellet mills, must be examined in more detail. The impact of competing demand on feedstock availability for pellets is twofold, a large existing wood and paper industry will likely result in lower availability of pulpwood but higher availability of logging and mill residues.

This study is not a full analysis of global feedstock availability, and other major pellet production regions, such as China and Vietnam, were not included [6]. On the other hand, other growing demand regions, such as Japan and South-Korea were also not considered (Strauss, n.d.). For a complete analysis on potential wood pellet imports, the local competition for feedstock as well as the international competition for pellets needs to be considered in future work.

4.4.2. Supply chain optimizations

Certain supply chain optimization options, such as the use of rail transport instead of road transport and the use of larger ships were not included in this study. Further research on the impact of several optimization strategies could provide additional results. Stricter future GHG criteria, as analysed in this work, could push towards the realization of such supply chain optimizations. Stricter criteria, and ongoing developments in renewable energy technologies will furthermore lower emissions of future electricity production, thereby lowering emissions of particularly pelletization. This is especially relevant for countries such as Latvia and Estonia, that have a higher than average emission factor and an obligation to meet EU regulated emission targets.

An optimization aspect which was analysed is the production of torrefied pellets. This study has shown that importing TOP can result in a larger import

potential that meets GHG reduction criteria. A drawback of TOP imports is that the transition from the use of biomass for bioenergy production to material production becomes limited to thermochemical routes, since biochemical conversion is not feasible using TOP.

A promising use of biomass to achieve negative emissions is the utilization of wood pellets in bio-energy plants combined with carbon capture and storage (BECCS). The largest global consumer of wood pellets, the Drax Power Station in the UK is aiming to transition towards the use of BECCS. Emission savings through carbon capture and storage can be subtracted from supply chain emissions according to the RED II prescribed methodology, thereby potentially resulting in a much larger import potential (European Parliament, 2018). Still, this does not take away the necessity of focussing on optimization of supply chains. Especially with the deployment of a costly, advanced technology such as BECCS it is important to maximize the GHG saving potential, even more so since carbon capture and storage requires energy, thereby increasing biomass consumption (Drax, 2019).

4.4.3. Necessity of including spatially explicit cost and emission calculations

Results show that pellet production and import potentials against acceptable costs and emissions depends on the availability of feedstock close to export ports. This also points at the shortcomings of integrated assessment models in not considering the spatially explicit cost variation of potential pellet supply. If models, for instance, do not include inland transport cost variation, this could result in an underestimation of costs and emissions of more than a factor of 2, likely resulting in very different results and conclusions on the potential of biomass trade. Supply chain costs and emissions in this study were calculated to the ARA region. Global assessment models should ideally use spatially explicit calculations for all export ports considered in the global trade of pellets, as well as consider potential infrastructure developments.

In the future, other markets besides electricity and heat production are likely to become more important, such as the use of biomass for the production of advanced transport fuels or biomaterials. Also for these end-uses, import

of (solid) biomass feedstocks may in principle be a viable option (Vera & Hoefnagels, 2019), especially since GHG reduction criteria for these end-uses are less strict, requiring at least 65% savings for produced bioliquids and biofuels consumed in the transport sector (European Parliament, 2018). Further work needs to be done to analyse different production routes and supply chains. For commodities such as transport fuels, it is especially interesting to consider the locations of pre-treatment, production and consumption. From a global emission perspective, it could be best to produce these fuels closer to the source of biomass rather than trading wood pellets to be upgraded in import regions. The most emission savings could be realized by not trading biofuels and instead focussing on maximized local utilization of biomass resources. On the other hand, the lack of biomass availability in many countries will likely only increase the demand for biomass imports. Some countries with large feedstock availability, like Brazil, have several other options of producing renewable energy, such as hydropower. Investments in biomass mobilization infrastructure and pellet production facilities could on the longer-term benefit sourcing countries in supplying local bioenergy as well as trading surplus biomass to countries with fewer resources.

4.5. CONCLUSIONS

This study has shown large differences in supply chain costs and emissions of pellets imported from different countries to the CIF ARA region. Cost for procuring feedstock is the largest part of most supply chains and determines to a large extent the order of countries. The difference between the lowest and highest costs is a factor 3, ranging between 90 and 280 €/t pellets for the total production potential calculated. The impact of inland transport is large, adding up to almost 150 €/t pellets to the total supply chain costs. Pellets exported from the United States for instance range from 103 to 252 €/t pellets CIF ARA, when varying the transport distance from pellet mills between 0 and 2000 km for pellet mills that are located far inland. The costs and emissions calculated in this study are based on several assumptions and are therefore uncertain to some degree. What is however considered very robust, is the large relative impact of feedstock availability and transport distance on total costs and emissions. This work therefore shows the

importance of considering spatial feedstock availability and competition in assessments on the potential contribution of bioenergy.

The cost limits analysed in this study clearly show diminished potentials for a cost limit of 150 €/t and especially 125 €/t. In the case of 125 €/t, production would be limited to only the coastal areas of Brazil and US SE. These costs are considered a good representation of spot and contract prices in previous years, even though no direct comparison can be made since pellet prices include profit margins for the different supply chain actors. Spot prices have varied between 110 and 160 €/t pellets between 2012 and 2017 and contract prices in the US and Canada have varied between 95 and 180 €/t pellets in the same years (FutureMetrics, 2018). Increasing demand for pellets could result in higher prices and more opportunities for supply chain optimizations, thereby increasing maximum supply chain costs. On the other hand, wood pellet consumption in previous years has been subsidized. If these subsidies were to be removed, the paying capacity and therefore maximum supply chain costs would reduce.

Stricter GHG thresholds have a significant impact on import potentials, especially in the case of electricity production. If the minimum GHG saving threshold is increased from 70% to 80%, the total potential will reduce from 61 to 16 Mt in the case of electricity production from pellets. With an 85% reduction threshold, only 1 Mt of the total export potential remains. For heat production, potentials decrease from 61 Mt under a 70% threshold, to 13 and 0.5 Mt using the stricter criteria. A shift to TOP would increase potentials to 39 Mt and 36 Mt for electricity and heat production respectively under the 80% criterium. The additional potential for TOP is however limited in the case of the 85% threshold, resulting in a total of 4 Mt. The sharp reductions of potentials towards the 85% threshold clearly indicates an upper limit for international trade of wood pellets and TOP. Increasing GHG thresholds will result in larger relative emission savings, but could also limit the amount of biomass use, and as such postpone the further decarbonisation of the European economy. Policy makers need to be aware of this trade-off between ambitious GHG thresholds and the potential contribution of biomass to renewable energy targets.

Exploring the limits to sustainable pellet production for international markets - The impact of increasing pellet production in the US Southeast on feedstock use and carbon sequestration in forest areas

Submitted to GCB Bioenergy

Lotte Visser, Greg Latta, Raju Pokharel, Ric Hoefnagels and
Martin Junginger

CHAPTER 5

5.1. INTRODUCTION

The consumption of wood pellets for energy purposes, as a means of phasing out fossil fuels and reducing greenhouse gas (GHG) emissions, is expected to increase in several world regions, including Europe and Asia (Bioenergy Europe, 2019c). While Asia is the largest producer of pellets in the world, Europe is the largest consumer, supplementing 19 Mt of production with 9 Mt of imports, largely from the US (Bioenergy Europe, 2019c). In the US, production of pellets for export markets has been growing significantly, from 0.5 Mt pellet export in 2000 to 7 Mt export in 2018 (Lamers et al., 2015; USDA Foreign Agricultural Service, 2020). The current dominance in wood pellet production coupled with extensive availability of additional forests for wood harvesting and the proximity to import regions in Europe make the US attractive for even higher levels of pellet production. The Southeast of the US (US SE) has been the dominant producer for the export market, benefitting from a developed timber market, sufficient feedstock availability and proximity to European markets.

The demand for bioenergy and biomaterials is expected to increase significantly in Europe as well as other world regions (Daioglou, 2016; Matzenberger et al., 2015). Considering the risks of using agricultural commodities, related to competition with food and feed, and the feasibility of using woody biomass for a range of purposes such as production of energy, biofuels and biomaterials, the demand for lignocellulosic biomass is expected to grow in the near future (Vera & Hoefnagels, 2019). Pellet supply chains were developed to facilitate long distance transport. The demand for pellet imports to especially western Europe is expected to increase with demand increases (Oberberger & Thek, 2010; Thrän et al., 2017). The question is what the impact will be of increased pellet production in production regions such as the US SE, and what the local limits are to pellet production and trade.

Whether biomass use contributes to the lowering of GHG emissions and the abatement of climate change depends amongst others on specific supply chain conditions. The European Commission has raised concerns about the sustainability impacts of using biomass for energy, especially relating to forestry biomass. Issues include the balance between supply chain and end

use emissions and carbon sequestration, and the competition for resources between bioenergy production and other forest products markets (European Commission, 2017). For pellets imported into the EU, the Renewable Energy Directive (RED II) imposes minimum sustainability criteria (European Parliament, 2018). Bioenergy can contribute to renewable energy targets, and be eligible for financial support, only if certain sustainability criteria are fulfilled (European Parliament, 2018). The prescribed criteria to analyze GHG emissions includes the impact of carbon stock changes, either by including carbon stock changes in GHG emission commitments, for countries that have ratified the Paris Agreement, or, if this is not the case, by having management systems in place ensuring that carbon stock and sink levels are maintained. What is not included in this methodology however is carbon flux changes within forested areas, for instance as a result of a different balance between tree growth and harvesting (European Parliament, 2018). To analyze the potential for carbon savings through wood pellet consumption, it is considered essential to also include landscape emissions resulting from forestry management. Only if the growth of carbon in forest areas exceeds the drain of carbon through tree harvesting can bioenergy produced from these forest areas be considered renewable carbon-neutral.

Research on forestry-based bioenergy systems has shown that the impact of increased bioenergy production depends amongst others on demand for timber and other products, price changes of timber, the context driving these changes as well as changes in forest management and land use (Cintas et al., 2017; Duden et al., 2017; Latta, Baker, Beach, Rose, & Mccarl, 2013; Rafal, Abt, Jonsson, Prestemon, & Cubbage, 2013). The impact of pellet production can only be analysed in relation to the existing forest products system. Pellets can be produced from primary feedstock (i.e. feedstocks harvested with the primary purpose of producing pellets) or secondary feedstock, (i.e. feedstocks that become available as a consequence of harvesting wood for other purposes, such as saw logs or pulp wood). Examples of the latter are logging residues left in the forest or sawmill residues. Use of primary feedstocks can be in competition with other industries, use of secondary feedstock usually deliver economic synergies (e.g. higher revenues for forest owners) but especially process residues may also be in competition

with other industries (e.g. panelboard producers). So far, the pellet industry sector in the US SE has not been constraint by wood fiber supply, with growth in wood inventories still outpacing removals (Forest2Market, 2017b). On a local level, additional demand for wood-products, including pellets, has resulted in increased competition for feedstocks such as industrial residues (Forest2Market, 2017b). Growth in pellet production has resulted in increased use of pulpgrade roundwood for pellet production, partly because of limited availability of industry residues and partly because of low prices for roundwood (Karen Lee Abt et al., 2014; Forest2Market, 2017b). On the other hand, low grade residues, such as forest residues, remain underutilized and available (Hoefnagels, Junginger, et al., 2014). Additional pellet production could result in better utilization of industry and forestry residues but also in increased consumption of harvested wood from production forests, whether this is in the form of roundwood or logging residues.

This study analyses the impact of increased pellet production in the US SE on feedstock allocation, the type of feedstock consumed in the pellet sector, the carbon flux in forest areas and costs of pre-treatment and transport of feedstock and pellets. Scenarios are included to analyse the impact of different levels of pellet production quantity. Based on the spatially explicit availability of feedstock and transport distances to export ports, the optimum location of additional pellet production will be modelled, thereby also resulting in an analysis of the changes in cost components related to the transport of feedstock and pellets. Additional scenarios are designed to analyse whether the impact of increased pellet production can be reduced by including limitations in new locations of pellet production, based on carbon growth in sourcing areas, or by including increased availability of logging residues. The combination of an integrated systems perspective with a spatial resolution high enough to allow for detailed analysis of regional differences can provide valuable information on the regional impact of increased pellet production. Increased pellet production and export is dependent on efficient production and supply chains, ensuring competitive prices of biomass to enable competition with fossil fuels. At the same time, while an open market is aimed at minimizing costs, sustainability impacts need to be guaranteed as well. Results will show the economic and sustainable limits of expanding

feedstock extraction in the US SE. Through the different scenarios used, this work will also show which policy decisions could increase the potential for sustainable production and exports.

5.2. METHOD

5.2.1. Geographical and temporal scope

This work will focus on biomass availability in the US Southeast (US SE). The definition of US SE used in this study includes the states of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North-Carolina, South-Carolina, Tennessee and Virginia. Whereas the focus will be on the US SE, products and feedstocks can move easily over state lines, and even internationally with relative ease. In order to account for any production shifts to other regions, and to avoid leakage of the impact of pellet production to other states, the modelling of resource availability and allocation was done on a US national level. This also includes imports and exports of the different types of wood-based products, which was set at FAOSTAT (Food and Agriculture Organization of the United Nations, 2019) reported trade volumes from 2014-2018 and then held constant at the 2018 levels through the remainder of the projection. The 126 export ports included in this study were taken from U.S. International Trade Commission port-specific trade data and represent 98% of the total value of forest products trade over the 2009 – 2013 time period (U.S. International Trade Commission (USITC), 2020). Pellets for the export market are modelled to be traded through a subset of ports, including ports through which pellets were actually exported as of 2017 (Southern Environmental Law Center, 2017).

Availability, demand and allocation of feedstock use for pellet production is analyzed until 2030. On the short to medium term, biomass trade in the form of wood pellets is expected to increase. On the longer term, developments in the bioenergy market become increasingly more uncertain, with an unknown future role of wood pellet imports into the EU.

5.2.2. General model description

This analysis of feedstock allocation and carbon flux in the US will be based on the Land Use and Resource Allocation (LURA) model (Latta et al., 2018), developed to link specific locations of forest biomass supply to locations of demand through supply-side logistics. Feedstock availability in the model consists of primary feedstocks based on Forest Inventory and Analysis (FIA) statistics (Roesch & Reams, 1999), primary residues in the form of logging residues as well as secondary residues consisting of by-products of manufacturing processes (Figure 5.1). Yearly changes in demand of forest products in the US, such as timber, pulp, paper and bioenergy, were modelled after exogenously projected macroeconomic developments, based on 2019 Annual Energy Outlook (AEO) projections (U.S. Energy Information Administration, 2019a), while changes in forestry feedstock supply resulted from tree growth and harvest levels in the previous year. The AEO projections were based on the reference scenario, assuming no new policies to mitigate climate change. Growth rates of forestry biomass were kept stable. Stand productivity increases as a result of improved forest management were therefore not included, even though historic trends point at significant improvements. Between 1953 and 2013, annual timberland growth increased with 112%, on an only 3% larger forest area (Oswalt, Smith, Miles, & Pugh, 2020).

Roundwood classified as sawlog has to be at least 2.4 m long and have a diameter at breast height of at least 23 cm in the case of softwood and 28 cm in the case of hardwood (U.S. Forest Service, 2019; Waddell, 2010). A maximum number of defects is generally specified in regional standards. Pulplogs is defined as roundwood that does not meet these quality standards but does contain a minimum of 50% sound wood fiber by volume (USDA U.S. Forest Service, n.d.; Waddell, 2010). Each plot can be harvested either through clear-cut harvesting or through thinning, which is modelled in the form of removal of 35% of the standing volume in a plot. This is a separate decision in every modelling run, independent of previous harvest operations, although future harvesting decisions are indirectly impacted by a change in feedstock availability on harvested plots. The proportion between total thinning and clear-cuts needs to be maintained, based on the

historic proportion as indicated in the FIA inventory data. Logging residues are generated alongside logging activities and consist of damaged and degraded small-diameter timber and tops and branches. The roundwood portion of logging residues consists of an assumed defect proportion of 3% of total logging volumes, except for Washington, Oregon, Montana and Idaho which have ownership-level estimates based on sampling of logging sites in these states (Martinkus et al., 2019). The amount of biomass available in the form of tops and branches depends on the type of tree and the tree size and was based on FIA methodology (Burrill, Elizabeth A.; Wilson, Andrea M.; Turner, Jeffery A.; Pugh, Scott A.; Menlove, James; Christiansen, Glenn; Conkling, Barbara L.; David, 2018). The carbon sequestered in sawlogs, pulplogs and logging residues is assumed to be emitted to the atmosphere at the moment of harvesting. This is a simplification which does not account for actual use or alternative scenarios. In reality, for instance, sawlogs used for timber production result in the storage of carbon for a considerable time and logging residues which are not utilized will either be burned in forest areas or will decay naturally over a longer period. This simplification is estimated to have a large impact on the absolute carbon flux calculated but only a small impact on the comparison between different pellet production scenarios, making it justifiable for the purpose of this work.

The supply of both primary and secondary feedstocks is spatially explicitly covered in the model. Primary feedstock is available at the locations of 150000 measured FIA plots, of which 35000 in the US SE. The spatial locations of demand and supply of secondary residues supply are based on actual locations of the different wood-based products industries. The mill locations and capacity data were updated from the 2365 facilities included in the original LURA database, as described in Latta et al. (Latta et al., 2018), to a total of 3365 facilities. The biggest changes were in hardwood lumber mills locations which increased from 290 to 1207. These updates to the original LURA mill database came largely from University of Georgia's Wood Demand Research Program and the RISI Mill Asset Database (RISI, n.d.). The pellet production quantities for the export market in 2014 – 2017 were updated based on pellet production statistics taken from the RISI Mill Asset Database and Forisk Wood Bioenergy US Project List (Forisk, n.d.; RISI,

n.d.). For each industry, the different types of feedstock used for production were assessed, as well as the secondary feedstocks generated during primary production, as illustrated in Figure 5.1. Some production processes, including pellet production, require the generation of heat for feedstock drying. This heat is assumed to be provided by the combustion of biomass, thereby contributing to total feedstock requirements. For pellet production, no distinction is made between different feedstock types whether these are used for heat production or end up as part of the final product. The precise quantity of feedstocks used and produced can be found in Appendix D.1. Allocation of feedstock from supply locations to demand locations is done for every yearly iteration, based on an economic optimization at system level without any form of foresight. This optimization includes the costs required to transport feedstock to mill gates and pre-treat it for further processing. This includes the costs of feedstock transport from forest plots to mill and from mills to mills. For those products being exported, including pellets also costs of transportation of products to ports is included. Costs of harvesting and chipping is also included in the case of sawlog and pulplog consumption. The model only allocates for lowest system costs and does not consider differences in feedstock prices or paying capacities of specific industries. Detailed information on LURA inputs and methodology can be found in Latta et al. (2018).

Figure 5.1 – Primary feedstocks used for the production of wood-based products and energy (blue arrows), secondary residues generated during primary production (brown arrows) and secondary feedstocks used for the production of wood-based products and energy (green arrows) in the LURA model.

5.2.3. Scenarios

Three variables were selected that have a major impact on feedstock availability and allocation to pellets: the variation in pellet export quantity, the locations of future pellet mills and the availability and utilization of logging residues (see Figure 5.2 and Table 5.1).

Figure 5.2 – Overview of the different scenario approaches used. Nationwide demand for other products is included to illustrate the quantity compared to pellet production. The pellet production as shown in this figure only applies to pellets produced for the export market, predominantly produced in the US SE. The production quantity of pellets for the domestic market is very minor compared to export pellets and is included in the Bioenergy category. A complete overview of demand development for the different products can be found in Appendix D.2.

Table 5.1 – Overview of the scenarios used in this study

Scenario	Inclusion of logging residues	Method of pellet mill expansion	Quantity of pellet exports in 2030 (Mt)
Zero pellets	No	Costs	0
Reference – Low	No	Costs	10
Reference – Mediumⁱ			20
Reference – High			30

i. The Reference – Medium scenario is used to show detailed results in the remainder of the article. When referring to the Reference scenario in the remainder of the article, an export quantity of 20 Mt in 2030 is implied.

Scenario	Inclusion of logging residues	Method of pellet mill expansion	Quantity of pellet exports in 2030 (Mt)
Carbon – Low	No	Carbon	10
Carbon – Medium			20
Carbon – High			30
RefLogRes – Low	Yes	Costs	10
RefLogRes – Medium			20
RefLogRes – High			30
CarbonLogRes – Low	Yes	Carbon	10
CarbonLogRes – Medium			20
CarbonLogRes – High			30

5.2.3.1. Variation in export level

Demand for wood pellets for export was varied exogenously: to capture the uncertainty in future pellet demand, three different projections were used. Pellet demand was assumed to increase linearly, varied in three different projections. In recent years, pellet exports from the US have increased from 1.9 Mt in 2012 to 6.9 Mt in 2015 (Thrän et al., 2017). Growth stalled in 2016 and 2017 as major demand markets in Europe slowed down, but increased again in 2018 with demand being picked up in several European countries (Canadian Biomass, 2019). Pellet exports increased with 970 kt between 2017 and 2018, and with 880 kt between 2018 and 2019 (U.S. Energy Information Administration, 2019d; USDA Foreign Agricultural Service, 2020). Future pellet production and export developments are uncertain, depending on market and policy developments. Fingerman et al. have reviewed export potentials as analyzed in different literature studies (Fingerman et al., 2017), resulting in a range of 0 – 28 Mt in 2030. The different projections used in this study therefore represent the full range of likely pellet export quantities. The Medium projection, considered the reference scenario, was based on a yearly increase of about 1 Mt of exported pellets, totaling 20 million Mt in 2030. The Low and High projections capture the uncertainty of future developments, ranging between almost no additional growth and a higher linear growth rate, amounting to 10 and 30 Mt of exported pellets in 2030 respectively. Next to these scenarios, a scenario without pellet production (Zero pellets scenario) was included as a baseline, in which pellet production

for export remains stable at 7 Mt between 2017 and 2019 and then reduces to 0 from 2020 onwards.

5.2.3.2. Driver of expansion

Across the entire modelling run, manufacturing locations of all industries are unchanged, with only the manufactured quantity per location changing from year to year. An exception to this modelling approach is the yearly addition of new locations of pellet mills. Considering the significant increase in total pellet manufacturing, it was not considered possible to achieve production increases solely by assuming capacity increases at existing locations since this would result in unrealistically large increases at individual mills. Total annual pellet production at existing locations is therefore capped at 9 Mt in the LURA model, the pellet production capacity in the US South at the end of 2019 (U.S. Energy Information Administration, 2020). Since the locations of pellet plants are based on the situation at the end of 2017, this still allows production at existing pellet plants to expand from the 7 Mt in 2017. Furthermore, although the total production quantity is fixed, manufacturing quantities of individual pellet plants are allowed to change based on relative cost effectiveness, as will be explained in more detail in section 2.4.3. The model used in this study focusses on feedstock allocation and does not include other cost factors such as capital costs of manufacturing facilities. Additional expenses for capacity expansion or building new pellet mills is not included, and therefore plays no part in the design of total manufacturing expansion. Additional pellet production beyond the 9 Mt will be placed at new locations from 2020 onwards. These new locations are modelled to be of a fixed size, as was dictated by modelling limitations. The creation of a set of potential locations will be further explained in section 2.4.3. For the method of actually selecting a new location from this set, two different approaches were used.

- The Cost optimization approach was used for the reference scenarios, and was based on market-driven expansion, with new mills being placed wherever costs are the lowest. For each of the potential new location the model first evaluated the potential logging residue supply costs from the prior year market solution radiating out from the mill site in €/g/dry tonne

increments until the required mill capacity was met. It then calculated the weighted average feedstock cost for the site including grinding, hauling forest to mill, and hauling mill to port. The potential mill location with the lowest weighted average feedstock cost was chosen and the process repeated until the desired number of new production sites were met. In each case the least cost export destination port capacity was increased to coincide with the mill capacity expansion.

- The Carbon constrained approach presumes the existence of policies prohibiting the use of feedstock from areas with a positive carbon flux, being the sum of carbon sequestration through tree growth (negative flux) and carbon removals in harvested trees (positive flux). In this approach, the net change in live tree carbon within a two-hour round trip hauling distance from each potential new mill location was calculated using the prior period harvesting activity and current period forest growth. The sites were then ranked by highest carbon growth rate and new locations chosen from the top of list. The least cost export location capacity was also expanded to meet the new production at each facility

5.2.3.3. Inclusion of logging residues

Logging residues are of lower quality, contain more contaminants and produce pellets with a higher ash content, and are therefore a suboptimal feedstock to use for pellet production. Therefore, the standard analysis was based on no utilization of logging residues. At the same time, utilizing this feedstock would reduce the amount of roundwood required for pellet production and could greatly contribute to the GHG efficiency of producing energy from wood pellets. Harvesting and mobilization of residues requires several processing steps such as the piling of residues into slash piles, drying of these piles for an extended period, subsequent loading of residues by grabbing biomass and chipping at roadside before transport. A specific issue with logging residues furthermore is contamination with sand and leaves, especially in the lower part of slash piles, preventing the collection of every last bit of feedstock. These mobilization steps require the development of new supply routes and procedures, while the potential biomass is of low value compared to the sawlog part of forests. For these reasons, the assumption was made that only 25% of the calculated availability of logging

residues can be mobilized cost effectively. This is on the conservative side when comparing with studies on the recovery rates of harvest residues. In a review study, Thiffault et al. have calculated an average recovery rate of 52% with a standard error of 18% across 68 studies, of which 17 studies are based on sites in the US (Thiffault, Béchard, Paré, & Allen, 2015). This study however also concludes that recovery rates are higher in the Nordic countries, Finland, Norway and Sweden than in Canada and the United States. The reasons for this are hypothesized to be high policy support, technological learning and uniformity of Nordic softwood plantations facilitating machinery tasks (Thiffault et al., 2015). The additional removal of nutrients from forest areas was assumed to be small. After harvesting, slash piles of tops and branches are presumably left to dry for an extended period. This allows for the decomposition of leaves, providing nutrients back to the soil while facilitating collection of the remaining wood (Rudolphi & Gustafsson, 2007; Thiffault et al., 2015). The use of logging residues in pellet plants could require adaptations since logging residues are expected to have a higher content of contaminants such as sand, leaves and twigs, providing a less clean feedstock. Consumption of logging residues is however considered feasible in a mixture with other residues or feedstocks, for instance to provide the heating fuel required or as a minor share in finished pellets. This is supported by examples in practice, in British Columbia for instance, forest residues accounted for 17% of feedstock used by pellet plants in the first quarter of 2017 according to (Wood Resources International LLC, 2017).

Varying these two variables results in the creation of different scenarios, summarized in Table 5.1. The Reference scenario was based as much as possible on business as usual, i.e. excluding the use of logging residues, and selecting new pellet mill locations based on lowest costs of all cost components included in the LURA model. The Reference scenario in combination with a pellet demand for export of 20 Mt is considered the most likely scenario based on current policies and pellet production trends and will be used to highlight the impact of expansion of pellet production. The other scenarios will be used to analyze the impact of uncertainty in total pellet demand and the potential impact of policies steering the location of pellet mills and the use of logging residues.

5.2.4. LURA Methodology

5.2.4.1. Feedstock allocation based on a total of cost components

The model optimization in this work is based on a lowest total cost principle, minimizing the total of cost components for all harvested, pre-processed and transported commodities and products. This total cost optimization determines the allocation of commodities to processing mills and is done for every yearly iteration. Total costs consist of a combination of harvesting and chipping costs, costs of hauling of feedstock from forest plots or mills and costs of transport of products from or to export ports if applicable.

Both harvesting costs and chipping costs are only required for sawlogs and pulplogs. In the case of harvest costs, the costs are highest for the first tonne and decrease with increasing harvested quantity per hectare. In principal no distinction is made between harvesting and chipping costs of pulplogs and sawlogs. This could, however, result in very unrealistic modelling of feedstock allocation compared to actual market dynamics. For instance, this lack of distinction would mean that clear cutting of large plots of pulplogs and sawlogs results in lower costs than thinning of only pulplogs, since costs are a function of harvested quantity per hectare. To prevent the extensive and unrealistic consumption of sawlogs in pellet manufacturing and other industries, additional downgrade costs of 19 €/dry tonne were included in case sawlogs are used by industries not requiring high quality wood, such as the pellet, pulp and paper industries.

Hauling costs of both forestry feedstock and products were calculated based on the travel distance and permitted speed on actual road networks. Calculations were based on a speed equal to the maximum speed. Total costs are a combination of a distance-based component, consisting of fuel costs, and a time-based component, consisting of hourly trucking costs including trucker wages, benefits and truck lease. Roundtrip costs were calculated by doubling one-way costs, assuming a simplified equal fuel efficiency and include 15 min. loading and unloading time. The cost factors used in the calculation are based on (Latta et al., 2018) and were converted from dollar to euro using the average exchange rate over 2019 (X-rates, 2019).

See Appendix D.3 for more details on the costs of different components and the full set of cost factors used.

5.2.4.2. Production locations

The production locations of all products except exported pellets were taken from a combination of sources (Latta et al., 2018; RISI, 2012; Smith, Rice, & Ince, 2000; Spelter, 1996; Spelter, McKeever, & Toth, 2009; U.S. Energy Information Administration, 2012b, 2012a). For an overview of currently active pellet mills, two different datasets were compared, a Forisk Wood Bioenergy US Database, updated as of October 13th, 2017 (Forisk, n.d.) and a RISI Wood Pellet Capacities database, updated at the beginning of 2018 (RISI, n.d.). The Forisk database contains information on the operational status of pellet plants whereas the RISI database contains information about the grade of pellets produced, either industrial export or domestic pellets. A cross-section of the two lists was made, keeping only the pellets plants that are operational or under construction and are producing industrial pellets. Several pellet plants were only included in one of the two databases. In these instances, additional information was used to determine the status and pellet grade, for instance from company websites. This resulted in the addition of three pellet plants to the list. The final list of pellet plants includes 23 pellet plants in the Southeast of the US, with a capacity to produce 8.3 million tonne pellets and 17 pellet plants in other US regions with a much smaller total capacity of 0.7 million tonne pellets.

5.2.4.3. Capacity changes

Demand changes of all products except pellets for the export market, to be referred to as "other products" were accommodated at existing production locations, with production capacities updated yearly to simulate responses to market changes. Capacity changes depend on the total demand change from year n to year $n+1$ and on whether a specific mill is cost competitive compared to the average of all mills in year n . A mill is classified as cost competitive if the costs of producing a commodity at the specified mill are lower than the average costs of all commodities produced at all mills. In case total demand for a specific commodity decreased, all mills performing below average are depreciated proportionally in that year. If total demand decreases, capacity at the poorly performing mills is depreciated with 5%

while capacity at all cost competitive mills is increased proportionally to accommodate the remaining demand, following the existing methodology in the LURA model (Latta et al., 2018).

For pellet mills producing for the export market, this method was applied to the existing pellet mills. Additionally, new mill locations were added each year, selected from a collection of potential locations, to accommodate the very large increase in total manufacturing quantities. The potential new mill locations were created in ArcGIS by overlaying a 50km grid on the US SE. The choice for a 50 km grid was a balance between adding enough potential locations to cover regional differences in feedstock availability and transport requirements, while keeping the model runtime manageable. Placing pellet plants in the centers of the grid cells resulted in a set of 545 potential new locations. The production of pellets for the export market at existing pellet mills, capped at 9 Mt, includes 17 potential production locations outside of the US SE. Since the new pellet mill locations are placed only in the US SE, the additional manufacturing quantities, especially in the Medium and High scenarios, will result in a large burden placed in one region. All new pellet mills were assumed to have a fixed capacity, depending on the total demand modelled. To model the Low pellet demand, one small mill of 100 kt/y production was added every year. The small increase in manufacturing in the Low scenario could also be realized by a modest growth of existing mills. However, the decision was made to use a uniform method for all three projections and to therefore also add new locations in case of Low pellet demand. In the Medium and High projections pellets mills of 400 and 800 kt/y were added respectively, two or three mills each year, following a linear growth curve as best as possible (see Figure 5.3). The size of 800 kt/y represents the size of the largest currently operating pellet plant in the US SE (Biomass Magazine, 2020). The production increases required to realize 30 Mt in 2030 are so significant that this requires a serious upscaling of pellet production activities. The assumption was made that this would be done using the largest feasible size of pellet plants. The size of 400 kt/y is representative of the average size of pellet mills currently producing for the export market, and is considered a good assumption to use in a projection of continuous business as usual increases in total production (Biomass Magazine, 2020; Southern Environmental Law Center, 2017)

The LURA model allows for the results to deviate 0.5 % from exogenous demand levels to account for potential inconsistencies as port and production facilities depreciate or expand over time that could result in an infeasible solution. The objective function structure minimizes those deviations yet it results in slightly different modelled growth rates and pellet mill additions in each scenario. Figure 5.3 shows the growth rates and the number of pellet mills added in each year for the Reference scenario. As explained previously, the selection of locations differs in the cost-based and carbon-based approaches, resulting in a different set of new pellet mills. The modelled locations of pellet mills in the different scenarios can be seen in Appendix D.4 together with the modelled growth rates in different scenarios.

Figure 5.3 – The modelled growth rates observed for the reference scenario. Also shown the number of pellet plants added each year in the Low scenario (of 100 kt size), the Medium scenario (of 400 kt size) and the High scenario (of 800 kt size).

5.2.5. Input data

5.2.5.1. Feedstock availability

Spatially explicit availability of biomass within the United States was estimated based on the Forest Inventory and Analysis (FIA) program of the US Forest Service. For the conterminous United States, data was collected from over 150 000 FIA plots, with measurements of just under 5 million trees. FIA plots are the result of random selection of a location within hexagonal cells positioned in a grid across the entire conterminous U.S. and consist of four subplots totaling 0.07 ha in size. FIA plot data contains additional information on the type of land and trees in the plots as well as data on ownership type.

Data on the type and size of trees is used to distinguish between softwood (SW) and hardwood (HW) and between pulplogs and sawlogs.

The development of forest stocks in future years was estimated by applying growth curves to existing forested areas. Growth rates are determined based on measured volume and age of plots and differ for unique combinations of productivity class, forest type and ecoprovince, which are areas with relatively consistent natural characteristics, including climate, geography, soil type and potential natural communities (Latta et al., 2018). Growth in the LURA model is limited to yield increases on existing forested plots and does not include land use change (e.g. conversion from agricultural or fallow land to plantations or conversion from natural pine stand to pine plantations) or forest management changes (e.g. changes in productivity due to improved fertilizer application or tree species selection and genetic engineering) (Duden et al., 2017; Noormets et al., 2015). Furthermore, potential impacts of management practices, such as fertilizer application, were not included. An exception to this is the impact of tree thinning. As a result of thinning, the average density of remaining trees is reduced, which then changes the growth equation for subsequent years. Total growth on each plot in every yearly time-step was recorded, distinguishing between net growth of standing trees, regenerative growth after a clear cut and additional growth resulting from thinning.

All feedstock types included can be seen in Table 5.2, including secondary residues. The assumed moisture content of residues is a modelling condition, used to model mass transfer of residues between different processes, and does not reflect realistic moisture contents. Availability of secondary residues was included by assuming fixed output of residues per production process, as can be seen in Table D.2 in Appendix D.1. These production processes, and the output in the form of by-products, were assumed to remain unchanged until the end of the modelling timeframe. Total mill feedstock availability changes in every iteration as production quantities and locations of wood and paper industries change.

Table 5.2 – All feedstock types included in this study

Feedstock	Type	Used for pellet production	Assumed moisture content
Sawlogs	Primary	Yes	47%
Pulplogs	Primary	Yes	47%
Logging residues	Forest residues	Yes	47%
Mill chips	Industry residues	Yes	0%
Shavings	Industry residues	Yes	0%
Sawdust	Industry residues	Yes	0%
Hog fuel	Industry residues	No	0%
Bark	Industry residues	No	0%

5.2.5.2. Feedstock demand

Future demand for other products was modelled after the Reference case of the US EIA 2019 Annual Energy Outlook (AEO). These AEO scenarios are modelled after economic and demographic trends while assuming unchanged laws and regulations (U.S. Energy Information Administration, 2018a). The initial 2014 demand levels for forest products were determined based on FAO statistics on production, exports and imports as well as various data sources on the location and capacity of several forest product mills (R. C. Abt, Galik, & Henderson, 2010; RISI, 2012; Smith et al., 2000; Spelter, 1996; Spelter et al., 2009; U.S. Energy Information Administration, 2012b, 2012a). A complete list of total base capacities and demand, as well as projected demand changes can be found in Appendix D.2. Pellets produced for domestic use were assumed to fall within the AEO projections for bioenergy development. Future demand for pellet export was modelled separately from non-pellet demand, in the Low, Medium and High projections, as explained above.

5.2.5.3. Costs

The LURA model calculates cost of pellet production excluding the price of feedstock, the most significant component of total supply chain costs of pellet production. To provide a better comparison with pellet prices, feedstock cost components were added to the total costs. For sawdust, shavings and chips, FOB (free on board) prices of residues were added, the price that sawmills get paid for their feedstock by consumers such as pellet mills, based on data from 2017, taken from (Forest2Market, 2017b). The FOB prices were averaged for a small difference between softwood and hardwood and were converted from short tons to metric tonnes and to Euros, using an exchange rate of 0.9 €/€ (X-rates, 2019), resulting in feedstock costs of 57 €/dry tonne of chips and 40 €/dry tonne of sawdust and shavings. For pulplogs and sawlogs, stumpage prices were added as feedstock costs, also from 2017 to provide a fair comparison with residue prices, taken from (Greene, 2019). Costs were again averaged over softwood and hardwood, converted to tonnes and Euros, as well as converted to dry tonnes using the same conversion rate as assumed in the LURA model, and as shown in Appendix D.1. This results in feedstock costs of 28 €/dry tonne for Pulplogs and 81 €/dry tonne for Sawlogs, excluding additional cost of harvesting and chipping, which were taken from the LURA model as explained previously. Costs for sawlogs furthermore includes the downgrade costs. Pelletizing and shipping costs vary less with feedstock specifics and were also included based on Chapter 2. In the case of pelletizing costs there is a small cost difference between the use of coarse or finely ground material, caused by the additional capital costs for a grinder. This was included by assuming different pelletizing costs for sawdust and shavings (Chapter 2).

Further details on costs calculations, as well as modelling results for the different scenarios are given in Appendix D.3.

5.3. RESULTS

The model was solved for each of the 12 scenarios along with a no export pellet scenario for the years 2014-2030. Model results are consistent through the "historic" period 2014-2017 based on actual trends, with scenario-specific variation occurring through the "projection" period of 2018-2030. The LURA results are nationwide and for all 20 final demand and intermediate products however we focus on the variation in export pellet feedstock and cost characteristics in the US SE in our results.

5.3.1. Feedstock composition

5.3.1.1. Feedstock use for pellet production in the Reference scenario in the US SE

Results for feedstock composition show that pellet production in 2014 - 2017 is largely based on milling residues, mainly SW shavings (ranging between 37-44%) and SW sawdust (ranging between 16-20%), see Figure 5.4. This can be explained by the fact that costs of all residues (logging and milling) in the LURA model are lower compared to costs of pulplogs and sawlogs since these feedstocks do not require harvesting and chipping. On the other hand, costs of collection and grinding of logging residues are significant. Grinding of logging residues is assumed to take place in forests, using diesel-powered grinders. Chipping of roundwood at mills, using electricity, is more cost effective. The ground logging residues can however be transported more efficiently, thereby lowering hauling costs. At short distance, the high costs of collection and grinding of logging residues can outweigh costs of pulplogs and sawlogs, at long-distance hauls use of logging residues is cheaper. Cost optimization results in increased production at mills located close to sources of available mill residues. Logging residue availability, however, depends on the production of timber and is therefore inherently limited. As lumber production increases until 2030, the utilization of mainly softwood mill residues for pellet production increases as well. Milling residue utilization by the entire forest products sector in the US SE increases from 70% in 2015 to 85% in 2030 in the reference scenario. The majority (70%) of total milling residue use is allocated to export pellet production. As shown in Figure 5.4, the increased availability and use of mill residues, including mill

chips, shavings and sawdust, is not enough to cover the entire increased production of pellets, most notably in the High projection. This results in increased use of hardwood pulplogs and to a lesser extent other roundwood types. In the reference scenario, even in 2030 the total share of residues is larger than the roundwood fraction, making up 77% of total feedstock use. The High projection very clearly shows the limits of mill residue availability, with the share of roundwood increasing from 18% in 2020 to 55% in 2030. The large consumption of pulpwood can partially be explained because of the additional downgrade costs of sawlogs and partially by the fact that demand of other industries is larger for sawlogs than for pulplogs, resulting in a larger availability for pulplogs for pellet production. The type of feedstock used depends on the availability close to pellet mills. The locations of pellet mills producing for the export market, as modelled using the Reference and Carbon approach, are visualized in Appendix D.4.

Harvesting costs decrease as harvested quantity increases and therefore there is a cost advantage to hauling large quantities from the same forest plots. This is not limited to pellet production, combined harvesting for pellet production and other industries results in lower system costs. Still, the spatial aspect of transport distance from forest plots to pellet mill locations quickly outweighs lower harvesting costs. Another aspect to consider is the balance between clear cut harvesting and thinning. As a result of the higher overall proportion of clear-cuts, as modelled in this study, roundwood used for pellet production is predominantly taken from clear-cuts, and only 14% of total sawlogs and pulplogs used are harvested through thinning. In real world practices, clear-cut harvesting is done based on a combination of different demand sources of sawlogs and pulplogs. The demand for low value feedstock for pellets is not expected to be the main driver behind clear-cuts (Forest2Market, 2015). In the modelling results, of the total sawlog quantity harvested in all scenarios and years, only 5% is harvested from plots on which the share of pulplogs harvesting is less than 10%.

Figure 5.4 – Feedstock used for pellet production in the US Southeast: historic (2014–2017), and in the Reference scenario for the Low, Medium and High projections in 2020, 2025 and 2030. Use of logging residues is excluded in this scenario.

5.3.1.2. Total feedstock consumption for all forest products in the US SE

When comparing use of feedstock for pellet production with other industries, the allocation of mill residues to pellets becomes apparent, as shown in Figure 5.5. In the Reference scenario, a minor share of total pellet production is sawlog- or pulplog-based, 20% for pulplogs and 3% for sawlogs in the reference scenario in 2030. The LURA model does not restrict the use of sawlogs for pellet production, however it does include additional downgrade costs of €19/t when consuming sawlogs in pulp, panel, or pellet operations, thereby favouring the use of pulplogs instead of sawlogs. In the case of clear-cut harvesting, limited local demand for sawlogs and high local demand for pulplogs, it could, however, be the case that sawlogs are a local by-product of pulplog demand and are the most cost-effective feedstock option to allocate to pellet production.

In the Medium and High projection, of all milling residues used in the forest products sector, the largest part is allocated to the production of export pellets. Part of this increase in process residue use can be explained by the increased total utilization of these residues, as explained in the previous section. However, as Figure 5.5 shows, part of the mill residues used for export pellet production were previously used in other production processes. This displaces part of the burden of increased pellet production onto other products.

Part of the increase in sawlog and pulplog consumption in the US SE is caused by a relative shift of lumber production towards the US SE, caused by the extensive availability of feedstock. Still, the additional demand for pellets also has an impact on total demand for roundwood. When comparing feedstock use in 2015 to the results for 2030, total pulplogs and sawlogs feedstock removal in tonnes increases to 121%, 126% and 137% in the Reference Low, Medium and High scenarios respectively. The largest part of this increase is caused by increased demand for other products than pellets. When compared to the Zero pellet scenario, the pulplog and sawlog removal increases to 101%, 107% and 116% in the Low, Medium and High scenarios respectively. The difference between these projections can be fully explained by the added pressure of additional pellet production on the forest system. As will be shown in section 3.2, changes in total harvesting has an impact on the net carbon flux.

Figure 5.5 – Roundwood and mill residues used for pellets and other products in the US Southeast, in the Reference scenario for the Low, Medium and High projections in 2030. Note the differences in scale of the vertical axis

5.3.1.3. Additional feedstock scenarios in the US SE

The impact of the scenarios with logging residues as additional feedstock source can be seen in Figure 5.6, showing the feedstock consumption in 2030 in the Medium projection. In the two scenarios including logging residues, the share of roundwood used for pellet production has reduced

considerably. The inclusion of logging residues can contribute to the feedstock consumption of pellet mills, making up 18% of total pellet production in 2030 in the CarbonLogRes Medium scenario and 22% in the RefLogRes Medium scenario. The use of logging residues largely replaces roundwood production. Interestingly, roundwood use for pellet production is higher in the CarbonLogRes scenario, assuming carbon-constrained selection of new pellet mill locations (10%), than in the RefLogRes scenario using cost-based expansion (3%). This could be explained by the fact that the carbon-based scenario results in the placement of pellet mills in areas with large availability of roundwood as opposed to close to mills with logging residue availability. Total residue consumption is also largest in the CarbonLogRes and RefLogRes scenarios, caused by the additionally available source of logging residues. When excluding logging residues, total residue consumption is largest in the Carbon scenario, although the difference with other scenarios is marginal. Use of logging residues also replaces the consumption of chips for pellet production to a significant extent. Of all the residue types, the use of softwood mill chips is the largest contributor to pellet production. The availability of logging residues replaces a significant share of softwood mill chip consumption, in turn increasing the share of mill chip use in other industries. Hence, stimulating logging residue availability decreases consumption of roundwood as well as competition with other industries for mill residues.

Figure 5.6 – Feedstock consumption in 2030 in the US Southeast for the Medium projections (20 Mt pellet production) across different scenarios varying the inclusion of logging residues and the allocation of new pellet mills.

5.3.2. Carbon flux

The increased demand for pellets as well as other wood-based products results in carbon flux changes in any scenario or projection (see Figure 5.7 and 5.8). In the US SE, where the majority of lumber is produced, as well as pellets for the export market, the increase in flux results in the region becoming a net source of emissions. This is based on an atmospheric approach, with positive carbon flux signifying an increase in atmospheric stock (carbon emissions) and negative flux signifying a decrease in atmospheric stocks (carbon sequestration) and based on the assumption that, consistent with IPCC methodology, all removals are counted as emissions. As shown in Figure 5.7, the transition from source to sink in the US SE occurs early in all scenarios. In the Reference 20 Mt scenario, net emissions increase until about 2019. After 2019, emissions start to decline as a response to increased

sequestration rates, partly because of increased growth of regenerated forests. Already after 2022, however, emissions start to increase again and continue to increase across the modelling horizon. A large part of the carbon flux increase compared to 2015 is caused by changes in the demand for other products, as can be seen when comparing the flux developments to the Zero pellet scenario. The difference between the Zero, Low, Medium and High projections can fully be accounted to pellet production. The modelling assumptions of overall increasing demand for timber, pulp and paper have a significant impact on total results. In the recent years since 2015, market reports have indeed signalled an increase in demand for forest products, although the exact growth cannot be quantified (Food and Agriculture Organization of the United Nations, 2019; Howard & Liang, 2019). Should demand for forest products develop significantly different from the modelling assumptions in this study then this would have a large impact on the feedstock availability for the pellet industry and the carbon flux results.

There are ways to minimize the impact of increased production of wood-based products, as shown especially for the LogRes scenarios in Figure 5.7. The lowest increase in flux is observed for the CarbonLogRes scenario, resulting in a total flux in the US SE of 10, 15 and 26 Mt CO₂/y. In this scenario, the difference between the Zero and Low scenarios is 1.2 Mt CO₂/y, the difference between Low and Medium 3 Mt CO₂/y and the difference between Medium and High 12 Mt CO₂/y. When comparing the different scenarios for exports of 20 Mt pellets in 2030, the LogRes scenarios result in avoided carbon emissions. The scenarios without logging residues result in net emissions in the US SE for the Reference and Carbon scenarios of 21 and 20 Mt CO₂/y. respectively. For the RefLogRes and CarbonLogRes scenarios, the total emissions are quite a bit lower, at 14 and 15 Mt CO₂/y respectively. The benefit of including logging residues is even larger when comparing the results for the entire US, resulting for instance in additional sequestration of 11 Mt CO₂/y. in the RefLogRes scenario compared to the Reference scenario.

Figure 5.7 – Total flux developments in the southeast of the US until 2030 – for a no pellets scenario and for the twelve scenarios varying total export quantity, inclusion of logging residues and allocation of new pellet mills. Negative fluxes indicate a net increase in forest carbon stocks while a positive flux signifies net emissions to the atmosphere.

The difference between scenarios was also analysed for the entire United States, as opposed to only the US SE, to account for displacement of manufacturing of products other than pellets, as shown in Figure 5.8. For the Reference scenario, the additional production in the Medium case results in increased emissions of 18 Mt CO₂/y in 2030, compared to the Zero pellets scenario in the entire US. This is much smaller for the Low scenario, at 5 Mt CO₂/y and much larger for the High scenario, resulting in additional emissions of 33 Mt CO₂/y compared to the Zero pellet scenario. The comparison between the Reference 2015 and the Zero pellets 2030 results shows an increase of 13 Mt CO₂/y in the entire US even in a scenario without pellet

production. The flux difference between these scenarios in the US SE alone amounts to 6 Mt CO₂/y.

Figure 5.8 - Flux in the entire United States (Total) and the southeast United States (US SE) – in the Reference scenario in 2015 and in the no pellets scenario plus the four different pellet scenarios for Low, Medium and High projections in 2030

Negative fluxes indicate a net increase in forest carbon stocks while a positive flux signifies net emissions to the atmosphere

5.3.3. Spatial carbon flux

The carbon flux resulting from harvesting and tree growth varies significantly throughout the US SE, depending largely on harvesting patterns. In areas with high demand for roundwood, harvesting of pulplogs and sawlogs tends to be high, resulting in positive carbon flux. In forested areas with little demand from timber and pellet industries, tree growth exceeds harvesting, resulting in negative flux. Figure 5.9 shows the regional flux difference between the various scenarios and the Zero pellet scenario, for the 20 Mt pellet export scenarios in 2030, aggregated to 50x50km areas. Pellet production has an impact on spatial flux throughout the entire US SE, with positive and negative impacts dispersed over the entire area. Not surprisingly, areas where flux has increased relative to the Zero pellet scenario (more carbon emissions) coincide quite well with the locations of pellet production, as shown in Appendix D.4, although there is by no means a perfect spatial match since regional expansion of pellet production has a spatial impact on other industries as well.

In the Reference scenario, areas with negative flux are located close to export ports, especially in Virginia and North Carolina. The Carbon scenario by comparison results in less negative flux in these states and more negative flux in Mississippi and Kentucky. Areas with positive carbon flux are scattered across the entire US SE, in the Reference scenario predominantly in South Carolina, Tennessee and Alabama and in the Carbon scenario predominantly in North and South Carolina as well as the inland areas of Kentucky, Tennessee and Arkansas. Both the RefLogRes and CostsLogRes scenarios result in less areas with negative flux and more areas with positive flux. These impacts are most pronounced in Virginia and North Carolina for the RefLogRes scenario compared to the Reference scenario. For the CarbonLogRes scenario compared to the Carbon scenario positive flux impacts are observed mainly for Mississippi, Alabama, Georgia and the border area between Virginia and Kentucky.

Figure 5.9 – Total CO₂ flux difference in the 20 Mt scenarios in 2030, of the different scenarios compared to the Zero pellets scenario, in the Southeast US, on a 50x50km grid. A positive carbon flux in this figure signifies increased emissions to the atmosphere.

The total amount of sawlog and pulplog harvesting, as well as the spatial distribution does differ significantly in the four scenarios, as shown in Figure 5.10. In the Reference and RefLogRes scenarios, logging for pellet production takes place close to export ports, especially the Chesapeake and Savannah ports. Considering the large distance from some pellet plants to export regions, compared to the much smaller sourcing areas of feedstock, it is not

surprising that mills close to export ports have a cost effectiveness advantage. In the Carbon and CarbonLogRes scenarios, logging for pellet mills occurs in the more inland regions of Mississippi, Tennessee and Kentucky.

Figure 5.10 – Harvesting of pulplogs and sawlogs for pellet manufacturing in the Southeast US for the 20 Mt scenarios, on a 50x50km grid.

5.3.4. Exploration of carbon footprint of pellets delivered to Europe

When compared to total supply chain emissions, the carbon flux increases shown in this article are significant. The smallest modelled carbon impact is observed for the CarbonLogRes Low scenario. The increase in emissions of 1.2 Mt CO₂/y for 10 Mt pellets translates to 17 g CO₂/MJel when assuming an energy content of 17.5 GJ/t and efficiency of electricity production of 40%. This is lower than total supply chain emissions of pellets imported to Europe from the US SE, as calculated in Chapter 4, amounting to 38 g CO₂/MJel for roundwood and 25 g CO₂/MJel for sawmill residues¹². The results for the Reference scenario show much larger carbon emissions. The 18 Mt difference between the Medium and Zero pellet scenario translates to 257 g CO₂/MJel, a factor 10 larger than supply chain emission for pellets from sawmill residues.

¹² Assuming 50 km feedstock transport, 200 km pellet transport and shipping between Savannah and Rotterdam. See Chapter 4 for more details.

Wood pellets imported into the EU are held to GHG reduction standards compared to a fossil fuel comparator, set to 183 g CO₂/MJ in case of electricity production and 80 g CO₂/MJ in case of heat production, as established in the RED II (European Parliament, 2018). For pellets to contribute to renewable energy targets or receive financial support, total supply chain GHG savings should be at least 70% for installations with a rated thermal input >20 MW starting from 1 January 2021, compared to these comparators. This will increase to 80% for installations starting operation from 1 January 2026. The additional carbon flux as calculated for the Reference scenario above, of 257 g CO₂/MJel, exceeds the fossil fuel comparator of 183 g CO₂/MJel entirely, thereby pointing at increased emissions compared to fossil fuel use and thus an exceedance of sustainable pellet production levels. An important disclaimer is that these results are sensitive to modelling approaches and can only be considered while acknowledging the methodological limitations. For instance, the inclusion of land use and forestry management impacts, or different assumptions on demand for forest products, could result in different findings, as discussed in more detail in section 4.2.

An aspect to point out is that the RED II methodology to calculate GHG savings of wood pellet consumption does not include the biogenic emission as calculated in this study. Emissions from carbon stock changes caused by land use change have to be included in supply chain emissions, but this is not the case for emission resulting from carbon stock changes as a consequence of altered management such as landscape emission impacts within forest areas (European Parliament, 2018). At the same time, biomass use is only eligible for financial support and can only contribute towards renewable energy target if changes in carbon stock are included in reporting of land use, land use change and forestry emissions or if systems or laws are in place to ensure that carbon stocks are maintained or increased in forest sourcing areas. Land use and forestry emissions do not need to be allocated to pellet production, which would be a very difficult exercise since forestry emissions are impacted by the entire forest products system, but instead have to be accounted for in national or sub-national laws or country commitments to GHG emission reductions (European Parliament, 2018). The results shown above therefore do not affect whether pellets would meet the

GHG reduction thresholds but do emphasize the need to carefully manage landscape carbon emission impacts in order to assure sustainable production of wood pellets.

5.4. DISCUSSION AND CONCLUSIONS

This article has analysed the impact of increased pellet production in the US SE on feedstock allocation, the type of feedstock consumed in the pellet sector, the carbon flux in forest areas and costs of pre-treatment and transport of feedstock and pellets. The feedstock portfolio use for pellet production changes quite significantly in the different projections until 2030 compared to current use. In all scenarios and projections, the utilization of milling residues increases. The utilization of residues increases significantly between the Reference Zero and Low scenarios, from 59% to 82%. Increased pellet production quantity results in an additional marginal increase, to 85% and 86% in the Reference Medium and High scenarios respectively. The consumption of milling residues for pellets exceeds the consumption of sawlogs and pulplogs in the Reference Low and Medium scenarios. In the High scenario, however, the share of pulpwood increases strongly to about half of the total feedstock consumption. This is considered undesirable from a sustainability perspective since research has shown that carbon parity times are much longer for additional harvest of roundwood than for industrial residues (Hanssen, Duden, Junginger, Dale, & Van der Hilst, 2017; Jan Gerrit Geurt Jonker et al., 2014). The increased utilization of roundwood in the 30 Mt scenario, caused by insufficient availability of residues, even in case of a growth in timber production as assumed in this work, indicates that this pellet production quantity exceeds the current limit of the wood products sector in the US SE.

5.4.1. The impact of increased pellet production on feedstock use and carbon flux

The balance between carbon sequestration through tree growth and carbon emissions through tree harvesting is negative in the model base year, with sequestration exceeding emissions, both in the entire US and in the US SE. In the US SE, however, carbon emissions start to exceed carbon sequestration,

in all scenarios from 2015 onwards, including the Zero pellets scenario. The largest difference between the scenarios can be observed for the different quantities of pellet production in 2030. At low levels of pellet production and expansion, up to 10 Mt pellets in 2030, there is little difference in carbon flux between the scenarios. At high levels of pellet production, of 30 Mt, there is a considerable difference from the assumed pellet mill expansion strategy and use of logging residues between scenarios. The pellet industry should mind the impact of production increases and should take this into consideration in the development of future additional capacity.

Our results show that the increased production of pellets results in increased harvesting. When pellet mills are using roundwood, this is often sourced from stands harvested primarily driven by timber production, with the lower quality roundwood being used for pellet production (Dale et al., 2017). The LURA model however makes no distinction between different quality trees and differences in paying capacity between industries, and results show additional fellings from plots solely harvested for pellet production. The wood products market in the US SE already makes good use of processing residues and the remaining availability of residues is limited (USDA, 2017c, 2017a, 2017b). Increased demand could therefore result in additional fellings, just as in our modelled results, either directly harvested for pellet mills or in the form of indirect wood use change for other industries previously using residues. On the other hand, these processing residues are mainly used as industrial fuel (USDA, 2017c, 2017a, 2017b). Replacing this by low grade, underutilized, logging residues such as tops and branches could increase the availability of processing residues for pellet production, thereby avoiding additional harvests. Furthermore, the distinction between roundwood and residues is partially defined by the end use of feedstocks, with unmerchantable roundwood being classified as logging residues. Because pellet production has lower quality standards, increased demand provides the opportunity to fully merchandise stands that are being harvested. Demand for pellets could incentivize the collection of these lower quality trees and other underutilized wood sources such as tops and branches. Part of the harvested wood allocated to pellet production in our results is therefore expected to be classified as logging residues in the current wood

products market. This again emphasizes the need to focus on optimizing the mobilization of wood resources in order to utilize forest resources as best as possible and to reduce the carbon impact of pellets.

When including mobilization of logging residues, most of the roundwood use for pellets can be displaced. This would also significantly lower the impact on carbon flux in forest areas (as logging residues are no additional harvests and are assumed to be emitted instantly also in scenarios where no pellets are used). The impact of optimizing for carbon stock in sourcing areas of pellet mills on the other hand is relatively small. Results from the Carbon scenarios show differences in regional spread of roundwood logging, but show very little impact on the total flux in the US SE. In other words, limiting the removal rate within sourcing areas of wood pellet mills might lead to new pellet mills being located in areas with higher carbon stocks, but overall removals across the entire US SE would remain the same. Only by increasing the overall feedstock availability, for instance through increased mobilization of logging residues, can the share of roundwood used for pellet production be reduced significantly. This leakage effect, of allocation of more sustainable feedstocks to pellet production pulling away from other sectors, has also been shown by Fingerman et al. (Fingerman et al., 2017). This work concludes that when applying sustainability criteria to all wood product sectors in the US SE, there is no additional feedstock available for pellet production.

Increased mobilization of residues and limits to pellet mill expansion based on carbon growth in sourcing areas reduces the severity of carbon flux impacts, but still leaves a considerable additional carbon impact that -in the most extreme case - would nullify supply chain GHG savings compared to their fossil counterparts. The spatially explicit impact of increased pellet production varies for different regions and years. On a system level, for the entire US SE landscape, increased pellet production affects the overall balance between carbon removals and sequestrations, resulting in net carbon removals in all scenarios with especially large increases observed for the High scenarios. This research therefore clearly points at hard limits of potential pellet production within the modelled system of feedstock availability and demand, that can only be stretched by reductions in demand for other products or by improvements in forest management intensity

and forest area. The exact limits however depend to a large extent on total demand for forest biomass and on land use and management responses of demand changes. The limits to growth therefore need to be explored in more detail in future work, by including different demand scenarios and the potential impact on land use and management of the entire forest products system.

The increased consumption of roundwood results in increased costs of pellet production supply chain components in 2030. This impact is especially large for the High scenarios without logging residues. These cost estimates do not account for increased feedstock prices as a result of increased demand and competition. Pellets imported into Western Europe depend on subsidies to compete with fossil fuels. Significant increases in pellet production, reaching 30 Mt in 2030, might well result in price levels that make production and trade infeasible. As such, economic constraints may well limit wood pellet production to levels well below 30 million tonnes. The increase in costs as pellet production quantities increase points at the difficulty of including potential future market developments in current decision-making. This also shows that current costs are not a good indicator for future costs. Location scoping of pellet plants should not only be focused on current feedstock and transport costs, but also on longer term feedstock availability.

5.4.2. Recommendations for future research

The results of modeling studies, such as presented in this study should be interpreted carefully. One of the major simplifications of this study was the assumption of constant forest area. Changes in forest management and intensity were also not included. In the US South, timberland area has increased a marginal 2% between 1953 and 2012. In the same period, the total growing stock has, however, grown significantly with 107% (Oswalt et al., 2020; United States Department of Agriculture, 2014). To place the CO₂ flux increase in forest areas as found in this study in perspective, a simplistic assumption was made that the growing stock increase was linear between 1953 and 2012 and continues until 2030. This results in an estimated growing stock in 2030 which is 14% larger than in 2014, the start of the modelling timeframe used in this article. When applying this growth rate to the quantity of carbon

sequestration in tree growth in the US SE in 2014, by 2030 an additional 22 Mt CO₂ would be sequestered annually. This exceeds the carbon flux increases in all of the Medium scenarios as well as the total carbon flux increase in the CarbonLogRes High scenarios, but not in the other High scenarios. In reality, further stock increases are not occurring by default, and are driven by changing management practices due to e.g. changing profitability of different forest product, which have not been assessed in this paper.

This article has used a simplified assumption of immediate emissions of all harvested wood. The impact of increased production of pellets and other wood products should be assessed by including production and waste scenarios of all relevant products. Increased production of timber could help to mitigate climate change, for instance through increased temporary sequestration of carbon and through the substitution of carbon-intensive materials such as concrete (Gret-Regamey, Hendrick, Hetsch, Pingoud, & Rüter, 2008). Energy recovery operations during the disposal of waste wood products could furthermore result in the production of bioenergy, thereby reducing the demand for primary or secondary feedstocks. As pellet production is part of a larger system of forest management and feedstock demand and supply, climate change impacts can only be assessed by analyzing the entire system of wood products demand, forest management and substitution of non-renewable resources (Berndes, Cowie, Englund, Simmons, & Thiffault, 2019). Only then can conclusions be drawn on the GHG emission impacts and benefits of wood pellet production and consumption. Further work needs to be done on the comparison of different alternative (no-) use scenarios, including alternatives for increased or decreased wood, paper and pellet production as well as alternative scenarios for use or decomposition of forestry biomass. This is especially relevant considering the economic impact of the ongoing COVID-19 pandemic. The uncertain development of the entire wood products sector could then also be included through the use of different scenarios.

Additional demand for pellets could be a driver for increases in forest area and improved management practices resulting in increased sequestration. The LURA model does not optimize for sustainability of forest production or the maximization of carbon stock, nor does it include market feedback

responses. Especially in the US SE, where a large share of forests is owned by small private landowners, the extent of forested area is largely determined by demand for forest feedstock. Landowners are expected to make decisions on the replanting of forest areas partly based on expected future income, and increased demand for feedstock is expected to result in land use and management response (R. Abt, Abt, Henderson, & Kanieski da Silva, 2019). An existing study on the impact of additional pellet demand on land use changes and forest dynamics for instance shows that increased demand may result in a larger growth in timberland area, mainly caused by large increases in pine plantation area (Duden et al., 2017). The total demand for pellets in this study is however significantly smaller at 12 Mt pellets, thereby not exploring the limits to growth as much as in his paper. Research by Jonker et al. (J G G Jonker, Hilst, Markewitz, Faaij, & Junginger, 2018) on the impact of improved management practices shows that a forest plot with additional thinnings after 10 years results in a better carbon flux than the conventional scenario of thinning only after 15 years.

The pellet industry is a low margin industry with a considerably lower paying capacity for feedstock than for instance the timber industry (Lechner & Carlsson, 2014). Timberland developments will never be based only on expected pellet demand but also on demand for higher value sawlogs and the overall portfolio of forest products. This study has modelled the allocation of woody biomass based on availability and lowest production costs. In reality, market prices are likely too high to allow for the use of saw timber (as projected in the High scenarios). The inclusion of paying capacities could have impacted the outcome of this study. Modelling the paying capacities of different industries could result in the shift of pellet production to other areas, where competition for feedstock is lower. The allocation of feedstock based on costs instead of prices is a limitation, but one that fits the scope of this paper in which market effects, such as supply and demand-based price and profit developments, were not considered. Future research should ideally combine price developments with a spatially explicit assessment of market responses in terms of land conversion and management changes.

If total demand decreases, capacity at the poorly performing mills is depreciated with 5% while capacity at all cost competitive mills is increased

proportionally to accommodate the remaining demand, following the existing methodology in the LURA model (Latta et al., 2018).

In this study, the US SE is rapidly becoming a source of carbon emissions instead of a sink, even without the addition of pellets. An important contributing factor to this is a modelled shift of sawtimber production from other regions in the US to the US SE, attracted by an abundance of timber and low production costs. In the LURA model, in every yearly iteration, part of the production is shifted between different locations. In case of increasing demand, capacity at mills with higher than average costs is depreciated with 5% while capacity at mills with lower than average costs is increased proportionally to accommodate the required demand. The model does not include limiting factors to production relocation such as sunk capital or the availability of infrastructure or qualified personnel, thereby likely overestimating the actual rate of spatial shifts in production capacity. Because actual forest industries are strongly embedded in current regions, we expect that the sawtimber demand and associated negative trend from a carbon sink towards a carbon source are overestimated by the LURA model. Recent figures show that the US SE currently is still a carbon sink, with a growth-to-drain ratio of pine sawtimber of 1.26 in 2019 (Forisk, 2020). However, as a result of increased production capacity in the US SE, the growth-to-drain ratio of pine sawtimber is expected to reduce to 0.95 by 2025, when new sawmills and pellet mills will have come online (Forisk, 2020). Trends in reality may point in the same direction of the US SE transitioning from a carbon sink to a carbon source. If this is the case, and if this is the result of a spatial shift in production capacity, the increase in harvest levels in the US SE will be compensated by decreased levels elsewhere in the US. The purpose of this study is not to mimic or model the overall dynamics in the forestry landscape of the US SE, but to focus on the addition of pellet demand to the region. The impact of pellet demand on total emissions is considered robust, even with slightly different trends of production of timber and other products. Although the proximity of timber mills does impact the availability of residues, the conclusion that increased pellet production will result in significantly increased consumption of sawlogs and pulplogs is not likely to change.

Pellet demand and feedstock availability were modelled only until 2030 in this study. For the period beyond 2030, the general findings of this study remain relevant as well. Uncertainty in demand developments for various products increase with a longer modelling timeframe but are inherently uncertain in any case. The scenarios used in this study are designed to reflect that uncertainty in terms of pellet demand. On the longer term however, the re-growth of forest areas and also land-use changes become even more important to consider. The uncertainty in developments of demand for other products becomes larger also, impacting feedstock availability and carbon landscape impacts.

5.4.3. Policy implications

The RED II requires the inclusion of carbon stock changes in GHG emission commitments for biomass to be eligible for support for countries that have ratified the Paris Agreement (European Parliament, 2018; Netherlands Enterprise Agency, n.d.). If this is not the case, which could be a relevant scenario for the US, management systems need to be in place to ensure that carbon stocks and sink levels are maintained (European Parliament, 2018). Additional legislation of Member States also highlights the importance of carbon stocks. The criterium for co-firing of biomass in the Dutch subsidy scheme SDE+ for instance requires the management of forest units for long-term conservation or expansion of carbon stocks (Netherlands Enterprise Agency, n.d.). These requirements prescribe the management of carbon stock in forest areas, but without specifying the specific spatial boundaries. In case of roundwood consumption, the actual forest areas harvested for pellet production will change continuously in response to wood availability and demand, making it difficult to establish a suitable unit area. As shown in this article, the spatial flux is partially the result of the modelled location of new pellet mills, although the spatial impact of existing wood and paper manufacturing locations is much larger, even at high wood pellet production scenarios. Removals for other purposes (timber, pulp, etc.) still strongly dominate the carbon flux trends. These findings show that defining the geographical system boundaries has a strong impact on whether individual pellet mills can meet the criterion of maintaining forest carbon stocks; and that there is little point in applying such a criterion only to a small subsector, instead of holistically to all wood removals

in a given area. The disproportionately large share of flux increase in the US SE compared to the entire US is indicative of the dominance of the region in not only pellet production but the entire wood products industry. This also means that the US SE, more than other regions, bears the burden of CO₂ impacts of increased wood, paper and pellet production. The net carbon flux in the entire US remains well below zero and forest regions outside the US SE remain a net carbon sink under the increased production potentials used in this study. The fact that the total carbon flux depends so strongly on the chosen boundaries reflects the need to clearly define spatial boundaries. The impact of increased production of pellets or other feedstocks on the long-term can only be assessed by consequently analysing the same spatial areas over time.

Our work has shown that a promising way to minimize additional landscape carbon emissions resulting from increased demand for forest products is to increase the total feedstock availability through mobilization of underutilized feedstock. Mobilization of logging residues is an important measure to lower carbon impacts and investing in development of new supply chains to utilize this feedstock source provides opportunities on the much longer term than 2030 (J G G Jonker et al., 2018). Logging residues are more difficult to collect and process than e.g. pulpwood and need dedicated supply chains. Such chains have been developed and used for decades in e.g. Scandinavia, for the production of wood chips in district heating plants (Ericsson & Werner, 2016; Thiffault et al., 2015). In British Columbia, logging residues make up 17% of total feedstock production of pellet producers, providing evidence for the feasibility of utilization of these residues in pellet mills (Wood Resources International LLC, 2017). Increased consumption of this potential source of biomass is only expected should prices for pulplogs increase beyond the paying capacity of pellet producers, or when supported or enforced through policies.

Use of logging residues is favored over use of roundwood in the RED II criteria, through the exclusion of GHG emission allocation to residues (European Parliament, 2018). Should total supply chain emissions become a limiting factor, utilization of logging residues could increase the export potentials of pellets to the EU. EU member states also have the option of

including additional criteria for production of bio-electricity or heat on top of the RED II and could therefore require e.g. the use of a minimum share of residues from forestry operations. Alternatively, a premium system could be designed to provide a monetary incentive to use low-grade biomass. In any case, new supply chains need to be developed to facilitate the increased mobilization of logging residues, for instance through integrated harvesting of high value timber products with logging residues. This would enable cost-effective mobilization of low-grade forest biomass. Not only would this improve the sustainability of wood pellet production and trade, on the longer term this would furthermore provide access to an affordable source of available biomass, potentially decreasing future supply chain costs and emissions. The pellet production sector should seize the opportunity to utilize more logging residues. Reducing carbon emissions associated with pellet production is important to ensure regulatory compliance as well as improve societal approval. By focussing on sustainable feedstock selection, the pellet sector will improve future business environments.

This research has shown the importance of including demand for other forest products in an analysis of feedstock availability for pellet production. Hardwood and softwood lumber production increases until 2030, resulting in more availability of mill and logging residues, however, not enough to cover the even larger increase in feedstock demand in certain scenarios. The production of 30 Mt of pellets in all scenarios results in very significant increases of carbon flux as well as supply chain costs. Based on this work, the conclusion is drawn that market interventions based on local or regional growth-to-drain ratios of forest resources are not very effective if they are only applied to the pellet sector. Ensuring that carbon stocks do not decrease within defined spatial boundaries should be safeguarded by the entire wood products industry and not just by pellet producers, who only have a limited impact on regional forestry management and practices. This work shows that a scenario with 30 million tonnes of pellet demand additional to growing demand for timber and paper products, without use of logging residues, is likely to result in positive carbon fluxes which are unlikely to be compensated by forest area or management improvements. Further research is needed to confirm this, ideally spatially explicit, as these impacts may vary strongly between different sourcing regions.

Synthesis and conclusion

CHAPTER 6

6.1. RESEARCH CONTEXT

The use of biomass for the production of bioenergy, biochemicals and biomaterials is considered pivotal in reaching GHG emission reduction targets and transitioning to a more sustainable energy and materials system. As a result, biomass demand has developed rapidly since the early 2000s in regions such as the EU and is projected to increase substantially still in the future. (Daioglou et al., 2019; European Commission, 2018; IPCC, 2019; Mandley et al., 2020; Matzenberger et al., 2015; Zappa et al., 2019). Between countries there are significant differences in biomass availability, cost of supply, and demand for different end-uses. Long-distance international trade of biomass from areas with large availability to areas with large demand is, however, limited by unfavourable characteristics, such as a high moisture content and low energy density. Pelletization has developed rapidly in the past two decades, and creates a solid biofuel with a much higher density than untreated biomass, allowing trade over a larger distance (Obernberger & Thek, 2010). Pelletization furthermore results in a higher quality and more homogenous fuel, increasing the suitability for a range of different applications (Hoefnagels, Searcy, et al., 2014; Obernberger & Thek, 2010; Thrän et al., 2017; Vera & Hoefnagels, 2019). The share of wood pellet imports is likely to increase with growing demand for bioenergy and materials (Bioenergy Europe, 2018, 2019c). In this thesis, the focus lies on pellets for industrial markets, transported in bulk and used to produce energy on a large scale. Pellets consumed in residential markets, for instance the use of bagged pellets in small scale pellet boilers, are not considered. When using the term "pellets", this is in reference to wood pellets, unless explicitly stated otherwise.

The use of (imported) wood pellet is amongst other factors limited by three major constraints: costs, sustainability criteria and feedstock availability. The industrial market currently depends on subsidies to utilize wood pellets, subsidy support is, however, limited and competition with other renewable energy technologies, such as wind and solar energy, is becoming increasingly difficult as these options are still experiencing cost reductions and do not have fuel costs. A way to improve the business case for pellets is to lower prices through supply chain optimization. Costs of wood pellets,

and the impact of varying cost factors have been analysed in several studies (Boukherroub et al., 2017; Ehrig et al., 2014; Hoefnagels, Searcy, et al., 2014; Sikkema et al., 2010; Thek & Obernberger, 2004). Results from these studies point at several potential optimization strategies, such as pre-treatment close to the source of biomass (Hoefnagels, Searcy, et al., 2014), the combination of pelletization with torrefaction (Sikkema et al., 2010), increasing plant capacity (Biomass Magazine, 2017a; Boukherroub et al., 2017; Thek & Obernberger, 2004) and selection of affordable feedstocks such as herbaceous biomass, industry residues or low-quality logs (Boukherroub et al., 2017; Hoefnagels, Searcy, et al., 2014; Sikkema et al., 2010). Market data on prices of wood pellets is available, with spot prices, CIF Western Europe, fluctuating around 130 €/2017/t in recent years, and contract prices fluctuating around 150 €/2017/t (FutureMetrics, 2018; Chapter 2). However, what is still missing is a good understanding of the cost structure of wood pellets. Increased comprehension of supply chain cost components and the potential for cost savings is necessary to analyze potential supply chain optimizations.

A second aspect to consider is the sustainability of pellet production and trade. The main sustainability concerns and risks of pellet supply chains are supply chain GHG emissions, emissions from carbon stock change in forests and impacts on soil and biodiversity, for example due to the removal of harvesting residues. Supply chain GHG emissions or energy consumption have been analysed by a number of authors, often focussing on the impact of changing supply chain parameters (Hoefnagels, Searcy, et al., 2014; Sikkema et al., 2010; Uasuf & Becker, 2011). Emission changes in forests and impacts of wood pellet production on forest dynamics and ecosystem services have also been analysed by several authors (Dale, Parish, Kline, & Tobin, 2017; Duden et al., 2018, 2017), with impacts including both negative impacts, such as a reduction in biodiversity or natural forests, and positive impacts, such as an increase in total forest area. These studies are lacking an analysis of how sustainability limitations restrict the potential to produce and trade wood pellets.

A third important consideration is the availability of feedstock. Local demand for biomass should be given priority in order to avoid distortion of local markets. Studies that have assessed the availability of biomass often include

the impact of policies, constraints and scenarios on biomass availability for local use and trade (Fingerman et al., 2017; Fulvio et al., 2016; Lamers et al., 2015; Skog & Stanturf, 2011; Welfle, 2017). Some studies also distinguish between different resource types, mobilization and logistics requirements and the impact on costs, thereby analysing availability in relation to cost thresholds (Fingerman et al., 2017; Fulvio et al., 2016). Current literature lacks, however, a system analysis of feedstock availability for pellet production in relation to other wood products industries.

It is considered essential to analyse costs and carbon implications of pellet production as well as availability of feedstock in sourcing areas, since all of these aspects determine the potential for pellet production to contribute to a more sustainable energy system. Furthermore, this must be analysed for entire supply regions and not just for individual supply chain designs in order to assess the consequences of shifting to new production areas as demand increases.

6.2. RESEARCH OBJECTIVE AND RESEARCH QUESTIONS

The objective of this thesis is to analyse the current and potential future impact of increased wood pellet production and international transport to the EU on costs and GHG emissions. The following research questions are addressed:

1. What are the factors that determine the cost and GHG emissions of long distance international lignocellulosic biomass feedstock supply chains and how can supply chains be optimized, including the pre-treatment options pelletization and torrefaction?
2. How do economic support policies and supply chain GHG emission constraints affect supply potentials of imported woody biomass and what is the impact on long distance international trade?
3. If export supply potentials are exploited in the future, what could be local impacts on costs, GHG emissions and carbon fluxes in forest areas, when considering the interaction with non-energy markets?

Variations in supply chain costs are analysed by accounting for regional and temporal differences in cost factors, by including the impact of supply chain design and by analysing the uncertainty of available data on cost components. The impact of supply chain design on costs and supply chain GHG emissions is assessed by considering structural differences in cost factors between supply regions and by accounting for different transport distances resulting from a spatially explicit representation of feedstock availability. Spatially explicit availability and resource allocation of feedstock for pellet production is assessed in relation to the competition and synergies with other wood-based products industries in the same production region and is used to analyse carbon impacts of increased pellet production in forest areas.

6.3. SUMMARY OF THE RESULTS

Chapter 2 addresses research question 1 by assessing the costs of pellet production components and total supply chain costs uncertainty in literature, combined with a techno-economic assessment of the impact of cost optimization strategies on supply chain costs. Chapter 2 demonstrates that many factors in pellet cost estimates in literature can be traced back to just a few initial studies that are between 14 and 16 years old. The lack of actual data from existing pellet plants means there are few data points available to assess cost uncertainty and the impact of supply chain design. Total supply chain costs in the analysed literature studies varies widely between 88 and 279 €/t pellets, with average and median values of 163 and 153 €/t respectively. The variation in underlying cost components is large, up to a factor 10, most notably in the costs of pelletizing, feedstock, handling & storage in ports and shipping. Results of the techno-economic analysis show that part of cost differences can be explained by difference in supply chain design and temporal variation in cost factors. The analysed literature studies, for instance, show lower costs for pellets made from sawdust and shavings than for pellets made from pulpwood, and slightly lower costs for pellet produced in Canada than in the US. Shipping costs vary a factor 4.2 between the different studies. This factor is reduced to 3.5 when correcting for differences in shipping distance and to a factor 1.8 when including historic differences in charter rates and fuel costs.

An analysis of the impact of locations of existing pellet plants in the US SE, using regional availability of feedstock and including competition with nearby pellet plants, shows significant differences. When assuming a similar pellet plant size of 50 kt/y, feedstock transport costs, for instance, vary between 0.3 and 10 €/t pellets. The impact of supply chain design and economies of scale was analysed by comparing production in a 50 kt/y plant, using sawmill residues, transporting pellets via road and shipping in a Handysize ship (23000 t pellets/ship) to production in a 500 kt/y plant, using pulpwood, transporting pellets via rail if located close to a rail network and shipping in a Supramax ship (47000 t pellets/ship). Results show that the total cost benefit is only about 6 €/t pellets for the 500 kt/y pellet plant, caused by a trade-off of increased costs for feedstock and feedstock transport and reduced costs of pelletizing, inland pellet transport and shipping, resulting from economies of scale. For different pellet plant locations analysed, results range between a cost saving of 38 €/t pellets and a cost increase of 31 €/t pellets for the large pellet plant compared to the small pellet plant.

Chapter 3 Provides input to answer research questions 1, 2 and 3 through an analysis of import potentials of wood pellets produced in several countries and transported to Western Europe, based on regional availability of primary and secondary lignocellulosic feedstocks and including several sustainability and market limitations. In all countries, forestry and agricultural residues are partially used already, most notably in Brazil, reducing the availability for pellet production. A significant share of the technical potential is furthermore excluded from the sustainable export potential due to lack of compliance with the assumed sustainability criteria, such as the amount of residues that need to be left on the field. The largest overall limiting factor is the lack of infrastructure, assuming it takes time to develop facilities to collect and pelletize biomass. In all countries except the US, there is hardly any pelletizing infrastructure, limiting export potentials in the near future. In a Business as Usual (BAU) scenario in 2030, the total export potential amounts to 270 PJ, mainly contributed by Indonesia (37%) and Brazil (27%). In the US, in the BAU scenario, the assumption was made that sustainability criteria were applied to the entire forest sector, and not just pellet production, completely eliminating the potential. In a High Export (HE) scenario, the total potential is

estimated to be 1580 PJ, largely supplied from the US (29%), Brazil (26%) and Indonesia (22%).

The calculated potentials were assumed to be limited by maximum supply chain costs and GHG emissions of pellets delivered to Western Europe. When using the upper range of pellet prices between 2009 and 2016, of about 140 €/t pellets, only 1 and 6 Mt pellets of the total potential remains in 2030 in the BAU and HE scenario respectively. If market prices were to increase to 170 €/t pellets, this would increase the import potential to 2 – 18 Mt in the different scenarios. GHG results show that total emissions are lowest in Brazil and Ukraine, and highest in Indonesia. Large contributing factors are feedstock cultivation emissions, pre-treatment, inland transport and shipping. Results differ in the various case study countries as a result of different feedstock types, requiring different levels of fertilizer use to substitute for nutrient removals, differences in transport distances from sourcing regions to export ports and differences in GHG emission factors of electricity production. When using the GHG reduction threshold of 70% for electricity production, the entire potential from Indonesia and most of the potentials from Kenya and Brazil are excluded, leaving a total of 8 Mt pellets in the BAU scenario and 65 Mt pellets in the HE scenario. The 80% target is only met by pellets from the Ukraine and part of the potential from Brazil, resulting in a total potential of 6 – 34 Mt pellets in the two scenarios in 2030.

Chapter 4 explores the impact of spatially explicit feedstock availability and transport distance on costs and emissions of imported wood pellets from several case study countries and is used to answer research questions 1, 2 and 3. The largest contributor to total emissions is the pelletizing component. Country differences in emission intensity of electricity production have a significant impact on results, explaining why total emissions are low in Lithuania and high in the nearby countries Latvia and Estonia. Another large factor is the emissions of shipping, which is the reason behind relatively low emissions of pellets from Canada SE and high emissions in the case of Canada SW, which is 15000 km further away from Western Europe. Brazil and the US SE have relatively low supply chain costs, largely caused by relatively low feedstock costs. Emissions of torrefied pellets (TOP) are lower than regular wood pellets (WP), a 12-24% saving in the case of pellets from

pulpwood and 2-10% in case of pellets from sawmill residues. Emissions of pellets from sawmill residues are 32 – 48% lower than emissions of roundwood pellets. Higher emissions for roundwood are due to silviculture and harvest emissions, the larger quantity of feedstock required because of the higher moisture content and grinding electricity requirements. Pulpwood pellets are slightly more expensive (90 – 280 €/t pellets) than pellets from sawmill residues (80 – 270 €/t). The large range of costs can be explained by the impact of inland transport distance. There is some correlation between costs and emissions. Large shipping and inland transport distances increase both costs and emissions. Part of the correlation is more coincidental, some countries with affordable feedstock, such as the US also happen to have low emission factors of electricity production.

Potential supply areas of pellets are determined by both cost and emission thresholds. A scenario of favourable cost developments, including lower cost factors and a high cost limit of 200 €/t pellets results in a total potential of almost 60 Mt of WP, largely from Brazil and the US, as explained by the much larger feedstock availability close to export ports compared to other countries. At the other end of the range, at assumed total costs of 125 €/t pellets, the total potential varies between 3 Mt in case of high cost factors and 28 Mt in case of low cost factors. A supply chain GHG emission reduction target of 70% results in a total potential of 61 Mt. A stricter target of 80% reductions lowers the total potential to 16 Mt in case of electricity production. This is reduced to just 1 Mt pellets in case of an 85% reduction threshold, unless supply chain GHG emissions can be reduced, for instance through a reduction emission factors of electricity supply. Since the production of TOP has significantly lower supply chain emissions, the total production areas and therefore potentials are increased at an 80% threshold, to 40 Mt in case of electricity production and 36 Mt in case of heat production.

Chapter 5 addresses research question 3 and analyses the impact of increased pellet production in the US SE until 2030, on feedstock allocation, the type of feedstock consumed in the pellet sector, the carbon flux in forest areas and costs of pre-treatment and transport of feedstock and pellets. In this chapter, spatially explicit locations of supply of forest biomass and industrial residues are linked to demand locations of pellets as well as other

wood-based products. The impact of uncertain ranges in future wood pellet production market developments were explored through three different scenarios of pellet production, ranging between 10 and 30 Mt in 2030, as well as through a scenario without pellet exports. Additional scenarios were developed, analysing the impact of additional inclusion of logging residues and optimization of pellet mill location based on either costs or total carbon stocks in sourcing areas. Results show increased use of pulplogs, and to a lesser extent, sawlogs as pellet export quantity increases. The increased consumption of roundwood can for the largest part be abated by additional utilization of logging residues.

Utilization of industry residues for the entire wood products sector increases in all scenario, for instance in the Reference scenario, increasing from an average 76% of utilization of mill chips, shavings and sawdust to a utilization of 85% in case of 20 Mt pellet production in 2030. The percentage of industry residues allocated to pellet production increases from 29% to 70% in the Reference scenario. This contributes to limiting the share of roundwood in pellet production but also pulls away residues from other industries, thereby impacting the sustainable sourcing of feedstock of these other sectors. This leakage effect must be considered when discussing the sustainability implications of pellet production. The increased utilization of roundwood, by the pellet industry as well as other industries which are projected to increase until 2030, results in an increase in carbon flux, defined as the sum of carbon extraction through harvested roundwood and logging residues and carbon sequestration through tree growth. In the US SE, in the Zero pellets scenario, the carbon flux increases with 16 Mt CO₂/year due to increasing demand for other forest products. In the Reference scenario, additional carbon fluxes are observed of 3, 12 and 30 Mt respectively in the different pellet export scenarios. The impact on carbon flux are somewhat reduced in the scenarios including logging residues, to 6 Mt in the RefLogRes scenario in case of 20 Mt pellet production for export. The selection of locations based on carbon stock does result in significant local impacts, changing the spatial patterns of pellet production and feedstock extraction, but has a much smaller impact on the total carbon flux in the US SE.

6.4. MAIN FINDINGS & CONCLUSIONS

RQ1: What are the factors that determine the cost and GHG emissions of long distance international woody biomass feedstock supply chains and how can supply chains be optimized, including the pre-treatment options pelletization and torrefaction?

The main factors that determine supply chain costs are feedstock (25-53%), pellet transport (8-23%) and shipping (6-19%), although this depends strongly on the specific supply chain design. For GHG emissions, especially the pelletizing step adds to total emissions (16-54%), followed by shipping (7-36%), feedstock transport (15-25%) and pellet transport (11-19%). Reducing costs through supply chain optimisation is complicated because of trade-offs between several cost components. Economies of scale, the production of torrefied pellets and the use of industry residues instead of roundwood could all result in cost savings. As will be explained in this section, total supply chain costs and cost saving potentials depend strongly on specific supply chain characteristics.

Supply chain costs and emissions of wood pellets depend on many factors. Varying one such factor, such as the production country or feedstock type, often impacts several if not all supply chain components. Underlying factors determining costs and emissions of supply chains include a number of aspects, such as the geographic locations of pellet production and consumption, the type of feedstock used to produce pellets, the size of pellet plants, available infrastructure and whether advanced pre-treatment technologies such as torrefaction are applied. Often, these aspects result in a trade-off between separate components. For instance, within established pellet production regions the search for affordable feedstock might result in a shift towards inland areas, avoiding competition with existing mills in coastal areas close to export ports. This could result in lower feedstock costs but higher transport costs.

Figure 6.1 shows the variation of **total supply chain cost for wood pellets** produced from roundwood at different locations and supplied to the port of Rotterdam, as assessed in Chapters 3 and 4. The largest contributor to supply chain costs, by far, is feedstock procurement. From a cost reduction

Figure 6.1 – Comparison of total supply chain costs for wood pellets made from roundwood for selected supply chain components. For transport costs, in Chapter 3, a different methodology was used for some countries, resulting in total costs of pellet transport costs for Indonesia, Kenya and Ukraine, including inland and international transport, and total costs of inland transport for the US, including feedstock and pellet transport. The results of Chapter 4 are based on a pellet transport distance of 500 km. For Estonia, Latvia and Lithuania a total distance of 300 km was assumed; the small size of these countries limits transport distances within country borders.

Optimizing supply chain design is complex, including several **trade-offs between components as well as trade-offs between optimizing for costs and optimizing for emissions**. There are no silver bullets that will guarantee a considerable reduction in costs or environmental impact of wood pellets. However, this work has resulted in a number of observations that should be considered when designing future supply chains. The addition of **torrefaction prior to pelletization** results in costs and emissions savings for most supply chains analysed. Cost savings, when normalized for the energy content of wood pellets, range between 6 – 21 €/t pellets for the different countries. The one exception to this is Brazil, where torrefaction results in a 9 €/t pellets cost increase. Torrefaction also has a positive impact on supply chain GHG emissions, resulting in 12-24% GHG savings for pulpwood pellets and up to 21% savings for pellets from sawmill residues. The combustion of released volatile compounds during torrefaction makes for a more efficient drying and pelletization process, slightly reducing the feedstock

requirement per unit of energy produced and therefore resulting in small cost and emission savings. Torrefaction results in more brittle biomass that is easier to grind. The additional expenditures for torrefaction equipment and additional electricity requirement are partly compensated for by reduced costs and electricity requirement of grinding. Total pelletizing emissions per unit of energy produced are in the order of 30% lower for torrefied pellets than for wood pellets. In addition, significant savings in supply chains of torrefied pellets are realized in the downstream logistics requirements after pellet production. The higher energy density of torrefied pellets reduces both costs and emissions of transport by truck, train or ship, offering large potential benefits for supply chains relying on long-distance shipping such as between Brazil and the Netherlands.

The impact of adding torrefaction to the pelletization process is still relatively uncertain since this has not been implemented on large scale. As a consequence, there is lack of empirical data on costs and emissions. The impact of torrefaction on the pelletization process and feedstock requirements is, for instance, relatively uncertain, relying on assumptions on processing efficiency and capital costs. This uncertainty is also reflected in mixed results in other scientific literature. Mobini et al. (Mobini et al., 2014) have analysed the impact of integration of torrefaction in a supply chain of pellet import from Vancouver to the port of Rotterdam. Their conclusions result in an increase of costs of torrefied pellets of 17% on an energy basis, caused by roughly a doubling in capital costs for a torrefied pellet mill. Thrän et al. (Thrän et al., 2016) compare economic and environmental properties of TOP and wood pellets made from different feedstock types and produced in different countries. Their results show significantly lower supply chain GHG emissions for torrefied pellets, ranging between about 24 – 45% savings. The costs comparison shows slightly lower cost savings, ranging between 0 – 34%.

The second optimization strategy that has the potential to result in lowered costs and emissions is the **use of industry residues instead of roundwood**. Using pulplogs requires harvesting and collection operations, on top of a stumpage fee to be paid for the right to harvest the wood. In case of industrial residue use, these costs are absorbed partially by the primary production

process that resulted in these residues. Market data of average prices paid by pellet producers in the US for feedstock shows very similar costs for different types of raw material (U.S. Energy Information Administration, 2020). In case of residues, however, these feedstocks have already been processed and dried to a certain extent, thereby reducing the input quantity required to produce dried pellets, as well as reducing expenditures on grinding and drying equipment and operating costs. In Chapter 4, costs of pellets from sawmill residues were found to have between 12 – 40 €/t pellets lower supply chain costs than pellets made from roundwood. When basing the calculation on market data from the US SE, a smaller cost benefit of 8 €/t pellets was found.

However, this optimization strategy works on paper but not always in reality, as the availability of residues is limited and depends on the extent of existing production processes of wood or agricultural products. Local conditions such as availability and competition of other demand sources affect prices of residues, making this cost reduction strategy uncertain and volatile to local conditions. In reality, pellet mills will often base their production process on a mixture of feedstocks, depending on regional and seasonal availability and prices. Future work on mapping spatially explicit production potentials should consider production locations of existing industries, and their feedstock demand and residues production potential. By focussing on feedstock availability in the site selection criteria of new pellet mills, including also low-value sources such as logging residues, supply chain costs could potentially be reduced.

Using residues instead of roundwood also results in lowered supply chain emissions, although this is not the result of market effects but largely the result of methodological standards used by researchers and policy makers. The main reason for industry residues to result in lower emissions is that all upstream processing steps are allocated to the primary production processes where these residues are generated. Chapter 4 shows lower supply chain GHG emissions when using sawmill residues instead of pulpwood, ranging between potential savings of 30 – 42% for pellets and 22 – 37% for torrefied pellets. What must be considered, however, is that there could already be an established local demand for residues. Additional

pellet production could in that case displace part of local usage, resulting in increased harvesting of wood for non-energy sectors as a direct effect of pellet manufacturing. From a sustainability perspective this is undesirable. Cascading use of biomass should give priority to the use of residues in higher value production processes, such as the production of materials, before being used for bioenergy. Therefore, the use of residues can only be said to result in reduced carbon impacts in case these feedstocks are underutilized by local markets. This could be the case for lower value residue types such as agricultural residues, logging residues and post-consumer wood waste, which should be focussed on by pellet producers developing new supply chains.

Increasing **pellet production quantities** in specific regions, such as the US SE, can have an **impact on costs and emissions**. The development of larger pellet mills could result in better utilization of economies of scale, specifically of pellet transport. This could include transport via rail instead of via road and transport overseas in larger ship types, potentially lowering costs and emissions, although this also depends on availability of rail and port infrastructure. As a result of economies of scale, supply chain costs for a 500 kt/y pellet plant were found to be, on average over multiple analysed locations, 6 €/t pellets lower than costs for a 50 kt/y pellet plant. Results vary widely for the different locations, between cost savings of 38 €/t pellets and increased costs of 31 €/t pellets for the large pellet plant. Increased pellet production could, however, also result in cost and emission increases not analysed in this thesis. Additional feedstock demand could result in new pellet plants being located in more inland areas, increasing the costs and emissions of pellet transport. Increased competition for feedstock, with other pellet producers or with other industries can result in increased prices, for new pellet mills as well as existing pellet mills. The specific impact of additional pellet production on supply chain costs and emission depends strongly on regional aspects, such as feedstock availability and availability of transport infrastructure, and should therefore be analysed spatially explicit. This is done in more detail for the US SE in the discussion of the third research question.

Optimization of current supply chain design has limited potential as explained above. The development of **new supply chains in emerging regions, based on low-value and low-cost feedstock** could potentially result in cost savings. In the US SE, logging residues are only partially collected and used. These residues are generated during harvesting practices and are, if not used, left in forest areas to decompose or are burned to prevent accumulation of dry biomass and subsequent increasing wildfire risk, and to prepare forests for plantation of new trees or alternative use. The carbon sequestered in this source of feedstock, therefore, will be emitted within a short time frame regardless of use by the pellet industry. Increased mobilization of logging residues could provide pellet mills with additional resources, for instance to provide the drying energy required during pelletization. Mobilization of logging residues requires the development of infrastructure for collection and transport of this feedstock from forest areas. These processing steps are likely time intensive and relatively costly, the potential for cost savings therefore is not directly imminent. However, costs could be reduced if improved, integrated, harvesting practices can be developed, collecting logging residues along with harvesting of sawlogs or pulplogs. Since logging residues currently are largely a wasted resource with low quality and low value, the feedstock costs after development of infrastructure and logistics practices could be significantly lower than alternative feedstocks.

This research has shown that **supply chains based on forestry resources in new emerging pellet production regions, such as Brazil, are not significantly more cost-effective than well-established production countries such as the US or Canada**. An interesting aspect, however, is a **potential shift to new regions in combination with the mobilization of affordable and low-carbon feedstock types**. A clear example of this is the potential use of sugarcane residues such as bagasse and straw in Brazil. Low labour and electricity costs make Brazil an interesting case study. The large sugarcane production sector results in the availability of large quantities of lignocellulosic residues, in the form of bagasse and straw. Part of this supply, especially bagasse, is used in sugar or ethanol production processes, to provide necessary processing heat and electricity (Cervi et al., 2019). However,

up until recently, large quantities of residues such as straw were simply discarded, often by ways of burning the residues in the sugarcane fields. These practices are now discouraged or even prohibited by law in several Brazilian states (Paraiso & Gouveia, 2015). Since these sugarcane residues are an available waste product with very low market value as of yet, pelletization of these residues would result in low cost and low emission pellets.

What this thesis has shown is the large impact of specific supply characteristics on supply chain costs and emissions. This makes it complicated to apply any findings to general supply chain design practices. The main lesson learned is the importance of feedstock availability for both supply chain costs and supply chain GHG emissions. New wood pellet mills and new supply chain designs should foremost be focussed on analysing the spatially explicit availability and costs of feedstock, preferably of underutilized sources of residues. Investing in technological improvements, such as torrefaction, could limit future cost increases and could unlock additional sources of low-value, sustainable biomass, such as agricultural residues, logging residues or post-consumer wood waste.

RQ 2: How do economic support policies and supply chain GHG emission constraints affect supply potentials of imported woody biomass and what is the impact on long distance international trade?

As will be shown in this section, as cost and GHG emission criteria become stricter, the potential to import pellets from selected case study countries almost disappears completely. The largest costs factors are feedstock costs and pelletizing costs. Assuming business as usual conditions, with an emission reduction threshold of 70% and a cost limit of 150 €/t pellets, the total potential that can be imported is up to 38 Mt pellets. A stricter GHG emission criteria of 80% reduces the potential to a maximum of 15 Mt pellets and a criterium of 85% to only 1 Mt pellets. GHG emissions are largely determined by the pelletizing step, feedstock transport and shipping transport. Optimizations such as the use of low-value residues, located close to pellet plants, or exogenous changes that lead to reduced emission intensity of electricity production will result in increased import potentials.

There are no clear or strict cost constraints for wood pellets. The maximum price that pellet importers are willing to pay varies in relation to alternative fuels, such as traditional fossil fuels but also renewable energy technologies. The impact of supply chain costs on the potential to import pellets was analyzed for a bandwidth of total supply chain costs, ranging from 100 – 200 €/t, based on current market prices and subsidy levels for wood pellets. In contrast to the uncertainty in market limits for pellet production costs and prices, **maximum supply chain GHG emission thresholds** are generally imposed by national or supra-national governments and are therefore both clearly defined and have to be strictly applied. These limits, as established in the RED II, increase from 75% to 85%, which is also the range explored in this thesis.

Within production countries **the range in costs and emissions can be very large, increasing with inland transport distances** (see Figure 6.2). This is especially relevant for large countries. For instance, pellet costs range between 95 – 135 €/t pellets in Estonia, with the impact of transport distance accounting for 21 €/t pellets of the cost increase. In the US on the other hand, costs range between 100 – 259 €/t pellets, with transport costs adding 141 €/t pellets to the most expensive share of the potential. These calculations were capped at a transport distance of 2000 km, which does not yet cover the entire geographical extent of countries such as Brazil, Canada, Russia and the US. The difference between countries is perhaps even more distinct for GHG emissions. In Estonia and Ukraine, emissions of pellets increase with only 16% and 32% respectively across the entire supply chain. In Russia and Brazil, the emission increase is much more significant at 104% and 175% respectively. This large range highlights the necessity to analyze supply chain costs and emissions in relation to spatially explicit feedstock availability.

Figure 6.2 - Range in costs in the different case study regions, as a result of differences in inland transport requirements, based on business as usual estimates in case of Chapter 3. In Chapter 4, a distinction between wood pellets (WP) and torrefied pellets (TOP) and between sawmill residues (SR) and roundwood (RW) was included.

The significant impact of inland transport on costs and emissions limits production areas and therefore **production potentials in the different case study countries** (see Figure 6.3). In countries with cheaper biomass sources and lower labour costs, such as Ukraine, a relatively large share of the potential is available at a cost limit of 150 €/t pellets. Low cost factors allows for high inland transport costs, unlocking pellet production potential in regions far away from ports. In Latvia and Lithuania on the other end of the scale, not even 50% of the total potential is available at a cost limit of 200 €/t pellets. The significant cost difference between Latvia and Lithuania on the one hand and Estonia on the other hand is largely caused by differences in feedstock costs, all other cost factors being more or less equal. In the case of the Baltic States, the limitations of using available literature data instead of spatially explicit empirical data are clearly shown. Pellet production and export is growing in the Baltic States, especially in Latvia and Estonia, even though spot prices for pellets have on average not been higher than 150 €/t pellets in recent years (Bioenergy Europe, 2019c; Strauss, 2020). The available data from the Baltic States is for the entire country and makes no difference between demand sectors. There could be large differences between local

opportunity costs and national averaged cost estimates that could not be included in this thesis.

Figure 6.3 - Percentage of maximum pellet production potential in the different case study countries, applying different maximum supply chain cost criteria, with the different colours denoting additional capacity under these higher cost criteria. Results are based on the production of wood pellets from roundwood. In case of Chapter 3, results are shown for a Business as Usual scenario (BAU) and a High Export scenario (HE)

GHG emission criteria also have a significant effect on potential supply areas where pellets can be produced, especially for the supply chains including long distance shipping, as shown in Figure 6.4 and Figure 6.5. This results for instance in all identified potential in Indonesia to be excluded because of lack of compliance to the minimum set GHG savings thresholds. The strengthening of GHG emission reduction criteria impacts the potential significantly in almost all countries. In Estonia and Latvia 100% of the potential is available at a 70% target, reducing to 0% at an 80% target. This large difference can be explained by the fact that the total potential and the range in emissions are small since transport distances are small and do not add as much to supply chain emissions as compared to the other countries. Neighbouring country Lithuania has lower emissions and as a result a higher potential. The defining factor for the Baltic states is the emission intensity of electricity production. This thesis uses country specific emission factors, instead of using the EU average, as is prescribed in the RED II methodology (Jacopo Giuntoli et al., 2015). In Lithuania, the emission factor is lower than

the EU average value, whereas in Latvia the emission factor is more than a factor 2 higher (J. Giuntoli et al., 2017). In regions with relatively low emissions, such as the East Coast of Canada and Brazil, a much larger share of the total potential remains, although also in these countries the production potential is affected by increasing reduction targets.

Figure 6.4 - Range in emissions in the different case study regions as a result of differences in inland transport requirements, based on business as usual estimates in case of Chapter 3. In Chapter 4, a distinction between wood pellets (WP) and torrefied pellets (TOP) was included.

Figure 6.5 - Percentage of maximum pellet production potential in the different case study countries, applying different maximum supply chain GHG emission criteria, with the different colours denoting additional capacity under these higher emission criteria. Results are based on the production of wood pellets (WP) from roundwood, as well as torrefied pellets (TOP) from roundwood for some case studies. In case of Chapter 3, results are shown for a Business as Usual scenario (BAU) and a High Export scenario (HE)

A combination of costs and emission criteria was applied by only including the potential for the most restrictive criterium in each country. **There is some trade-off between low costs and emissions in the different countries.** For example, in Chapter 3 costs are relatively high for Brazil whereas emission are relatively low. In a "Business as Usual" situation, total supply chain costs of 150 €/t pellets and an emission reduction threshold of 70%, the total potential varies between 4 – 38 Mt pellets in the different chapters and scenarios, largely supplied from Ukraine and Colombia in Chapter 3 and from Brazil and the US in Chapter 4. The same emission threshold with a higher cost limit of 175 €/t pellets results in a higher upper limit of 36 Mt in Chapter 3, and 50 Mt in Chapter 4. The difference between these results for the different Chapters can partially be explained by the different methodologies applied. For instance, in Chapter 3, pellet mill capacity is included as a limiting factor, thereby lowering the total potentials significantly. Stricter GHG criteria evidently results in a lowered total potential, the total potential pellet production meeting an emission threshold of 80% reduction and a cost limit of 150 €/t pellets is reduced to 3 – 15 Mt. Since this emission threshold is the main limitation, stretching the cost limit to 175 €/t pellets has only a small impact on the potential, increasing the maximum to 16 Mt. These figures show that especially the GHG emission reduction criteria could become a serious limitation to future pellet production and import. Ultimately there is a trade-off between import quantity and GHG footprint, which is discussed in section 6.6.

From January 2026, EU GHG savings thresholds increase to 80% for electricity, heating and cooling. This work has shown that **this 80% GHG emission limit will heavily restrict pellet import potential unless a shift is made to more favourable feedstock or pretreatment options such as the use of residues and the integration of torrefaction into pellet production.** Focussing on the development of new supply chains based on underutilized feedstocks could potentially increase pellet imports from the included countries beyond the results shown in this article. For certain countries, such as Latvia and Estonia, there is a lot of potential to lower the emission intensity of grid electricity. This can have a significant impact on future supply chain emissions and could reduce the GHG footprint of pellets from these countries significantly, also resulting in larger import potentials.

RQ 3: If export supply potentials are exploited in the future, what could be local impacts on costs, GHG emissions and carbon fluxes in forest areas, when considering the interaction with non-energy markets?

Current policies and market mechanisms stimulate a reduction in supply chain costs and GHG emissions, for instance through the use of industry residues. However, from a systems perspective this could lead to suboptimal results since these industry residues are often already used locally. Both research and policy should therefore focus on optimizing the entire wood products system.

As shown in Chapter 5, where such a systems perspective was applied, spatially explicit availability of industrial residues is limited. At the start of the modelling period, all pellet production is based on industrial residues. As a result of demand increases of other sectors until 2030, the total availability of industry residues increases, however, not enough to cover the additional quantities of pellet production modelled. Increased pellet production results in higher overall utilization of industry residues, but also in the use of minor shares of pulplogs and sawlogs for pellet production and the reduction of residue use in other industries, resulting in more roundwood harvesting for pulp and paper production as well. The increase in harvesting leads to a shifting balance between carbon sequestration, through tree growth, and emissions, through tree removal, resulting in increased carbon flux in forest areas. Additional use of logging residues can reduce part of the carbon flux increase, however beyond 20 Mt production in 2030 also the availability of logging residues is limited.

The impact of increased pellet production depends largely on the **spatial availability of feedstock, whether in the form of forestry feedstock such as pulpwood or saw wood or in the form of residues from other industries such as chips, shavings or sawdust**. The availability of industry feedstock is determined by the existence of certain production processes, such as lumber production. These residues are furthermore also used for the production of, for instance, paper or oriented strand board. The specific impact of surrounding industries on feedstock availability develops over time as spatial production of pellets as well as other industries changes until 2030. Results from Chapter 5 show that in the Zero pellet scenario, the utilization

rate of these industry residues decreases from 75% to 59% as availability increases more quickly than demand. In the pellet scenarios, additional demand for these feedstocks however increases the utilization rate, in case of the 20 Mt scenario in 2030 to a total of 85%.

Increasing pellet production not only results in increased utilization of harvested feedstock for pellet production but also likely pulls away residues from other industries.

This thesis has shown that consumption of industry residues in other sectors than pellet production decreases as the demand for feedstock for pellet production grows. In this thesis, feedstock is allocated based on system costs, which is determined by proximity to demand sources. A limitation of this approach is that it does not consider direct competition between industries, including differences in willingness to pay for different feedstock types. Still, this thesis shows that a large additional source of feedstock demand will impact the feedstock availability and the market for different feedstock types.

The additional impact of pellet production on wood harvesting in the US SE is relatively small.

In a scenario of 20 Mt pellet production in 2030, only 4.4% of harvested pulplogs and 0.6% of harvested sawlogs is used for pellet production. Still from the perspective of pellet producers, there are significant changes with respect to feedstock availability and use. In 2030, pulplogs and sawlogs combined consist of 23% of all feedstock used in pellet plants in the Reference scenario. The increase in industrial residue availability is insufficient to allow for the large growth in pellet production quantity assumed. Additional harvesting for pellet production is furthermore on top of already increasing harvest and carbon flux levels, as a result of demand increases of other products.

As a result of increased harvesting in the US SE, carbon flux increases are observed in all scenarios with increasing pellet production.

In the scenarios of low pellet production, of 10 Mt in 2030, this impact is still lower than supply chain emissions as analysed in research question 2. In the 20 Mt scenario, and especially the 30 Mt scenario, carbon flux impacts are much larger than total supply chain emissions found for all different case study countries. The carbon flux increase is a factor two larger going from 20 to 30 Mt than going from 10 to 20 Mt. In the Zero pellet production scenario the

carbon flux increases as well, particularly in the US SE. In this scenario, the total flux in the US SE (i.e. 11 states¹³), increases with 16 Mt CO₂ between 2014 and 2030. In the other 37 states of the conterminous US, the total flux increases with 18 Mt CO₂. The top 5 states with the largest flux increase include 4 states in the US SE, plus Texas. Spatial shifts in this thesis are the result of optimizing for lowest costs of feedstock transport, effectively optimizing for proximity to feedstock sources. The large increase of carbon flux in the US SE can be explained by a spatial shift of timber industries towards the area, caused by large availability of roundwood.

Two potential strategies aimed at minimizing the impact of pellet production on carbon flux were analysed in this work.

The first strategy is to select the location of new pellet mills based on maximum carbon stocks in sourcing areas. As a result of this carbon stock optimization approach, total consumption of roundwood in the US SE is about 10% lower than in the scenario not including carbon considerations. This is reflected in a slightly lower increase in carbon flux, also about 10% lower than in the Reference scenario. This carbon stock approach has a large local impact on the locations of pellet production and spatially explicit carbon flux but has limited impact on the entire US SE. The interaction between individual pellet mills and between the pellet industry and other industries result in an ongoing response to spatially explicit changes, continuously balancing overall demand with supply.

Assumed **increased utilization of logging residues** has a much larger impact on feedstock consumption and carbon flux. These residues are generated during the harvesting of sawlogs or pulplogs and are often not fully utilized (Thiffault et al., 2015). Instead logging residues are generally either left in piles to decompose naturally or incinerated to prepare forest areas for replanting. In any case, the carbon content is extracted from forest plots, whether these residues are utilized or not. The utilization of this feedstock source replaces a significant share of roundwood consumption, about 85% in the case of 20 Mt pellet production in 2030. Consumption of logging residues also replaces a share of industry residues used for pellet production, making these available for use in other industries. This results in a significant impact

¹³ Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia

on the total carbon flux increases resulting from pellet consumption. In the 20 Mt pellet production case, the total carbon flux increase including logging residue mobilization is 54% lower than in the Reference scenario. This carbon flux impact is smaller than the reduction in roundwood consumption for pellets, which can be explained by the interaction with other industries. Less roundwood consumption by pellet producers increases the availability of this source for other industries. Increased utilization of logging residues can compensate for part of the modelled demand increase, but also this impact is limited by availability, as shown in the scenario beyond 20 Mt pellet production. Additional carbon flux of the pellet production scenarios including logging residues, compared to the Zero pellet scenario, amount to 2 and 6 Mt CO₂ for the 10 and 20 Mt pellet production scenarios. In the case of 30 Mt pellet production, the additional flux increase is a much larger at 24 Mt CO₂.

As pellet production forms a small part of the total wood products market compared to timber and paper production, the demand for these products has far more impact on total flux developments. **This means that the limits to sustainable pellet production to a large extent are decided by demand developments of the entire sector.** The limits to pellet production must therefore be explored further while accounting for potentially different futures in terms of demand for products such as timber, paper products and bioenergy. Furthermore, **to properly assess the sustainability of pellet production, alternative scenarios must be defined and explored.** The total impact of all forest operations in a specific area must be assessed on a landscape level, by comparing sequestration and carbon removal but also by accounting for the (fossil) products replaced by wood or bioenergy consumption and the avoided patterns of grow and decay of non-harvested wood (Berndes, Cowie, Englund, Simmons, & Thiffault, 2019a; Cintas et al., 2017). Carbon accumulation rates decline as trees age. If forest plantations are not harvested, for energy or other purposes, the carbon stock increases eventually diminish, as tree growth is more or less balanced with tree mortality (Pukkala, 2017). From a landscape perspective, optimizing carbon production from forest areas could therefore include periodic harvesting of trees to rejuvenate forest areas, thereby temporarily lowering carbon stocks

and increasing spatial carbon flux. Better spreading of pellet impact on forest areas, through optimizing for carbon stocks in sourcing areas, could be potentially useful strategy on the longer term to rejuvenate forests throughout the US SE. Carbon flux impacts must therefore ideally be assessed on a longer timescale and must be compared to avoided carbon emissions of (fossil) alternatives.

6.5. RESEARCH LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Wood pellet supply chain cost and GHG emission calculations in this thesis highlight the sensitivity of results to transport distances, especially of road transport. The impact of transport distances in costs of pellets should explicitly be included in assessments analysing the potential role of biomass trade in future energy systems. The relatively large costs of road transport offers opportunities for cost optimization of this supply chain step which were not analysed in detail in this thesis. Further research could analyse potential optimization strategies of long-distance supply chains, for instance by focussing on the development of rail or barge transport. This could be assessed in combination with a hub and spoke design of pellet storage and transport. This design enables the production of pellets close to feedstock sources, in medium sized facilities optimized for feedstock sourcing area, while also utilizing the cost savings of economies of scale in rail or barge transport. An optimization of inland transport costs could have a significant impact on the upper range of pellet costs and emissions and could add to the necessary knowledge to analyse impacts of scenarios with large increases in pellet production and trade.

The impact of pellet production depends strongly on the type of feedstock used by the pellet industry. Available feedstock in certain regions must furthermore often be allocated over various different demand types. In this thesis, either the prioritization of all other demand sectors before pellet mills was presumed to avoid distortion of local markets, or the allocation of feedstock to all demand sectors based on lowest system costs. In reality, feedstock allocation will not be organized top-down, but will depend on the

competitiveness and paying capacities of industries and individual pellet mills. Further research into the feedstock consumption of pellet mills must include an analysis of relative paying capacities of industries. This must also include cost factors such as stumpage fees or prices for industrial residues. This thesis considers the use of various types of roundwood for pellet production in several case studies. High quality roundwood, however, is likely too expensive to use for pellet production. An analysis of feedstock consumption by the pellet industry using data on feedstock prices, assumptions on price changes in response to demand changes, and relative paying capacities could help to refine the findings of this thesis.

The use of various types of woody residues for pellet production is an important strategy to reduce supply chain costs and emissions, as well as carbon impacts in forest areas. Increased pellet production based on residue feedstocks, however, might pull away from local markets utilizing these feedstocks, whether for bioenergy or other purposes. This may in turn result in displaced demand for other feedstock types such as pulplogs, with cost and emission impacts. What needs to be analysed in more detail is the current, and potential future, usage of several industrial residue feedstock types. The extraction of logging residues also has sustainability risks. Part of residues must be left in fields and forest areas to maintain soil organic carbon and soil structure. The percentage that can be extracted while staying below sustainable limits is uncertain and depends on local aspects such as soil type, vegetation type and climate. In conclusion, future research must focus on the availability of different residue types, in relation to local demand of other sectors and sustainability requirements.

Developments in feedstock demand and feedstock prices have an impact on the business case of wood product industries but in turn also impact the availability of wood sources. Future research should analyse the response in feedstock availability to feedstock demand changes. Owners of timber plantations will partially base their operations on long-term planning, optimizing tree rotation age based on maximum revenue or sustainable yields (Sedjo, 2003). The decision to harvest and sell timber is dependent on future price expectations as well as current demand and prices (Sedjo, 2003). Low demand can be a reason to delay harvesting in hopes of better circumstances

while high demand and high prices could persuade landowners to clear-cut or thin sooner than intended. Responses to changes in demand depend on aspects such as price developments of wood products and prospects of alternative land use and could differ per type of landowner in different case study regions. Analysing the impact of different demand scenarios on growth of forest areas, forest composition and management of forests will add to the understanding of the limits to sustainable and cost effective pellet production.

In this thesis we have concluded that the production of 30 Mt pellets in the US SE exceeds sustainable limits. However, this depends strongly on demand developments in other sectors. In case demand for timber, pulp and paper decreases instead of increases, a share of the avoided demand could likely be used for pellet production without exceeding carbon stock limits. In chapter 5, only one demand scenario for other products was included. The impact of wood pellet production must be assessed for different demand scenarios to further explore the limits to sustainable production.

The maintenance of carbon stocks is a prerequisite for sustainable pellet production, as for instance included in the RED II, but is difficult to safeguard by the pellet industry alone, especially in situations of changing demand for other products. The impact of pellet production on feedstock consumption and carbon flux should therefore be analysed in more detail while including several potential demand scenarios of other products. These analyses should also include the impact of pellet consumption and the avoided production of energy or materials from alternative sources. The comparison between carbon impacts in forest areas and avoided emissions from alternative use scenarios would allow for a full analysis of carbon impacts of pellet production on a landscape level (Berndes et al., 2019a; Cintas et al., 2017).

Analysing whether pellet production results in net carbon savings over time can be done by calculating the carbon parity point, defined as the time to the point when the utilization of biomass for pellet production is favourable over a defined reference scenario. Research into this subject has shown that the impact of pellet production depends to a large extent on methodological assumptions, such as the type of ecosystem and land-use, the feedstock

type used for pellet production, the choice of reference scenario, the management intensity assumed and land-use change and management feedback responses, resulting in carbon parity points varying from 1 year to >100 year (Hanssen et al., 2017; Jan Gerrit Geurt Jonker et al., 2014; Mitchell, Harmon, & O'Connell, 2012; Ter-Mikaelian et al., 2015). Lessons learned from these studies are that parity periods are typically relatively short for the use of residues and long for the use of roundwood. Analysing the carbon parity points of additional feedstock consumption for pellets, as found in this thesis, can inform the debate on the impact of different levels of wood pellet production on carbon reduction strategies.

6.6. POLICY AND INDUSTRY RECOMMENDATIONS

This thesis has expanded on the sustainability impacts of pellet production for bioenergy. These impacts should be considered by policy makers against the potential contribution of pellets to reaching GHG emission reduction targets and transitioning to a more sustainable energy and materials system. The strict GHG emission reduction criteria, as identified in the RED II criteria, safeguard a minimum level of GHG emission savings. The fact that the reduction criteria increases from 70% to 80% over time encourages the sector to optimize supply chains. On the other hand, this thesis has shown that it is difficult to reduce costs and emissions and that there is a large difference in potential pellet production quantities between meeting the 70% and 80% criteria. Stricter GHG emission reduction targets could therefore result in significantly lowered contributions of wood pellets to the production of renewable energy and lowering of overall GHG emissions. Policy makers should realize the impact of GHG emission reduction targets on the trade-off between quality and quantity of pellets imported. Other impacts of wood pellets, such as the impact on forest carbon flux, are not included in these supply chain emission criteria. Complying only with GHG emission criteria could result in the use of wood pellets with negative landscape emissions. To prevent negative impacts of wood pellet consumption, the pellet industry should carefully select pellet sourcing areas and feedstock types and proactively consider landscape emissions as well as supply chain emissions. Pellet producers should explicitly consider and safeguard sustainable limits

in business operations to ensure a future role for pellet production. Policy makers could improve the sustainability of pellets by excluding certain feedstock types, such as saw logs, although interactions with other markets make it difficult to assess the precise impact of sustainability criteria for just pellet production.

Another relevant aspect to consider with GHG emission reduction criteria is the balance between lowest costs and lowest emissions. The use of pellets relies on incentives such as subsidies. These policies, as well as market mechanisms, will result in supply chain optimizations focussing on lowest supply chain costs. From a GHG emission perspective this could result in the import of suboptimal pellets in terms of supply chain and landscape GHG emissions. The optimum between supply chain costs and emissions is difficult to assess in case of specific supply chains, since it could be unfeasible to determine landscape emissions considering the interaction with other markets and the potential for changes in local feedstock demand and supply. There are however strategies that could result in both optimized costs and emissions, such as the increased mobilization of logging residues.

Current policies do not explicitly stimulate the use of logging residues, while utilizing this feedstock type for pellet production is considered to be a no-regret measure resulting in lowered costs as well as GHG emissions associated with wood pellet production. Collection of these residues requires several labour intensive steps making logging residues mobilisation relatively expensive and unattractive (Yoshioka, Sakurai, Kameyama, Inoue, & Hartsough, 2017). On the other hand, the development of suitable supply chains could lower costs. Combined harvesting of roundwood and logging residues could for instance result in cost optimizations (Kallio & Leinonen, 2005). After the initial investments of developing supply chain infrastructure to collect and transport these feedstocks, costs of feedstock could be significantly lower compared to more in demand feedstock types such as mill chips. Strategies aimed at increasing mobilisation can be shaped in different ways. The EU or individual Member States could enforce use of residues through criteria establishing the use of a minimum share of certain feedstocks in subsidized pellets. Alternatively, the use of these feedstock types can be stimulated directly through subsidies or other monetary incentives.

This thesis has highlighted the complex interaction between pellet producers and other consumers of lignocellulosic biomass. Targeting policies at influencing the type of feedstock used in pellet production, either by restricting or incentivizing certain feedstocks, will likely have an impact on other industries. If pellet plants are, for instance, incentivized to use only mill residues, this could draw residues from pulp and paper producers, by increasing the prices of these residues, resulting in increased roundwood consumption of these non-energy sectors. The same holds for the spatial location of pellet production. If only pellet producers are restricted in their site selection by carbon stock considerations, then the impact of such restrictions is expected to be limited. Pellet production makes up a small share of the entire wood products industries (even in the US SE, the dominant global pellet exporter), and has relatively little influence or impact on forestry operations. Therefore, to ensure that feedstock extraction and use remains within sustainable limits, the same policies should be targeted holistically at the entire wood products sector.

Using agricultural residues also requires some technical challenges to overcome, potentially requiring additional pelletizing steps such as washing of the feedstock, to avoid a high ash content in pellets and to provide some of the extracted nutrients back to the soil (Nilsson, Bernesson, & Hansson, 2010). A potential strategy to utilize larger shares of low-value feedstocks in pellet plants is to use these to provide the process heat required to dry other, higher-value, feedstock types prior to pelletization. Besides these challenges, the benefits and potential of using agricultural residues are also recognized by the industry.

An option to further facilitate the use of low-grade lignocellulosic resources is by stimulating the addition of torrefaction to the pellet production process. Torrefied pellets have shown to potentially result in cost and GHG emission savings. An additional potentially interesting benefit of torrefaction is that it allows for the use of lower quality feedstocks such as logging residues. Research into the production of torrefied biomass or pellets is plentiful, and pilot plants have confirmed the feasibility of torrefied pellet production. This thesis has shown that importing torrefied pellets is possible against comparable or lower costs than wood pellets, while at the same time resulting

in significant GHG emission savings. What is now needed is to prove this concept on a larger commercial scale. Subsidizing or otherwise incentivizing the development of torrefied pellet supply chains, preferably based on lower-quality residues, could help to confirm whether or not torrefied pellets result in cost and emission benefits compared to wood pellets.

This thesis has demonstrated the importance of explicitly establishing spatial boundaries. Carbon flux impacts vary strongly on a regional level, ranging from flux increase to flux decrease. Measuring the impact of pellet production would therefore lead to different conclusions depending on the specific region and the spatial boundaries applied. The appropriate scale of spatial boundaries was not analysed specifically in this thesis. A suitable scale includes at least the entire sourcing area of pellet mills, but perhaps has to be extended even further to include the interaction with other nearby industries. The impact of spatial boundaries can also be accounted for by monitoring carbon flux on different levels, ranging for instance from sourcing areas to entire states. What is considered to be most important is that calculation rules and guidelines with clearly defined spatial boundaries are implemented in policies, thereby avoiding potential risks such as the deliberate drawing of boundaries to show impacts in the light best suited to, for instance, either pellet producers or environmentalist. What is also crucial is that these spatial boundaries remain the same as much as possible. Carbon stock or carbon flux impacts vary over time as a result of plantation rotations. Only by assessing the impacts continuously for the same area over a longer time period can conclusions on the impact of pellet production be drawn.

REFERENCES

1. Abbott, D. (2017). Peterson helps keep Highland Pellets on-line, on target. Retrieved June 12, 2019, from <https://www.petersoncorp.com/highland-pellets-article/>
2. Abdullah, N., & Sulaim, F. (2013). The Oil Palm Wastes in Malaysia. *Biomass Now - Sustainable Growth and Use*. <https://doi.org/10.5772/55302>
3. Abt, Karen L., Abt, R. C., & Galik, C. (2012). Effect of Bioenergy Demands and Supply Response on Markets, Carbon, and Land Use. *Forest Science*, 58(919), 523–539. <https://doi.org/10.5849/forsci.11-055>
4. Abt, Karen Lee, Abt, R. C., Galik, C. S., & Skog, K. E. (2014). Effect of Policies on Pellet Production and Forests in the U . S . South Update of the 2010 RPA Assessment, (December).
5. Abt, R., Abt, K., Henderson, J., & Kanieski da Silva, B. (2019). Update of a presentation for the Southern Forest Resource Assessment Consortium (SOFAC), August 2019. Raleigh, NC. *Presenter and Corresponding Author.
6. Abt, R. C., Galik, C. S., & Henderson, J. D. (2010). The Near-Term Market and Greenhouse Gas Implications of Forest Biomass Utilization in the Southeastern United States. *Climate Change Policy Partnership*. Retrieved from <https://nicholasinstitute.duke.edu/sites/default/files/publications/near-term-market-and-ghg-implications-of-forest-biomass-in-southeast-paper.pdf>
7. AEBIOM. (2014). *European Bioenergy Outlook 2014- a growing sector in figures*. Brussels, Belgium: European Biomass Association (AEBIOM).
8. Agar, D. A. (2017). A comparative economic analysis of torrefied pellet production based on state-of-the-art pellets. *Biomass and Bioenergy*, 97, 155–161. <https://doi.org/10.1016/j.biombioe.2016.12.019>
9. Aguiar, L., Márquez-Montesinos, F., Gonzalo, A., Sánchez, J. L., & Arauzo, J. (2008). Influence of temperature and particle size on the fixed bed pyrolysis of orange peel residues. *Journal of Analytical and Applied Pyrolysis*, 83, 124–130. <https://doi.org/10.1016/j.jaap.2008.06.009>
10. American Transportation Research Institute. (2017). *An Analysis of the Operational Costs of Trucking: 2017 Update*. TRB 2010 Annual Meeting, (October), 51. <https://doi.org/http://truckexec.typepad.com/files/atri-operational-costs-of-trucking-2013-final.pdf>
11. ArcGIS. (2019). World Railroads. Retrieved June 6, 2019, from <https://www.arcgis.com/home/item.html?id=5ef3425348954c84a45860bcf86c78ab>
12. Argonne National Laboratory. (n.d.). Greet Model. Retrieved December 21, 2014, from <https://greet.es.anl.gov>
13. Argus. (2018). *Argus Biomass Markets - Issue 18-5*. <https://doi.org/2041-2503>
14. Baltpool. (n.d.). Review of Timber Market 2018, 1–14. Retrieved from <https://www.baltpool.eu/en/review-of-timber-market-2018/>
15. Barrette, J., Thiffault, E., Achim, A., Junginger, M., Pothier, D., & De Grandpré, L. (2017). A financial analysis of the potential of dead trees from the boreal forest of eastern Canada to serve as feedstock for wood pellet export. *Applied Energy*, 198, 410–425. <https://doi.org/10.1016/j.apenergy.2017.03.013>

16. Batidzirai, B., Smeets, E. M. W., & Faaij, A. P. C. (2012). Harmonising bioenergy resource potentials—Methodological lessons from review of state of the art bioenergy potential assessments. *Renewable and Sustainable Energy Reviews*, 16(9), 6598–6630. <https://doi.org/10.1016/j.rser.2012.09.002>
17. Batidzirai, Bothwell. (2013a). Design of Sustainable Biomass Value Chains. Utrecht
18. Batidzirai, Bothwell. (2013b). Design of Sustainable Biomass Value Chains. Utrecht University, Utrecht
19. Bergman, P. C. A. (2005). Combined torrefaction and pelletisation The TOP process. Retrieved from <https://www.ecn.nl/docs/library/report/2005/c05073.pdf>
20. Berndes, G., Abt, B., Asikainen, A., Cowie, A., Dale, V., Egnell, G., ... Yeh, S. (2016). Forest biomass, carbon neutrality and climate change mitigation. From Science to Policy. Retrieved from <https://doi.org/10.36333/fs03>
21. Berndes, G., Cowie, A., Englund, O., Simmons, A., & Thiffault, E. (2019a). Methods and tools to assess the sustainability of bioenergy supply chains - Summary of findings under Objective 1 of the IEA Bioenergy inter-Task project "Measuring, governing and gaining support for sustainable bioenergy supply chains." Retrieved May 6, 2020, from <http://www.ieabioenergy.com/wp-content/uploads/2018/11/201-Chalmers-Berndes.pdf>
22. Berndes, G., Cowie, A., Englund, O., Simmons, A., & Thiffault, E. (2019b). Methods and tools to assess the sustainability of biomass and bioenergy supply chains - Summary of findings under Objective 1 of the IEA Bioenergy inter-Task project "Measuring, governing and gaining support for sustainable bioenergy supply chains." Retrieved from <https://edepot.wur.nl/496728>
23. Bhattacharya, S. C., Pham, H. L., Shrestha, R. M., & Vu, Q. V. (1993). CO₂ emissions due to fossil and tradition fuels, residues and wastes in Asia. In Workshop on Global Warming Issues in Asia, Asian Institute of Technology., 8-10 September 1992, Bangkok, Thailand.
24. BID-MME. (2012). Evaluacion del ciclo de vida de la cadena de produccion de biocombustibles en Colombia. Retrieved March 20, 2012, from www.fedebiocombustibles.com
25. Bimco. (2019). Dry Bulk Shipping: Q1 requires careful handling as seasonal cargo demand drops. Retrieved May 24, 2019, from https://www.bimco.org/news/market_analysis/2018/20180220_drybulksmoo_2018_01
26. Bioenergy. (2014). Ukrainian Biomass Pellet Market. Retrieved from http://ukraineagrovalley.com/site/files/Biomass_Pellets_Market.pdf
27. Bioenergy Europe. (2018). Statistical Report 2018. Brussels. Retrieved from <https://bioenergyeurope.org/statistical-report-2018/>
28. Bioenergy Europe. (2019a). Statistical report 2019 - Bioelectricity.
29. Bioenergy Europe. (2019b). Statistical report 2019 - Biofuels for transport.
30. Bioenergy Europe. (2019c). Statistical Report 2019 - Report Pellet. Brussels.
31. Bioenergy International. (2005). The pellets map 2005, (17).
32. Bioenergy International. (2014). The World of Pellets 2014. Stockholm: SBSAB/Bioenergy International Magazine.
33. Bioenergy International. (2017). The World of Pellets 2017. Stockholm: SBSAB/Bioenergy International Magazine.

34. Bioenergy International. (2019). *The World of Pellets 2019*. Stockholm: SBSAB/Bioenergy International Magazine.
35. Bioenergy Technologies Office. (n.d.). Retrieved December 14, 2014, from <https://www.energy.gov/eere/bioenergy/bioenergy-technologies-office>
36. BioGrace-II. (2015). The BioGrace-II GHG calculation tool for electricity, heating and cooling products. Retrieved from http://www.biograce.net/app/webroot/biograce2/content/ghgcalculationtool_electricityheatingcooling/overview
37. Biograce II. (2015). BioGrace-II Publishable final report. Retrieved from biograce.net/img/files/BioGrace_-_Final_publishable_report.pdf
38. Biomass Magazine. (2016). Market price trend of wood pellets (2009-2020). Retrieved April 6, 2017, from <http://biomassmagazine.com/articles/13796/futuremetrics-offers-wood-pellet-demand-spot-pricing-estimates>
39. Biomass Magazine. (2017a). Pellet Plants. Retrieved April 11, 2017, from <http://biomassmagazine.com/plants/listplants/pellet/US/Operational/>
40. Biomass Magazine. (2017b). U.S. Pellet Plants. Retrieved August 12, 2017, from <http://biomassmagazine.com/plants/listplants/pellet/US/>
41. Biomass Magazine. (2018). A shifting market. Retrieved from <http://biomassmagazine.com/articles/15008/a-shifting-market>
42. Biomass Magazine. (2020). U.S. Pellet Plants. Retrieved February 24, 2020, from <http://biomassmagazine.com/plants/listplants/pellet/US/page:1/sort:plant/direction:asc>
43. Biopact. (2006). Crop residues: How much biomass energy is out there. Retrieved November 23, 2014, from <http://news.mongabay.com/bioenergy/2006/07/crop-residues-how-much-biomass-energy.html>
44. BioSustain. (n.d.). Biomass supply potentials for the EU and biomass demand from the material sector by 2030 - Technical Background Report of the "BioSustain" study: Sustainable and optimal use of biomass for energy in the EU beyond 2020. Manuscript in Preparation.
45. BIX Bunker Index. (2019). BIX World indices. Retrieved May 7, 2019, from <https://www.bunkerindex.com/>
46. Boer, R., Nurrochmat, D. R., Ardiansyah, M., Hariyadi, Purwawangsa, H., & Ginting, G. (2012). Reducing agricultural expansion into forests in Central Kalimantan - Indonesia: Analysis of implementation and financing gaps. Retrieved from https://pcfsu.org/wp-content/uploads/pdfs/FINAL-REPORT-CCROM-Reducing_agricultural_expansion_into_forests_23_May_2012-2.pdf
47. Bortolin, T. A., Trentin, A. C., Peresin, D., & Schneider, V. E. (2012). Estimativa da geração de resíduos florestais no Brasil. In 3o Congresso Internacional de Tecnologias para o Meio Ambiente., 25-27 April 2012, Bento Gonçalves.
48. Boukherroub, T., LeBel, L., & Lemieux, S. (2017). An integrated wood pellet supply chain development: Selecting among feedstock sources and a range of operating scales. *Applied Energy*, 198, 385-400. <https://doi.org/10.1016/j.apenergy.2016.12.013>
49. Boundy, B., Diegel, S. W., Wright, L., & Davis, S. C. (2011). *Biomass Energy Data Book - Edition 4*. Knoxville, Tennessee: Oak Ridge National Laboratory. Retrieved from cta.ornl.gov/bedb

50. BP. (2018). BP Statistical Review of World Energy - Coal. Retrieved from <https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-coal.pdf>
51. Briggs, D. G. (1994). Forest products measurements and conversion factors: With special emphasis on the US Pacific Northwest. Seattle: College of Forest Resources, University of Washington.
52. Bryngemark, E. (2019). Second generation biofuels and the competition for forest raw materials : A partial equilibrium analysis of Sweden. *Forest Policy and Economics*, 109(November). <https://doi.org/10.1016/j.forpol.2019.102022>
53. Bunker Index. (2018). Bunker Index 380 CST. Retrieved May 4, 2017, from http://www.bunkerindex.com/prices/bix.php?priceindex_id=2
54. Buongiorno, J. (2015). Global modelling to predict timber production and prices: the GFPM approach. *Forestry*, (December 2014), 291–303. <https://doi.org/10.1093/forestry/cpu047>
55. Burrill, Elizabeth A.; Wilson, Andrea M.; Turner, Jeffery A.; Pugh, Scott A.; Menlove, James; Christiansen, Glenn; Conkling, Barbara L.; David, W. (2018). The Forest Inventory and Analysis Database: database description and user guide version 8.0 for Phase 2. U.S. U.S. Department of Agriculture, Forest Service. 946 p.
56. Canada, N. R. (2019). Average Retail Prices for Diesel in Canada. Retrieved May 10, 2019, from http://www2.nrcan.gc.ca/eneene/sources/price/priceindex_id=2
57. Canadian Biomass. (2017). Canada, U.S. pellets using more residues, byproducts. Retrieved January 28, 2020, from <https://www.canadianbiomassmagazine.ca/canada-us-pellets-using-more-residues-byproducts-6184/>
58. Canadian Biomass. (2019). 2019 global wood pellet markets outlook. Retrieved January 14, 2019, from <https://www.canadianbiomassmagazine.ca/pellets/2019-wood-pellet-markets-outlook-7190>
59. Carvalho, J. L. N., Nogueira, R. C., Menandro, L. M. S., Bordonal, R. de O., Borges, C. D., Cantarella, H., & Franco, H. C. J. (2017). Agronomic and environmental implications of sugarcane straw removal : a major review. *GCB Bioenergy*, 9(7), 1181–1195. <https://doi.org/10.1111/gcbb.12410>
60. CBS StatLine. (2019). Aardgas en elektriciteit, gemiddelde prijzen van eindverbruiker. Retrieved June 5, 2019, from <https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81309NED/table?ts=1557225400290>
61. CEIC. (2019). Russia Average Producer Price: Electricity and Thermal Energy. Retrieved June 5, 2019, from <https://www.ceicdata.com/en/russia/average-producer-price-electricity-and-thermal-energy%0A>
62. Centralas Statistikas Parvaldes Datubazes. (2018). MEG050. Average purchase prices of wood (EUR/m3 (excluding VAT)). Retrieved from https://data1.csb.gov.lv/pxweb/en/lauks/lauks__mezsaime__mezizstr__ikgad/MEG050.px/
63. Cervi, W. R., Lamparelli, R. A. C., Seabra, J. E. A., Junginger, M., & Van der Hilst, F. (2019). Spatial assessment of the techno-economic potential of bioelectricity production from sugarcane straw. *Renewable Energy*. <https://doi.org/10.1016/j.renene.2019.11.15>

64. Cintas, O., Berndes, G., Cowie, A. L., Egnell, G., Holmström, H., Marland, G., & Agren, G. I. (2017). Carbon balances of bioenergy systems using biomass from forests managed with long rotations : bridging the gap between stand and landscape assessments. *GCB Bioenergy*, 1238–1251. <https://doi.org/10.1111/gcbb.12425>
65. Citrosuco. (2015). In our process the orange is used in the following way. Retrieved June 13, 2015, from <http://www.citrosuco.com.br/en/products.php#NFC>
66. Clark, A., & Daniels, R. F. (2000). Estimating moisture content of tree-length roundwood. Retrieved from https://www.srs.fs.usda.gov/pubs/ja/ja_clark015.pdf
67. Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., ... Van Vuuren, D. P. (2014). Assessing Transformation Pathways In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
68. Clarkson Research Services Limited. (2018). Shipping Intelligence Network - Timeseries. Retrieved February 21, 2018, from <https://sin.clarksons.net/Home>
69. Coelho, S. T., & Escobar, J. (2013). Possibilities of sustainable woody energy trade and impacts on developing countries: Country Case Study Brazil. Sao Paulo: Centro Nacional de Referência em Biomassa - CENBIO. Retrieved from http://www.iinas.org/tl_files/iinas/downloads/CENBIO_2013_Brazil-Case-Study_GLZ.pdf
70. Coelho, S. T., Monteiro, M. B., Karniol, M. R., & Ghilardi, A. (2008). Atlas de Bioenergia do Brasil. São Paulo. Retrieved from <https://www.scribd.com/document/40479685/Atlas-Bioenergia-CNEBIO>
71. Coleman, K., Jenkinson, D. S., Crocker, G. J., Grace, P. R., Klir, J., Körschens, M., ... Richter, D. D. (1997). Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. *Geoderma*, 81(1-2), 29–44. [https://doi.org/10.1016/S0016-7061\(97\)00079-7](https://doi.org/10.1016/S0016-7061(97)00079-7)
72. Conrad, J. L. (2018). Costs and Challenges of Log Truck Transportation in Georgia, USA. *Forests*, 9. <https://doi.org/10.3390/f9100650>
73. Conservation Biology Institute. (2001). Forest Intactness Database. Retrieved September 13, 2019, from <https://consbio.org/products/projects/forest-intactness-database>
74. Conservation Biology Institute. (2018). Canada's Intact Forest Landscapes. Retrieved September 4, 2019, from <https://databasin.org/articles/c6c75b7c47fe4965a5ba55670fd28983>
75. Croezen, H., Vroonhof, J., & Rooijers, F. (2006). Welke nieuwe energiecentrale in Nederland? Delft, Netherlands. Retrieved from <https://www.ce.nl/publicaties/download/445%0A>
76. Cubero-abarca, R., Moya, R., Valaret, J., & Filho, M. T. (2014). Use of coffee (*Coffea arabica*) pulp for the production of briquettes and pellets for heat generation. *Ciência e Agrotecnologia*, 38(5), 461–470.
77. Da Silva, S. S., & Chandel, A. K. (2014). *Biofuels in Brazil - Fundamental Aspects, Recent Developments, and Future Perspectives*. Cham Heidelberg New York Dordrecht London: Springer.
78. Dafnomilis, I., Lodewijks, G., Junginger, M., & Schott, D. L. (2018). Evaluation of wood pellet handling in import terminals. *Biomass and Bioenergy*, 117(July), 10–23. <https://doi.org/10.1016/j.biombioe.2018.07.006>

79. Dafnomilis, Ioannis, Hoefnagels, R., Pratama, Y. W., Schott, D. L., Lodewijks, G., & Junginger, M. (2017). Review of solid and liquid biofuel demand and supply in Northwest Europe towards 2030 – A comparison of national and regional projections. *Renewable and Sustainable Energy Reviews*, 78(May), 31–45. <https://doi.org/10.1016/j.rser.2017.04.108>
80. Daioglou, V. (2016). The role of biomass in climate change mitigation - Assessing the long-term dynamics of bioenergy and biochemicals in the land and energy systems.
81. Daioglou, V., Doelman, J. C., Wicke, B., Faaij, A., & Vuuren, D. P. Van. (2019). Integrated assessment of biomass supply and demand in climate change mitigation scenarios. *Global Environmental Change*, 54(April 2018), 88–101. <https://doi.org/10.1016/j.gloenvcha.2018.11.012>
82. Dale, V. H., Kline, K. L., Parish, E. S., Cowie, A. L., Emory, R., Malmsheimer, R. W., ... Wellisch, M. (2017). Status and prospects for renewable energy using wood pellets from the southeastern United States. *GCB Bioenergy*, 1–10. <https://doi.org/10.1111/gcbb.12445>
83. Dale, V. H., Parish, E., Kline, K. L., & Tobin, E. (2017). Forest Ecology and Management How is wood-based pellet production affecting forest conditions in the southeastern United States ? *Forest Ecology and Management*, 396, 143–149. <https://doi.org/10.1016/j.foreco.2017.03.022>
84. de Paula Protásio, T., Bufalino, L., Tonoli, G. H. D., Guimarães Junior, M., Trugilho, P. F., & Mendes, L. M. (2013). Brazilian Lignocellulosic Wastes for Bioenergy Production: Characterization and Comparison with Fossil Fuels. *BioResources*, 8(1), 1166–1185.
85. Deloitte. (2008). Wood pellet plant cost study for the forests of North Eastern Ontario.
86. Denadai, M. S., Guerra, S. P. S., Bueno, O. de C., & Lancas, K. P. (2013). Custo do enfiamento de palha de milho em diferentes percentuais de recolhimento. In 8 Congresso internacional de Bioenergia São Paulo - SP - 05 a 07 de Novembro de 2013.
87. Derks, M. (2018). Co-firing white or torrefied wood pellets in the Netherlands? - An assessment of GHG emissions and emission savings (unpublished master's thesis). Utrecht University. Retrieved from [https://dspace.library.uu.nl/bitstream/handle/1874/371128/Thesis Maria Derks - Public version.pdf?sequence=2&isAllowed=y](https://dspace.library.uu.nl/bitstream/handle/1874/371128/Thesis%20Maria%20Derks%20-%20Public%20version.pdf?sequence=2&isAllowed=y)
88. Dowling, T. N., Bolding, M. C., Aust, W. M., Fox, T. R., & Dowling, T. (2010). An Analysis of Log Truck Turn Times at Harvest Sites and Mill Facilities An Analysis of Log Truck Turn Times at Harvest Sites and Mill Facilities.
89. Drax. (2019). Carbon dioxide now being captured in first of its kind BECCS pilot. Retrieved February 4, 2020, from https://www.drax.com/press_release/world-first-co2-beccs-ccus/
90. Duden, A. S., Rubino, M. J., Tarr, N. M., Verweij, P. A., Faaij, A. P. C., & Van der Hilst, F. (2018). Impact of increased wood pellet demand on biodiversity in the south-eastern United States. *GCB Bioenergy*, 10, 841–860. <https://doi.org/10.1111/gcbb.12554>
91. Duden, A. S., Verweij, P. A., Junginger, H. M., Abt, R. C., Henderson, J. D., Dale, V. H., ... Hilst, F. van der. (2017). Modeling the impacts of wood pellet demand on forest dynamics in southeastern United States, 1007–1029. <https://doi.org/10.1002/bbb>
92. Duscha, V., Ragwitz, M., Breitschopf, B., Schade, W., Walz, R., Pfaff, M., ... Boitier, B. (2014). Employment and growth effects of sustainable energies in the European Union - Final Report. Retrieved April 2, 2020, from [https://ec.europa.eu/energy/sites/ener/files/documents/EmployRES-II final report_0.pdf](https://ec.europa.eu/energy/sites/ener/files/documents/EmployRES-II%20final%20report_0.pdf)

93. E3MLab. (2015). PRIMES MODEL 2013-2014. E3MLab/Institute of Communication and Computer Systems (ICCS) at National Technical University of Athens. Retrieved from https://ec.europa.eu/clima/sites/clima/files/strategies/analysis/models/docs/primess_model_2013-2014_en.pdf
94. ECN. (n.d.). Phyllis 2 - Database for biomass and waste. Retrieved December 14, 2014, from <https://www.ecn.nl/phyllis2/>
95. EcoTransIT World Initiative (EWI). (2014). Ecological Transport Information Tool for Worldwide Transports, (December 2014).
96. Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., ... Stechow, C. von. (2011). Renewable Energy Sources and Climate Change Mitigation - Summary for policymakers and technical summary. Retrieved from https://www.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf
97. EFI - European Forest Institute. (n.d.). Wood production maps for European forests. Retrieved September 3, 2019, from <https://www.efi.int/knowledge/maps/woodproduction>
98. Ehrig, R., Behrendt, F., Wörgetter, M., & Strasser, C. (2014). Economics and Price Risks in International Pellet Supply Chains. Cham Heidelberg New York Dordrecht London: Springer.
99. Elbersen et al. (n.d.). To be published in this Special Issue - more information can be requested through corresponding authors.
100. Elbersen, W., Diaz-Chavez, R., & Elbersen, B. (2016). Progress report on biomass potentials of Colombia.
101. Empresa de Pesquisa Energética. (2014). Balanço energético nacional - year 2013. Retrieved March 20, 2015, from https://ben.epe.gov.br/downloads/Relatorio_Final_BEN_2014.pdf
102. Ericsson, K., & Werner, S. (2016). The introduction and expansion of biomass use in Swedish district heating systems. Biomass and Bioenergy, 94, 57-65. <https://doi.org/10.1016/j.biombioe.2016.08.011>
103. Escalante Hernández, H., Orduz Prada, J., Zapata Lesmes, H. J., Cardona Ruiz, M. C., & Duarte Ortega, M. (n.d.). Atlas del Potential Energético de la Biomasa Residual en Colombia. Retrieved from <https://biblioteca.minminas.gov.co/pdf/ATLAS POTENCIAL ENERGETICO BIOMASA RESIDUAL COL. UPME.pdf>
104. European Biomass Association (AEBIOM). (2016). AEBIOM Statistical Report 2016. Brussels: European Biomass Association.
105. European Commission. (2014). Commission Staff Working Document - State of play on the sustainability of solid and gaseous biomass used for electricity, heating and cooling in the EU. Retrieved from ec.europa.eu/energy/sites/ener/files/2014_biomass_state_of_play_.pdf
106. European Commission. (2015). JRC Science and Policy report - Solid and gaseous bioenergy pathways: input values and GHG emissions. Luxembourg. <https://doi.org/10.2790/299090>
107. European Commission. (2016a). Commission Staff Working Document - Impact Assessment - Sustainability of Bioenergy.

108. European Commission. (2016b). Maximising the yield of biomass from residues of agricultural crops and biomass from forestry. Berlin: Ecofys. Retrieved from [https://ec.europa.eu/energy/sites/ener/files/documents/Ecofys - Final_report_ EC_max yield biomass residues 20151214.pdf](https://ec.europa.eu/energy/sites/ener/files/documents/Ecofys_-_Final_report_EC_max_yield_biomass_residues_20151214.pdf)
109. European Commission. (2016c). Proposal for a Directive of the European Parliament and of the Council - on the promotion of the use of energy from renewable sources (recast), 2016/0382(COD).
110. European Commission. (2017). Sustainable and optimal use of biomass for energy in the EU beyond 2020 - Final report.
111. European Commission. (2018). A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy (COM(2018) 773 final).
112. European Commission. (2019). Consumer prices of petroleum products (Inclusive of duties and taxes). Retrieved June 5, 2019, from http://ec.europa.eu/energy/maps/maps_weekly_oil_bulletin/latest_Oil_Prices_DIE.pdf
113. European Parliament. (2013). Regulation (EU) No 1307/2013 of the European Parliament and of the Council of 17 December 2013 establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and repealing Council Regulation. <https://doi.org/10.1017/CBOg781107415324004>
114. European Parliament. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 - on the promotion of the use of energy from renewable sources (recast). Retrieved from <https://eur-lex.europa.eu/eli/dir/2018/2001/oj>
115. European Soil Data Centre. (2013). European Soil Database Derived data. Retrieved January 9, 2018, from <https://esdac.jrc.ec.europa.eu/content/european-soil-database-derived-data>
116. Eurostat. (2017a). Harmonised index of consumer prices (HICP). Retrieved October 21, 2017, from <http://ec.europa.eu/eurostat/web/hicp/data/database>
117. Eurostat. (2017b). International trade in goods in a nutshell. Retrieved April 6, 2017, from <http://ec.europa.eu/eurostat/web/international-trade-in-goods/statistics-illustrated>
118. Eurostat. (2019a). Electricity prices for non-household consumers - bi-annual data (from 2007 onwards). Retrieved June 5, 2019, from http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_205&lang=en%0A
119. Eurostat. (2019b). Hourly labour costs. Retrieved May 28, 2019, from https://ec.europa.eu/eurostat/statistics-explained/index.php/Hourly_labour_costs%0A
120. Facts and Details. (2015). Land and Geography of Indonesia. Retrieved May 30, 2017, from http://factsanddetails.com/indonesia/Nature_Science_Animals/sub6_8a/entry-4078.html
121. FAO. (n.d.). Potential forest species for plantations in Brazilian Amazonia. Retrieved from <http://www.fao.org/3/xii/0537-b1.htm>
122. FAO. (2001). Mean annual volume increment of selected industrial forest plantation species by L. Ugalde & O. Pérez. Rome. Retrieved from <http://www.fao.org/3/xii/0537-b1.htm>
123. FAO. (2012). The Russian federation forest sector - Outlook study to 2030. Rome.

124. Farina, R., Coleman, K., & Whitmore, A. P. (2013). Modification of the RothC model for simulations of soil organic C dynamics in dryland regions. *Geoderma*, 200–201, 18–30. <https://doi.org/10.1016/j.geoderma.2013.01.021>
125. Ferreira-Leitão, V., Gottschalk, L. M. F., Ferrara, M. A., Nepomuceno, A. L., Molinari, H. B. C., & Bon, E. P. S. (2010). Biomass Residues in Brazil : Availability and Potential Uses. *Waste Biomass Valorization*, 1(1), 65–76. <https://doi.org/10.1007/s12649-010-9008-8>
126. Fingerman, K. R., Nabuurs, G.-J., Iriarte, L., Fritsche, U. R., Staritsky, I., Visser, L., ... Martin Junginger. (2017). Opportunities and risks for sustainable biomass export from the south-eastern United States to Europe. *Biofuels, Bioproducts and Biorefining*. <https://doi.org/10.1002/bbb>
127. Fletcher, K. (2015). Report concludes US pellet exports no threat to southern forests.
128. Food and Agriculture Organization of the United Nations. (2019). FAOSTAT. Forestry Production and Trade (dataset). Retrieved March 2, 2020, from <http://www.fao.org/faostat/en/#data/FO>; last accessed Feb. 28, 2020.
129. Forest Research. (2018). Tools & Resources - Moisture content. Retrieved October 11, 2018, from <https://www.forestresearch.gov.uk/tools-and-resources/biomass-energy-resources/reference-biomass/facts-figures/moisture-content/>
130. Forest2Market. (2015). Wood Supply Market Trends in the US South Wood Supply Trends in the US South. Retrieved from [http://www.theusipa.org/Documents/ USSouthWoodSupplyTrends.pdf](http://www.theusipa.org/Documents/USSouthWoodSupplyTrends.pdf)
131. Forest2Market. (2017a). Brazil's Changing Role in the Global Pulp Market. Retrieved December 20, 2019, from <https://www.forest2market.com/blog/brazils-changing-role-in-the-global-pulp-market>
132. Forest2Market. (2017b). Changes in the Residual Wood Fiber Market , 2004 to 2017. Retrieved from https://www.forest2market.com/hubfs/2016_Website/Documents/20181130_Forest2Market_Residuals_Market_Assessment_Final.pdf
133. Forest2Market. (2018). The Disconnect Between Log Prices and Lumber Prices in the US South. Retrieved January 8, 2019, from <https://blog.forest2market.com/the-disconnect-between-log-prices-and-lumber-prices-in-the-us-south>
134. Forisk. (n.d.). Wood Bioenergy US Project List. Retrieved March 2, 2020, from <https://forisk.com/product/wood-bioenergy-us/>
135. Forsell, N., Korosuo, A., Havlik, P., Valin, H., Lauri, P., Gusti, M., ... Obersteiner, M. (2016). Study on impacts on resource efficiency of future EU demand for bioenergy - Task 3 : Modelling of impacts of an increased EU bioenergy demand on biomass production , use Authors :
136. Forster-carneiro, T., Berni, M. D., Dorileo, I. L., & Rostagno, M. A. (2013). Resources , Conservation and Recycling Biorefinery study of availability of agriculture residues and wastes for integrated biorefineries in Brazil. *Resources, Conservation & Recycling*, 77, 78–88. <https://doi.org/10.1016/j.resconrec.2013.05.007>
137. Fritsche, U., Hennig, C., Hess, J. R., Hoefnagels, R., Lamers, P., Li, C., ... Haufe, H. (2019). Margin potential for a long- term sustainable wood pellet supply chain - IEA Bioenergy Task 40: 5/2019. Retrieved from <http://task40.ieabioenergy.com/wp-content/uploads/2019/05/Fritsche-et-al-2019-IEA-Bio-T40-Margin-Pellet-Study.pdf>

138. Fritsche, U., & Iriarte, L. (2014). Biomass Policies - Task 2.4: Sustainable Imports. Cost supply curves for medium- to longer-term potentials for sustainable biomass and bioenergy (pellets, biomethane, liquid biofuels) imports to the EU-27. Darmstadt, Madrid.
139. Fritsche, U. R., & Iriarte, L. (2018). Methodology to estimate sustainable biomass potentials for bioenergy production.
140. Fulp, M. (2017). The 14-Year Record of the Baltic Dry Index. Retrieved March 23, 2020, from <https://www.kitco.com/commentaries/2016-12-21/The-14-Year-Record-of-the-Baltic-Dry-Index.html>
141. Fulvio, F. Di, Forsell, N., Lindroos, O., Korosuo, A., & Gusti, M. (2016). Spatially explicit assessment of roundwood and logging residues availability and costs for the EU28. *Scandinavian Journal of Forest Reserach*, 31(7), 691–707. <https://doi.org/10.1080/02827581.2016.1221128>
142. Fundação Nacional do Índio. (n.d.). Mapas. Retrieved September 11, 2019, from <http://www.funai.gov.br/index.php/servicos/geoprocessamento>
143. FutureMetrics. (n.d.). Global Wood Pellet Trade 2019. Retrieved June 26, 2020, from <https://www.mapprovision.com/viewer/Viewer.html?&dclid=40uje6gw#view>
144. FutureMetrics. (2018). North American Pellet Market Quarterly (Vol. 1).
145. Galik, C. S., & Abt, R. C. (2016). Sustainability guidelines and forest market response: An assessment of European Union pellet demand in the southeastern United States. *GCB Bioenergy*, 8(3), 658–669. <https://doi.org/10.1111/gcbb.12273>
146. Gavrilescu, D. (2004). Solid waste generation in kraft pulp mills. *Environmental Engineering & Management Journal*, 3(3), 399.
147. Geletukha, G., & Zheliezna, T. (2014). Prospects for the use of agricultural residues for energy production in Ukraine. Kyiv. Retrieved from www.uabio.org/activity/uabio-analytics
148. Gelten, R. (2010). Spatial assessment of the environmental impacts of wheat and switchgrass bioethanol chains in Ukraine - Master thesis. Retrieved from <https://dspace.library.uu.nl/handle/1874/191522>
149. Geofabrik. (2019). OpenStreetMap data extracts. Retrieved April 15, 2019, from <http://download.geofabrik.de/>
150. Giuntoli, J., Agostini, A., Edwards, R., & Marelli, L. (2017). Solid and gaseous bioenergy pathways. Input values and GHG emissions: calculated according to the methodology set in COM(2016) 767 - Compendium. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/biogas_and_solid_biomass_database_jrc_red-recast_v1a_july2017_protected.xlsx
151. Giuntoli, Jacopo, Agostini, A., Edwards, R., & Marelli, L. (2015). Solid and gaseous bioenergy pathways : input values and GHG emissions. <https://doi.org/10.2790/299090>
152. GlobalPetrolPrices.com. (2018). Brazil Electricity prices. Retrieved October 9, 2018, from https://www.globalpetrolprices.com/Brazil/electricity_prices/%0A
153. GlobalPetrolPrices.com. (2019a). Brazil Diesel prices, liter. Retrieved May 10, 2019, from https://www.globalpetrolprices.com/Brazil/diesel_prices/
154. GlobalPetrolPrices.com. (2019b). Russia Diesel prices, liter. Retrieved June 5, 2019, from https://www.globalpetrolprices.com/Russia/diesel_prices/

155. Gonzales, D., Searcy, E. M., & Ekşioğlu, S. D. (2013). Cost analysis for high-volume and long-haul transportation of densified biomass feedstock. *Transportation Research Part A: Policy and Practice*, 49, 48–61. <https://doi.org/10.1016/j.tra.2013.01.005>
156. Graham, R. L., Nelson, R., Sheehan, J., Perlack, R. D., & Wright, L. L. (2005). Current and Potential U.S. Corn Stover Supplies. *Agronomy Journal*, 99(1), 1–11. <https://doi.org/10.2134/agronj2005.0222>
157. Granath, J. (2015). The Global wood pellet market. Williamsburg: Pellet Fuels Institute. Retrieved from http://www.pelletheat.org/assets/docs/2015_Conference/speaker_presentations/2015_pfi_conf_presentation_granath_monday_900.pdf
158. Greene, J. (2019). Southern Timber Prices Skyrocket in 1Q2019. Retrieved April 29, 2020, from <https://www.forest2market.com/blog/southern-timber-prices-skyrocket-in-1q2019>
159. Gret-Regamey, A., Hendrick, E., Hetsch, S., Pingoud, K., & Rüter, S. (2008). Challenges and Opportunities of Accounting for Harvested Wood Products - Background paper to the Workshop on Harvested Wood Products in the Context of Climate Change Policies 9-10 September 2008, Geneva, Switzerland. Retrieved from <https://www.unece.org/forests/outlook/carbonstorage.html>
160. Günthner, W. A., Tilke, C., & Rakitsch, S. (2010). Energy Efficiency in Bulk Material Handling. *Bulk Solids Handling* Vol. 30 No. 3, 30(3), 138–142. Retrieved from http://www2.fml.mw.tum.de/fml/images/Publikationen/Günthner_Tilke_Rakitsch_BulkSolidsHandling_03-10_EnergyEfficiency.pdf
161. Hansen, E., Panwar, R., & Vlosky, R. (2013). *The Global Forest Sector: Changes, Practices, and Prospects*. CRC Press.
162. Hansen, K. (2019). Decision-making based on energy costs : Comparing levelized cost of energy and energy system costs. *Energy Strategy Reviews*, 24(February), 68–82. <https://doi.org/10.1016/j.esr.2019.02.003>
163. Hanssen, S. V., Duden, A. S., Junginger, M., Dale, V. H., & Van der Hilst, F. (2017). Wood pellets . what else ? Greenhouse gas parity times of European electricity from wood pellets produced in the south-eastern United States using different softwood feedstocks, 1406–1422. <https://doi.org/10.1111/gcbb.12426>
164. Hassuani, S. J., Leal, M. R. L. V., & Macedo, I. de C. (2005). Biomass power generation - Sugar cane bagasse and trash. In S. J. Hassuani, M. R. L. V. Leal, & I. de C. Macedo (Eds.), *Biomass power generation - Sugar cane bagasse and trash* (1st ed., pp. 24–26). Piracicaba, Brazil: PNUD - Programa das Nações Unidas para o Desenvolvimento CTC - Centro de Tecnologia Canavieira.
165. Heilman Jr., G. E., Strittholt, J. R., Slosser, N. C., & Dellasala, D. A. (2002). Forest Fragmentation of the Conterminous United States : Assessing Forest Intactness through Road Density and Spatial Characteristics. *BioScience*, 52(5), 411–422. [https://doi.org/10.1641/0006-3568\(2002\)052](https://doi.org/10.1641/0006-3568(2002)052)
166. Hember, R. A., Kurz, W. A., & Coops, N. C. (2014). Global Biogeochemical Cycles. *Global Biogeochemical Cycles*, 134–158. <https://doi.org/10.1002/2016GB005459>
167. Henderson, J. E., Joshi, O., Parajuli, R., & Hubbard, W. G. (2017). Biomass and Bioenergy A regional assessment of wood resource sustainability and potential economic impact of the wood pellet market in the U . S . South. *Biomass and Bioenergy*, 105, 421–427. <https://doi.org/10.1016/j.biombioe.2017.08.003>

168. Hilst, F. Van Der. (2018). Location, location, location. *Nature Energy*, 3(March), 164–165. <https://doi.org/10.1038/s41560-018-0094-3>
169. Hoefnagels, R., Junginger, M., & Faaij, A. (2014). The economic potential of wood pellet production from alternative, low-value wood sources in the southeast of the U.S. *Biomass and Bioenergy*, 71, 443–454. <https://doi.org/10.1016/j.biombioe.2014.09.006>
170. Hoefnagels, R., Junginger, M., & Resch, G. (2015). Coordination of biomass resource availability import strategies and demand. Retrieved April 2, 2020, from http://www.diacore.eu/images/files2/Coordination_of_biomass_resource_availability_import_strategies_and_demand.pdf
171. Hoefnagels, R., Resch, G., Junginger, M., & Faaij, A. (2014). International and domestic uses of solid biofuels under different renewable energy support scenarios in the European Union. *Applied Energy*, 131, 139–157. <https://doi.org/10.1016/j.apenergy.2014.05.065>
172. Hoefnagels, R., Searcy, E., Cafferty, K., Junginger, T. C. M., Jacobson, J., & Faaij, A. (2014). Lignocellulosic feedstock supply systems with intermodal and overseas transportation. *Biofuels, Bioproducts and Biorefining*, 8(6), 794–818. <https://doi.org/10.1002/bbb>
173. Hoque, M., Sokhansanj, S., Bi, T., Mani, S., Jafari, L., Lim, J., & Zaini, P. (2006). Economics of Pellet Production for Export Market. In CSBE/SCGAB Annual Conference. Edmonton.
174. Howard, J. L., & Liang, S. (2019). U.S. Timber Production, Trade, Consumption, and Price Statistics, 1965 – 2017. Retrieved from <https://www.fs.usda.gov/treesearch/pubs/58506>
175. IEA. (2019). Renewables 2019 - market analysis and forecast from 2019 - 2024. Retrieved June 19, 2020, from <https://www.iea.org/reports/renewables-2019/transport>
176. IETA, & PwC. (2019). GHG Market Sentiment Survey 2019. Retrieved from https://www.ieta.org/resources/Resources/GHG_Market_Sentiment_Survey/GHG_Market_Sentiment_Survey-2019.Web_HIGH_RESOLUTION.pdf
177. IINAS - International Institute for Sustainability Analysis and Strategy, EFI - European Forest Institute, & JR - Joanneum Research. (2014). Forest biomass for energy in the EU: current trends, carbon balance and sustainable potential. Prepared for BirdLife Europe, EEB, and Transport & Environment. Darmstadt, Madrid, Joensuu, Graz. Retrieved from http://www.birdlife.org/sites/default/files/attachments/IINAS_EFI_JR_2014_Forest_biomass_energy_EU.pdf
178. Index mundi. (2018). Crude oil (petroleum) monthly price - US dollars per barrel. Retrieved May 4, 2017, from <https://www.indexmundi.com/commodities/?commodity-crude-oil&months=180>
179. Indufor. (2018). Forest Industry in Finland & Russia: Opportunities & Challenges. Retrieved June 20, 2019, from <https://induforgroup.com/forest-industry-in-finland-russia-opportunities-challenges/>
180. Instituto Brasileiro de Geografia e Estatística (IBGE). (2016). Monitoramento da Cobertura e Uso da Terra. Retrieved September 4, 2019, from <https://www.ibge.gov.br/geociencias/informacoes-ambientais/cobertura-e-uso-da-terra/15831-cobertura-e-uso-da-terra-do-brasil.html?=&t=downloads>
181. International Energy Agency (IEA). (2016). World Energy Outlook 2016. https://doi.org/http://www.iea.org/publications/freepublications/publication/WEB_WorldEnergyOutlook2015ExecutiveSummaryEnglishFinal.pdf

182. International Energy Agency (IEA). (2017). The Future of Trucks. Retrieved from <https://www.iea.org/publications/freepublications/publication/TheFutureofTrucksImplicationsforEnergyandtheEnvironment.pdf>
183. International Maritime Organisation. (2015). Third IMO Greenhouse Gas Study 2014. Suffolk, UK. Retrieved from [http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third Greenhouse Gas Study/GHG3 Executive Summary and Report.pdf](http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf)
184. IPCC. (2007). IPCC Fourth Assessment Report: Climate Change 2007 - 4.4.3.1 Plant efficiency and fuel switching. Geneva, Switzerland.
185. IPCC. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Geneva, Switzerland: IPCC.
186. IPCC. (2018a). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change..
187. IPCC. (2018b). Global Warming of 1.5C - Summary for Policymakers. Retrieved from https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf
188. IPCC. (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Retrieved May 15, 2020, from <https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SRCCL-Complete-BOOK-LRES.pdf>
189. IRENA. (2015). Renewable energy prospects: United States of America, REMap 2013 analysis. Abu Dhabi. Retrieved from www.irena.org/remap
190. Jenkins, B. M., Baxter, L. L., Miles Jr., T. R., & Miles, T. R. (1998). Combustion properties of biomass. *Fuel Processing*, 54, 17-46.
191. Jenkinson, D. S., & Coleman, K. (2008). The turnover of organic carbon in subsoils. Part 2. Modelling carbon turnover. *European Journal of Soil Science*, 59(2), 400-413. <https://doi.org/10.1111/j.1365-2389.2008.01026.x>
192. Jiang, D., Zhuang, D., Fu, J., Huang, Y., & Wen, K. (2012). Bioenergy potential from crop residues in China : Availability and distribution. *Renewable and Sustainable Energy Reviews*, 16(3), 1377-1382. <https://doi.org/10.1016/j.rser.2011.12.012>
193. Johnston, C. M. T., & Van Kooten, G. C. (2016). Global trade impacts of increasing Europe's bioenergy demand. *Journal of Forest Economics*, 23, 27-44. <https://doi.org/10.1016/j.jfe.2015.11.001>
194. Jonker, J G G, Hilst, F. Van Der, Markewitz, D., Faaij, A. P. C., & Junginger, H. M. (2018). Carbon balance and economic performance of pine plantations for bioenergy production in the Southeastern United States. *Biomass and Bioenergy*, 117(July), 44-55. <https://doi.org/10.1016/j.biombioe.2018.06.017>
195. Jonker, Jan Gerrit Geurt, Junginger, M., & Faaij, A. (2014). Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United. *GCB Bioenergy*, (6), 371-389. <https://doi.org/10.1111/gcbb.12056>

196. Jonsson, R., & Rinaldi, F. (2017). The impact on global wood-product markets of increasing consumption of wood pellets within the European Union. *Energy*, 133(2017), 864–878. <https://doi.org/10.1016/j.energy.2017.05.178>
197. Kallio, M., & Leinonen, A. (2005). Production Technology of Forest Chips in Finland.
198. Kenya National Bureau of Statistics. (2015). Kenya Facts and Figures. Retrieved March 24, 2017, from http://www.knbs.or.ke/index.php?option=com_phocadownload&view=category&id=20&Itemid=1107.
199. Kenya Sugar Board. (2013). Yearbook of Sugar Statistics 2013.
200. Kheang, L. S., Subramaniam, V., & Ngatiman, M. (2012). Oil Palm Biomass - Energy Resource Data. Malaysian Palm Oil Board.
201. Kibulo, R. (2007). Biomass Waste study. Nairobi.
202. Kim, S. J., Baker, J. S., Sohngen, B. L., & Shell, M. (2018). Cumulative global forest carbon implications of regional bioenergy expansion policies. *Resource and Energy Economics*, 53, 198–219. <https://doi.org/10.1016/j.reseneeco.2018.04.003>
203. KMEC Engineering. (n.d.). Building of pellet plant promote the market development. Retrieved from <http://www.biomasspelletplant.com/news/building-of-pellet-plant.html>
204. Korean Ministry of Environment. (2014). Import of Solid Refuse Fuel to be permitted with more stringent quality test.
205. Lamers, P., Hoefnagels, R., Junginger, M., Hamelinck, C., & Faaij, A. (2015). Global solid biomass trade for energy by 2020: An assessment of potential import streams and supply costs to North-West Europe under different sustainability constraints. *GCB Bioenergy*, 7(4), 618–634. <https://doi.org/10.1111/gcbb.12162>
206. Lamers, P., Jacobson, J., & Wright, C. (2014). Expected international demand for woody and herbaceous feedstock. Idaho Falls. Retrieved from <https://www.osti.gov/scitech/servlets/purl/1177235>
207. Lamers, P., Junginger, M., Hamelinck, C., & Faaij, A. (2012). Developments in international solid biofuel trade - An analysis of volumes, policies, and market factors. *Renewable and Sustainable Energy Reviews*, 16(5), 3176–3199. <https://doi.org/10.1016/j.rser.2012.02.027>
208. Lang, A., & Copley, A. (2016). Wood Bioenergy Update and North American Pellet Capacity: Q3 2016. Retrieved July 23, 2018, from <http://forisk.com/blog/2016/08/17/wood-bioenergy-update-north-american-pellet-capacity-q3-2016/>
209. Latta, G. S., Baker, J. S., Beach, R. H., Rose, S. K., & McCarl, B. A. (2013). A multi-sector intertemporal optimization approach to assess the GHG implications of U.S. forest and agricultural biomass electricity expansion. *Journal of Forest Economics*, 19(4), 361–383. <https://doi.org/10.1016/j.jfe.2013.05.003>
210. Latta, G. S., Baker, J. S., & Ohrel, S. (2018). A Land Use and Resource Allocation (LURA) modeling system for projecting localized forest CO₂ effects of alternative macroeconomic futures. *Forest Policy and Economics*, 87(November 2017), 35–48. <https://doi.org/10.1016/j.forpol.2017.10.003>
211. Lechner, H., & Carlsson, J. (2014). The Risk of Indirect Wood Use Change - Final Report prepared for Energie Nederland. London, UK. Retrieved from <https://english.rvo.nl/sites/default/files/2017/07/IWUC-Report-20140728.pdf>

212. Leitão, F. M. da L., Perez, N. B., Trentin, G., Sisti, R. N., & Nunes, C. L. R. (2012). Avaliação comparativa de variedades de arroz irrigado cultivadas sob pivô central na Região da Campanha do Rio Grande do Sul. In II Simpósio de Iniciação Científica da Embrapa Pecuária Sul (p. 19). Bagé. Retrieved from <http://ainfo.cnptia.embrapa.br/digital/bitstream/item/72337/1/leitao-final.pdf>
213. Levin, R., Krigstin, S., Wetzel, S., & Levin, R. (2011). Biomass availability in eastern Ontario for bioenergy and wood pellet initiatives. *The Forestry Chronicle*, 33–42.
214. Leyssens, G., Trouve, G., Schönnenbeck, C., & Cazier, F. (2015). Energetic performances and environmental impact of the combustion of cardboard / sawdust in a domestic boiler. *FUEL*, 122(April 2014), 21–27. <https://doi.org/10.1016/j.fuel.2014.01.034>
215. Lindholm, E. (2010). Energy Use and Environmental Impact of Roundwood and Forest Fuel Production in Sweden. Swedish University of Agricultural Sciences, Uppsala.
216. Lindstrom, M. J. (1986). Effects of residue harvesting on water runoff, soil erosion and nutrient loss. *Agriculture, Ecosystems & Environment*, 16(2), 103–112.
217. Liu, Z., Quek, A., & Balasubramanian, R. (2014). Preparation and characterization of fuel pellets from woody biomass, agro-residues and their corresponding hydrochars. *Applied Energy*, 113, 1315–1322. <https://doi.org/10.1016/j.apenergy.2013.08.087>
218. Lu, X., Withers, M. R., Seifkar, N., Field, R. P., Barrett, S. R. H., & Herzog, H. J. (2015). Biomass logistics analysis for large scale biofuel production : Case study of loblolly pine and switchgrass. *Bioresource Technology*, 183, 1–9. <https://doi.org/10.1016/j.biortech.2015.02.032>
219. Mai-Moulin, T., Dardamanis, A., & Junginger, M. (2016). Assessment of Sustainable Lignocellulosic Biomass Potentials from Kenya for export to the European Union 2015 to 2030. Retrieved from <http://www.biobased2020plus.eu/publications-reports.html>
220. Mai-moulin, T., & Visser, L. (2019). Sourcing overseas biomass for EU ambitions : assessing net sustainable export potential from various sourcing countries. *Biofuels, Bioproducts and Biorefining*, 13, 293–324. <https://doi.org/10.1002/bbb.1853>
221. Mandley, S. J., Daioglou, V., Junginger, H. M., Vuuren, D. P. Van, & Wicke, B. (2020). EU bioenergy development to 2050. *Renewable and Sustainable Energy Reviews*, 127(July 2019), 109858. <https://doi.org/10.1016/j.rser.2020.109858>
222. Mani, S., Tabil, L. G., & Sokhansanj, S. (2006). Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. *Biomass and Bioenergy*, 30(7), 648–654. <https://doi.org/10.1016/j.biombioe.2005.01.004>
223. Mansur, P. T. B. (2014). Viabilidade do Confinamento de Bovinos com Feno de Resíduos Culturais de Soja no Sistema Triângulo. Fundação Getúlio Vargas Escola de Economia de São Paulo.
224. Martinkus, N., Latta, G., Rijkhoff, S. A. M., Mueller, D., Hoard, S., Sasatani, D., ... States, U. (2019). A multi-criteria decision support tool for biorefinery siting : Using economic , environmental , and social metrics for a refined siting analysis. *Biomass and Bioenergy*, 128. <https://doi.org/10.1016/j.biombioe.2019.105330>
225. Matzenberger, J., Kranzl, L., Tromborg, E., Junginger, M., Daioglou, V., Sheng Goh, C., & Keramidas, K. (2015). Future perspectives of international bioenergy trade. *Renewable and Sustainable Energy Reviews*, 43, 926–941. <https://doi.org/10.1016/j.rser.2014.10.106>

226. Mayer, F. D., Salbego, P. R. S., Almeida, T. C. De, & Hoffmann, R. (2015). Quantification and use of rice husk in decentralized electricity generation in Rio Grande do Sul State , Brazil, 17(4), 993–1003. <https://doi.org/10.1007/s10098-014-0850-4>
227. McKechnie, J., Saville, B., & Maclean, H. L. (2016). Steam-treated wood pellets : Environmental and financial implications relative to fossil fuels and conventional pellets for electricity generation. *Applied Energy*, 180, 637–649. <https://doi.org/10.1016/j.apenergy.2016.08.024>
228. Mendes Souza, G., Ballester, M. V. R., de Brito Cruz, C. H., Chum, H., Dale, B., Dale, V. H., ... Wielen, L. van der. (2017). The role of bioenergy in a climate-changing world. *Environmental Development*, 23(October 2016), 57–64. <https://doi.org/10.1016/j.envdev.2017.02.008>
229. Miles, T. R., Miles, T. R. J., Baxter, L. L., Bryers, R. W., Jenkins, B. M., & Oden, L. L. (1995). Alkali deposits found in biomass power plants - A preliminary investigation of their extent and nature (Vol. II). Springfield, VA: Thomas R. Miles, Consulting Design Engineers.
230. Ministério do Meio Ambiente. (n.d.). Áreas Protegidas. Retrieved September 11, 2019, from <https://www.mma.gov.br/areas-protegidas.html>
231. Ministry of Economy Trade and Industry. (2016). Settlement of FY 2016 Purchase Prices and FY 2016 Surcharge Rates under the Feed-in Tariff Scheme for Renewable Energy. Retrieved March 24, 2017, from http://www.meti.go.jp/english/press/2016/0318_03.html
232. Missagia, B. (2011). Agricultural and forestry residues for decentralized energy generation in Brazil. Brandenburgischen Technischen Universität Cottbus. Retrieved from https://opus4.kobv.de/opus4-btu/files/2440/Diss_Missagia.pdf
233. Mitchell, S. R., Harmon, M. E., & O'Connell, K. B. (2012). Carbon debt and carbon sequestration parity in forest bioenergy production. *GCB Bioenergy*, 818–827. <https://doi.org/10.1111/j.1757-1707.2012.01173.x>
234. Mobini, M., Meyer, J., Trippe, F., Sowlati, T., Fröhling, M., & Schultmann, F. (2014). Assessing the integration of torrefaction into wood pellet production. *Journal of Cleaner Production*, 78, 216–225. <https://doi.org/10.1016/j.jclepro.2014.04.071>
235. Mobini, M., Sowlati, T., & Sokhansanj, S. (2013). A simulation model for the design and analysis of wood pellet supply chains. *Applied Energy*, 111, 1239–1249. <https://doi.org/10.1016/j.apenergy.2013.06.026>
236. MOTTIE. Second Korea Energy Master Plan: Outlook & Policies To 2035, 1 § (2015). Seoul. <https://doi.org/10.1017/CBO9781107415324.004>
237. Murray, G. (2016). Emerging Pellet Markets in Asia. Wood Pellet Association of Canada.
238. Murray, G. (2017). Canadian Bioenergy Situation and Opportunities in Canada ' s Wood Pellet Sector.
239. Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestedt, J., Huang, J., ... Zhang, H. (2013). Anthropogenic and Natural Radiative Forcing. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
240. Nabavi, V., Azizi, M., Tarmian, A., & David, C. (2019). Feasibility study on the production and consumption of wood pellets in Iran to meet return-on-investment and greenhouse gas emissions targets. *Renewable Energy*, (xxxx). <https://doi.org/10.1016/j.renene.2019.10.140>

241. Natural Resources Canada. (2018). Electricity Facts. Retrieved May 24, 2019, from <https://www.nrcan.gc.ca/energy/facts/electricity/20068>
242. Netherlands Enterprise Agency. (n.d.). SDE+ sustainability requirements for co-firing and large scale heat production. Retrieved May 1, 2020, from https://english.rvo.nl/sites/default/files/2015/04/SDE%2B_sustainability_requirements_for_co-firing_and_large_scale_heat_production.pdf
243. Nilsson, D., Bernesson, S., & Hansson, P. (2010). Pellet production from agricultural raw materials - A systems study. *Biomass and Bioenergy*, 35(1), 679–689. <https://doi.org/10.1016/j.biombioe.2010.10.016>
244. Nogueira, L. A. H., Lora, E. E. S., Trossero, M., & Frisk, T. (2000). *Dendroenergia : fundamentos e aplicações* (pp. 24–45). Brasília: ANEEL.
245. Noormets, A., Epron, D., Domec, J. C., McNulty, S. G., Fox, T., Sun, G., & King, J. S. (2015). Forest Ecology and Management Effects of forest management on productivity and carbon sequestration : A review and hypothesis q. *Forest Ecology and Management*, 355, 124–140. <https://doi.org/10.1016/j.foreco.2015.05.019>
246. OANDA. (2017). Average Exchange Rates. Retrieved October 17, 2017, from <https://www.oanda.com/currency/average>
247. Obernberger, I., & Thek, G. (2010). *The pellet handbook*. London, UK, Washington, DC, USA: Earthscan.
248. OFX. (2019). Historical Exchange Rates. Retrieved January 9, 2019, from <https://www.ofx.com/en-au/forex-news/historical-exchange-rates/>
249. Orangeville, L. D., Houle, D., Duchesne, L., Phillips, R. P., Bergeron, Y., & Kneeshaw, D. (2018). Beneficial effects of climate warming on boreal tree growth may be transitory. *Nature Communications*, 1–10. <https://doi.org/10.1038/s41467-018-05705-4>
250. Oswalt, S. N., Smith, W. B., Miles, P. D., & Pugh, S. A. (2020). *Forest Resources of the United States, 2017 - A Technical Document Supporting the Forest Service 2020 RPA Assessment*. Retrieved from https://www.fs.fed.us/research/publications/gtr/gtr_w097.pdf
251. Paltseva, J., Searle, S., & Malins, C. (2016). Potential for Advanced Biofuel Production from Palm Residues in Indonesia. Retrieved from http://www.theicct.org/sites/default/files/publications/ICCT_palm_residues_2016.pdf
252. Papendick, R. I., & Moldenhauer, W. C. (1995). Crop residue management to reduce erosion and improve soil quality - Northwest. Agricultural Research Service. Retrieved from <https://archive.org/details/cropresiduemanag40pape>
253. Paraiso, M. L. de S., & Gouveia, N. (2015). Health risks due to pre-harvesting sugarcane burning in São Paulo State , Brazil. *Revista Brasileira de Epidemiologia*, 18(3), 691–701. <https://doi.org/10.1590/1980-5497201500030014>
254. Parks Canada. (2003). *Terrestrial Ecozones of Canada Arctic Cordillera Ecozone*. Retrieved from <http://parkscanadahistory.com/publications/fact-sheets/eng/ecozones.pdf>
255. Patel, M. K., Crank, M., Dornburg, V., Hermann, B., Roes, A. L., Hüsing, B., .. Recchia, E. (2006). *The BREW Project - Medium and Long-term Opportunities and Risks of the Biotechnological Production of Bulk Chemicals from Renewable Resources - The Potential of White Biotechnology*. <https://doi.org/10.1111/j.1442-8903.2004.00172.x>

256. Pelkmans, L., Devriendt, N., Junginger, M., Hoefnagels, R., Resch, G., Matzenberger, J., ... Bálint, J. (2012). Benchmarking biomass sustainability criteria for energy purposes. Study carried out for the European Commission, Directorate-General for Energy 2011/TEM/R/190. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/2014_05_biobench_report.pdf
257. Pelkmans, L., Van Dael, M., Junginger, M., Fritsche, U. R., Diaz-Chavez, R., Nabuurs, G.-J., ... Janssen, R. (2017). Long-term strategies for sustainable biomass imports in European bioenergy markets. *Biofuels, Bioproducts and Biorefining*, (13), 388–404. <https://doi.org/10.1002/bbb.1857>
258. Peng, J. H., Bi, H. T., Sokhansanj, S., Lim, J. C., Melin, S., Bi, H. T., ... Economical, S. M. A. (2010). An Economical and Market Analysis of Canadian Wood Pellets. *International Journal of Green Energy*, 7:2(April), 128–142. <https://doi.org/10.1080/15435071003673518>
259. Perlack, R. D., & B.J.Stokes. (2011). *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*. Oak Ridge: Oak Ridge National Laboratory.
260. Phillips, S., Flach, B., Lieberz, S., & Bolla, S. (2019). EU Biofuels Annual 2019. Retrieved from [https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels Annual_The Hague_EU-28_7-15-2019.pdf](https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels%20Annual_The%20Hague_EU-28_7-15-2019.pdf)
261. Pirraglia, A., Gonzalez, R., & Saloni, D. (2010). Techno-economical analysis of wood pellets production for U.S. manufacturers. *BioResources*, 5(4), 2374–2390.
262. Pirraglia, A., Gonzalez, R., Saloni, D., & Denig, J. (2013). Technical and economic assessment for the production of torrefied ligno-cellulosic biomass pellets in the US. *Energy Conversion and Management*, 66, 153–164. <https://doi.org/10.1016/j.enconman.2012.09.024>
263. Ports.com. (2018). Sea route & distance. Retrieved January 9, 2018, from <http://ports.com/sea-route/port-of-rotterdam,netherlands/port-of-savannah,united-states/>
264. Portugal-Pereira, J., Soria, R., Rathmann, R., Schaeffer, R., & Szklo, A. (2015). Biomass and Bioenergy Agricultural and agro-industrial residues-to-energy : Techno- economic and environmental assessment in Brazil. *Biomass and Bioenergy*, 81, 521–533. <https://doi.org/10.1016/j.biombioe.2015.08.010>
265. Potapov, P., Yaroshenko, A., Turubanova, S., Dubinin, M., Laestadius, L., Thies, C., ... Tsybikova, E. (2008). Mapping the World ' s Intact Forest Landscapes by Remote Sensing. *Ecology and Society*, 13(2).
266. Power, K., & Gillis, M. (2006). *Canada ' s Forest Inventory 2001*.
267. Proskurina, S., Junginger, M., Heinimö, J., Tekinel, B., & Vakkilainen, E. (2018). Global biomass trade for energy — Part 2 : Production and trade streams of wood pellets, liquid biofuels, charcoal, industrial roundwood and emerging energy biomass. *Biofuels, Bioproducts and Biorefining*, 1–17. <https://doi.org/10.1002/bbb.1858>
268. Pukkala, T. (2017). Does management improve the carbon balance of forestry? *Forestry*, (90), 125–135. <https://doi.org/10.1093/forestry/cpw043>
269. Qian, Y., & McDow, W. (2013). *The Wood Pellet Value Chain*.
270. Rafal, C., Abt, R. C., Jonsson, R., Prestemon, J. P., & Cubbage, F. W. (2013). Modeling the Impacts of EU Bioenergy Demand on the Forest Sector of the Southeast U.S. *Journal of Energy and Power Engineering*, 7, 1073–1081.

271. Ramírez, N., Arévalo, A., & Garcia-Nunez, J. A. (2015). Inventario de la biomasa disponible en plantas de beneficio para su aprovechamiento y caracterización fisicoquímica de la tusa en Colombia. *Revista Palmas*, 36(4), 41–54.
272. Regis, M., Leal, L. V., Galdos, M. V., Seabra, J. E. A., Walter, A., & Oliveira, C. O. F. (2013). Sugarcane straw availability , quality , recovery and energy use : A literature review. *Biomass and Bioenergy*, 53, 11–19. <https://doi.org/10.1016/j.biombioe.2013.03.007>
273. REN21. (2016). *Renewables 2016 Global Status Report*. Global Status Report. Paris. <https://doi.org/ISBN 978-3-9818107-0-7>
274. Rentizelas, A. A., & Li, J. (2016). Techno-economic and carbon emissions analysis of biomass torrefaction downstream in international bioenergy supply chains for co- firing. *Energy*, 114, 129–142. <https://doi.org/10.1016/j.energy.2016.07.159>
275. RISI. (n.d.). Asset Database. Retrieved March 2, 2020, from <https://www.risiinfo.com/product/asset-database/>
276. RISI. (2012). *Lockwood-Post Directory of Pulp & Paper Mills. The Americas. 2011 Traveler's Edition*.
277. Roesch, F. A., & Reams, G. A. (1999). Analytical Alternatives for an Annual Inventory System. *Journal of Forestry*, 97(12), 33–37.
278. Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., – Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, 8(April). <https://doi.org/10.1038/s41558-018-0091-3>
279. Roni, M. S., Chowdhury, S., Mamun, S., Marufuzzaman, M., Johnson, S., & Lein, W. (2017). Biomass Co-Firing Technology with Policies , Challenges , and Opportunities : A Global Review. *Renewable and Sustainable Energy Reviews*, 78, 1089–1101. <https://doi.org/10.1016/j.rser.2017.05.023>
280. Rose, S. K., Kriegler, E., Bibas, R., Calvin, K., Popp, A., Vuuren, D. P. Van, & Weyant, J. (2014). Bioenergy in energy transformation and climate management. *Climatic Change*, 123, 477–493. <https://doi.org/10.1007/s10584-013-0965-3>
281. Rudolphi, J., & Gustafsson, L. (2007). Effects of forest-fuel harvesting on the amount of deadwood on clear-cuts. *Scandinavian Journal of Forest Reserach*, 7581. <https://doi.org/10.1080/02827580510036201>
282. SAACKE. (2012). Liquids with Low Heating Value. Retrieved from www.saacke.com/fileadmin/Media/Documents/pdfs/EN/Brochures/0-0750-0020-02_Ansicht.pdf
283. Scarlat, N., Dallemand, J., Monforti-ferrario, F., & Banja, M. (2015). Renewable energy policy framework and bioenergy contribution in the European Union – An overview from National Renewable Energy Action Plans and Progress Reports, 51, 969–985. <https://doi.org/10.1016/j.rser.2015.06.062>
284. Schøjlset, S. (2014). The MSR: Impact on market balance and prices.
285. Sedjo, R. A. (2003). *Economics of Forestry*. New York, NY, US: Routledge.
286. See Freight Calculator. (n.d.). See Freight Calculator.
287. Senelwa, K., & Sims, R. E. H. (1999). Opportunities for small scale biomass-electricity systems in Kenya. *Biomass and Bioenergy*, 17, 239–255.

288. Sikkema, R., Junginger, M., Pichler, W., Hayes, S., & Faaij, A. P. C. (2010). The international logistics of wood pellets for heating and power production in Europe: Costs , energy-input and greenhouse gas balances of pellet consumption in Italy , Sweden and the Netherlands. *Biofuels, Bioproducts and Biorefining*, 132–153. <https://doi.org/10.1002/bbb>
289. Simoes, S., Nijis, W., Ruiz, P., Sgobbi, A., Radu, D., Bolat, P., ... Peteves, S. (2013). The JRC-EU-TIMES model - Assessing the long-term role of the SET Plan Energy technologies. Petten: Publicatoin Office of the European Union. <https://doi.org/10.2790/97596>
290. Skog, K. E., & Stanturf, J. A. (2011). Forest Biomass Sustainability and Availability. In *Sustainable Production of Fuels, Chemicals and Fibers from Forest Biomass* (pp. 3–25). <https://doi.org/10.1021/bk-2011-1067>
291. Smeets, E. M. W., & Faaij, A. P. C. (2010). The impact of sustainability criteria on the costs and potentials of bioenergy production – Applied for case studies in Brazil and Ukraine. *Biomass and Bioenergy*, 34(3), 319–333. <https://doi.org/10.1016/j.biombioe.2009.11.003>
292. Smeets, E. M. W., & Lewandowski, I. M. (2009). The economical and environmental performance of miscanthus and switchgrass production and supply chains in a European setting, 13, 1230–1245. <https://doi.org/10.1016/j.rser.2008.09.006>
293. Smith, B. R., Rice, R. W., & Ince, P. J. (2000). Pulp Capacity in the United States , 2000. Retrieved from <https://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr139.pdf>
294. Southern Environmental Law Center. (2015). Wood Pellet Plants and European Export - Southeast Wood Pellet Plants. Retrieved from https://www.southernenvironment.org/uploads/maps/southeastUSwoodepelletproduction_mapandtable.pdf
295. Southern Environmental Law Center. (2017). Southeast U. S. Wood Pellet Plants Exporting to Europe.
296. Spelter, H. (1996). Capacity, Production, and Manufacture of Wood-Based Panels in the United States and Canada. Retrieved from <https://www.fs.usda.gov/treesearch/pubs/9672>
297. Spelter, H., McKeever, D., & Toth, D. (2009). Profile 2009: Softwood Sawmills in the United States and Canada. Retrieved from <https://www.fs.usda.gov/treesearch/pubs/34525>
298. Stehfest, E., Van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., ... Prins, A. G. (2014). Integrated Assessment of Global Environmental Change with IMAGE 3.0 - Model description and policy applications. The Hague: PBL Netherlands Environmental Assessment Agency.
299. Stolbovoi, V. (2006). Soil Carbon in the Forests of Russia. *Mitigation and Adaptation Strategies for Global Change*, 2, 203–222.
300. Strauss, W. (n.d.). Industrial Wood Pellets in Japan Market Drivers and Potential Demand The FutureMetrics Team for Power Plant Co-firing and Full-firing. In 6th Annual Exporting Pellets Conference. Miami Beach, FL.
301. Strauss, W. (2018). Forecasting Industrial Wood Pellet Prices - A new model for calculating future prices. Bethel. Retrieved from <https://www.futuremetrics.info/wp-content/uploads/2018/09/Forecasting Industrial Wood Pellet Prices by FutureMetrics.pdf>
302. Strauss, W. (2020). 2020 global pellet markets outlook. Retrieved April 23, 2020, from <https://www.canadianbiomassmagazine.ca/2020-global-pellet-markets-outlook/>

303. Stuber, D., & Forest2Market. (2017). Global Wood Fiber Prices: 2Q2017 Insights from Forest2Market's Western Hemisphere Benchmark. Retrieved May 9, 2019, from <https://blog.forest2market.com/global-wood-fiber-prices-2q2017-insights-from-forest2markets-western-hemisphere-benchmark>
304. SugarCane. (n.d.). SugarCane Best Cultivation Practices. Retrieved May 10, 2016, from <http://sugarcane.org/sustainability/best-practices>
305. Suharno, D. I., Dehen, D. Y. A., Barbara, D. B., & Ottay, M. J. B. (2013). Opportunities for Increasing Productivity & Profitability of Oil Palm Smallholder Farmers in Central Kalimantan. Retrieved from <https://climatepolicyinitiative.org/wp-content/uploads/2015/04/Opportunities-for-Increasing-Productivity-Profitability-of-Oil-Palm-Smallholder-Farmers-in-Central-Kalimantan-Full-Report1.pdf>
306. Sultana, A., & Kumar, A. (2012). Ranking of biomass pellets by integration of economic, environmental and technical factors. *Biomass and Bioenergy*, 39, 344–355. <https://doi.org/10.1016/j.biombioe.2012.01.027>
307. Svanberg, M., Olofsson, I., Flodén, J., & Nordin, A. (2013). Bioresource Technology Analysing biomass torrefaction supply chain costs. *Bioresource Technology*, 142, 287–296. <https://doi.org/10.1016/j.biortech.2013.05.048>
308. T. Chopin (Blackwood Technology). (2019). Personal communication.
309. Teder, M., & Raudsaar, M. (2017). Functioning of Estonian roundwood market. In Roundwood markets in the Baltic Sea Region - now and tomorrow. Helsinki, Finland. Retrieved from http://www.idanmetsatieto.info/tiedostot/tiedotteet/Estonia_BNFSG_Raudsaar.pdf
310. Ter-mikaelian, M. T., Colombo, S. J., & Chen, J. (2015). The Burning Question: Does Forest Bioenergy Reduce Carbon Emissions? A Review of Common Misconceptions about Forest Carbon Accounting. *Journal of Forestry*, 113(January), 57–68.
311. Ter-Mikaelian, M. T., Colombo, S. J., Lovekin, D., McKechnie, J., Reynolds, R., Titus, B., ... Maclean, H. L. (2015). Carbon debt repayment or carbon sequestration parity? Lessons from a forest bioenergy case study in Ontario, Canada. *GCB Bioenergy*, 704–716. <https://doi.org/10.1111/gcbb.12198>
312. Terrapon-pfaff, J. C. (2012). Linking Energy- and Land-Use Systems: Energy Potentials and Environmental Risks of Using Agricultural Residues in Tanzania, 278–293. <https://doi.org/10.3390/su4030278>
313. Terrapon-pfaff, J., Fischedick, M., & Monheim, H. (2012). Energy potentials and sustainability — the case of sisal residues in Tanzania. *Energy for Sustainable Development*, 16(3), 312–319. <https://doi.org/10.1016/j.esd.2012.06.001>
314. The Conference Board. (2018). International Comparisons of Hourly Compensation Costs in Manufacturing, 2016 - Summary Tables. Retrieved August 8, 2018, from <https://www.conference-board.org/ilcprogram/index.cfm?id=38269>
315. Thek, G., & Obernberger, I. (2004). Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. *Biomass and Bioenergy*, 27(6), 671–693. <https://doi.org/10.1016/j.biombioe.2003.07.007>
316. Thiffault, E., Béchard, A., Paré, D., & Allen, D. (2015). Recovery rate of harvest residues for bioenergy in boreal and temperate forests : A review. *WIREs Energy and Environment*, 4(October). <https://doi.org/10.1002/wene.157>

317. Thompson, J. D., Klepac, J., & Sprinkle, W. (2012). Trucking Characteristics for an In-woods Biomass Chipping Operation, 1–4.
318. Thrän, D., Peetz, D., Schaubach, K., Backéus, S., Benedetti, L., Bruce, L., ... Wild, M. (2017). Global Wood Pellet Industry and Trade Study 2017. IEA Bioenergy Task 40.
319. Thrän, D., Schaubach, K., Peetz, D., Junginger, M., Mai-moulin, T., Schipfer, F., ... Falls, I. (2018). The dynamics of the global wood developments and impact factors. *Biofuels, Bioproducts and Biorefining*, (13), 267–280. <https://doi.org/10.1002/bbb.1910>
320. Thrän, D., Witt, J., Schaubach, K., Kiel, J., Carbo, M., Thr, D., ... Schipfer, F. (2016). Moving torrefaction towards market introduction – Technical improvements and economic-environmental assessment along the overall torrefaction supply chain through the SECTOR project. *Biomass and Bioenergy*, 89. <https://doi.org/10.1016/j.biombioe.2016.03.004>
321. Tomaselli, I. (2011). Otimização da gestão de resíduos e o desenvolvimento florestal. In II Encontro Nacional de Gestão de Resíduos,. 4–6 May, 2011, Curitiba: ENEGER.
322. Torén, J., Matthias Dees, Vesterinen, P., Rettenmaier, N., Smeets, E., Vis, M., ... Ermert, J. (1994). Biomass Energy Europe: Executive Summary, Evaluation and Recommendations. *Journal of School Health* (Vol. 64). <https://doi.org/10.1111/j.1746-1561.1994.tb06189.x>
323. Trading Economics. (2018). Russia Average Monthly Nominal Wages in Manufacturing. Retrieved from <https://tradingeconomics.com/russia/wages-in-manufacturing>
324. Trømborg, E., Ranta, T., Schweinle, J., Solberg, B., Skjevraak, G., & Tiffany, D. G. (2013). Economic sustainability for wood pellets production - A comparative study between Finland, Germany, Norway, Sweden and the US. *Biomass and Bioenergy*, 57, 68–77. <https://doi.org/10.1016/j.biombioe.2013.01.030>
325. Tumuluru, J. S., Sokhansanj, S., Hess, J. R., Wright, C. T., & Boardman, R. D. (2011). A review on biomass torrefaction process and product properties for energy applications. *Industrial Biotechnology*, (october). <https://doi.org/10.1089/ind.2011.0014>
326. U.S. Energy Information Administration. (2012a). 2012: EIA-860. Retrieved from <https://www.eia.gov/electricity/data/eia860/>
327. U.S. Energy Information Administration. (2012b). 2012: EIA-923. Retrieved from <https://www.eia.gov/electricity/data/eia923/>
328. U.S. Energy Information Administration. (2018a). Annual Energy Outlook 2018 with projections to 2050. Washington. Retrieved from <https://www.eia.gov/outlooks/aeo/pdf/AEO2018.pdf>
329. U.S. Energy Information Administration. (2018b). Gasoline and Diesel Fuel Update. Retrieved August 21, 2018, from <https://www.eia.gov/petroleum/gasdiesel/%0A>
330. U.S. Energy Information Administration. (2018c). Monthly densified biomass fuel report - December 18, 2018. Retrieved January 14, 2019, from https://www.eia.gov/biofuels/biomass/#table_data
331. U.S. Energy Information Administration. (2019a). Annual Energy Outlook 2019 with projections to 2050. Washington, DC. Retrieved from <https://www.eia.gov/outlooks/archive/aeo19/>
332. U.S. Energy Information Administration. (2019b). Gasoline and Diesel Fuel Update. Retrieved May 10, 2019, from <https://www.eia.gov/petroleum/gasdiesel/>

333. U.S. Energy Information Administration. (2019c). Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2019, 1–25. Retrieved from https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf
334. U.S. Energy Information Administration. (2019d). Monthly densified biomass fuel report - April 17 2019. Retrieved April 17, 2019, from https://www.eia.gov/biofuels/biomass/#table_data
335. U.S. Energy Information Administration. (2019e). Short-term Energy Outlook. Retrieved June 5, 2019, from <https://www.eia.gov/outlooks/steo/report/electricity.php>
336. U.S. Energy Information Administration. (2020). Monthly densified biomass fuel report - January 15, 2020. Retrieved February 6, 2020, from https://www.eia.gov/biofuels/biomass/#table_data
337. U.S. Forest Service. (2019). Glossary of forest engineering terms. Retrieved December 6, 2019, from <https://www.srs.fs.usda.gov/forestops/glossary/#P>
338. U.S. International Trade Commission (USITC). (2020). Interactive Tariff and Trade Database (DataWeb). Retrieved March 2, 2020, from <http://dataweb.usitc.gov>
339. Uasuf, A., & Becker, G. (2011). Wood pellets production costs and energy consumption under different framework conditions in Northeast Argentina. *Biomass and Bioenergy*, 35(3), 1357–1366. <https://doi.org/10.1016/j.biombioe.2010.12.029>
340. UNICA. (n.d.). Sugarcane Industry in Brazil. Retrieved from <http://sugarcane.org/resource-library/books/Folder and Brochure.pdf>
341. United Nations Framework Convention on Climate Change. (2015). Paris Agreement. <https://doi.org/FCCC/CP/2015/L.9>
342. United States Department of Agriculture. (2014). U . S . Forest Resource Facts and Historical Trends.
343. Urbanowski, E. (2005). Strategic Analysis of a Pellet Fuel Opportunity in Northwest British Columbia. Simon Fraser University.
344. USDA Foreign Agricultural Service. (2020). Global Agricultural Trade System Home. Retrieved February 9, 2020, from <https://apps.fas.usda.gov/Gats/default.aspx>
345. USDA Forest Service. (2019). Download National Datasets. Retrieved September 4, 2019, from <https://data.fs.usda.gov/geodata/edw/datasets.php?xmlKeyword=FIA>
346. USDA U.S. Forest Service. (n.d.). Glossary of Forest Engineering Terms. Retrieved February 20, 2020, from <https://www.srs.fs.usda.gov/forestops/glossary/>
347. Uslu, A., Faaij, A. P. C., & Bergman, P. C. A. (2008). Pre-treatment technologies , and their effect on international bioenergy supply chain logistics . Techno-economic evaluation of torrefaction , fast pyrolysis and pelletisation. *Energy*, 33, 1206–1223. <https://doi.org/10.1016/j.energy.2008.03.007>
348. Van der Hilst, F., Versteegen, J. a., Karssenbergh, D., & Faaij, A. P. C. (2012). Spatiotemporal land use modelling to assess land availability for energy crops - illustrated for Mozambique. *GCB Bioenergy*, 4(6), 859–874. <https://doi.org/10.1111/j.1757-1707.2011.01147.x>
349. Van der Hilst, F., Versteegen, J. a., Zheliezna, T., Drozdova, O., & Faaij, A. P. C. (2014). Integrated spatiotemporal modelling of bioenergy production potentials, agricultural land use, and related GHG balances; demonstrated for Ukraine. *Biofuels, Bioproducts and Biorefining*, 8(3), 391–411. <https://doi.org/10.1002/bbb.1471>

350. Velthof, G. L., Oudendag, D. a., & Oenema, O. (2007). Development and application of the integrated nitrogen model MITERRA-EUROPE. Retrieved from <http://content.alterra.wur.nl/Webdocs/PDFFiles/Alterraraapporten/AlterraRapport16631.pdf>
351. Vera, I., & Hoefnagels, R. (2019). Modeling and Analysis of multi-output biorefineries with study for the Netherlands. *Biofuels, Bioproducts and Biorefining*, 1–27. <https://doi.org/10.1002/bbb.2052>
352. Verkerk, P. J., Levers, C., Kuemmerle, T., Lindner, M., Valbuena, R., Verburg, P. H., & Zudin, S. (2015). Forest Ecology and Management Mapping wood production in European forests. *Forest Ecology and Management*, 357, 228–238. <https://doi.org/10.1016/j.foreco.2015.08.007>
353. Verstegen, J. A., van der Hilst, F., Woltjer, G., Karssenbergh, D., de Jong, S. M., & Faaij, A. P. C. (2016). What can and can't we say about indirect land-use change in Brazil using an integrated economic - land-use change model? *GCB Bioenergy*, 8(3), 561–578. <https://doi.org/10.1111/gcbb.12270>
354. Visser, L., Hoefnagels, R., & Junginger, M. (2020). Wood pellet supply chain costs – A review and cost optimization analysis. *Renewable and Sustainable Energy Reviews*, 118(November 2019), 109506. <https://doi.org/10.1016/j.rser.2019.109506>
355. Vuuren, D. P. Van, Stehfest, E., Gernaat, D. E. H. J., Berg, M. Van Den, Bijl, D. L., Boer, H. S. De, ... Sluisveld, M. A. E. Van. (2018). the need for negative emission technologies. *Nature Climate Change*, 8(May). <https://doi.org/10.1038/s41558-018-0119-8>
356. Waddell, K. (2010). FIA Volume Equation Documentation. Retrieved from <https://www.climateactionreserve.org/wp-content/uploads/2011/03/Volume-Equations-Updated-3-25-2011.pdf>
357. Wang, L., Barta-rajnai, E., Skreiberg, Ø., Khalil, R., Czégény, Z., Jakab, E., ... Grønli, M. (2018). Effect of torrefaction on physiochemical characteristics and grindability of stem wood , stump and bark. *Applied Energy*, 227, 137–148. <https://doi.org/10.1016/j.apenergy.2017.07.024>
358. Wang, X., Bi, H., Ximenes, F., Ramos, J., & Li, Y. (2017). Product and Residue Biomass Equations for Individual Trees in Rotation Age Pinus radiata Stands under Three Thinning Regimes in New South Wales , Australia. *Forests*, 1–29. <https://doi.org/10.3390/f8110439>
359. Wear, D. N., & Greis, J. G. (2013). The Southern Forest Futures Project: technical report. Retrieved from <https://www.srs.fs.usda.gov/pubs/44183>
360. Welfle, A. (2017). Biomass and Bioenergy Balancing growing global bioenergy resource demands - Brazil ' s biomass potential and the availability of resource for trade. *Biomass and Bioenergy*, 105. <https://doi.org/10.1016/j.biombioe.2017.06.011>
361. Wild, M., & Visser, L. (2018). Biomass pre-treatment for bioenergy - Case study 1: Biomass torrefaction. Retrieved from <http://itp-fuelstreatment.ieabioenergy.com/wp-content/uploads/2018/09/CS1-Torrefaction.pdf>
362. Wilhelm, W. W., Johnson, J. M. F., Hatfield, J. L., Voorhees, W. B., & Linden, D. R. (2004). Crop and Soil Productivity Response to Corn Residue Removal: A Literature Review. *Agronomy Journal*, 96(1), 1–17. <https://doi.org/10.2134/agronj2004.0001>
363. Wood Pellet Association of Canada. (n.d.). Canadian Wood Pellet Production. Retrieved from <http://www.pellet.org/production/production>

364. Wood Resources International LLC. (2017). Almost 50% of the fiber feedstock for wood pellet plants in the US South was industry and forest residues in the 1Q/17, up from 33% five years ago. Retrieved January 27, 2020, from <https://news.cision.com/wood-resources-international-llc/r/almost-50--of-the-fiber-feedstock-for-wood-pellet-plants-in-the-us-south-was-industry-and-forest-res,c2213284>
365. World Bioenergy Association. (2018). WBA Global Bioenergy Statistics 2018. Retrieved from https://worldbioenergy.org/uploads/181017_WBA_GBS_2018_Summary_hq.pdf
366. World Forest Institute. (n.d.). Brazil. Retrieved September 11, 2019, from <https://www.worldforestry.org/wp-content/uploads/2015/11/brazil-m.camargo.pdf>
367. X-rates. (2019). Monthly average. Retrieved January 15, 2020, from <https://www.x-rates.com/average/?from=USD&to=EUR&amount=1&year=2019>
368. XE. (2019a). XE Currency Converter: 1 BRL to EUR = 0.230170 Euros. Retrieved June 5, 2019, from <https://www.xe.com/currencyconverter/convert/?Amount=1&From=BRL&To=EUR>
369. XE. (2019b). XE Currency Converter: 1 CAD to EUR = 0.662810 Euros. Retrieved June 5, 2019, from <https://www.xe.com/currencyconverter/convert/?Amount=1&From=CAD&To=EUR%0A>
370. XE. (2019c). XE Currency Converter: 1 RUB to EUR = 0.0136261 Euros. Retrieved June 5, 2019, from <https://www.xe.com/currencyconverter/convert/?Amount=1&From=RUB&To=EUR%0A>
371. XE. (2019d). XE Currency Converter: 1 USD to EUR = 0.886807 Euros. Retrieved June 5, 2019, from <https://www.xe.com/currencyconverter/convert/?Amount=1&From=USD&To=EUR%0A>
372. Yoshioka, T., Sakurai, R., Kameyama, S., Inoue, K., & Hartsough, B. (2017). The Optimum Slash Pile Size for Grinding Operations : Grapple Excavator and Horizontal Grinder Operations Model Based on a Sierra Nevada , California Survey entitled entitled, 1–11. <https://doi.org/10.3390/f8110442>
373. Zappa, W., Junginger, M., Broek, M. Van Den, & Cover, C. L. (2019). Is a 100 % renewable European power system feasible by 2050 ? *Applied Energy*, 233–234(July 2018), 1027–1050. <https://doi.org/10.1016/j.apenergy.2018.08.109>
374. Zuijlen, B. Van, Zappa, W., Turkenburg, W., & Schrier, G. Van Der. (2019). Cost-optimal reliable power generation in a deep decarbonisation future. *Applied Energy*, 253(June), 113587. <https://doi.org/10.1016/j.apenergy.2019.113587>

APPENDIX A - APPENDICES TO CHAPTER 2

A.1 – context variables

Shipping cost factors

Differences in shipping costs between the different studies could be the result of fluctuations in charter rates and fuel costs. Literature data was compared with calculated fuel and charter costs throughout time to analyze this component. A time lag of one year between data gathering and publication was assumed, hence, costs from literature studies were compared to shipping costs one year prior to the publication year.

Shipping costs calculated in this study, as shown in figure A.1. fall below the indicative freight prices as calculated by Argus Media. Costs between Savannah and the ARA ports for Handysize ships lie between about 12 – 20 €/t in the period 2014 – 2018 according to available data (OFX, 2019; Strauss, 2018). One of the reason behind the underestimation of shipping costs could be the exclusion of additional costs such as insurance, customs clearance or import taxes (Qian & McDow, 2013). Data on these cost factors is not available in public literature. Total cost estimates in literature are generally given without explicit information on the cost components included.

Figure A.1 - Calculated shipping costs in Handysize and Supramax ships, calculated between Savannah and Rotterdam based on time specific fuel costs and charter rates

Exchange rate

The impact of varying exchange rates throughout the years was analyzed by calculating the average cost of the different components against average exchange rates in the years 2000 – 2017. These years were included to match the temporal scope of the studied literature. Next to the averages, also the minimum and maximum values of the components are analyzed. This analysis is repeated for only the set of literature studies that consist of values in dollar and Canadian dollar, to highlight the effect of exchange rates on cost estimates.

Shipping costs results

Calculated average shipping costs, based on historical charter rates and fuel costs, vary between 0.08 €/t/tkm in February 2016 and 0.48 €/t/tkm in May 2008 and. Yearly averages vary between 0.06 €/t/tkm and 0.36 €/t/tkm in 2016 and 2007 respectively. Comparing the normalized costs from literature with the calculated costs shows some correlation (figure A.2). In some cases, the literature values and calculated values overlap nicely. In several other occasions however, there is a significant difference between the literature values and calculated values. The distance-normalized shipping costs were again normalized for the historic difference, by factoring in the calculated costs in a given year compared to the average of all years. The resulting shipping costs vary a factor 4.2, when excluding the outlier however, the variation is reduced to a factor 1.8.

Figure A.3 – Normalized and original shipping costs

Exchange rate results

Over the analyzed years, the average total costs range between 150 €/t pellets against the exchange rates of 2008 and 195 €/t against the exchange rate in 2001. The average over all years is 168 €/t pellets. The average of only those studies that use non-euro values ranges between 145 and 220 €/t pellets on average, in respectively 2008 and 2001. Looking at individual cost components, the absolute impact is especially large for the feedstock component and pelletizing costs. For these components costs range between 34.6 and 55.7 €/t pellets and between 39.1 and 59.0 €/t respectively. Especially the impact of the dollar to euro exchange is significant, with the exchange rate varying between 0.9 \$/€ in 2001 and 1.47 \$/€ in 2008. The Canadian dollar to euro exchange rate ranged between 1.29 C\$/€ in 2012 and 1.62 C\$/€ in 2004.

A.2 – transport costs calculations

Table A.1 – Road/rail transport model costs factors

	Value	Source
General		
Labor costs (€/h)	21	American Transportation Research Institute, 2017
Diesel cost	0.684	U.S. Energy Information Administration, 2018
Road		
Loading/unloading time (h)	1	
Roundtrip factor ²	2.5	
Capacity (tonne)	25	Jacopo Giuntoli, Agostini, Edwards, & Marelli, 2015
Variable costs (€/h)	18.4	Smeets & Lewandowski, 2009
Diesel consumption (l/km)	0.61	Smeets & Lewandowski, 2009
Rail		
Loading/unloading time (h)	1	
Rail car tariff (€/tonne)	12.93	Gonzales, Searcy, & Ekşioğlu, 2013
Capacity (tonne)	3600	Personal communication with US pellet plant representative ⁴
Diesel consumption (l/km)	12.79	Jacopo Giuntoli et al., 2015

1. Only applied to loading and unloading time requirements, other costs are included in the rail car tariff.
2. Every hour of transport time is multiplied by a factor 2.5 to account for empty returns, breaks and delays.
3. Assuming rail car costs for a 65 car unit train of 90 MT grain cars (1588 \$/car), applying exchange rate and inflation from 2012 (Gonzales et al., 2013).
4. In line with Obernberger & Thek (2010)
5. Data of 08-06-2018, assuming a dollar-euro exchange rate of 0.9

Shipping costs methodology

Fuel consumption for the outward and return trip, $FC_{pellets}$ and FC_{empty} were calculated relative to the fuel consumed at full load, FC_{full} . This is based on the Admiralty formula, stating that, other factors such as speed being equal, the fuel consumption is approximately proportional to the cube root of the displacement (J. Giuntoli et al., 2017):

$$FC_{full} = Con * (DWT - AT) \quad \text{Eq. 2.B.1}$$

$$FC_{pellets} = FC_{full} * \sqrt[3]{D_{pellets} / D_{full}} \quad \text{Eq. 2.B.2}$$

$$FC_{empty} = FC_{full} * \sqrt[3]{D_{empty} / D_{full}} * ETF \quad \text{Eq. 2.B.3}$$

The displacement of a ship at full load, D_{full} , is equal to the sum of deadweight tonnage, DWT, and lightweight tonnage, LWT:

$$D_{full} = DWT + LWT \quad \text{Eq. 2.B.4}$$

The displacement of a ship filled with pellets equals the lightweight tonnage, additional tonnage such as fuel, water and crew, AT, and the weight of a full pellet load, FPL. Pellet loads are volume-limited, with the maximum load depending on the Stowage ratio, SR, and the density of the transported pellets, pellets:

$$d_{pellets} = LWT + AT + FPL \quad \text{Eq. 2.B.5}$$

$$FPL = DWT - AT / SR * \delta_{pellets} \quad \text{Eq. 2.B.6}$$

The displacement of an empty ship is calculated from the lightweight tonnage, additional tonnage and ballast weight, BWT. Furthermore, an empty trip factor, ETF allocates a share of empty trips to the outward journey, depending on the capacity factor, CF, the share of distance travelled without load:

$$D_{empty} = LWT + AT + 0.8 * BWT \quad \text{Eq. 2.B.7}$$

$$ETF = CF / (1 - CF) \quad \text{Eq. 2.B.8}$$

Total fuel costs were calculated for the different included ship classes. The total specific fuel consumption for each ship type was calculated by dividing the fuel consumed during the outward and return trip for the specific ship types over the load of pellets carried:

$$Total\ costs = \frac{FC_{pellets} + FC_{empty} * ETF}{Load} \quad \text{Eq. 2.B.9}$$

Table A.2 – Assumed characteristics of the three different ship classes included in calculations, Handysize, Handymax and Supramax.

Ship class	Handysize	Handymax	Supramax
Deadweight tonnage (t) [23]	28000	40000	57000
Lightweight tonnage (t) [23]	8000	13000	13000
Additional tonnage (t) [23]	2000	3000	3000
Cargo capacity, weight (t) [23]	26000	37000	54000
Volume limited load (t)	22533	32067	46800
Stowage ratio (t/m³) [23]	0.75	0.75	0.75
Capacity Factor [64]	0.3	0.3	0.3
CO₂ emissions, fully loaded (g HFO/tkm) [66]	4.9	3.9	3.0
Speed (knots)¹	11.15	11.44	11.75
Fuel consumption, full (g HFO/tkm)	1.6	1.2	1.0
Density pellets, 10% MC (kg/m³) [67]	650		
Emission factor HFO (t CO₂eq/t HFO) [66]	3.17		
Ballast[23]	25% of DWT		
Distance[67]	8710 km		
Loading/unloading capacity (t/day)[68] 2	10000		

1. Average speed at sea was taken from the International Maritime Organization's third GHG study (2015). This data is provided for different ship types, with specifics on average deadweight. Interpolating between these data points yielded the assumed speed for the ship characteristics assumed in this study.

2. An additional 50% of the total time was added to accommodate for periods of precipitation, when handling needs to be stopped to avoid adding moisture to the pellets.

A.3 – Average cost of biomass for pellet plants

Table A.4 – Feedstock prices as paid by U.S. pellet producers (U.S. Energy Information Administration, 2019d)

		Roundwood/ pulpwood [76]		Sawmill residuals [76]		Exchange rate (euro/ dollar) [61]
		quantity (short tons)	cost (\$ per ton)	quantity (short tons)	cost (\$ per ton)	
2017	January	203	29.3	156	33.8	0.84
	February	173	29.6	169	31.9	0.82
	March	227	29.5	164	32.3	0.81
	April	124	29.2	129	32.6	0.81
	May	234	29.3	134	32.0	0.81
	June	234	29.3	134	32.0	0.85
	July	206	29.4	136	29.8	0.86
	August	202	28.3	160	32.7	0.86
	September	288	29.7	163	29.4	0.87
	October	234	28.4	183	30.0	0.86
	November	236	29.5	177	29.9	0.87
	December	224	29.4	156	29.8	0.88
2018	January	260	30.3	181	29.7	0.95
	February	198	30.8	147	30.9	0.94
	March	266	30.7	212	28.7	0.94
	April	236	29.1	188	29.6	0.94
	May	208	29.1	215	29.7	0.93
	June	-	-	205	30.0	0.90
	July	201	28.5	195	31.2	0.89
	August	246	28.5	255	31.1	0.87
	September	248	29.9	202	31.3	0.85
	October	354	30.0	235	32.0	0.84
	November	329	29.8	239	31.0	0.85
	December	223	30.0	223	31.7	0.85

A.4 – Moisture contents assumed in literature studies

Table A.5 – Moisture content of different feedstocks assumed in the analysed literature studies

Source reference	Feedstock	MC	Feedstock	MC
1	Sawdust	55%		
2	Sawdust	57%	Wood chips	57%
3	Sawdust	53%	Shavings	19%
4	Sawdust	40%	Shavings	40%
5	Sawdust	40%		
6	Sawdust	55%		
7	Debarked pulpwood	55%		
8	Wood residues	40%		
9	Sawdust	53%	Shavings	19%
10	Sawmill residues	50%		
11	Sawdust	55%	Shavings	10%
12	Sawdust	29%	Shavings	11%
13	Debarked pulpwood	45%		
14	Pine pulpwood			
15	Chipped pulpwood	42%		
16	Pulpwood – Norway	45%	Shavings	10%
17	Sawdust/shavings - Canada	36%		
	Sawdust/woodchips - Australia	45%		
	Sawdust - Russia	55%		
18	Sawdust	29%	Shavings	11%
19	Pine pulpwood	35%		
23	-	48%		

A.5 – list of pellet plants

Table A.6 – List of pellet plants included in the analyses in this study

American Wood Fibers Marion	Lee Energy Solutions
Amite BioEnergy	Lignetics of Virginia Inc
Appling County Pellets LLC	LJR Forest Products
Enova Wood Pellets Nahunta	LowCountry Biomass
Enviva Ahoskie Plant	Morehouse BioEnergy
Enviva Amory Plant	Nature's Earth Pellets NC LLC Laurinburg
Enviva Pellets Cottondale LLC	Nature's Earth Pellets NC LLC Reform
Enviva Pellets Northampton LLC	New Biomass Energy LLC
Enviva Pellets Southampton LLC	NFR BioEnergy White Castle
Enviva Pellets Wiggins	O'Malley Wood Pellets
Equustock Chester	Potomac Supply LLC
Equustock Montebrook	Somerset Pellet Fuel
Equustock Troy	Southern Kentucky Pellet Mill Inc.
Fiber Energy Products AR LLC	Telfair Forest Products LLC
Fiber Resources Inc	Trae Fuels Ltd
Georgia Biomass	Turman Hardwood Pellets
German Pellets Louisiana LLC	Varn Wood Pellets
Hassell & Hughes Lumber Co	Westervelt Renewable Energy LLC
Hazlehurst Wood Pellets LLC	Wood Fuel Developers LLC
Henry County Hardwoods Inc	Zilkha Biomass Selma
Highland Pellets LLC Pine Bluff	

A.6 – Reference numbers literature studies

Table A.7 – Reference numbers used in the labelling of literature studies in figures and tables.

Reference number	
1	(Thek & Obernberger, 2004)
2	(Bergman, 2005)
3	(Urbanowski, 2005)
4	(Mani et al., 2006)
5	(Hoque et al., 2006)
6	(Obernberger & Thek, 2010)
7	(Pirraglia et al., 2010)
8	(Peng et al., 2010)
9	(Sikkema et al., 2010)
10	(Levin et al., 2011)
11	(Uasuf & Becker, 2011)
12	(Mobini et al., 2013)
13	(Pirraglia et al., 2013)
14	(Qian & McDow, 2013)
15	(Svanberg et al., 2013)
16	(Trømborg et al., 2013)
17	(Ehrig et al., 2014)
18	(Mobini et al., 2014)
19	(Lu et al., 2015)
20	(Mckechnie et al., 2016)
21	(Barrette et al., 2017)
22	(Boukherroub et al., 2017)
23	(Agar, 2017)

Table A.8 – Reference codes and numbers used for different countries, feedstock types and product types.

Country codes		Feedstock type	Product type
Netherlands- NL	South Africa – ZA	Roundwood – 1	White wood pellets – 1
Europe – EUR	Australia – AU	Damaged roundwood – 2	Torrefied wood pellets – 2
United States - US	Russia – RU	Thinnings – 3	Chips – 3
Canada – CA	Argentina – AR	Sawdust – 4	
Austria – AT	Finland – FI	Shavings – 5	
Sweden – SE	Germany – DE		
Belgium – BE	Norway – NO		

A.7 – Supply chain costs of pellet plants at different locations

Figure A.4 – Supply chain costs of specific pellet plants at different locations within the Southeast United States

APPENDIX B - APPENDICES TO CHAPTER 3

B.1 - Classification of feedstocks

Table B.1 – Classification of feedstocks used in this article

Agricultural resources	
Primary	Crop residues from major crops – corn stover, small grain straw, and others Grains (corn and soybeans) used for ethanol, biodiesel, and bio products Perennial grasses Perennial woody crops
Secondary	Animal manures Food/feed processing residues
Tertiary	Municipal solid waste and post-consumer residues and landfill gases
Forest resources	
Primary	Logging residues from conventional harvest operations and residues from forest management and land clearing operations Removal of excess biomass (fuel treatments) from
Secondary	Primary wood processing mill residues Secondary wood processing mill residues Pulping liquors (black liquor)
Tertiary	Urban wood residues – construction and demolition debris, tree trimmings, packaging wastes and consumer durables

B.2 - RPR & LHV values & SRF

Table B.2 – Residue to product ratios (RPR), lower heating values (LHV) and sustainable recovery factors (SRF) used in this study

	Feedstock	RPR (t/t)	LHV (MJ/kg) (%)	SRF (%)
Brazil	Sugarcane tops/straw	0.34(Nogueira, Lora, Trossero, & Frisk, 2000)	17.38(Hassuani, Leal, & Macedo, 2005)	50i
	Sugarcane bagasse	0.30(Nogueira et al., 2000)	17.71(Miles et al., 1995)	100(Lindstrom, 1986)
	Soybean straw	1.40(Nogueira et al., 2000)	12.38(Miles et al., 1995)	25(Papendick & Moldenhauer, 1995)
	Corn stalk	0.78(Bhattacharya, Pham, Shrestha, & Vu, 1993)	17.45i	30(Gavrilescu, 2004; Graham et al., 2005; Papendick & Moldenhauer, 1995)
	Corn cob	0.22(Ferreira-Leitão et al., 2010)	16.28(Lindstrom, 1986)	30(Briggs, 1994; de Paula Protásio et al., 2013; Gavrilescu, 2004; Papendick & Moldenhauer, 1995)
	Corn husk	0.20(Lindstrom, 1986)	12.00(Miles et al., 1995)	30(Briggs, 1994; de Paula Protásio et al., 2013; Gavrilescu, 2004; Papendick & Moldenhauer, 1995)
	Cassava straw	0.80(Nogueira et al., 2000)	17.50(Miles et al., 1995)	30(Briggs, 1994; de Paula Protásio et al., 2013; Gavrilescu, 2004; Papendick & Moldenhauer, 1995)

	Feedstock	RPR (t/t)	LHV (MJ/kg) (%)	SRF (%)
	Rice straw	1.48(Nogueira et al., 2000)	16.02(Miles et al., 1995)	25(Papendick & Moldenhauer, 1995)
	Rice husk	0.22(Nogueira et al., 2000)	14.17(Coelho, Monteiro, Karniol, & Ghilardi, 2008)	100
	Coffee husk	0.21(Nogueira et al., 2000)	17.71(Hassuani et al., 2005)	100
	Orange peel	0.50(Forster-carneiro, Berni, Dorileo, & Rostagno, 2013)	17.11(Aguiar, Márquez-Montesinos, Gonzalo, Sánchez, & Arauzo, 2008)	100
	Field residues	0.15(Coelho & Escobar, 2013; Tomaselli, 2011)	19.05(Boundy, Diegel, Wright, & Davis, 2011)	52.5(AEBIOM, 2014)
	Paper and cellulose production residues	0.117(Briggs, 1994; Gavrilescu, 2004)	18.18(de Paula Protásio et al., 2013)	100
	Sawmill and furniture industry residues	0.3825(Bortolin, Trentin, Peresin, & Schneider, 2012; Coelho et al., 2008; Ferreira-Leitão et al., 2010)	18.18(Aguiar et al., 2008)	100
		RPR (t/t)	HHV (MJ/kg)	SRF (%) (BID-MME, 2012)
Colombia	Sugarcane trash	3.26(Leyssens, Trouve, Schönnenbeck, & Cazier, 2015)	18.69(ECN, n.d.)	50-70ii
	Oil palm shell	0.22(Escalante Hernández, Orduz Prada, Zapata Lesmes, Cardona Ruiz, & Duarte Ortega, n.d.)	21.5(Ramírez, Arévalo, & García-Núñez, 2015)	83-92iii
	Oil palm fibre	0.63(Leyssens et al., 2015)	19.2(Ramírez et al., 2015)	83-92iii
	Oil palm empty fruit bunch	1.06(Leyssens et al., 2015)	17.9(Ramírez et al., 2015)	83-92iii

	Feedstock	RPR (t/t)	LHV (MJ/kg) (%)	SRF (%)
	Sugarcane bagasse	2.68(Leyssens et al., 2015)	19.37(ECN, n.d.)	100
Indonesia		RPR (%) (Abdullah & Sulaim, 2013; Kheang et al., 2012)	LHV (MJ/kg) (Kheang et al., 2012)	SRF (%) (Abdullah & Sulaim, 2013; Kheang et al., 2012)
	Palm EFB	21.07	18.88	95
	Palm shell	4.29	20.09	85
	Palm fibre	15.42	19.06	85
		Dry quantity(t/ha)		
	Palm frond	10.88	15.72	100
	Palm trunk	2.48	17.47	100
		RPR (t/t) (Biopact, 2006; Jiang, Zhuang, Fu, Huang, & Wen, 2012; Kenya Sugar Board, 2013; Kibulo, 2007; J. Terrapon-pfaff, Fishedick, & Monheim, 2012)	LHV (MJ/kg) (Cubero-abarca, Moya, Valaret, & Filho, 2014; Kenya Sugar Board, 2013; Kheang et al., 2012; SAACKE, 2012; J. C. Terrapon-pfaff, 2012)	SRF (%) (Cubero-abarca et al., 2014; Kenya Sugar Board, 2013; Kheang et al., 2012; SAAC-KE, 2012; J. C. Terrapon-pfaff, 2012)
Kenya	Bagasse	0.38	12.93	40
	Sugarcane stalks & leaves	0.22	16.61	9
	Molasses	0.04	8.50	100
	Sisal ball	4.10iv	14.85	83 iv
	Sisal bogas	19.80v	14.85	100 v
	Coffee husk	0.24vi	14.10	83 vi
	Coffee pulp	2.42vi	0.01	100 vi
	Coconut husk	1.10	17.66	100
	Rice straw	2.19	13.45	3
	Rice husk	0.29	16.17	100

	Feedstock	RPR (t/t)	LHV (MJ/kg) (%)	SRF (%)
	Off-cuts & chips (share in timber waste)	57,5%(Bothwell Batidzirai, 2013b; Senelwa & Sims, 1999)	19,2(Argonne National Laboratory, n.d.; "Bioenergy Technologies Office," n.d.; Jenkins, Baxter, Miles Jr., & Miles, 1998; Leyssens et al., 2015)	81
	Sawdust (share in timber waste)	19,5%vii, (Bothwell Batidzirai, 2013b)	16,8(Argonne National Laboratory, n.d.; "Bioenergy Technologies Office," n.d.; Leyssens et al., 2015; Senelwa & Sims, 1999)	0
		RPR (t/t)	LHV (MJ/kg)	SRF (%)^{vii}
Ukraine	Barley	0.8	13,6(Geletukha & Zheliezna, 2014) (wet)	0 – 100
	Maize	1.3	7,6(Geletukha & Zheliezna, 2014)	0 – 100
	Rapeseed	1.8	14,3(Geletukha & Zheliezna, 2014)	0 – 100
	Sunflower	1.9	5,7(Geletukha & Zheliezna, 2014)	0 – 100
	Wheat	1	13,3(Geletukha & Zheliezna, 2014)	0 – 100
	Primary forestry residues		16,0	0 – 75
	Secondary forestry residues		17,9	0 – 75

	Feedstock	RPR (t/t)	LHV (MJ/kg) (%)	SRF (%)
		RPR	LHV (MJ/kg, wet)	SRF (%) (Perlack & B.J. Stokes, 2011)
United States	Mill residue	viii	6.95	100
	Logging residue	viii	6.95	50 – 67 ⁱⁱ
	Softwood biomass	viii	6.95	ix
	Hardwood biomass	viii	6.95	ix
	Other removals	viii	6.95	50

i. A. Roozen, personal communication

ii. Varies per scenario.

iii. Varies per scenario, total for oil palm residues (including empty fruit bunch, fiber and shell).

iv. This price is calculated based on data from Real Vipingo sisal estate in Kilifi County. Per year 300 ha is harvested, per ha 3000 plants are produced, with a sisal ball weighing 20 kg. Fiber production was 5,100 t in 2014.

v. The lower limit of sisal bogas RPR is provided by Real Vipingo's estate measurements.

vi. Data from Kofinaf (coffee mill) in Kiambu County.

vii. Varies per region in Ukraine, calculated using spatial data on soil type, production intensity, crop type and climate.

viii. Calculated using spatial data on forest product removal (on county level) from the US Forest Service Timber Products Output (TPO) database (USDA-USFS 2015).

ix. Varies per region in the US, calculated using spatial data on protected areas of conservation significance, rarity-weighted species richness and forest types (taking into account exclusion of gum-cypress and a 10% exclusion of oak-pine forest types)(IIINAS - International Institute for Sustainability Analysis and Strategy, EFI - European Forest Institute, & JR - Joanneum Research, 2014).

B.3 - Local demand

Table B.3 – Share of sustainable potential not available due to local demand being prioritized (%)

		Cur- rent	2020 BAU	2020 HE	2030 BAU	2030 HE
Brazil	Sugarcane bagasse	90	100	90	100	90
	Sugarcane tops/ straw	0	0	0	50	25
	Soybeans straw	0	10	0	30	0
	Corn stover	60	60	50	60	30
	Cassava straw	100	100	100	100	100
	Rice straw	0	0	0	0	0
	Rice husk	75	85	67	100	67
	Coffee husk	100	100	100	100	100
	Oranges peel	100	100	100	100	100
	Forestry field		0-15	0-5	0-40	0-25
	Paper & cellulose production		75	70	85	70
	Lumber processing		75	70	85	70
Ukraine	Combined residues (straw)	31	31	15.5	31	15.5
Colom- bia	Sugar cane trash	0	5	10	20	10
	Palm EFB	36	10	15	10	15
	Palm shell	9	3	10	5	10
	Palm fibre	25	2	10	5	10
Indone- sia	Palm frond	0	0	10	10	15
	Palm trunk	0	0	10	10	15
	Palm EFB	10	10	15	15	20
	Palm shell	10	10	15	15	20
	Palm fibre	10	10	10	15	20
Kenya	Bagasse	0	0	0	0	0
	Sugarcane stalks & leaves	6	4	4	6	6
	Molasses	50	50	50	50	50
	Sisal ball	0	0	0	0	0

	Current	2020 BAU	2020 HE	2030 BAU	2030 HE
Sisal bogas	0	0	0	0	0
Coffee husk	100	100	100	100	100
Coffee pulp	100	100	100	100	100
Coconut husk	17	16	16	16	16
Rice straw	0	0	0	0	0
Rice husk	7	5	5	7	7
Off-cuts & chips (share in timber waste)	21	18	18	21	21
Sawdust (share in timber waste)	100	100	100	100	100
US Forest biomass	69	73	63	76	57

B.4 - Cost factors & country specific cost factors

Table B.4 – Cost factors used in the different countries

			Brazil	Colom- bia ¹⁴	Kenya	Indone- sia	Ukraine	United States
Feed- stock	Moistu- re content (fresh)	%	50%	50%	50	73	50%	50%
	Moistu- re content (dry)	%	8.5%	8.5%	8.5	7	8.5%	8.5%
	Cal. Value after drying	MJ / kg ar (LHV)	16.35	16.35	16	16.35	16	16
	Interest rate (IRR)		10%		10	10	10%	10%
Pellet plant	Scale	MT/ year	120,000			120,000	120,000	120,000
	Ope- rating hours	h/ year	7,000			7,000	7,000	7,000
	Elec- tricity price	€ / MWh	121.9		49.6	73.4	14.5	60.0
	Labour	€ /h	8.1		0.5	1.1	1.8	25.0
	Heat source		Bio- mass	Bio- mass	Bio- mass	Biomass	iomass	Biomass
	Pelle- tizing cost	€/t	58.9	50	55.9	79.4	58.9	107.9
Trans- port	Distan- ce to pellet plant	km	50		110	55	i	l

¹⁴ Due to data limitations it was not possible to use country specific factors for Columbia to calculate the pellet production cost, instead total pelletizing cost were assumed

			Brazil	Colom- bia ⁴⁴	Kenya	Indone- sia	Ukraine	United States
	Trans- port cost (truck)	€ / km/t	0.09	0.08	0.16	0.42	i	0.071ii
	Truck loading			1.50				
	Trans- port cost (train)	€ / km/t			0.16	-	i	0.03
	Harbor cost	€ /t	7.26	21.50	1.46	0.37	i	i
	Ocean cost			15 / 20				
	Profit	%	10%		10	10	10%	10%
Agri resi- dues	Field proces- sing site	€ /t field site	12.1	21.25/ 32.3iii	2.04	3.36	12.1	-
Forest resi- dues	Field proces- sing site	€ /t field site	20.0		2.04	-	20.0	iv
Ener- gy crops	Field proces- sing site	€ /t field site	12.1			-	12.1	-

i. For these two countries, it was possible to calculate the transport cost in more detail by making use of the existing BIT-UU model (Hoefnagels, Resch, et al., 2014). In the case of Ukraine, transport cost from any point in the Ukraine until the Port of Rotterdam could be calculated. In the case of the US, the BIT-UU model included transport cost from several export ports to the Port of Rotterdam. Calculated based on (Hoefnagels, Searcy, et al., 2014), with time cost and variable cost taken from data about trucks in the EU.

ii. Biomass cost, including cleaning of trash.

iii. Cost are taken from the Billion Ton Update (Perlack & B.J.Stokes, 2011). This study reports increasing production costs with increased mobilization of biomass. This is considered more realistic in a well-developed market such as the US.

B.5 - Included states Brazil case study

Figure B.1 – States included in the Brazil case study

B.6 - National electricity emission coefficients

Table B.5 – Electricity emission coefficients used for the different countries

Country	Electricity emission coefficient gCO ₂ -eq/MJ(BioGrace-II, 2015)
United States	180
Ukraine	167
Colombia	45
Brazil	31
Indonesia	296
Kenya	81

B.7 - Other emissions factors

Table B.6 – Emission factors used in this study

Nutrient substitution - emission factor chemicals (European Commission, 2015)					
Fertilizer		CO ₂	CH ₄	N ₂ O	CO ₂ -eq.
N	kg/t	2,670.87	6.94	2.10	0
P₂O₅	kg/t	1,459.04	3.73	0.00	0
K₂O	kg/t	409.20	0.17	0.00	0
Pesticides	kg/t	6,650.33	10.03	1.68	7,402.33

Pre-treatment (European Commission, 2015)					
		CO ₂	CH ₄	N ₂ O	CO ₂ -eq.
Cultivation	g/MJ wood pellets	0.842	0.0000088	0.0000368	0.85
Chipping	g/MJ wood pellets	0.248	0.0000026	0.0000109	0.25
Drying	g/MJ wood pellets	0.070	0.0000007	0.0000031	0.07
Pellet Mill	g/MJ wood pellets	0.146	0.0000015	0.0000064	0.15
Pellet Mill	MJ/MJ wood pellets	0.050			

B.8 – Costs sensitivity results

Table B.7 – Total emissions in the different countries when varying different impacting factors (in €/GJ)

Country	Impacting factor	50%	75%	90%	100%	110%	125%	150%
Brazil	Electricity			12.7	12.9	13.1		
	Transport		11.8	12.4	12.9	13.3	14.0	
	Pre-processing		11.8	12.5	12.9	13.3	13.9	
	Capital	12.0	12.4	12.7	12.9	13.1	13.3	13.8
	Labour		12.9	12.9	12.9	12.9	12.9	
Indonesia	Electricity			13.5	13.6	13.6		
	Transport		12.0	13.0	13.6	14.2	15.1	
	Pre-processing		12.5	13.1	13.6	14.0	14.6	
	Capital	12.5	13.0	13.3	13.6	13.8	14.1	14.6
	Labour		13.5	13.6	13.6	13.6	13.6	
Kenya	Electricity			11.9	12.0	12.1		
	Transport		10.0	11.2	12.0	12.8	14.0	
	Pre-processing		11.8	11.9	12.0	12.1	12.3	
	Capital	11.1	11.6	11.8	12.0	12.2	12.4	12.9
	Labour		12.0	12.0	12.0	12.0	12.0	
Ukraine	Electricity			8.8	8.8	8.8		
	Transport		8.3	8.6	8.8	9.0	9.3	
	Pre-processing		7.8	8.4	8.8	9.2	9.8	
	Capital	7.9	8.3	8.6	8.8	9.0	9.2	9.7
	Labour		8.8	8.8	8.8	8.8	8.8	
The US	Electricity			11.6	11.7	11.8		
	Transport		11.0	11.4	11.7	12.0	12.4	
	Pre-processing		10.7	11.3	11.7	12.1	12.7	
	Capital	11.0	11.4	11.6	11.7	11.8	12.0	12.4
	Labour		11.6	11.7	11.7	11.7	11.8	

B.9 - Emissions sensitivity results

Table B.8 - Total emissions in the different countries when varying different impacting factors (in kg CO₂-eq./GJ)

Country	Impacting factor	Low range	Base case	High range
Brazil	Nutrient substitution	12.4	12.9	13.7
	Local Transport	12.1	12.9	14.0
	Electricity	13.0	12.9	13.1
Colombia	Nutrient substitution	10.3	11.1	12.3
	Local Transport	11.1	11.1	11.5
	Electricity	11.2	11.1	11.4
Indonesia	Nutrient substitution	13.5	14.8	16.1
	Local Transport	14.6	14.8	15.0
	Electricity	14.7	14.8	14.9
Kenya	Nutrient substitution	12.7	13.3	13.8
	Local Transport	12.7	13.3	13.9
	Electricity	13.2	13.3	13.4
Ukraine	Nutrient substitution	6.5	7.3	8.1
	Local Transport	7.3	7.3	7.3
	Electricity	7.1	7.3	7.5
The US	Nutrient substitution	8.6	8.7	8.7
	Local Transport	8.3	8.7	9.0
	Electricity	8.5	8.7	8.8

APPENDIX C - APPENDICES TO CHAPTER 4

C.1 – Country specific cost factors used

Table C.1 - Feedstock costs for the different feedstock types, in €/t of wet feedstock.

Country	Pulpwood	Logging residues	Sawmill residues	Source
US SE	30	30	30	(U.S. Energy Information Administration, 2018c)
US NE	35.2	35.2	35.2	(Stuber & Forest2Market, 2017)
Canada SE	35.2	35.2	35.2	(Stuber & Forest2Market, 2017)
Canada BC	36.2	36.2	36.2	(Stuber & Forest2Market, 2017)
Brazil	22.4	22.4	22.4	(Stuber & Forest2Market, 2017)
Estonia	28.6	25.7	25.7	(Teder & Raudsaar, 2017)
Lithuania	57.9	52.1	52.1	(Baltpool, n.d.)
Latvia	56.8	42.5	42.5	(Centras Statistikas Parvaldes Datubazes, 2018)
Russia	39.3	35.4	35.4	(Indufor, 2018)

Table C.2 - Diesel costs used in this study, in €/l.

Country	Diesel price	Source
Netherlands	1.39	(European Commission, 2019)
US SE	0.70	(U.S. Energy Information Administration, 2019b; XE, 2019d)
US NE	0.70	(U.S. Energy Information Administration, 2019b; XE, 2019d)
Canada SE	0.85	(Canada, 2019; XE, 2019b)
Canada BC	0.85	(Canada, 2019; XE, 2019b)
Brazil	0.81	(GlobalPetrolPrices.com, 2019a; XE, 2019a)
Estonia	1.39	(European Commission, 2019)
Lithuania	1.18	(European Commission, 2019)
Latvia	1.25	(European Commission, 2019)
Russia	0.62	(GlobalPetrolPrices.com, 2019b; XE, 2019c)

Table C.3 – Hourly labor costs in the manufacturing industry used in this study, in €/h.

Country	Costs	Source
Netherlands	35.9	(Eurostat, 2019b)
US SE	34.6	(The Conference Board, 2018)
US NE	34.6	(The Conference Board, 2018)
Canada SE	26.7	(The Conference Board, 2018)
Canada BC	26.7	(The Conference Board, 2018)
Brazil	7.1	(The Conference Board, 2018)
Estonia	12.4	(Eurostat, 2019b)
Lithuania	9.0	(Eurostat, 2019b)
Latvia	9.3	(Eurostat, 2019b)
Russia	3.1	(Trading Economics, 2018)

Table C.4 – Grid electricity costs used in this study, in €/kWh.

Country	Costs	Type	Period	Source
Netherlands	0.0680	> 150 000 MWh, incl. taxes	2018	(CBS StatLine, 2019)
US SE	0.0582	Industrial sector, retail price	2018	(U.S. Energy Information Administration, 2019e)
US NE	0.0582	Industrial sector, retail price	2018	(U.S. Energy Information Administration, 2019e)
Canada SE	0.0564	Industrial sector, incl. taxes	2017	(Natural Resources Canada, 2018)
Canada BC	0.0705	Industrial sector, incl. taxes	2017	(Natural Resources Canada, 2018)
Brazil	0.1427	General data	2018	(GlobalPetrolPrices.com, 2018; XE, 2019a)
Estonia	0.1109	500 – 2500 MWh, non-household, incl. taxes	2018S2	(Eurostat, 2019a)
Lithuania	0.1089	500 – 2500 MWh, non-household, incl. taxes	2018S2	(Eurostat, 2019a)
Latvia	0.1267	500 – 2500 MWh, non-household, incl. taxes	2018S2	(Eurostat, 2019a)
Russia	0.0139	General data	2017	(CEIC, 2019)

Table C.5 – Shipping fuel and charter costs variation, in €/t for fuel costs and €/day for charter costs.

Scenario	Fuel costs (IFO380)	Source	Charter costs Handymax ⁱ	Period	Source
Low	300	(BIX Bunker Index, 2019)	2000	2018	(Bimco, 2019)
Medium	400	(BIX Bunker Index, 2019)	6000	2018	(Bimco, 2019)
High	500	(BIX Bunker Index, 2019)	10000	2018	(Bimco, 2019)

i. Handysize costs are assumed to be 10% lower and Supramax costs are assumed to be 10% higher

C.2 – Pelletizing costs and energy requirements

Table C.6 – Pelletizing costs and energy requirements, for a small (50 kt/y) and large (500 kt/y) pellet mill in the United States, based on Chapter 2..

Parameter	Unit	Small pellets	Large pellets	Small TOP	Large TOP	Source
CAPEX	€/t pellets	14.1	7.9	17.3	10.2	Chapter 2
CAPEX, saw-mill residues	€/t pellets	11.5	6.1	16.0	9.3	Chapter 2
CAPEX torrefaction reactor ⁱⁱ	€/t pellets			4.5	3.2	Svanberg et al., 2013
Service & Maintenance	€/t pellets	5.0	5.0	5.0	5.0	Chapter 2
Labor ⁱⁱⁱ	€/t pellets	13.1	7.4	13.1	7.4	Chapter 2
Energy re-quirements						
Drying	kWh/t pellets	36	36	36	36	Chapter 2
Course grinding ^{iv}	kWh/t pellets	20	20	20	20	Chapter 2
Grinding ^v	kWh/t pellets	31	31	15.5	15.5	(Chapter 2; L. Wang et al., 2018)

Parameter	Unit	Small pellets	Large pellets	Small TOP	Large TOP	Source
Pelletizing	kWh/t pellets	78	78	78	78	Chapter 2
Cooling	kWh/t pellets	4	4	4	4	Chapter 2
Peripheral equipment	kWh/t pellets	16	16	16	16	Chapter 2
Torrefaction	kWh/t pellets			21	21	[27]
Required heat	kWh/t ev. w.	1200	1200	1200	1200	[38]
Boiler efficiency		85%	85%	85%	85%	

- i. Based on Chapter 2, assumed scale factor of 0.85, and a reference pellet plant size of 100 kt/a. The difference between costs of sawmill residues and other feedstocks is the cost of grinding equipment
- ii. Based on investment costs of 5.5 M€ for an annual production of 200 kt/a [95]. Assumed interest rate of 10% and lifetime of 15 years. Assumed scale factor of 0.85
- iii. Based on Chapter 2, assumed economies of scale factor of 0.25, and a reference pellet plant size of 100 kt/a. Based on costs in the United States, labour costs in other countries are calculated based on the percentage of hourly wages in the United States
- iv. Only required for pulpwood.
- v. As reported by Wang et al. (L. Wang et al., 2018), the energy requirement of grinding is reduced by half for torrefied material.

C.3 – Country specific methodology and data used to calculate available feedstock

Table C.7 – Methodology used for the calculation of available feedstock.

Country	Forest area	Annual increment	Restricted area
Estonia Latvia Lithuania	Predicted volume of wood production per km ² , based on statistics, productivity and tree species composition (EFI - European Forest Institute, n.d.; Verkerk et al., 2015).	Assumed to be included in Forest area estimate	
Russia	Forest cover dataset of all forested areas in Russia (Stolbovoi, 2006).	Growing stock estimates per administrative division, average annual increment per growing stock factor for the entire country (FAO, 2012)i.	-
Canada	Canada's Forest Inventory 2001 – data on percentage forested area and predominant species (Power & Gillis, 2006). Productivity was calculated based on the percentage of forested area and the annual increment.	Productivity varied for different ecoregions, based on five ecozones. Other regions were based on temperature differences and geographic proximity, mainly the latitude (Hember, Kurz, & Coops, 2014)ii.	The extent of intact forests in 2010 was subtracted, based on spatial data from (Conservation Biology Institute, 2018).
US	Average annual volume growth based on USDA Forest Inventory and Analysis (FIA) data (USDA Forest Service, 2019). Data consists of most recent data per county from 2015, 2016 and 2017iii.		Old forest areas, from a database of relative forest intactness were subtracted, based on (Heilman Jr., Strittholt, Slosser, & Dellasala, 2002), taken from (Conservation Biology Institute, 2001).

Country	Forest area	Annual increment	Restricted area
Brazil	Based on land cover-age and use data-base of the Instituto Brasileiro de Geografia e Estatística (Instituto Brasileiro de Geografia e Estatística (IBGE), 2016). Areas classified as forest vegetation were included.	Mean annual increment data for pine, eucalyptus and Brazilian firetree (FAO, n.d., 2001). In states with tropical wood vegetation, the firetree value was used. In other states, an average of pine and eucalyptus was used, except for states where one species is dominant, based on (World Forest Institute, n.d.)iv.	Areas classified as (1) indigenous land, (2) protected or established for sustainable use only and (3) intact forest areas were subtracted (Fundação Nacional do Índio, n.d.; Ministério do Meio Ambiente, n.d.; Potapov et al., 2008).

- i. This is considered a suboptimal approach, made necessary by a lack of data. In reality the link between growing stock and annual increment is non-linearly and depends on aspects such as tree species, age and climate.
- ii. Growth in the Taiga Shield and Taiga Plains ecozones were calculated based on the assessment of the impact of temperature increase on productivity in Eastern Canada, assuming an equal productivity difference between the warmer Boreal zones and the Taiga zones (Orangeville et al., 2018). Average temperature differences range between 7.5 °C in January and 4 °C in July (Parks Canada, 2003), based on this the results for the highest temperature difference of 4 °C were used, calculated for the dominant tree species in the ecozones (Orangeville et al., 2018). Atlantic Maritime, Boreal Plains, Boreal Shield, Montane Cordillera, Pacific Maritime. Other ecozones were based on the existing data: Boreal Cordillera/ Taiga Cordillera - Taiga Plain, Arctic Cordillera, Southern Arctic - Taiga Shield, Mixedwood Plains - Atlantic Maritime, Hudson Plains - Average Taiga Shield & Boreal Shield, Prairies - Average Montane Cordillera & Boreal Shield
- iii. FIA data is based on measured plots within a grid overlay across the conterminous US. The location of plots however varies, and some plots are swapped within a country for privacy reasons. For this reason, the results aggregated per county were used, instead of actual plot data. Country aggregates are subsequently averaged across the area, assuming a homogenous spread to obtain a 1 km² raster dataset.
- iv. Eucalyptus: Sao Paulo, Minas Gerais, Espirito Santo. Pine: Sao Paulo, Mato Grosso, Parana, Santa Catarina, Rio Grande do Sul. Eucalyptus + Pine: Goias, Federal district, Bahia, Piaui, Ceara, Rio Grande do Norte, Paraiba, Pernambuco, Alagoas, Sergipe. Tropical wood: Acre, Amazonas, Roraima, Rondônia, Mato Grosso, Pará, Amapá, Tocantins, Maranhão

C.4 – Results of supply chain costs per export port and cost component

Table C.8 – Overview of supply chain costs of pellets produced from sawmill residues, transported over 500 km to export ports and including 50 km feedstock transport, in €/t pellets. Components included in the table: 1. Feedstock transport; 2. Feedstock; 3. Pelletizing; 4. Pellet transport; 5. Shipping; 6. Port operations.

Export port	Total	1	2	3	4	5	6
Savannah	140.9	8.4	55.6	22.3	37.2	15.1	2.2
Mobile	144.5	8.4	55.6	22.3	37.2	18.7	2.2
Norfolk	139.2	8.4	55.6	22.3	37.2	13.4	2.2
Portland	147.6	8.4	65.2	22.9	37.2	11.7	2.2
Halifax	141.7	7.8	65.2	21.2	34.9	10.4	2.2
Montreal	142.2	7.8	65.2	21.2	34.9	10.9	2.2
Quebec	141.8	7.8	65.2	21.2	34.9	10.4	2.2
Vancouver	170.3	7.8	67.1	21.3	34.9	36.9	2.3
Prince Rupert	171.2	7.8	67.1	21.3	34.9	37.8	2.3
Maceio	107.3	5.4	41.6	15.4	24.8	17.5	2.6
Salvador	108.2	5.4	41.6	15.4	24.8	18.4	2.6
Rio de Janeiro	110.6	5.4	41.6	15.4	24.8	20.8	2.6
Rio Grande	113.4	5.4	41.6	15.4	24.8	23.6	2.6
St. Petersburg	134.5	4.3	75.5	16.4	19.7	16.5	2.0
Paldiski	132.0	7.6	54.9	17.5	35.6	14.1	2.2
Kunda	133.1	7.6	54.9	17.5	35.6	15.3	2.2
Pärnu	131.5	7.6	54.9	17.5	35.6	13.7	2.2
Ventspils	163.3	6.9	90.7	18.8	32.0	12.6	2.3
Liepāja	162.8	6.9	90.7	18.8	32.0	12.1	2.3
Riga	164.4	6.9	90.7	18.8	32.0	13.7	2.3
Butinge	182.2	6.6	111.1	19.9	30.8	11.5	2.2
Klaipėda	182.2	6.6	111.1	19.9	30.8	11.5	2.2

Table C.9 – Overview of supply chain costs of pellets produced from roundwood, transported over 500 km to export ports and including 50 km feedstock transport, in €/t pellets. Components included in the table: 1. Feedstock transport; 2. Feedstock; 3. Pelletizing; 4. Pellet transport; 5. Shipping; 6. Port operations.

Export port	Total	1	2	3	4	5	6
Savannah	156.0	10.0	55.6	35.9	37.2	15.1	2.2
Mobile	159.6	10.0	55.6	35.9	37.2	18.7	2.2
Norfolk	154.3	10.0	55.6	35.9	37.2	13.4	2.2
Portland	164.5	10.0	65.2	38.2	37.2	11.7	2.2
Halifax	158.4	9.3	65.2	36.3	34.9	10.4	2.2

Export port	Total	1	2	3	4	5	6
Montreal	158.9	9.3	65.2	36.3	34.9	10.9	2.2
Quebec	158.5	9.3	65.2	36.3	34.9	10.4	2.2
Vancouver	187.4	9.3	67.1	36.8	34.9	36.9	2.3
Prince Rupert	188.3	9.3	67.1	36.8	34.9	37.8	2.3
Maceio	118.9	6.6	41.6	25.9	24.8	17.5	2.6
Salvador	119.8	6.6	41.6	25.9	24.8	18.4	2.6
Rio de Janeiro	122.1	6.6	41.6	25.9	24.8	20.8	2.6
Rio Grande	125.0	6.6	41.6	25.9	24.8	23.6	2.6
St. Petersburg	162.1	5.2	83.9	34.8	19.7	16.5	2.0
Paldiski	154.5	9.3	61.0	32.3	35.6	14.1	2.2
Kunda	155.7	9.3	61.0	32.3	35.6	15.3	2.2
Pärnu	154.1	9.3	61.0	32.3	35.6	13.7	2.2
Ventspils	184.5	8.4	90.7	38.5	32.0	12.6	2.3
Liepāja	184.0	8.4	90.7	38.5	32.0	12.1	2.3
Riga	185.5	8.4	90.7	38.5	32.0	13.7	2.3
Butinge	222.2	8.1	123.5	46.1	30.8	11.5	2.2
Klaipeda	222.2	8.1	123.5	46.1	30.8	11.5	2.2

Table C.10 – Overview of supply chain costs of torrefied pellets produced from sawmill residues, transported over 500 km to export ports and including 50 km feedstock transport, in €/t pellets. Components included in the table: 1. Feedstock transport; 2. Feedstock; 3. Pelletizing; 4. Pellet transport; 5. Shipping; 6. Port operations.

Export port	Total	1	2	3	4	5	6
Savannah	155.3	7.5	63.6	32.1	35.7	14.2	2.2
Mobile	158.8	7.5	63.6	32.1	35.7	17.6	2.2
Norfolk	153.8	7.5	63.6	32.1	35.7	12.6	2.2
Portland	163.1	7.5	74.5	32.1	35.7	11.0	2.2
Halifax	163.8	8.0	74.5	31.4	37.8	9.8	2.2
Montreal	164.2	8.0	74.5	31.4	37.8	10.2	2.2
Quebec	163.8	8.0	74.5	31.4	37.8	9.8	2.2
Vancouver	193.5	8.0	76.7	33.8	37.8	34.9	2.3
Prince Rupert	194.3	8.0	76.7	33.8	37.8	35.7	2.3
Maceio	140.7	5.6	47.5	42.3	26.2	16.5	2.6
Salvador	141.5	5.6	47.5	42.3	26.2	17.4	2.6
Rio de Janeiro	143.8	5.6	47.5	42.3	26.2	19.6	2.6
Rio Grande	146.4	5.6	47.5	42.3	26.2	22.3	2.6
St. Petersburg	144.8	4.2	86.3	17.4	19.7	15.2	2.0
Paldiski	157.3	7.7	62.8	36.1	35.6	13.0	2.2
Kunda	158.3	7.7	62.8	36.1	35.6	14.0	2.2

Export port	Total	1	2	3	4	5	6
Pärnu	156.9	7.7	62.8	36.1	35.6	12.6	2.2
Ventspils	194.5	6.9	103.7	38.0	32.0	11.6	2.3
Liepaja	194.0	6.9	103.7	38.0	32.0	11.2	2.3
Riga	195.5	6.9	103.7	38.0	32.0	12.6	2.3
Butinge	212.2	6.7	127.0	34.9	30.8	10.6	2.2
Klaipeda	212.2	6.7	127.0	34.9	30.8	10.6	2.2

Table C.11 – Overview of supply chain costs of torrefied pellets produced from roundwood, transported over 500 km to export ports and including 50 km feedstock transport, in €/t pellets. Components included in the table: 1. Feedstock transport; 2. Feedstock; 3. Pelletizing; 4. Pellet transport; 5. Shipping; 6. Port operations.

Export port	Total	1	2	3	4	5	6
Savannah	159.3	9.3	63.6	34.3	35.7	14.2	2.2
Mobile	162.8	9.3	63.6	34.3	35.7	17.6	2.2
Norfolk	157.7	9.3	63.6	34.3	35.7	12.6	2.2
Portland	167.1	9.3	74.5	34.3	35.7	11.0	2.2
Halifax	167.9	9.9	74.5	33.5	37.8	9.8	2.2
Montreal	168.3	9.9	74.5	33.5	37.8	10.2	2.2
Quebec	167.9	9.9	74.5	33.5	37.8	9.8	2.2
Vancouver	197.8	9.9	76.7	36.2	37.8	34.9	2.3
Prince Rupert	198.7	9.9	76.7	36.2	37.8	35.7	2.3
Maceio	146.1	7.1	47.5	46.2	26.2	16.5	2.6
Salvador	147.0	7.1	47.5	46.2	26.2	17.4	2.6
Rio de Janeiro	149.2	7.1	47.5	46.2	26.2	19.6	2.6
Rio Grande	151.8	7.1	47.5	46.2	26.2	22.3	2.6
St. Petersburg	156.7	5.3	95.9	18.6	19.7	15.2	2.0
Paldiski	169.5	9.9	69.7	39.2	35.6	13.0	2.2
Kunda	170.6	9.9	69.7	39.2	35.6	14.0	2.2
Pärnu	169.2	9.9	69.7	39.2	35.6	12.6	2.2
Ventspils	199.9	8.9	103.7	41.5	32.0	11.6	2.3
Liepaja	199.4	8.9	103.7	41.5	32.0	11.2	2.3
Riga	200.9	8.9	103.7	41.5	32.0	12.6	2.3
Butinge	231.2	8.5	141.1	38.0	30.8	10.6	2.2
Klaipeda	231.3	8.5	141.1	38.0	30.8	10.6	2.2

C.5 – Results of supply chain GHG emissions per export port and cost component

Table C.12 – Overview of supply chain GHG emissions of pellets produced from sawmill residues, transported over 500 km to export ports and including 50 km feedstock transport, in kg CO₂-eq/t pellets. Components included in the table: 1. Silviculture and harvest; 2. Feedstock transport; 3. Pelletizing; 4. Pellet transport; 5. Shipping; 6. Port operations.

Export port	Total	1	2	3	4	5	6
Savannah	12.5	1.1	4.5	2.7	0.2	2.9	1.1
Mobile	13.2	1.1	4.5	2.7	0.2	3.6	1.1
Norfolk	12.2	1.1	4.5	2.7	0.2	2.6	1.1
Portland	11.8	1.1	4.5	2.7	0.2	2.2	1.1
Halifax	8.8	1.1	1.7	2.7	0.2	2.0	1.1
Montreal	8.9	1.1	1.7	2.7	0.2	2.1	1.1
Quebec	8.8	1.1	1.7	2.7	0.2	2.0	1.1
Vancouver	13.9	1.1	1.7	2.7	0.2	7.1	1.1
Prince Rupert	14.0	1.1	1.7	2.7	0.2	7.2	1.1
Maceio	9.3	1.1	0.9	2.7	0.1	3.4	1.1
Salvador	9.4	1.1	0.9	2.7	0.1	3.5	1.1
Rio de Janeiro	9.9	1.1	0.9	2.7	0.1	4.0	1.1
Rio Grande	10.4	1.1	0.9	2.7	0.1	4.5	1.1
St. Petersburg	12.2	1.1	4.9	2.7	0.2	2.2	1.1
Paldiski	15.0	1.1	7.9	2.7	0.3	1.9	1.1
Kunda	15.1	1.1	7.9	2.7	0.3	2.0	1.1
Pärnu	14.9	1.1	7.9	2.7	0.3	1.8	1.1
Ventspils	17.0	1.1	10.1	2.7	0.3	1.7	1.1
Liepāja	16.9	1.1	10.1	2.7	0.3	1.6	1.1
Riga	17.1	1.1	10.1	2.7	0.3	1.8	1.1
Butinge	10.0	1.1	3.4	2.7	0.2	1.5	1.1
Klaipėda	10.0	1.1	3.4	2.7	0.2	1.5	1.1

Table C.13 – Overview of supply chain GHG emissions of pellets produced from roundwood, transported over 500 km to export ports and including 50 km feedstock transport, in kg CO₂-eq/t pellets. Components included in the table: 1. Silviculture and harvest; 2. Feedstock transport; 3. Pelletizing; 4. Pellet transport; 5. Shipping; 6. Port operations.

Export port	Total	1	2	3	4	5	6
Savannah	16.9	2.5	2.2	6.1	2.7	0.2	2.9
Mobile	17.6	2.5	2.2	6.1	2.7	0.2	3.6
Norfolk	16.6	2.5	2.2	6.1	2.7	0.2	2.6
Portland	16.3	2.5	2.2	6.1	2.7	0.2	2.2
Halifax	12.9	2.5	2.2	3.0	2.7	0.2	2.0
Montreal	12.9	2.5	2.2	3.0	2.7	0.2	2.1
Quebec	12.9	2.5	2.2	3.0	2.7	0.2	2.0
Vancouver	17.9	2.5	2.2	3.0	2.7	0.2	7.1
Prince Rupert	18.1	2.5	2.2	3.0	2.7	0.2	7.2
Maceio	13.3	2.5	2.2	2.1	2.7	0.1	3.4
Salvador	13.5	2.5	2.2	2.1	2.7	0.1	3.5
Rio de Janeiro	13.9	2.5	2.2	2.1	2.7	0.1	4.0
Rio Grande	14.4	2.5	2.2	2.1	2.7	0.1	4.5
St. Petersburg	16.7	2.5	2.2	6.6	2.7	0.2	2.2
Paldiski	19.8	2.5	2.2	10.0	2.7	0.3	1.9
Kunda	19.9	2.5	2.2	10.0	2.7	0.3	2.0
Pärnu	19.7	2.5	2.2	10.0	2.7	0.3	1.8
Ventspils	22.1	2.5	2.2	12.4	2.7	0.3	1.7
Liepaja	22.0	2.5	2.2	12.4	2.7	0.3	1.6
Riga	22.3	2.5	2.2	12.4	2.7	0.3	1.8
Butinge	14.3	2.5	2.2	4.9	2.7	0.2	1.5
Klaipeda	14.3	2.5	2.2	4.9	2.7	0.2	1.5

Table C.14 – Overview of supply chain GHG emissions of torrefied pellets produced from sawmill residues, transported over 500 km to export ports and including 50 km feedstock transport, in kg CO₂-eq/t pellets. Components included in the table: 1. Silviculture and harvest; 2. Feedstock transport; 3. Pelletizing; 4. Pellet transport; 5. Shipping; 6. Port operations.

Export port	Total	1	2	3	4	5	6
Savannah	10.8	0.0	1.3	4.5	2.4	0.2	2.2
Mobile	11.3	0.0	1.3	4.5	2.4	0.2	2.7
Norfolk	10.5	0.0	1.3	4.5	2.4	0.2	2.0
Portland	10.3	0.0	1.3	4.5	2.4	0.2	1.7
Halifax	7.3	0.0	1.3	1.7	2.4	0.1	1.5
Montreal	7.3	0.0	1.3	1.7	2.4	0.1	1.6
Quebec	7.3	0.0	1.3	1.7	2.4	0.1	1.5
Vancouver	11.1	0.0	1.3	1.7	2.4	0.1	5.4
Prince Rupert	11.3	0.0	1.3	1.7	2.4	0.1	5.6
Maceio	7.5	0.0	1.3	0.9	2.4	0.1	2.6
Salvador	7.6	0.0	1.3	0.9	2.4	0.1	2.7
Rio de Janeiro	7.9	0.0	1.3	0.9	2.4	0.1	3.1
Rio Grande	8.4	0.0	1.3	0.9	2.4	0.1	3.5
St. Petersburg	10.8	0.0	1.3	4.9	2.4	0.2	1.9
Paldiski	13.6	0.0	1.3	7.9	2.4	0.2	1.6
Kunda	13.8	0.0	1.3	7.9	2.4	0.2	1.7
Pärnu	13.6	0.0	1.3	7.9	2.4	0.2	1.6
Ventspils	15.7	0.0	1.3	10.1	2.4	0.3	1.4
Liepāja	15.7	0.0	1.3	10.1	2.4	0.3	1.4
Riga	15.9	0.0	1.3	10.1	2.4	0.3	1.6
Butinge	8.7	0.0	1.3	3.4	2.4	0.1	1.3
Klaipėda	8.7	0.0	1.3	3.4	2.4	0.1	1.3

Table C.15 – Overview of supply chain GHG emissions of torrefied pellets produced from roundwood, transported over 500 km to export ports and including 50 km feedstock transport, in kg CO₂-eq/t pellets. Components included in the table: 1. Silviculture and harvest; 2. Feedstock transport; 3. Pelletizing; 4. Pellet transport; 5. Shipping; 6. Port operations.

Export port	Total	1	2	3	4	5	6
Savannah	14.5	2.5	2.5	4.5	2.4	0.2	2.2
Mobile	15.1	2.5	2.5	4.5	2.4	0.2	2.7
Norfolk	14.3	2.5	2.5	4.5	2.4	0.2	2.0
Portland	14.0	2.5	2.5	4.5	2.4	0.2	1.7
Halifax	11.0	2.5	2.5	1.7	2.4	0.1	1.5
Montreal	11.1	2.5	2.5	1.7	2.4	0.1	1.6
Quebec	11.0	2.5	2.5	1.7	2.4	0.1	1.5
Vancouver	14.9	2.5	2.5	1.7	2.4	0.1	5.4
Prince Rupert	15.0	2.5	2.5	1.7	2.4	0.1	5.6
Maceio	11.2	2.5	2.5	0.9	2.4	0.1	2.6
Salvador	11.4	2.5	2.5	0.9	2.4	0.1	2.7
Rio de Janeiro	11.7	2.5	2.5	0.9	2.4	0.1	3.1
Rio Grande	12.1	2.5	2.5	0.9	2.4	0.1	3.5
St. Petersburg	14.6	2.5	2.5	4.9	2.4	0.2	1.9
Paldiski	17.4	2.5	2.5	7.9	2.4	0.2	1.6
Kunda	17.5	2.5	2.5	7.9	2.4	0.2	1.7
Pärnu	17.4	2.5	2.5	7.9	2.4	0.2	1.6
Ventspils	19.5	2.5	2.5	10.1	2.4	0.3	1.4
Liepaja	19.4	2.5	2.5	10.1	2.4	0.3	1.4
Riga	19.6	2.5	2.5	10.1	2.4	0.3	1.6
Butinge	12.5	2.5	2.5	3.4	2.4	0.1	1.3
Klaipeda	12.5	2.5	2.5	3.4	2.4	0.1	1.3

APPENDIX D - APPENDICES TO CHAPTER 5

D.1 – Required feedstock and production of by-products

Table D.1 – Required feedstock to produce different forest products

Product	Wood type	Feedstock type	Quantity (oven dry, per unit product)	Unit
Lumber	Softwood	Sawlogs	1.93	m3
Lumber	Hardwood	Sawlogs	2.44	m3
Plywood	Softwood / Hardwood	Sawlogs	2.12	m3
OSB	Softwood / Hardwood	Sawlogs	1.59	m3
		Pulplogs	1.59	m3
		Millchips	1.04	t
Other panels	Softwood / Hardwood	Shavings	0.70	t
		Sawdust	0.70	t
		Millchips	0.70	t
MDF	Softwood / Hardwood	Shavings	0.79	t
		Sawdust	0.79	t
		Millchips	0.79	t
		Millchips	0.79	t
Pellets	Softwood / Hardwood	Sawlogs	2.93	m3
		Pulplogs	2.93	m3
		Millchips	0.91	t
		Shavings	0.91	t
		Sawdust	0.91	t
Biopower	Softwood / Hardwood	Pulplogs	1.92	m3
		Millchips	1.25	t
		Hogfuel	1.25i	t
		Sawdust	1.25	t
		Shavings	1.25	t
		Bark	1.25	t
Chemical pulp	Softwood / Hardwood	Sawlogs	3.08	m3
		Pulplogs	3.01	m3
		Millchips	2.00	t

Product	Wood type	Feedstock type	Quantity (oven dry, per unit product)	Unit
Mechanical pulp	Softwood / Hardwood	Sawlogs	1.71	m3
		Pulplogs	1.71	m3
		Millchips	1.11	t
Newsprint		Chem / mech pulp	1.07	t
		Recycled pulp	1.17	t
P_W_Paper		Chem / mech pulp	0.85	t
		Recycled pulp	0.95	t
Paperboard		Chem / mech pulp	1.04	t
		Recycled pulp	1.14	t
Tissue		Chemical pulp	1.05	t
		Recycled pulp	1.15	t

Table D.2 – Residue produced alongside primary production

Product	Wood type	Feedstock type	Quantity (t per unit product)
Lumber	Softwood	Millchips	0.214
		Sawdust	0.04
		Shavings	0.091
		Bark	0.097
		Hogfuel	0.001
Lumber	Hardwood	Millchips	0.284
		Sawdust	0.117
		Shavings	0.119
		Bark	0.053
		Hogfuel	0.17
Plywood	Softwood	Millchips	0.388
		Sawdust	0.0022
		Shavings	0.058
		Bark	0.0636
		Hogfuel	0.0284
Plywood	Hardwood	Millchips	0.388

Product	Wood type	Feedstock type	Quantity (t per unit product)
OSB	Softwood	Sawdust	0.0022
		Shavings	0.058
		Bark	0.0636
		Hogfuel	0.0284
		Sawdust	0.0144
OSB	Hardwood	Bark	0.0695
		Hogfuel	0.1727
		Sawdust	0.0144
Other panels	Softwood	Bark	0.0695
		Hogfuel	0.1727
MDF	Softwood	Sawdust	0.025
		Hogfuel	0.0072
Chemical pulp	Softwood	Sawdust	0.07
	Hardwood	Hogfuel	0.054
Chemical pulp	Softwood	Hogfuel	0.491
		Hogfuel	0.491
Cross laminated timber	Softwood	Hogfuel	0.024
		Sawdust	0.008

D.2 - Manufacturing developments of all products until 2030

Figure D.2 – Development in manufactured quantities of all modelled products until 2030

D.3 – Cost calculations

CH,i , the harvest costs for plot i , are 134 €/tonne for the first harvested tonne, with costs decreasing with increased harvested quantity, Q , in tonnes, as shown in Equation D.1. Thinning costs, CT,i for plot i , are modelled in the same way but start out at 179 €/tonne, as shown in Equation D.1. Certain production processes require chipping of sawlogs and pulplogs, namely the production of OSB, pellets, chemical and mechanical pulp and biopower. For this combination of commodities and products, chipping costs were included at 9 €/tonne of feedstock.

$$C_{H,i} = 134 * Q^{-0.65}$$

Eq.D.1

$$C_{T,i} = 134 * Q^{-0.65}$$

Eq.D.2

Hauling of forestry feedstock was calculated for the travelling routes from each forest plot to each processing mill, calculated across actual road networks. Total costs are a combination of a distance-based component and a time-based component. Distance related fuel costs were calculated by assuming fuel efficiency of 2.3 km/liter and a diesel price of 0.93 €/liter (Latta et al., 2018; X-rates, 2019). Time costs were included by assuming trucking costs of 45 €/hour, including trucker wage, benefits and truck lease and include 15 min. of loading time additional to calculated driving times based on permitted road speeds (Latta et al., 2018; X-rates, 2019). Roundtrip costs were calculated by doubling one-way costs. Assumed load limits are 12.5 t for chips and pulp and 38 m3 for logs and lumber, all based on dry feedstock (Latta et al., 2018).

Product transport costs consist of transport of final products to export ports as well as the transport of intermediary products from one mill to the other. Calculations largely follow the same methodology as for hauling costs, except for the assumed loading capacities. Load capacities were generally assumed to be 12.5 dry tonnes. Pellet transport capacity was assumed to be 25.5 t of pellets, at an assumed moisture content of 10%. For the transport of pellets from mills to ports the use of rail transport was included as an option. The availability of rail infrastructure was considered by only allowing rail transport for those pellet mills located within 20 km of an existing railroad. Different railroads operate in the Southeast of the United States¹⁵. These are modelled separately, based on the assumption that freight will not be transferred between railroad companies. Rail transport costs were calculated as in Chapter 2, assuming a capacity of 3600 tonne pellets per train, and using regression based unit rail car tariffs from Gonzales et al. (2013). These tariffs were calculated specifically for BNSF and CSXT shipments. For the other railway operators active in the US SE, costs were calculated using both BNSF and CSXT tariffs, selecting the cheapest of the two.

¹⁵ BNSF Railway, CSX Transportation, Norfolk Southern Railway, Union Pacific Railroad

Results

Total costs of pre-treatment and pellet hauling increases with increased pellet production and increased demand for biomass, as shown in Figure 5.11. Increases in costs are largely the result of the use of pulplogs and especially sawlogs for pellet production since these feedstocks come at the expense of additional feedstock and pre-treatment costs. Transport costs of feedstock from forest plots to pellet mills is very low as a result of allocation of feedstock based on costs. The extensive availability of forestry feedstock means there are almost always forest plots located close to pellet mills. As pellet production increases, as shown in the Medium and High projections, total costs increase, again as a result of the growing use of pulplogs and sawlogs. The plot to mill transport requirements increase especially in the High scenarios, as logging feedstock is pulled from increasingly further away. The larger assumed sizes of pellet mills also contribute to the increased feedstock sourcing areas. In all different scenarios, the mill to port transport requirements reduce slightly as expansion of pellet production is allocated to pellet mills relatively close to export ports. Transport costs of residues from processing mills to pellet mills reduce slightly in the different projections. This is likely the result of a lower share of mill residues in the total pellet feedstock mix, thereby reducing this transport component per tonne of produced pellets.

The difference between the scenarios clearly highlights the impact of logging residue availability. In the two scenarios utilizing this additional source of feedstock, total costs for logging feedstock reduces. Logging residues also require collection, chipping and transport, but are assumed to have no stumpage fee thereby resulting in low feedstock costs. Collection and chipping costs are taken equal to harvesting and chipping costs for roundwood. Harvesting and collection costs of a combination of pulplogs, sawlogs and logging residues are slightly lower since costs of pre-treatment go down with increasing volume, assuming economies of scale. The additional sourcing of logging residues combined with pulplogs or sawlogs increases the harvested volume, thereby lowering costs. Transport costs are likewise lowered since logging residues in plots close to pellet mills can be allocated completely to pellet production.

A seemingly surprising result is that the costs in the Reference and RefLogRes scenarios are not lower than the scenarios including Carbon restrictions in pellet mill expansion. In fact, the lowest observed costs for the High scenarios are for the CarbonLogRes scenario. This indicates that current low costs, at each year of new mill location selection, as modelled through a myopic approach in this article, are not necessarily a good indicator of future low costs. High forest growth and positive growth-to-drain values, an aspect included in the Carbon scenarios, is perhaps a better indicator of future low costs. Furthermore, since expansion of pellet manufacturing is modelled through expansion of fixed capacity pellet mills, there is no continued response to changed supply feedstock and demand of other product manufacturers.

Figure 5.11 – Costs of several supply chain components for the different scenarios and projections. Costs of feedstock, pelletizing, port operations and shipping to the port of Rotterdam, the Netherlands, were based on Chapter 2 (Forest2Market, 2017b; Greene, 2019) (i.e. not on the modelling results from this article) and added to provide a better comparison with current pellet prices.

D.4 – Pellet mill locations in 2030 in the different scenarios

The below figures show the pellet mill locations as modelled in the four different scenarios. The size of pellet mill symbols represents the manufacturing quantity, ranging from 5 to almost 1200 kt/year.

D.5 – Export pellet growth rates and expansion in the different scenarios

Table D.3 – The modelled growth rate observed for the Reference scenarios, including the number of pellet mills added in each year.

Year	Linear growth rate (Kt pellets)			Modelled growth rate (Kt pellets)			# new mills/year		
	Low	Med	High	Low	Med	High	Low	Med	High
2018	8251	8251	8251	8251	8251	8251			
2019	9000	9000	9000	9000	9000	9000			
2020	9091	10000	10909	9000	10200	11400	1	3	3
2021	9182	11000	12818	9100	11000	13000	1	2	2
2022	9273	12000	14727	9200	11800	14600	1	2	2
2023	9364	13000	16636	9300	13000	16200	1	3	2
2024	9455	14000	18545	9400	13800	17800	1	2	2
2025	9545	15000	20455	9500	14600	20200	1	2	3
2026	9636	16000	22364	9600	15400	21800	1	2	2
2027	9727	17000	24273	9700	16600	23400	1	3	2
2028	9818	18000	26182	9800	17400	25000	1	2	2
2029	9909	19000	28091	9900	18200	26600	1	2	2
2030	10000	20000	30000	10000	19000	28200	1	2	2

Table D.4 – The modelled growth rate observed for the Carbon scenarios, including the number of pellet mills added in each year.

Year	Linear growth rate (Kt pellets)			Modelled growth rate (Kt pellets)			# new mills/year		
	Low	Med	High	Low	Med	High	Low	Med	High
2018	8251	8251	8251	8251	8251	8251			
2019	9000	9000	9000	9000	9000	9000			
2020	9091	10000	10909	9100	10200	11400	1	3	3
2021	9182	11000	12818	9200	11000	13000	1	2	2
2022	9273	12000	14727	9300	11800	14600	1	2	2
2023	9364	13000	16636	9400	13000	16200	1	3	2
2024	9455	14000	18545	9500	13800	17800	1	2	2
2025	9545	15000	20455	9600	14600	20200	1	2	3
2026	9636	16000	22364	9700	15400	21800	1	2	2
2027	9727	17000	24273	9800	16600	23400	1	3	2
2028	9818	18000	26182	9900	17400	25000	1	2	2
2029	9909	19000	28091	10000	18200	26600	1	2	2
2030	10000	20000	30000	10000	19000	28200	0	2	2

Table D.5 – The modelled growth rate observed for the RefLogRes scenarios, including the number of pellet mills added in each year.

Year	Linear growth rate (Kt pellets)			Modelled growth rate (Kt pellets)			# new mills/year		
	Low	Med	High	Low	Med	High	Low	Med	High
2018	8251	8251	8251	8251	8251	8251			
2019	9000	9000	9000	9000	9000	9000			
2020	9091	10000	10909	9100	10200	11400	1	3	3
2021	9182	11000	12818	9200	11000	13000	1	2	2
2022	9273	12000	14727	9300	11800	14600	1	2	2
2023	9364	13000	16636	9400	13000	16200	1	3	2
2024	9455	14000	18545	9500	13800	17800	1	2	2
2025	9545	15000	20455	9600	14600	19400	1	2	2
2026	9636	16000	22364	9700	15400	21000	1	2	2
2027	9727	17000	24273	9800	16600	22600	1	3	2
2028	9818	18000	26182	9900	17400	24200	1	2	2
2029	9909	19000	28091	10000	18200	25800	1	2	2
2030	10000	20000	30000	10000	19000	27400	0	2	2

Table D.6 – The modelled growth rate observed for the CarbonLogRes scenarios, including the number of pellet mills added in each year.

Year	Linear growth rate (Kt pellets)			Modelled growth rate (Kt pellets)			# new mills/year		
	Low	Med	High	Low	Med	High	Low	Med	High
2018	8251	8251	8251	8251	8251	8251			
2019	9000	9000	9000	9000	9000	9000			
2020	9091	10000	10909	9100	10200	11400	1	3	3
2021	9182	11000	12818	9200	11000	13000	1	2	2
2022	9273	12000	14727	9300	11800	14600	1	2	2
2023	9364	13000	16636	9400	13000	16200	1	3	2
2024	9455	14000	18545	9500	13800	17800	1	2	2
2025	9545	15000	20455	9600	14600	20200	1	2	3
2026	9636	16000	22364	9700	15400	21800	1	2	2
2027	9727	17000	24273	9800	16600	23400	1	3	2
2028	9818	18000	26182	9900	17400	25000	1	2	2
2029	9909	19000	28091	10000	18200	26600	1	2	2
2030	10000	20000	30000	10000	19000	28200	0	2	2

NEDERLANDSE SAMENVATTING

Context

Het gebruik van biomassa voor de opwekking van bio-energie en productie van biochemicalïen en biomaterialen is cruciaal voor het behalen van de reductiedoelstellingen van broeikasgasemissies en de transitie naar een duurzamer energiesysteem. In de afgelopen twee decennia is de vraag naar biomassa in regio's zoals de EU al sterk ontwikkeld, en dit zal naar verwachting in de toekomst nog verder toenemen (Daioglou et al., 2019; European Commission, 2018; IPCC, 2019; Mandley et al., 2020; Matzenberger et al., 2015; Zappa et al., 2019). Er zijn grote regionale verschillen tussen landen betreffende de beschikbaarheid, leveringskosten en vraag naar biomassa voor verschillende doeleinden. Biomassa heeft in onbewerkte vorm over het algemeen ongunstige eigenschappen voor transport over lange afstand. Zo beperken een hoog vochtgehalte en lage energiedichtheid de internationale handel van onbewerkte biomassa tussen regio's met een groot aanbod naar regio's met een grote vraag. Het pelletiseren van biomassa tot houtpellets creëert een vaste biobrandstof met een hogere dichtheid dan onbehandelde biomassa, en maakt daarmee handel over een grotere afstand mogelijk (Obernberger & Thek, 2010). Ook resulteert pelletiseren in een meer homogene brandstof van hogere kwaliteit, wat houtpellets geschikt maakt voor een breed scala aan toepassingen (Hoefnagels, Searcy, et al., 2014; Obernberger & Thek, 2010; Thrän et al., 2017; Vera & Hoefnagels, 2019). Een groeiende vraag naar bio-energie en materialen leidt waarschijnlijk tot een stijgende vraag naar geïmporteerde houtpellets (Bioenergy Europe, 2018, 2019c). Dit proefschrift focust zich op houtpellets voor industriële markten. Deze houtpellets worden in bulk vervoerd en gebruikt voor grootschalige opwekking van bio-energie. Kleinschalig gebruik, bijvoorbeeld voor het stoken van kleine pelletkachels voor decentrale opwekking van warmte, wordt niet meegenomen. De term "pellets" verwijst in dit proefschrift naar houtpellets, tenzij expliciet anders wordt vermeld.

Het gebruik van (geïmporteerde) houtpellets kent een aantal grote beperkingen: hoge productiekosten, duurzaamheidscriteria en de

beschikbaarheid van biomassa. De industriële markt van houtpellets is momenteel nog afhankelijk van subsidies. Deze subsidies zijn echter maar beperkt beschikbaar. Daarnaast wordt de competitie met andere vormen van hernieuwbare energie, zoals wind- en zonne-energie, steeds moeilijker. De kosten van deze technologieën blijven dalen en, in tegenstelling tot bio-energie, hebben wind- en zonne-energie geen brandstofkosten. Een manier om de business case van pellets te verbeteren is het verlagen van kostprijzen door middel van supply chain optimalisatie. Meerdere bestaande studies hebben de kosten van houtpellets en de verschillende kostenfactoren in de keten geanalyseerd (Boukherroub et al., 2017; Ehrig et al., 2014; Hoefnagels, Searcy, et al., 2014; Sikkema et al., 2010; Thek & Obernberger, 2004). Potentiële mogelijkheden voor kostreductie zijn het voorbehandelen van biomassa vroeg in de keten (Hoefnagels, Searcy, et al., 2014), het produceren van getorreficeerde houtpellets (Sikkema et al., 2010), het inzetten op schaalvergroting in pelletfabrieken (Biomass Magazine, 2017a; Boukherroub et al., 2017; Thek & Obernberger, 2004) en het gebruik van laagwaardige grondstoffen, zoals reststromen uit de industrie, lage kwaliteit boomstammen en niet-houtachtige biomassa (Boukherroub et al., 2017; Hoefnagels, Searcy, et al., 2014; Sikkema et al., 2010). Marktgegevens over de prijzen van houtpellets zijn beschikbaar. Prijzen van houtpellets op de spotmarkt, CIF West Europa, fluctueerden in recente jaren rond de 130 €/t₂₀₁₇ en contractprijzen rond de 150 €/t₂₀₁₇, zoals is laten zien in Hoofdstuk 2 (FutureMetrics, 2018). Wat echter nog ontbreekt is een goed begrip van de kostenstructuur van internationaal verhandelde houtpellets. Meer kennis over de huidige kostprijs en verbeteringsmogelijkheden van verschillende componenten is nodig om de mogelijkheden te analyseren voor kostenbesparing van de gehele keten.

Een tweede aspect waarmee rekening moet worden gehouden is de duurzaamheid van pelletproductie en -handel. De voornaamste duurzaamheidsproblemen en risico's zijn broeikasgasemissies in de keten, emissies door verandering van koolstofvoorraden in bossen en gevolgen voor bodem en biodiversiteit, bijvoorbeeld door het verwijderen van bos- en landbouwresiduen. De broeikasgasemissies en energieconsumptie van pellet supply chains zijn verschillende keren geanalyseerd in bestaande studies, vaak met de focus op de impact van het veranderen van supply

chain parameters (Hoefnagels, Searcy, et al., 2014; Sikkema et al., 2010; Uasuf & Becker, 2011). Bestaande studies over emissieveranderingen in bossen en de impact van de productie van houtpellets op bosdynamiek en ecosysteemdiensten laten zien dat er zowel negatieve impacts zijn, zoals een reductie in biodiversiteit of verandering van natuurlijke bossen in productiebossen, als ook positieve impacts, zoals een toename in het totale bosareaal (Dale, Parish, Kline, & Tobin, 2017; Duden et al., 2018, 2017). Wat deze studies echter niet laten zien is hoe de productie en handel van houtpellets wordt beperkt door mogelijke duurzaamheidscriteria.

Een derde belangrijke overweging is het duurzame aanbod van biomassa voor de productie van houtpellets. Zo zou de lokale vraag naar biomassa voorrang moeten krijgen om verstoring van lokale markten door pelletproductie te voorkomen. Bestaande onderzoeken naar de beschikbaarheid van biomassa voor lokaal gebruik en export omvatten vaak de impact van beleid, beperkende factoren zoals duurzaamheidscriteria, en andere scenario ontwikkelingen (Fingerman et al., 2017; Fulvio et al., 2016; Lamers et al., 2015; Skog & Stanturf, 2011; Welfle, 2017). Ook is het economische potentieel van houtpellets in verschillende studies berekend. Deze studies hebben de impact berekend van verschillende biomassasoorten, de mobilisatie van biomassa en de vereiste logistieke infrastructuur op supply chain kosten, waarmee beschikbaarheid van biomassa wordt gelinkt aan verschillende kostengrenzen (Fingerman et al., 2017; Fulvio et al., 2016). In de huidige literatuur ontbreekt echter een systeemanalyse van de beschikbaarheid van biomassa voor pelletproductie, waarbij ook rekening wordt gehouden met de dynamische interactie tussen pelletproductie en andere hout- en houtverwerkende industrieën.

Om te kunnen bepalen of de productie van pellets kan bijdragen aan een duurzamer energiesysteem, is het essentieel om de kosten en broeikasgasemissies in de keten en door veranderingen in koolstofvoorraden te analyseren, evenals de beschikbaarheid van biomassa in productieregio's. Dit moet bovendien worden geanalyseerd voor complete productieregio's en niet alleen voor individuele ketens, om zo de gevolgen in te kunnen schatten van het verschuiven naar nieuwe productiegebieden bij een stijgende vraag naar pellets.

Doel en onderzoeksvragen

Het doel van dit proefschrift is het analyseren van de gevolgen van stijgende houtpelletproductie en internationaal transport naar de EU op kosten en broeikasgasemissies van pellets. De volgende onderzoeksvragen komen aan bod:

1. Welke factoren bepalen de kosten en broeikasgasemissies van internationale supply chains van houtachtige biomassa, vervoerd over lange afstanden, en hoe kunnen supply chains worden geoptimaliseerd, door voorbehandelingstechnieken als pelletisering en torrefactie?
2. Hoe wordt de aanbod-aangeïmporteerde houtachtige biomassa beïnvloed door criteria op het gebied van subsidies en broeikasgasemissiereducties, en wat is hiervan de impact op internationale handel over lange afstanden?
3. Hoe worden lokale kosten, broeikasgasemissies en koolstofstromen in bosgebieden beïnvloed wanneer het exportpotentieel in de toekomst wordt benut, en er rekening wordt gehouden met de interactie met niet-energetisch gebruik van biomassa voor materialen?

Voor het inzichtelijk maken van variaties in supply chain kosten van pellets zijn de verschillen geanalyseerd tussen regio's en in tijd, in het type supply chain en in de onzekerheid in data van verschillende kostencomponenten. In de berekening van kosten en broeikasgasemissies van pellets uit verschillende productieregio's zijn variaties in transportafstanden, als gevolg van geografische variaties in beschikbaarheid van biomassa, ruimtelijk expliciet meegenomen. In de analyse van de ruimtelijk expliciete beschikbaarheid van biomassa, de toewijzing hiervan voor de productie van pellets en de impact van een stijgende pelletproductie op de koolstofbalans in bosgebieden, zijn competitie en synergieën met andere hout- en houtverwerkende industrieën meegenomen.

Samenvatting van de resultaten

Hoofdstuk 2 beantwoordt onderzoeksvraag 1 door het analyseren van de onzekerheid in bestaande literatuur op het gebied van de kosten van de totale pellet supply chain en de verschillende componenten van pelletproductie, gecombineerd met een technisch-economische evaluatie van de impact van kostenoptimalisatiestrategieën op supply chain kosten. Hoofdstuk 2 laat zien dat veel kostenramingen van supply chain componenten teruggeleid kunnen worden naar een beperkt aantal studies van 14 tot 16 jaar oud. Het gebrek aan openbare marktdata van bestaande pellet producenten resulteert in beperkte mogelijkheden om onzekerheid in kosten en de impact van supply chain ontwerp te analyseren. De totale supply chain kosten in de geanalyseerde literatuur varieert sterk, van 88 tot 279 €/t pellets, met een gemiddelde en mediaanwaarde van respectievelijk 163 en 153 €/t. De variatie in onderliggende kostencomponenten is groot, tot een factor 10, met name voor de kosten van pelletiseren, biomassa, op- en overslag in havens en de zeevrachtkosten. Resultaten van de technisch-economische evaluatie laten zien dat een gedeelte van kostenverschillen verklaard kan worden door verschillen in supply chain ontwerp en temporele variatie in kostenfactoren. Zo laten de geanalyseerde studies lagere kosten zien voor pellets van houtzaagsel en -schaafsel dan voor pellets van pulphout, en iets lagere kosten voor pellets geproduceerd in Canada dan voor pellets geproduceerd in de VS. Zeevrachtkosten variëren bijvoorbeeld een factor 4.2 tussen de verschillende studies. Dit kan worden teruggebracht naar een factor 3.5 als verschillen in transportafstand worden meegenomen, en naar een factor 1.8 als er ook wordt gecorrigeerd voor de historische ontwikkeling in brandstofkosten en chartertarieven.

Een analyse van de impact van de locatie van pelletfabrieken in het zuidoosten van de VS op supply chain kosten, gebaseerd op regionale beschikbaarheid van biomassa en competitie met nabij gelegen pelletfabrieken, resulteert in significante verschillen. Transportkosten van biomassa variëren bijvoorbeeld tussen de 0,3 en 10 €/t pellets, gebaseerd op een vaste pelletfabriekgrootte van 50 kt/jaar. De gecombineerde impact van supply chain ontwerp en schaalgrootte is geanalyseerd door het vergelijken van productiekosten in een 50 kt/jaar fabriek op basis van zaagafval inclusief vervoer over

de weg en scheepstransport in een Handysize schip (23000 t pellets/schip) met een 500 kt/jaar fabriek op basis van pulphout inclusief vervoer via spoor en scheepstransport in een Supramax schip (47000 t pellets/schip). Resultaten hiervan wijzen op een kostenvoordeel van ongeveer 6 €/t voor de 500 kt/jaar pelletfabriek, het gevolg van hogere kosten voor biomassa en biomassatransport en lagere kosten van pelletiseren en vervoer van pellets over land en zee. De resultaten variëren sterk voor de verschillende productielocaties die geanalyseerd zijn in dit hoofdstuk, van een kostenbesparing van 38 €/t pellets tot een kostenstijging van 31 €/t voor de grote pelletfabriek in vergelijking met de kleine fabriek.

Hoofdstuk 3 levert input voor het beantwoorden van onderzoeksvragen 1, 2 en 3 in de vorm van een analyse van het importpotentieel van houtpellets vanuit verschillende landen naar West Europa, gebaseerd op regionale beschikbaarheid van primaire en secundaire houtige biomassa inclusief een aantal duurzaamheids- en marktbeperkingen. Bos- en agrarische reststromen worden in alle geanalyseerde landen in meer of mindere mate gebruikt, wat de beschikbaarheid voor pellet productie beperkt. Dit is vooral sterk het geval in Brazilië. Verder is een significant aandeel van het technisch beschikbare potentieel van biomassa uitgesloten van duurzame export, aangezien er voldaan moet worden aan een aantal geselecteerde duurzaamheidscriteria. Een deel van het snoei- en agrarisch afval moet bijvoorbeeld achtergelaten worden in het bos of op het land. De grootste beperkende factor is het gebrek aan infrastructuur, er vanuit gaande dat het tijd kost om de benodigde faciliteiten te ontwikkelen om biomassa te verzamelen en te pelletiseren. In alle landen is deze infrastructuur onvoldoende aanwezig, behalve in de VS. Het totale exportpotentieel komt uit op 270 PJ in een Business As Usual (BAU) scenario in 2030, voornamelijk uit Indonesië (37%) en Brazilië (27%). In dit scenario is voor de VS de aanname gemaakt dat duurzaamheidscriteria worden toegepast op de hele bossector in plaats van alleen op de productie van pellets. Hierdoor blijft er geen biomassa over voor export. Het exportpotentieel in een High Export (HE) scenario wordt geschat op 1580 PJ, met grote bijdrages vanuit de VS (29%), Brazilië (26%) en Indonesië (22%).

De berekende exportpotentielen kunnen niet allemaal geleverd worden naar West Europa aangezien er maximale supply chain kosten en broeikasgasemissies aangenomen worden. De bovengrens van pellet prijzen tussen 2009 en 2016, ongeveer 140 €/t pellets, beperkt het potentieel tot slechts 1 en 6 Mt pellets in respectievelijk het BAU en HE scenario. Een stijging van marktprijzen naar 170 €/t pellets resulteert in een hoger exportpotentieel van 2 - 18 Mt in de twee scenarios. Broeikasgasemissies zijn het laagst voor pellets uit Brazilië en Oekraïne en het hoogst voor pellets uit Indonesië. Met name de teelt, voorbehandeling, binnenlands transport en scheepstransport dragen bij aan totale emissies. Resultaten voor de landen variëren als gevolg van verschillen in biomassa types, met variatie in de benodigde toepassing van kunstmest om te compenseren voor de onttrokken nutriënten, verschillen in transportafstanden naar export havens en verschillen in broeikasgasemissiefactoren van elektriciteitsproductie. Een vereiste minimale besparing in broeikasgasemissies van 70% voor elektriciteitsopwekking resulteert in een totaal van 8 Mt pellets in het BAU scenario en 65 Mt pellets in het HE scenario in 2030, na uitsluiting van het grootste gedeelte van het potentieel vanuit Kenya en Brazilië, en alles vanuit Indonesië. Aan een 80% reductie doelstelling kan alleen worden voldaan door pellets vanuit Oekraïne en een gedeelte van de pellets vanuit Brazilië, waardoor er een potentieel van 6 - 34 Mt pellets overblijft in de twee scenarios in 2030.

In **Hoofdstuk 4** wordt de impact van ruimtelijk expliciete beschikbaarheid van biomassa en bijbehorende transportafstanden op de kosten en emissies van geïmporteerde houtpellets vanuit verschillende landen geanalyseerd. Dit hoofdstuk wordt gebruikt om onderzoeksvragen 1, 2 en 3 te beantwoorden. Het pelletiseren van biomassa draagt het meest bij aan de totale supply chain emissies. Verschillen in de emissies van elektriciteitsproductie in verschillende landen heeft een significante impact op de resultaten. Dit verklaart waarom totale emissies laag zijn in Litouwen en hoog in de buurlanden Letland en Estland. Een andere belangrijke factor is scheepstransport, waardoor emissies relatief laag zijn vanuit het zuidoosten van Canada en relatief hoog vanuit het zuidwesten van Canada, omdat hiervandaan 15000 km verder gevaren moet worden naar West Europa. Supply chain kosten zijn relatief laag vanuit Brazilië en het zuidoosten van VS, wat voornamelijk het resultaat is

van relatief lage biomassa kosten. Emissies van getorreficeerde pellets (TOP) zijn lager dan gewone houtpellets (WP), 12-24% lager in het geval van pellets gemaakt van pulphout en 2-10% voor pellets van zaagafval. Emissies van pellets gemaakt van zaagafval zijn 32-48% lager dan emissies van rondhout pellets. De emissies van pellets uit rondhout zijn met name hoger vanwege bosbouw en oogstemissies, de grotere benodigde hoeveelheid biomassa door het hogere vochtgehalte en het elektriciteitsgebruik voor het malen van de grondstof. Pellets van pulphout zijn ook iets duurder (90 - 280 €/t pellets) dan pellets van zaagafval (80 - 270 €/t pellets). De grote variatie in kosten kan verklaard worden door de impact van binnenlands transport. Er is enige correlatie tussen kosten en emissies, grotere transportafstand over land en zee resulteert bijvoorbeeld in hogere kosten en emissies. Een gedeelte van de correlatie is toevallig, sommige landen met goedkope biomassa, zoals de VS, hebben ook lage emissiefactoren van elektriciteitsproductie.

De potentiële productiegebieden van pellets worden bepaald door zowel kosten- als emissie drempels. Een scenario met gunstige kostenontwikkelingen, met lage kostenfactoren en een relatief hoge prijsgrens van 200 €/t pellets resulteert in een potentieel van bijna 60 Mt pellets, grotendeels vanuit Brazilië en de VS, als gevolg van de relatief grote beschikbaarheid van biomassa dichtbij exporthavens. Aan de meer conservatieve kant, bij een pellet prijs van 125 €/t pellets, varieert het totale exportpotentieel tussen 3 - 28 Mt voor respectievelijk hoge en lage kostenfactoren. Een minimale vereiste emissiereductie van 70% voor elektriciteitsproductie resulteert in een totaal exportpotentieel van 61 Mt. Een strengere eis van minimaal 80% besparing reduceert het exportpotentieel tot 16 Mt. In het geval van een 85% eis blijft hiervan nog maar 1 Mt over, tenzij emissies in de keten gereduceerd kunnen worden, bijvoorbeeld door het reduceren van de emissies van elektriciteit bij pelletproductie. De totale potentiële exportgebieden en dus het productiepotentieel zijn groter voor TOP, als gevolg van de lagere supply chain emissies, tot 40 Mt in het geval van elektriciteitsproductie en een 80% reductie doelstelling en 36 Mt voor warmteproductie bij een 80% reductie-eis.

Hoofdstuk 5 behandelt de derde onderzoeksvraag en analyseert de impact van verhoogde pelletproductie in het zuidoosten van de VS tot 2030 op

de allocatie van biomassa, het type biomassa gebruikt in de pelletsector, de koolstofstroom in bosgebieden en de kosten van voorbehandeling en transport van biomassa en pellets. Ruimtelijk expliciete locaties van beschikbare biomassa, bosgebieden en houtindustrieën waar residustromen beschikbaar komen, zijn in dit hoofdstuk gelinkt aan vraaglocaties van zowel pellets als ander hout- en houtverwerkende industrieën. De onzekerheid van toekomstige ontwikkelingen in pelletproductie zijn onderzocht door het gebruik van drie scenarios, variërende van 10 tot 30 Mt pellet productie in 2030, en een scenario zonder pellet productie in 2030. Door middel van aanvullende scenario's is de impact geanalyseerd van het meenemen van extra beschikbaarheid van bosbouwresiduen alsmede het optimaliseren van de locatie van pelletfabrieken op basis van ofwel kosten ofwel totale koolstofvoorraden in supply regio's. Resultaten laten zien dat als de pelletproductie stijgt, er steeds meer gebruik gemaakt wordt van pulphout net als, in mindere mate, zaaghout van hoge kwaliteit. Het toegenomen gebruik van dit rondhout kan voor het grootste gedeelte worden weggenomen door het extra benutten van deze bosbouwresiduen.

De benutting van industrie-reststromen voor de gehele hout- en houtverwerkende industrie neemt toe in alle scenario's. In het Reference scenario neemt de benutting van houtsnippers, schaafsel en zaagsel toe van 76% tot 85% in het geval van 20 Mt pelletproductie in 2030. Het percentage reststromen uit de industrie wat gealloceerd is aan pelletproductie stijgt van 29% tot 70% in dit scenario. Dit draagt bij aan het beperken van de hoeveelheid rondhout voor pelletproductie. Deze reststromen worden echter weggetrokken van andere sectoren. Deze indirecte houtgebruiksverandering moet worden meegenomen in de discussie over duurzaamheidsimplicaties van pelletproductie. De toename van consumptie van rondhout, door de pelletindustrie maar ook door andere industrieën, waarvan de totale houtvraag naar verwachting toeneemt richting 2030, resulteert in een stijgende koolstofstroom uit bosgebieden, gedefinieerd als de som van koolstof extractie door houtkap en koolstofvastlegging door de groei van bomen. In het zuidoosten van de VS neemt de koolstofstroom uit bosgebieden toe met 16 Mt CO₂/jaar in het Zero pellets scenario in 2030, als gevolg van een toenemende vraag naar houtproducten. De extra

pelletvraag in het Reference scenario leidt tot een extra koolstofstroom van 3, 12 en 30 Mt CO₂/jaar in de verschillende pellet export scenario's. Deze impact is lager voor de scenario's waarin wordt aangenomen dat er extra bosbouwresiduen beschikbaar zijn, tot 6 Mt CO₂/jaar in het RefLogRes scenario voor 20 Mt pellet productie voor export in 2030, in vergelijking met 12 Mt CO₂/jaar zonder beschikbaarheid van deze reststromen. De selectie van locaties voor pelletproductie op basis van koolstofvoorraad in omliggende bosgebieden leidt tot significante veranderingen in de ruimtelijke patronen van pelletproductie en houtkap, maar heeft een stuk minder impact op de totale koolstofstromen in het hele zuidoosten van de VS, omdat overige houtsectoren niet aan deze eis hoeven te voldoen.

Belangrijkste bevindingen en conclusies

Vraag 1: Welke factoren bepalen de kosten en broeikasgasemissies van internationale supply chains van houtachtige biomassa, vervoerd over lange afstanden, en hoe kunnen supply chains worden geoptimaliseerd, door voorbehandelingstechnieken als pelletisering en torrefactie?

De voornaamste factoren die de supply chain kosten bepalen zijn de kosten van biomassa (25-53%), pellet transport over land (23%) en scheepstransport van pellets (6-19%), al hangt dit sterk af van het specifieke supply chain ontwerp. Aan broeikasgasemissies draagt vooral het pelletiseren bij (16-54%), gevolgd door scheepstransport (7-36%), transport van de ruwe biomassa (15-25%) en transport van pellets over land (11-19%). Het reduceren van kosten door supply chain optimalisatie is gecompliceerd, aangezien er verschillende trade-offs zijn tussen de verschillende kosten componenten. Mogelijke kostenbesparende opties omvatten de productie van getorreficeerde pellets, het gebruik van industriële reststromen in plaats van rondhout als grondstof en het toepassen van schaalvoordeel. Zoals zal worden uitgelegd in deze thesis worden de totale supply chain kosten en kostenbesparingsmogelijkheden uiteindelijk sterk bepaald door specifieke supply chain kenmerken.

Supply chain kosten en emissies van houtpellets hangen af van vele factoren. Het variëren van één enkele factor, zoals het land waar de pellets geproduceerd worden of het type biomassa, beïnvloedt vaak meerdere, zo

niet alle, supply chain componenten. De verschillende factoren die supply chain kosten en emissies bepalen zijn onder andere de geografische locatie van de productie en consumptie van pellets, het type biomassa dat gebruikt wordt om pellets te produceren, de grootte van pelletfabrieken, beschikbare infrastructuur en/of geavanceerde voorbehandelingstechnologieën zoals torrefactie worden toegepast. Vaak leidt het veranderen van deze aspecten tot een trade-off tussen afzonderlijke supply chain componenten. Binnen bestaande pellet productieregio's leidt een zoektocht naar voordeligere biomassa wellicht naar een verschuiving weg van de kustregio's dicht bij exporthavens, waar minder competitie is met bestaande fabrieken. De goedkopere biomassa uit het binnenland heeft dan echter hogere transportkosten voor het vervoer van pellets tot gevolg.

Figuur 6.1 toont de variatie in **totale supply chain kosten van houtpellets**, geproduceerd van rondhout op verschillende locaties en getransporteerd naar de haven van Rotterdam, zoals geanalyseerd in hoofdstukken 3 en 4. De kosten voor biomassa vormt verreweg de grootste bijdrage aan de totale supply chain kosten. Vanuit een kostenperspectief is het dus belangrijk om te focussen op de beschikbaarheid van goedkope biomassa. Vanuit een broeikasgasperspectief is het echter vooral belangrijk om te voorkomen dat pellets over lange afstand over de weg of zee getransporteerd worden. Een andere belangrijke factor is de land-specifieke broeikasgasintensiteit van elektriciteitsproductie, aangezien dit significant kan bijdragen aan pelletiseeremissies, en daarmee aan supply chain emissies.

Figuur 6.1 – Vergelijking van de totale supply chain kosten van houtpellets gemaakt van rondhout, voor geselecteerde supply chain componenten. In Hoofdstuk 3 is voor een aantal landen een afwijkende methode gebruikt om transportkosten te berekenen, wat resulteert in totale kosten voor pellet transport in het geval van Indonesië, Kenia en Oekraïne, inclusief binnenlands en internationaal transport. In het geval van de VS zijn er totale kosten berekend voor binnenlands transport, inclusief het transport van ruwe biomassa en pellets. De resultaten van Hoofdstuk 4 zijn gebaseerd op binnenlandse pellet transportafstanden van 500 km. Voor Estland, Letland en Litouwen is een totale afstand van 300 km aangenomen, aangezien de transportafstand wordt beperkt door de grootte van de landen.

Het optimaliseren van supply chains is ingewikkeld, aangezien **er trade-offs zijn tussen verschillende componenten en tussen optimaliseren voor kosten en voor emissies**. Er bestaat dan ook geen wondermiddel dat gegarandeerd resulteert in lagere kosten of een lagere milieu impact. Dit werk wijst echter wel op een aantal aspecten die in het achterhoofd gehouden moeten worden bij het ontwerp van toekomstige supply chains. Het toevoegen van **torrefactie voor het pelletiseren** van biomassa resulteert in zowel kosten- als emissiebesparingen voor de meeste

geanalyseerde supply chains. De kostenbesparingen, genormaliseerd voor de energie-inhoud van pellets, variëren tussen de 6 - 21 €/t pellets voor de verschillende landen. De enige uitzondering hierop is Brazilië, waar torrefactie juist resulteert in 9 €/t duurdere pellets. Torrefactie heeft ook een positief effect op de supply chain broeikasgasemissies, resulterend in een besparing van 12-24% voor pellets van rondhout en tot 21% voor pellets van zaagafval. De verbranding van vrijgekomen vluchtige stoffen tijdens torrefactie zorgt voor een efficiënter droog- en pelletiseringsproces, waardoor de behoefte aan biomassa per eenheid geproduceerde energie wordt verminderd, en waardoor kosten en emissies bespaard worden. Daarnaast is het gemakkelijker om getorreficeerde biomassa fijn te malen, aangezien het torrefactieproces de biomassa bros maakt. De extra uitgaves voor een torrefactie installatie en de benodigde elektriciteit tijdens torrefactie wordt enigszins gecompenseerd door verminderde kapitaal- en operationele kosten voor het fijnmalen van biomassa. Deze voordelen resulteren ook in verminderde broeikasgasemissies van het pelletiseren van biomassa, welke ongeveer 30% lager zijn voor getorreficeerde biomassa dan voor gewone biomassa. Daarnaast worden er ook nog significante besparingen gerealiseerd in het transport van pellets na de productie. De hogere energiedichtheid van getorreficeerde pellets zorgt voor besparingen in alle transportstappen, wat vooral grote reducties oplevert voor supply chains op basis van lange transportafstanden, zoals bijvoorbeeld het geval is tussen Brazilië en Nederland.

De precieze impact van het toevoegen van torrefactie aan het pelletiseerproces is echter nog onzeker, aangezien dit nog niet op grote schaal geïmplementeerd wordt. Als gevolg hiervan is er weinig empirische data beschikbaar. Het effect van torrefactie op kosten en emissies van pelletproductie is bijvoorbeeld relatief onzeker, en afhankelijk van aannames over de efficiëntie van het hele proces en de kapitaalkosten van verschillende onderdelen. Deze onzekerheid komt ook tot uiting in de gemengde resultaten in bestaande wetenschappelijke literatuur. Mobini et al. (Mobini et al., 2014) hebben de impact geanalyseerd van het integreren van torrefactie in een supply chain van pelletproductie en -transport van Vancouver naar Rotterdam. Dit werk laat een toename van kosten voor getorreficeerde pellets

zien van 17% (op energiebasis), veroorzaakt door grofweg een verdubbeling in de benodigde kapitaalkosten als gevolg van de extra torrefactie installatie. Thrän et al. (Thrän et al., 2016) maken een vergelijking van de economische- en milieu-eigenschappen van TOP en WP van verschillende soorten biomassa, geproduceerd in verschillende landen. Zij berekenen in hun werk significant lagere supply chain emissies voor getorreficeerde pellets, ongeveer 24 - 54%, en een kleine kostenbesparing van 0 - 24%

De tweede strategie die kan resulteren in een besparing van kosten en emissies is **het gebruik van industriële reststromen in plaats van rondhout**. Rondhout moet gekapt, verzameld en getransporteerd worden en daarnaast moet een stamvergoeding worden betaald voor het recht om het hout te oogsten. In het geval van secundaire, industriële, reststromen zijn deze kosten al gedeeltelijk doorberekend in het primaire productieproces, waardoor de biomassa goedkoper kan zijn. Marktdata van gemiddelde prijzen voor biomassa, betaald door pellet producenten in de VS, laten zeer vergelijkbare kosten zien (U.S. Energy Information Administration, 2020). Het verschil is echter dat reststromen zoals snippers, zaagsel en schaafsel al geheel of gedeeltelijk fijngemalen of gedroogd zijn. Hierdoor is er minder biomassa nodig om pellets te produceren en kan er worden bespaard op kapitaalkosten en operationele kosten. Hoofdstuk 4 laat zien dat kosten van pellets gemaakt van zaagafval ongeveer 12 - 40 €/t pellets goedkoper zijn over de hele supply chain dan pellets gemaakt van rondhout, voor verschillende landen. Berekeningen gebaseerd op marktdata vanuit het zuidoosten van de VS laten een kleinere kostenbesparing zien van 8 €/t pellets.

Deze optimalisatie strategie werkt goed op papier, maar is in de werkelijkheid niet altijd effectief, aangezien de beschikbaarheid van secundaire reststromen beperkt is en afhankelijk is van het bestaan van primaire productieprocessen in de regio. Lokale omstandigheden, zoals de beschikbaarheid van biomassa en de competitie met bestaande vraag, zijn sterk van invloed op de prijzen van reststromen, wat deze reductiestrategie onzeker maakt en afhankelijk van externe factoren. In werkelijkheid zullen pelletfabrieken hun productieproces vaak baseren op een mix van grondstoffen, afhankelijk van regionale- en seizoensgebonden

beschikbaarheid en prijzen. Toekomstig onderzoek naar het ruimtelijk expliciet productiepotentieel van pellets zou rekening moeten houden met de productielocaties van bestaande industrieën, de bestaande vraag naar biomassa en in hoeverre er overschotten aan reststromen zijn.

Het gebruik van residuen in plaats van rondhout resulteert ook in lagere supply chain emissies, al is dit niet zozeer het resultaat van markteffecten,

maar meer het gevolg van methodologische standaarden gebruikt door onderzoekers en beleidsmakers. De voornaamste reden achter de emissiebesparingen is het feit dat alle emissies die gepaard gaan met de teelt, kap of oogst en met het transport van ruwe biomassa gealloceerd wordt aan het primaire productieproces. De potentiële emissiebesparing in de verschillende case studies varieert tussen de 30 - 42% voor houtpellets en 22 - 37% voor getorreficeerde pellets, zoals beschreven in Hoofdstuk 4. Wat echter ook moet worden meegenomen is het feit dat er vaak bestaande vraag is naar reststromen. Extra pellet productie kan er in dat geval voor zorgen dat er biomassa weggetrokken wordt bij bestaande sectoren, wat resulteert in indirecte houtgebruikverandering en daardoor mogelijk toch extra houtkap, wat onwenselijk is vanuit het perspectief van koolstofemissies. Het cascaderend inzetten van biomassa geeft prioriteit aan het zo hoogwaardig mogelijk inzetten van biomassa, bijvoorbeeld voor de productie van materialen en niet voor energie. Het gebruik van reststromen kan dus alleen resulteren in een reductie in koolstofemissies indien deze stromen nog niet lokaal worden gebruikt. Dit kan met name het geval zijn voor laagwaardige reststromen, zoals landbouw residuen, bosbouwresiduen en houtafval uit bijvoorbeeld de bouwsector. Pellet producenten zouden zich met name op deze laagwaardige stromen moeten richten om de impact van pelletproductie op het milieu te verminderen.

Een toename van pellet productiehoeveelheden in specifieke regio's, zoals het zuidoosten van de VS, **kan een effect hebben op kosten en emissies**.

De ontwikkeling van grotere pelletfabrieken zou kunnen resulteren in kosten- en emissiebesparingen door het benutten van schaalgrootte, bijvoorbeeld door pellets te transporteren met de trein in plaats van met vrachtwagens, of met grotere schepen, indien hiervoor de juiste haveninfrastructuur aanwezig is. De supply chain kosten voor een pelletfabriek met een productie van

500 kt/jaar blijken volgens onze berekeningen 6 €/t pellets lager te liggen dan voor een 50 kt/jaar pelletfabriek. Resultaten variëren echter sterk voor verschillende locaties die geanalyseerd zijn, van een kostenbesparing van 38 €/t pellets, tot 31 €/t pellets extra kosten voor de grotere pelletfabriek. Daarnaast kan een stijgende pelletproductie resulteren in extra kosten en emissies door factoren die niet zijn meegenomen in dit proefschrift. Extra vraag naar biomassa kan bijvoorbeeld resulteren in een verplaatsing van productiecapaciteit naar het binnenland van productieregio's, waardoor transportkosten hoger worden. Een hogere vraag kan ook resulteren in meer competitie voor biomassa, waardoor prijzen van biomassa kunnen stijgen, voor zowel nieuwe als bestaande installaties. De specifieke impact van toegenomen pelletproductie op supply chain kosten en emissies hangt sterk af van regionale aspecten, zoals de beschikbaarheid van biomassa en de aanwezigheid van infrastructuur, en zou daarom ruimtelijk expliciet geanalyseerd moeten worden. Dit wordt in meer detail behandeld voor het zuidoosten van de VS in Hoofdstuk 5 bij het beantwoorden van de derde onderzoeksvraag.

Er zijn beperkte mogelijkheden voor het optimaliseren van bestaande supply chain ontwerpen, zoals hierboven uitgelegd. Het ontwikkelen van **nieuwe pellet productie ketens in opkomende regio's, op basis van laagwaardige en goedkope biomassa**, kan resulteren in besparingen. In het zuidoosten van de VS worden bosbouwresiduen slechts gedeeltelijk verzameld en gebruikt. Deze reststromen ontstaan tijdens het kappen van bomen in productiebos en worden, indien niet gebruikt, achtergelaten in bosgebieden om vervolgens langzaam te vergaan, of worden verbrand om het risico op bosbranden door ophoping van droge biomassa te verkleinen en om bossen te prepareren voor de aanplant van nieuwe bomen of ander gebruik. De koolstof opgeslagen in dit hout wordt dus sowieso binnen een kort tijdsbestek uitgestoten, ongeacht eventueel gebruik door de pelletindustrie. Verhoogde mobilisatie van bosbouwresiduen zou pelletfabrieken van extra middelen kunnen voorzien, bijvoorbeeld om de benodigde proceswarmte te leveren die nodig is tijdens het pelletiseren. Voor de mobilisatie van dit soort reststromen is infrastructuur nodig om de biomassa te verzamelen en transporteren uit bosgebieden. Deze stappen

zijn relatief tijdrovend, arbeidsintensief en daarom duur in vergelijking met de kap van rondhout, en leidt dus niet automatisch tot kostenbesparingen. Kosten zouden echter gereduceerd kunnen worden door de ontwikkeling van verbeterde, geïntegreerde oogstmethoden, waarbij residuen worden verzameld tijdens de kap van rondhout. Aangezien dit type biomassa op dit moment grotendeels wordt verspild, en van lage kwaliteit en waarde is, zou er na de ontwikkeling van de benodigde infrastructuur en logistiek wel een significante potentie voor kostenbesparingen zijn.

Dit onderzoek toont aan dat **supply chains op basis van hout uit bossen in opkomende pelletproductie regio's, zoals Brazilië, niet significant kosten-effectiever zijn dan die uit gevestigde productielanden zoals de VS of Canada.** Een interessant aspect is echter de potentiële **verschuiving naar nieuwe regio's in combinatie met de mobilizatie van betaalbare en milieuvriendelijke biomassa.** Een duidelijk voorbeeld hiervan is het potentiële gebruik van suikerrietresiduen zoals bagasse en stro in Brazilië. De lage arbeidskosten en elektriciteitsprijs maken van Brazilië een interessante case study. Door de grote suikerrietsector komen er heel veel residuen beschikbaar in de vorm van bagasse en stro. Een gedeelte van deze biomassa, met name bagasse, wordt al gebruikt om proceswarmte en -elektriciteit te leveren voor de productie van suiker of ethanol (Cervi et al., 2019). Tegelijkertijd werden tot voor kort ook nog grote hoeveelheden van deze reststromen verspild, vaak door verbranding in de suikerrietvelden. Deze aanpak wordt tegenwoordig echter ontmoedigd of zelfs verboden in verschillende staten in Brazilië (Paraiso & Gouveia, 2015). Deze suikerrietreststromen zijn dus een nog beschikbaar afvalproduct met een lage marktwaarde, waardoor het gebruik zou kunnen resulteren in goedkope en emissiearme pellets.

Dit proefschrift heeft laten zien dat de specifieke supply chain kenmerken van grote invloed zijn op de totale kosten en emissies. Dit maakt het lastig om specifieke bevindingen toe te passen op het algemene ontwerp van pellet supply chains. De voornaamste les die getrokken kan worden uit het werk dat in deze thesis gepresenteerd is, is het belang van biomassa beschikbaarheid voor zowel supply chain kosten als -koolstofemissies. Nieuwe pelletfabrieken en nieuwe supply chains zouden zich voornamelijk moeten focussen op het analyseren van ruimtelijk expliciete beschikbaarheid

en kosten van biomassa, en bij voorkeur van onderbenutte laagwaardige stromen. Investeren in technologische verbeteringen, zoals torrefactie, zou in de toekomst kosten en emissies kunnen besparen, en kan er bovendien voor zorgen dat er extra bronnen van laagwaardige duurzamere biomassa worden ontsloten, zoals landbouwreststromen en bosbouwresiduen.

Vraag 2: Hoe wordt het aanbod aan geïmporteerde houtachtige biomassa beïnvloed door criteria op het gebied van subsidies en broeikasgasemissiereducties, en wat is hiervan de impact op internationale handel over lange afstanden?

Zoals in deze sectie zal worden aangetoond, verdwijnt het potentieel om pellets uit geselecteerde casestudielanden te importeren vrijwel geheel naarmate de criteria voor kosten en broeikasgas emissiereducties strenger worden. De voornaamste pellet kostenfactoren zijn de kosten voor biomassa en het pelletiseren. Als er uitgegaan wordt van een emissiereductie-eis van ten minste 70% ten opzichte van fossiele alternatieven, en een kostenlimiet van 150 €/t, dan kan er een totaal van 38 Mt pellets geïmporteerd worden naar Europa, uit een aantal geselecteerde landen. Een strengere emissiereductie-eis van 80% reduceert dit tot 15 Mt pellets, en bij 85% blijft er slechts 1 Mt over. Broeikasgasemissies worden grotendeels bepaald door het pelletiseren, het transport van ruwe biomassa en scheepstransport. Supply chain optimalisatie, zoals het gebruik van laagwaardige reststromen die dicht bij pellet plants beschikbaar zijn, leiden tot extra importpotentielen. Exogene ontwikkelingen, zoals een verbetering van de emissies van elektriciteitsproductie, kunnen ook een grote rol spelen.

Voor houtpellets zijn er geen duidelijke kostenbeperkingen. De maximale prijs die pelletimporteurs bereid zijn te betalen varieert in verhouding tot alternatieve brandstoffen, zoals traditionele fossiele brandstoffen, maar ook in verhouding tot andere hernieuwbare opties. Om deze reden is de impact van supply chain kosten op het importpotentieel van houtpellets geanalyseerd voor een bandbreedte van totale kosten, variërend van 100 - 200 €/t pellets, gebaseerd op de huidige marktprijzen en subsidiebedragen voor houtpellets. In tegenstelling tot de onduidelijke grenzen aan productiekosten en pelletprijzen, worden er strict gehanteerde maximale broeikasgasemissies

opgelegd door nationale overheden en de EU. De reductie-eisen in de EU, in vergelijking met fossiele alternatieven en zoals vastgelegd in de RED II, zullen stijgen van 75% tot 85% waardoor dit gekozen is als de bandbreedte waarvan de impact in dit proefschrift wordt onderzocht.

Binnen productielanden **kan de variatie in kosten en emissies groot zijn, toenemend met stijgende transportafstanden (Figuur 6.2)**. Dit is vooral relevant voor grote landen. In Estland variëren de pelletkosten bijvoorbeeld tussen de 95 - 135 €/t pellets, waar de impact van transportafstand goed is voor 21 €/t pellets van dit verschil. In de VS daarentegen variëren de kosten tussen de 100 - 259 €/t pellets en bedragen de transportkosten van de duurste pellets 141 €/t pellets. Deze kosten zijn berekend tot een afstand van 2000 km, wat minder is dan de grootst mogelijke afstand in een aantal landen zoals Brazilië, Canada, Rusland en de VS. Het verschil tussen landen is nog duidelijker voor broeikasgasemissies. In Estland en Oekraïne nemen de supply chain emissies van pellets toe met 16% en 32% over de hele bandbreedte. In Rusland en Brazilië is er echter een significantere toename van respectievelijk 104% en 175%. Deze grote bandbreedte benadrukt de noodzaak om supply chain kosten en emissies te analyseren in relatie tot de ruimtelijk expliciete beschikbaarheid van biomassa.

Figuur 6.2 – De kostenbrandbreedte van houtpellets uit verschillende case study gebieden, als gevolg van verschillende transportafstanden, gebaseerd op het Business as Usual scenario in Hoofdstuk 3. In Hoofdstuk 4 is dit berekend voor zowel houtpellets (WP) als getorreficeerde pellets (TOP), en voor pellets gemaakt van zaagafval (SR) en rondhout (RW).

De aanzienlijke impact van het vervoer over land op de kosten en emissies van pellets beperkt de mogelijke productiegebieden, en daarmee het **productiepotentieel in de verschillende casestudielanden** (zie Figuur 6.3). In landen met relatief goedkope biomassa en arbeidskrachten, zoals Oekraïne, is er een relatief grote hoeveelheid van het productiepotentieel beschikbaar tegen supply chain kosten van 150 €/t pellets. Aan de andere kant, in Letland en Litouwen is nog geen 50% van het potentieel beschikbaar bij totale kosten van 200 €/t pellets. De grote verschillen tussen Letland en Litouwen aan de ene kant en Estland aan de andere kant worden voornamelijk veroorzaakt door verschillen in de kosten voor biomassa, aangezien alle andere kostenposten ongeveer gelijk zijn. In het geval van de Baltische staten is er weinig empirische data over biomassa prijzen beschikbaar, wat resulteert in beperkte betrouwbaarheid van de resultaten. Pelletproductie en -export neemt echter al jaren toe in de Baltische staten, vooral in Letland en Estland, terwijl de spotprijzen voor pellets in recente

jaren rond een gemiddelde van ongeveer 150 €/t fluctueerden (Bioenergy Europe, 2019c; Strauss, 2020). De gebruikte data voor de Baltische staten maakt geen onderscheid tussen verschillende regio's of verschillende houtgebruikende sectoren. Potentieel grote verschillen tussen kosten en landelijke gemiddeldes zijn hierom niet meegenomen in de berekeningen in dit proefschrift.

De impact van databeperkingen wordt ook duidelijk in het geval van Brazilië, waarvoor een veel groter percentage van het potentieel beschikbaar is volgens de resultaten van Hoofdstuk 4 (200% bij 200 €/t pellets) dan volgens de resultaten van Hoofdstuk 3 (13% bij 200 €/t pellets). Dit is grotendeels het gevolg van een tijdsverschil van 4 jaar tussen de twee studies, en de extra data die in de tussentijd beschikbaar is gekomen. Gegevens over biomassakosten in de verschillende landen is zeer moeilijk te verkrijgen, en bestaat vaak uit een enkel getal voor een heel land, ongeacht het eindgebruik. Er is sterke behoefte aan empirische data om sectorale en regionale kostenverschillen te kunnen analyseren en om kostenveranderingen mee te kunnen nemen als gevolg van marktontwikkelingen. In de tussentijd is het vooral belangrijk om te benadrukken dat deze resultaten zeer gevoelig zijn voor veranderingen in aannames en gebruikte data.

Figuur 6.3 – Percentage van het maximale houtpellet productiepotentieel in de verschillende case study landen, met de toepassing van verschillende criteria voor maximale supply chain kosten. De verschillende kleuren duiden op het extra potentieel als gevolg van hogere maximale kosten. Resultaten zijn gebaseerd op de productie van pellets van rondhout. Voor Hoofdstuk 3 worden de resultaten van de Business as Usual (BAU) en High Export (HE) scenario's apart getoond.

Criteria voor maximale broeikasgasemissies hebben ook een grote impact op potentiële productieregio's voor pellets, met name voor de supply chains op basis van scheepstransport over lange afstanden, zoals weergegeven in Figuur 6.4 en Figuur 6.5. Dit zorgt er bijvoorbeeld voor dat pelletimport uit Indonesië in het geheel niet haalbaar is, omdat de broeikasgasemissie reductie criteria niet gehaald kunnen worden. Het aanscherpen van emissie reductie-eisen heeft een effect op het beschikbare potentieel in bijna alle landen. In Estland en Letland is er bijvoorbeeld 100% van het potentieel beschikbaar bij een 70% reductie-eis, wat afneemt naar 0% bij een 80% reductie-eis. Dit grote verschil kan worden verklaard door het feit dat het totale potentieel en de variatie in emissies klein zijn, aangezien de transportafstanden klein zijn en niet zoveel bijdragen aan de totale supply chain emissies in vergelijking met de andere landen. De emissies in buurland Litouwen zijn veel lager, en daarmee het potentieel veel hoger. De bepalende factor voor de Baltische

staten is de emissiefactor van elektriciteitsproductie. De berekeningen in dit proefschrift zijn gebaseerd op landspecifieke emissiefactoren, in plaats van het EU gemiddelde zoals wordt voorgeschreven in de RED II methodologie (Jacopo Giuntoli et al., 2015). De emissie intensiteit in Litouwen is lager dan EU gemiddelde, terwijl dit in Letland meer dan een factor 2 hoger is dan gemiddeld. In gebieden met een relatief lage emissie intensiteit, zoals Canada en Brazilië, is een veel groter gedeelte van het totale potentieel beschikbaar, hoewel ook in deze landen het totaal wel wordt beperkt door strenger wordende reductiestandaarden.

Figuur 6.4 – Emissie bandbreedte in de verschillende case study regio's als gevolg van verschillende binnenlandse transport eisen, gebaseerd op Business As Usual schattingen in het geval van Hoofdstuk 3. In Hoofdstuk 4 is onderscheid gemaakt tussen gewone houtpellets (WP) en getorreficeerde pellets (TOP).

Figuur 6.5 - Percentage van het maximale houtpellet productiepotentieel in de verschillende case study landen, met de toepassing van verschillende criteria voor maximale supply chain emissies. De verschillende kleuren duiden op het extra potentieel als gevolg van de hogere maximale emissies. Resultaten zijn gebaseerd op de productie van pellets (WP) en getorreficeerde pellets (TOP) van rondhout. Voor Hoofdstuk 3 worden de resultaten van de Business as Usual (BAU) en High Export (HE) scenario's apart getoond.

Eris ook een combinatie van kosten- en emissie-reductiecriteria toegepast door voor elk land alleen het potentieel mee te nemen van de meest beperkende reductie-eis. **Hierbij is er sprake van een trade-off tussen de laagste kosten en laagste emissies in de verschillende landen.** In Hoofdstuk 3 bijvoorbeeld zijn voor Brazilië de kosten relatief hoog maar de emissies relatief laag. In een Business as Usual situatie, met totale kosten van 150 €/t pellets en een emissiereductie-eis van 70%, varieert het totale potentieel tussen de 4 - 38 Mt pellets in de verschillende hoofdstukken en scenario's, voornamelijk beschikbaar vanuit Oekraïne en Colombia in Hoofdstuk 3, en Brazilië en de VS in Hoofdstuk 4. Dezelfde emissiereductie-eis met een hogere kosten limiet van 175 €/t pellets resulteert in een hogere bovengrens van respectievelijk 36 en 50 Mt in Hoofdstukken 3 en 4. Het verschil tussen de resultaten in de verschillende hoofdstukken kan gedeeltelijk worden verklaard door de verschillen in de gebruikte methodologie. In Hoofdstuk 3 is de productiecapaciteit van houtpellets bijvoorbeeld meegenomen

als beperkende factor, wat het totale potentieel sterk verlaagd. Strengere emissie eisen verlagen logischerwijs ook het totale productie potentieel, in het geval van een 80% reductie-eis en kosten van 150 €/t pellets tot 3 - 15 Mt. Aangezien deze emissiereductie-eis de voornaamste beperkende factor is zorgt het oprekken van de totale kosten tot 175 €/t pellets voor een nauwelijks hoger potentieel van 16 Mt. Deze cijfers laten zien dat vooral de emissiereductie-eisen een serieuze beperking zou kunnen betekenen voor toekomstige houtpellet productie en transport. Uiteindelijk is er ook een trade-off tussen de hoeveelheid pellets die geïmporteerd kunnen worden om daarmee fossiele brandstoffen te vervangen, en de totale broeikasgas emissie-intensiteit van pellets, zoals verder besproken wordt in sectie 6.6.

Vanaf januari 2026 stijgen de broeikasgas emissiereductie-eisen naar 80% in de EU, voor elektriciteitsproductie en warmte- en koude productie. Dit werk laat zien dat **deze 80% reductie-eis het importpotentieel van houtpellet zeer sterk zal beperken, tenzij er een verschuiving wordt gemaakt naar gunstigere biomassa types of naar de integratie van technologische verbeteringen, zoals het toevoegen van torrefactie aan het pellet productieproces**. Door te focussen op de ontwikkeling van nieuwe supply chains op basis van onderbenutte grondstoffen kan de invoer van pellets uit de geanalyseerde landen mogelijk toenemen tot voorbij de resultaten die in dit proefschrift worden getoond. Voor sommige landen, zoals Letland en Estland, zijn er ook nog veel mogelijkheden om de emissiefactor van elektriciteitsproductie te verlagen. Dit kan een aanzienlijke impact hebben op de toekomstige supply chain broeikasgasemissies en kan de impact van pellets uit deze landen aanzienlijk verkleinen, wat ook resulteert in een groter importpotentieel.

Vraag 3: Hoe worden lokale kosten, broeikasgasemissies en koolstofstromen in bosgebieden beïnvloed, wanneer het exportpotentieel in de toekomst wordt benut, en er rekening wordt gehouden met de interactie met niet-energetisch gebruik van biomassa voor materialen?

Het huidige beleid en de huidige marktmechanismen zijn gericht op het verlagen van de kosten en emissies van individuele supply chains,

bijvoorbeeld door het gebruik van industriële residuen. Vanuit een systeemperspectief zou dit echter tot suboptimale resultaten kunnen leiden, aangezien deze residuen vaak al lokaal worden gebruikt. Zowel onderzoek als beleid zou daarom gericht moeten zijn op het optimaliseren van het hele biomaterialen en bio-energie systeem.

Zoals blijkt uit Hoofdstuk 5, waar een dergelijk systeemperspectief is toegepast, is de ruimtelijk expliciete beschikbaarheid van industriële reststromen beperkt. Aan het begin van de modelperiode in dit hoofdstuk is alle pelletproductie gebaseerd op het gebruik van secundaire residuen. Als gevolg van een stijgende vraag naar houtproducten tot aan 2030 stijgt ook de beschikbaarheid van deze secundaire restproducten, echter niet genoeg om te voldoen aan de veronderstelde houtpellet productiestijging. Een stijgende pelletproductie resulteert in een hogere benutting van reststromen maar ook in het gebruik van een klein gedeelte pulphout en zaaghout voor pelletproductie. Daarnaast daalt het gebruik van reststromen in andere industrieën, wat resulteert in meer houtkap voor pulp- en papierproductie. De toename van houtkap leidt tot een verschuivende balans tussen koolstofvastlegging, door groei van bomen, en emissies, door het kappen van bomen, wat resulteert in een verhoogde stroom van koolstofemissies uit bosgebieden. Extra gebruik van bosbouwresiduen kan een deel van deze koolstofstroom verminderen. Ook deze beschikbaarheid is echter beperkt. Tot aan de productie van 20 Mt in 2030 heeft dit veel impact, maar bij 30 Mt is het totale effect veel kleiner.

De impact van een verhoogde pelletproductie hangt grotendeels af van **de ruimtelijke beschikbaarheid van biomassa, of dit nu in de vorm van rondhout is, zoals pulphout of zaaghout, of in de vorm van secundaire residuen, zoals snippers, schaafsel of zaagsel**. De beschikbaarheid van deze industriële residuen is afhankelijk van de lokale aanwezigheid van bepaalde sectoren, zoals de houtindustrie. Deze reststromen worden daarnaast ook gebruikt voor de productie van bijvoorbeeld papier. De beschikbaarheid van biomassa in relatie tot omliggende industrieën verandert in de loop der tijd, naarmate de ruimtelijk expliciete productie van pellets en andere producten verandert richting 2030. De resultaten uit Hoofdstuk 5 laten zien dat in het Zero pellet scenario de benuttingsgraad van industriële residuen afneemt

van 75% naar 59% aangezien de beschikbaarheid sneller toeneemt dan de vraag. In de verschillende pellet productie scenario's zorgt de extra vraag naar biomassa voor een verhoogde benuttingsgraad, in het geval van het 20 Mt scenario tot een totaal van 85% in 2030.

Toenemende pelletproductie resulteert niet alleen in meer houtkap voor pelletproductie maar onttrekt daarnaast ook waarschijnlijk reststromen aan andere industrieën. Dit proefschrift heeft aangetoond dat de consumptie van reststromen in andere sectoren dan pelletproductie daalt terwijl de biomassa vraag voor pelletproductie stijgt. Biomassa wordt in dit proefschrift gealloceerd gebaseerd op de laagste systeemkosten, wat wordt bepaald door de afstand tussen aanbod en vraag. Een beperking van deze aanpak is dat er geen rekening wordt gehouden met directe concurrentie tussen bedrijfstakken, inclusief verschillen in de betalingsbereidheid voor verschillende soorten biomassa. Dit proefschrift laat in ieder geval duidelijk zien dat een grote extra vraag naar biomassa een groot effect zal hebben op de biomassa beschikbaarheid en de markt voor verschillende soorten hout en reststromen zal beïnvloeden.

De impact van de productie van pellets op de houtoogst in het zuidoosten van de VS is relatief klein. In een scenario van 20 Mt pelletproductie in 2030, wordt slechts 4,4% van het geoogste pulphout en 0,6% van het geoogste zaaghout gebruikt voor de productie van pellets. En toch, vanuit het perspectief van pelletproducenten, verandert er hiermee veel op het gebied van de beschikbaarheid en het gebruik van grondstoffen. In het 20 Mt pellet productie scenario bestaat in 2030 23% van alle biomassa voor pellets uit een combinatie van pulphout en zaaghout. De toename van de beschikbaarheid van industriële residuen is onvoldoende om de veronderstelde grote groei van pelletproductie mogelijk te maken. Extra houtkap voor de productie van pellets komt bovendien bovenop de reeds stijgende houtkap en koolstofemissies als gevolg van een toename van de vraag naar andere producten dan pellets.

Als gevolg van de stijgende houtkap in het zuidoosten van de VS **worden er koolstofemissie toenames geobserveerd in alle scenario's waarin de pelletproductie stijgt.** In het scenario met lage pelletproductie, tot 10 Mt in 2030, is de impact nog steeds lager dan de supply chain emissies

zoals geanalyseerd in onderzoeksvraag 2. In het 20 Mt scenario, en vooral in het 30 Mt scenario, zijn de koolstofemissie impacten echter groter dan de totale berekende supply chain emissies voor de verschillende case study landen. De toename in netto emissies uit bosgebieden is een factor 2 groter tussen het 20 en 30 Mt scenario dan tussen het 10 en 20 Mt scenario. In het Zero pelletproductie scenario, met 0 Mt productie in 2030, stijgen de netto emissies ook, en een stuk sterker in het zuidoosten van de VS dan in de rest van het land. In dit scenario is de netto toename in het zuidoosten van de VS (11 staten¹) in totaal 16 Mt CO₂/jaar in 2030 in vergelijking met 2014. In de andere 37 aaneengesloten staten is de stijging vrijwel even groot met 18 Mt CO₂/jaar. Van de top 5 staten met de grootste stijging liggen er 4 in het zuidoosten, en de 5^e is het aangrenzende Texas. Ruimtelijke verschuivingen van productiecapaciteit zijn in dit proefschrift het resultaat van het optimaliseren voor de laagste kosten voor biomassa transport, waarbij effectief wordt geoptimaliseerd voor de nabijheid van biomassa. De grote toename van de koolstofemissies in het zuidoosten van de VS kan worden verklaard door een ruimtelijke verschuiving van de houtindustrie naar dit gebied, veroorzaakt door de grote beschikbaarheid van rondhout.

Dit werk heeft twee potentiële strategieën geanalyseerd om de impact van pelletproductie op koolstofemissies te beperken. De eerste strategie is het selecteren van nieuwe pellet productielocaties op basis van een maximale koolstofvoorraad in omliggende bosgebieden. Als gevolg van deze optimalisatie is de consumptie van rondhout voor pelletproductie ongeveer 10% lager dan in het scenario waarin dit niet als beperkende factor wordt meegenomen. Dit heeft als effect dat ook de netto koolstofemissie toename ongeveer 10% lager is dan in het Reference scenario. Deze aanpak heeft een grote lokale impact op de locaties van pelletproductie en de ruimtelijk expliciete koolstofbalans, maar heeft een beperkte impact op het hele zuidoosten van de VS. De interactie tussen individuele pelletfabrieken en tussen de pelletindustrie en andere industrieën zorgt ervoor dat er voortdurend gereageerd wordt op ruimtelijk expliciete veranderingen van vraag en aanbod, waarbij de totale vraag en aanbod constant min of meer in evenwicht wordt gehouden.

¹ Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia

Het veronderstelde **gebruik van bosbouwresiduen** heeft een veel grotere impact op het biomassa gebruik en de koolstofbalans. Deze reststromen ontstaan tijdens het oogsten van rondhout, en worden vaak nog niet volledig gebruikt (Thiffault et al., 2015). In plaats daarvan worden deze residuen in het bos opgestapeld en achtergelaten om op natuurlijke wijze te vergaan, of worden ze verbrand ter voorbereiding van herplanting van de productiebossen. De koolstof, opgeslagen in deze biomassa wordt dus onttrokken aan het bos, en uitgestoten in de lucht, ongeacht of deze biomassa gebruikt wordt of niet. De benutting van dit type biomassa kan een significant gedeelte van het rondhoutgebruik voor pelletproductie vervangen, ongeveer 85% in het geval van 20 Mt pelletproductie in 2030. Consumptie van deze residuen vervangt daarnaast ook nog een gedeelte van de secundaire reststromen, zodat deze beschikbaar worden voor andere industrieën. Dit alles resulteert in een grote impact op de totale extra koolstofemissies. In het 20 Mt pelletproductie scenario inclusief bosbouwresiduen is de totale stijging in koolstofemissies 54% lager dan in het Reference scenario. Deze impact is iets kleiner dan de totale reductie in rondhout consumptie voor pellets, wat verklaard kan worden door de interactie met andere industrieën. Toegenomen benutting van bosbouwresiduen compenseert gedeeltelijk voor de gemodelleerde stijging in de vraag naar grondstof voor pelletproductie. Ook deze impact wordt echter beperkt door de beschikbaarheid, voornamelijk als pelletproductie verder stijgt dan 20 Mt in 2030. Extra netto koolstofemissies van de pelletproductie scenario's inclusief bosbouwresiduen bedragen 2 en 6 Mt/jaar in 2030 voor respectievelijk het 10 en 20 Mt pellet scenario. In het geval van 30 Mt pellet productie in 2030 is de extra koolstofemissie stijging veel hoger met een totaal van 24 Mt CO₂/jaar.

Pelletproductie is verantwoordelijk voor een klein gedeelte van de totale vraag naar biomassa in vergelijking tot de hout- en papierindustrie. De vraag naar deze andere producten dan pellets heeft dan ook veel meer impact op de ontwikkeling van de koolstofbalans in bossen. **De limiet aan duurzame pelletproductie wordt dus voor een groot gedeelte bepaald door vraagontwikkelingen van de hele hout- en houtverwerkende industrie.** De grenzen aan pelletproductie moeten daarom verder worden geanalyseerd, rekening houdend met verschillende potentiële scenarios

voor de toekomstige vraag naar producten zoals hout, papier en bioenergie. **Om de duurzaamheid van pelletproductie goed te kunnen beoordelen, zullen er bovendien scenario's van alternatief gebruik moeten worden gedefinieerd en geanalyseerd.** De totale impact van houtkap in een specifiek gebied moet worden beoordeeld op het niveau van het hele landschap, door koolstofuitstoot en -opslag met elkaar te vergelijken maar ook door rekening te houden met de (fossiele) producten die worden vervangen door hout- of bio-energieconsumptie en de groei en de vermeden ontbinding van niet gekapte bomen en snoeiafval (Berndes, Cowie, Englund, Simmons, & Thiffault, 2019a; Cintas et al., 2017). De koolstofaccumulatie in bomen neemt af naarmate bomen ouder worden. Als bosplantages niet worden geoogst, voor energie of andere doeleinden, neemt de toename in koolstofvoorraad uiteindelijk af, aangezien de groei van bomen min of meer in evenwicht raakt met de sterfte van bomen (Pukkala, 2017). Vanuit een landschapsperspectief kan de koolstofproductie uit bosgebieden worden geoptimaliseerd door het periodiek oogsten van bomen om bosgebieden te verjongen, ook al worden koolstofvoorraden hierdoor tijdelijk verlaagd. Een betere verspreiding van de impact van pellets op bosgebieden, door het optimaliseren van koolstofvoorraden in gebieden waar biomassa wordt geoogst, zou een potentieel nuttige strategie kunnen zijn op de langere termijn om bossen in het zuidoosten van de VS te verjongen. Koolstofbalansen moeten daarom idealiter worden geanalyseerd over een langere periode en moeten worden vergeleken met de vermeden koolstofemissies van (fossiele) alternatieven.

Aanbevelingen voor verder onderzoek

De berekeningen van kosten en broeikasgasemissies van houtpellets in dit proefschrift benadrukken de gevoeligheid van resultaten voor transportafstanden, met name van wegvervoer. Studies die de potentiële rol van geïmporteerde biomassa in de energiesystemen van de toekomst analyseren, zouden de impact van transportafstand op de kosten van houtpellets expliciet mee moeten nemen. De relatief hoge kosten van wegtransport biedt ook mogelijkheden voor kostenoptimalisatie in de keten, welke niet in detail onderzocht zijn in dit proefschrift. Verder onderzoek zou zich hier op kunnen richten, bijvoorbeeld door te focussen op de ontwikkeling

van trein- of binnenvaartvervoer, eventueel in combinatie met pelletopslag en transport via verschillende centraal gelegen op- en overslagpunten. Dit maakt het mogelijk om de productie van pellets dichtbij beschikbare biomassa te lokaliseren, in middelgrote fabrieken met een optimaal sourcing gebied, te combineren met lagere kosten door schaalvoordeel in het transport van pellets. Optimalisatie van transport over land leidt potentieel tot een reductie van kosten en emissies, met name voor het gedeelte van de potentiële beschikbaarheid van pellets met de langste transportafstand en daardoor de hoogste kosten en emissies. Meer inzicht in potentiële kostenoptimalisatie van transport is nodig bij het analyseren van de impact van scenarios waarin de pelletvraag sterk toeneemt.

De impact van pelletproductie hangt sterk af van het type biomassa dat gebruikt wordt door de pelletindustrie. De beschikbare biomassa in bepaalde gebieden moet bovendien ook nog worden gealloceerd aan verschillende vraagsectoren. Dit proefschrift gaat uit van, ofwel, de prioritering van alle bestaande lokale vraag in plaats van pelletproductie, om zo verstoring van de lokale markt te voorkomen, ofwel, de allocatie van biomassa op basis van de laagste systeemkosten. In de werkelijkheid zal feedstock allocatie niet top-down georganiseerd worden maar hangt het af van het concurrentievermogen en de betaalkracht van verschillende industrieën en individuele pellet producenten. Verder onderzoek naar het biomassagebruik in pelletfabrieken zou de relatieve betaalkracht van verschillende industrieën mee moeten nemen. Er worden in dit proefschrift verschillende type biomassa voor pelletproductie geanalyseerd, in verschillende case studies. Het gebruik van hoogwaardige stromen, zoals hoge kwaliteit rondhout, is vanuit een economisch perspectief waarschijnlijk niet rendabel. Een analyse van biomassa consumptie in de pelletindustrie, inclusief biomassaprijzen, aannames over prijsveranderingen als gevolg van verschillende vraagontwikkelingen, en de relatieve betaalkracht van de pelletindustrie kunnen helpen bij het verfijnen van de bevindingen van dit proefschrift.

Het gebruik van verschillende soorten restproducten is een belangrijke strategie om de supply chain kosten en emissies van pelletproductie te beperken, net als de koolstofimpact in bosgebieden. Een toename van het gebruik van residuen door de pelletindustrie beïnvloedt echter mogelijk

ook de beschikbaarheid van deze residuen voor andere markten, zoals bio-energie of papierproductie. Dit kan op zijn beurt zorgen voor een verplaatsing van de vraag van deze sectoren naar hogere kwaliteit biomassa zoals rondhout. De huidige en toekomstige vraag naar verschillende types secundaire residuen zou in meer detail geanalyseerd moeten worden. De extractie van primaire residuen, die ontstaan bij houtkap in bosgebieden, gaat gepaard met duurzaamheidsrisico's. Een gedeelte van deze residuen moet achterblijven op het land of in het bos om te zorgen voor een goede bodemstructuur en het behoud van organische koolstof. Het percentage dat gebruikt kan worden zonder negatieve duurzaamheidseffecten is onzeker, en hangt af van verschillende locatie-specifieke aspecten zoals grondsoort, vegetatie en klimaat. Toekomstig onderzoek moet zich dus richten op de beschikbaarheid van verschillende soorten reststromen, ook in relatie tot de lokale vraag van andere sectoren en de impact van verschillende duurzaamheidscriteria op het beschikbare potentieel.

Veranderingen in de vraag naar biomassa en in de prijs van biomassa beïnvloeden de business case van hout- en houtverwerkende industrieën, maar hebben ook invloed op biomassa beschikbaarheid. Toekomstig onderzoek zou moeten analyseren hoe het aanbod van biomassa verandert in reactie op de vraagontwikkelingen van verschillende sectoren. Eigenaren van houtplantages baseren hun operationele beslissingen gedeeltelijk op een optimalisatie van de maximale of van de duurzame opbrengst (Sedjo, 2003). De beslissing om hout te kappen en verkopen hangt daarmee gedeeltelijk af van de huidige vraag en prijzen van biomassa, maar ook van verwachte prijsontwikkelingen (Sedjo, 2003). Een beperkte vraag naar biomassa kan een reden zijn om de kap uit te stellen in de hoop dat prijzen gaan stijgen in de toekomst, terwijl een hoge vraag ertoe kan leiden dat landeigenaren eerder zullen oogsten dan gepland. Hoe landeigenaren reageren op vraagontwikkelingen is waarschijnlijk afhankelijk van verschillende aspecten, zoals prijsontwikkelingen van verschillende houtproducten en de mogelijkheden tot alternatief landgebruik. Dit kan bovendien variëren per type landeigenaar en per case study gebied. Het onderzoeken van de impact van verschillende vraagscenarios op de groei van bosgebieden en de samenstelling en management van bos is nodig om de grenzen aan duurzame en kosteneffectieve pelletproductie beter te begrijpen.

In dit proefschrift hebben we geconcludeerd dat de jaarlijkse productie van 30 Mt pellets in het zuidoosten van de VS de duurzame grenzen overschrijdt. Dit hangt echter sterk af van vraagontwikkelingen in andere sectoren. Als de vraag naar hout, pulp en papier daalt in plaats van stijgt kan een gedeelte van de vermeden houtvraag waarschijnlijk worden gebruikt voor pelletproductie zonder dat dit ten koste gaat van verlies aan koolstofvoorraden in bosgebieden. In hoofdstuk 5 is slechts één vraagscenario voor andere producten dan pellets meegenomen. Door gebruik te maken van verschillende vraagscenarios kunnen de grenzen aan duurzame pelletproductie in meer detail geanalyseerd worden. Het behoud van koolstofvoorraden is een vereiste aan duurzame pelletproductie, zoals bijvoorbeeld opgenomen in de RED II, maar is moeilijk te garanderen door alleen de pelletindustrie. Dit is zeker het geval bij een stijgende vraag naar andere houtproducten. De impact van pelletproductie op de vraag naar biomassa en koolstofstromen in bossen zou daarom geanalyseerd moeten worden binnen verschillende scenario's van vraagontwikkeling in de hout- en papierindustrie. Wat hierin ook meegenomen moet worden is de impact van pellet consumptie op de vermeden productie van energie of materialen uit fossiele grondstoffen. Een vergelijking tussen broeikasgasemissies uit bosgebieden en de vermeden emissies van alternatieve gebruiksscenario's is nodig om een volledige analyse van de impact van het gebruik van biomassa voor pellets op broeikasgasemissies of -sequestratie te kunnen maken (Berndes et al., 2019a; Cintas et al., 2017).

Het analyseren of pelletproductie in de loop van de tijd resulteert in een netto koolstofbesparing kan gedaan worden door het koolstof pariteitspunt te berekenen. Dit is het punt in de tijd vanaf wanneer het gebruik van biomassa voor pelletproductie besparing oplevert ten opzichte van een gedefinieerd referentiescenario. Onderzoek naar dit onderwerp heeft aangetoond dat de impact van pelletproductie in grote mate afhangt van methodologische aannames zoals het type ecosysteem en landgebruik, het soort biomassa, het gebruikte referentiescenario, de veronderstelde management intensiteit en veranderingen in landgebruik en management als gevolg van vraagveranderingen, resulterend in koolstof pariteitspunten variërende tussen de 1 en 100 jaar (Hanssen et al., 2017; Jan Jonker et al., 2014; Mitchell,

Harmon, & O'Connell, 2012; Ter-Mikaelian et al., 2015). Deze onderzoeken leren ons dat pariteitsperiodes doorgaans relatief kort zijn voor het gebruik van residuen en relatief lang voor het gebruik van rondhout. Het analyseren van de koolstof pariteitspunten van de additionele vraag naar biomassa voor pellets, geanalyseerd in dit proefschrift, kan helpen bij het voeren van het debat over de impact van verschillende niveaus van pelletproductie op koolstofreductie strategieën.

Aanbevelingen voor beleid en industrie

De potentiële duurzaamheidsimpact van pelletproductie moet door beleidsmakers worden afgewogen tegen de potentiële bijdrage van pellets aan het behalen van de doelstellingen voor het reduceren van broeikasgasemissies en het maken van een transitie naar een duurzamere productie van energie en materialen. De strikte broeikasgasemissiereductiecriteria, zoals vastgelegd in de RED II, waarborgen een minimumniveau aan emissiereducties. Het gaandeweg strenger worden van de reductiecriteria van 70% naar 80% stimuleert de pelletsector om supply chain optimalisaties door te voeren. Dit proefschrift heeft echter ook aangetoond dat het niet eenvoudig is om supply chain kosten en emissies te reduceren, en dat er een groot verschil is in mogelijke pelletproductie kwantiteit bij het strenger worden van de criteria. Een 80%, in plaats van 70%, doelstelling zou daarom ook kunnen resulteren in een significant lagere bijdrage van houtpellets aan de productie van hernieuwbare energie en verlaging van totale broeikasgasemissies. Beleidsmakers moeten zich daarom realiseren dat er een trade-off is tussen de kwaliteit en kwantiteit van geïmporteerde pellets.

Verder zijn andere impacten van houtpellets, zoals de impact op koolstofstromen in het bos, niet meegenomen in deze minimale reductie-eisen. Het alleen voldoen aan de criteria voor broeikasgasemissies zou kunnen resulteren in het gebruik van pellets met een negatieve impact op landschapsemisies. Om dit soort negatieve effecten van houtpelletconsumptie te voorkomen zou de pelletindustrie zorgvuldig moeten selecteren waar, en van welk soort biomassa, pellets geproduceerd worden, en zullen ze hier ook nadrukkelijk landschapsemisies in mee moeten nemen naast de supply chain emissies. Pelletproducenten moeten expliciet rekening houden met de grenzen

aan duurzaamheid. Door deze te waarborgen kunnen ze zorgen voor een toekomstige rol voor pelletproductie. Beleidsmakers zouden bovendien de duurzaamheid van pellets kunnen verbeteren door bepaalde soorten biomassa uit te sluiten, zoals hoge kwaliteit rondhout. Hierbij moet gezegd worden dat de interactie met andere houtverwerkingsindustrieën het lastig maken om de precieze impact van duurzaamheidscriteria voor alleen pellets te analyseren.

Een ander relevant aspect is de balans tussen laagste kosten en laagste emissies. Het gebruik van houtpellets is grotendeels afhankelijk van ondersteunend beleid zoals subsidies. Dit beleid, naast marktwerking, zorgt ervoor dat supply chain optimalisatie gericht zal zijn op het verlagen van kosten. Vanuit het perspectief van broeikasgasemissies kan dit resulteren in hogere emissies in de supply chain en van landgebruik dan nodig of wenselijk. Het optimum tussen supply chain kosten en emissies is moeilijk vast te stellen voor specifieke ketens, aangezien het vaak onhaalbaar is om emissies van landgebruik te bepalen gezien de interactie met andere markten en de potentiële ontwikkelingen in lokale vraag en aanbod van biomassa. Er zijn echter wel duidelijke strategieën die kunnen resulteren in zowel lage kosten als lage emissies, zoals een grotere mobilisatie van bosbouwresiduen.

Huidig beleid stimuleert nog niet expliciet het gebruik van bosbouwresiduen, terwijl het gebruik van dit type biomassa een no-regret maatregel is: het resulteert in zowel lagere kosten als lagere emissies van pelletproductie. Het mobiliseren en gebruiken van deze reststromen uit bossen vereist echter een aantal arbeidsintensieve stappen, waardoor dit relatief duur en onaantrekkelijk is (Yoshioka, Sakurai, Kameyama, Inoue, & Hartsough, 2017). De ontwikkeling van supply chains gebaseerd op dit type biomassa kan op de langere termijn wel resulteren in lagere kosten. Kosten kunnen bijvoorbeeld gereduceerd worden door het gecombineerd kappen en verzamelen van rondhout en de reststromen, zoals tak- en tophout (Kallio & Leinonen, 2005). Na de initiële investering om de benodigde infrastructuur te ontwikkelen om deze reststromen te benutten zouden de kosten significant lager kunnen zijn in vergelijking met meer gewilde biomassa soorten zoals houtsnippers. Het stimuleren van mobilisatie van reststromen kan op verschillende manieren plaatsvinden. De EU of individuele lidstaten kunnen bijvoorbeeld een

minimum percentage reststromen afdwingen door aanvullende criteria te verbinden aan het verlenen van subsidie voor houtpellets. Als alternatief kan het gebruik rechtstreeks worden gestimuleerd door middel van subsidies of andere financiële prikkels.

Wat dit proefschrift echter ook heeft laten zien is de complexe interactie tussen pelletproducenten en andere gebruikers van houtige biomassa. Beleid gericht op het beïnvloeden van het gebruik van een bepaald soort biomassa, door het stimuleren, afdwingen of uitsluiten van biomassastromen, zal waarschijnlijk ook een effect hebben op andere sectoren. Als pelletproducenten bijvoorbeeld worden gestimuleerd om alleen nog maar secundaire industrie reststromen te gebruiken, dan kan dit ervoor zorgen dat de prijs hiervan stijgt waardoor andere sectoren meer rondhout zullen gebruiken. Daarnaast zijn er grenzen aan de absolute beschikbaarheid van reststromen. Hetzelfde geldt voor de locatie van pelletfabrieken. Als alleen pelletproducenten worden beperkt in de locatiekeuze door het stellen van eisen aan de koolstofbalans in omringende bosgebieden, en andere industrieën niet, dan zal de impact van dit soort restricties waarschijnlijk beperkt zijn. De productie van pellets maakt een klein deel uit van de gehele hout- en houtverwerkende industrie (zelfs in het zuidoosten van de VS, 's werelds grootste exporteur van pellets) en heeft naar verwachting relatief weinig invloed op bosbouwactiviteiten. Om ervoor te zorgen dat het gebruik van biomassa binnen duurzame grenzen blijft zou het duurzaamheidsbeleid holistisch moeten worden toegepast op de hele biomaterialen- en bioenergiesector.

Het gebruik van landbouw reststromen vereist ook dat er een aantal technische uitdagingen overwonnen worden. Zo zijn er bijvoorbeeld extra voorbereidingsstappen nodig zoals het wassen van residuen om een hoog asgehalte in pellets te voorkomen (Nilsson, Bernesson, & Hansson, 2010). Een mogelijke strategie om hogere gehalten van dit soort laagwaardige biomassa te gebruiken in pelletfabrieken is om deze stromen te gebruiken voor het produceren van proceswarmte en daarmee andere, hogere kwaliteit, biomassa beschikbaar te maken als pelletgrondstof. Naast deze uitdagingen worden de voordelen en mogelijkheden van het gebruik van landbouw residuen ook herkend door de industrie.

Een optie om het gebruik van laagwaardige houtige biomassa verder te vergemakkelijken is door het stimuleren van de toevoeging van torrefactie aan het productieproces van pellets. Dit proefschrift laat zien dat getorreficeerde pellets mogelijk resulteren in zowel besparing van kosten als broeikasgasemissies. Een ander interessant voordeel van torrefactie, is dat dit het gebruik van laagwaardige biomassa zoals bosbouwresiduen mogelijk maakt. Onderzoek naar de productie van getorreficeerde biomassa of pellets is vaak gedaan, en pilot installaties hebben laten zien dat het mogelijk is om getorreficeerde pellets te produceren. Wat dit proefschrift laat zien is dat de import van getorreficeerde pellets mogelijk is tegen gelijke of lagere kosten dan reguliere houtpellets en daarnaast resulteert in lagere broeikasgasemissies. Nu is het nodig om dit concept uit te testen en te bewijzen op een grote, commerciële, schaal. Het subsidiëren of op een andere manier stimuleren van getorreficeerde pellet supply chains, bij voorkeur gebaseerd op lage kwaliteit reststromen, kan helpen om aan te tonen of het importeren van getorreficeerde pellets daadwerkelijk resulteert in lagere kosten en emissies.

Dit proefschrift heeft het belang aangetoond van het expliciet vaststellen van geografische grenzen. Koolstofstromen variëren sterk op regionale schaal, variërend van een toename tot een afname van koolstof. Het meten van de impact van pelletproductie leidt daarom tot heel andere resultaten afhankelijk van de geografische systeemgrenzen. De meest geschikte ruimtelijke schaal om impacts te analyseren is niet onderzocht in dit proefschrift. Een toepasselijke systeemgrens omvat minstens het gehele gebied waar een individuele pelletfabriek biomassa vandaan haalt, maar moet misschien nog uitgebreider zijn zodat ook de interactie met nabij gelegen industrieën kan worden meegenomen. De impact van ruimtelijke systeemgrenzen kan ook worden ondervangen door het monitoren van koolstofstromen op verschillende niveaus, van bosgebieden rondom een pelletfabriek tot aan hele staten of landen. Wat voornamelijk belangrijk is, is dat de rekenregels en richtlijnen duidelijk vastgesteld worden in beleid, zodat het risico van het manipuleren van systeemgrenzen, om een bepaalde positieve of negatieve impact te laten zien, weggenomen kan worden. Verder is het cruciaal dat systeemgrenzen zoveel mogelijk constant blijven. Koolstofstromen in bossen

variëren in de tijd, en zijn moeilijk te analyseren per jaar aangezien de groei van bomen op een lange termijn plaatsvindt, maar houtkap op een zeer korte, incidentele schaal. Alleen door dezelfde gebieden over een langere termijn te monitoren kunnen er echt conclusies worden getrokken over de impact van pelletproductie op koolstofvoorraden en -stromen.

ACKNOWLEDGEMENTS

During the five years that I've worked on this project, so many people have helped and supported me, in so many different ways. These few words are not going to be enough to mention everything and everyone, but I am not going to let that stop me from naming a few people.

First of all, my supervisors, Martin and Ric. Martin, you've always helped and inspired me with new and interesting ideas and approaches. It was so useful having access to your vastly extensive knowledge of everything related to bioenergy, whenever I wasn't sure of anything, you were always able to help me. Thanks as well for being critical and challenging me at times. Ric, thanks for always being ready to help, and for always seeing the bigger picture. What I have greatly appreciated from you was your feedback and suggestions. You have this wonderful ability to frame all feedback in a positive way. And on top of that your suggestions often made so much sense. Thanks for giving me the confidence when I needed it.

Anna and Will, I couldn't have wished for better office mates. Thanks for all the laughter, fun, coffee, cookies and conversations. I'm pretty sure there will never be another office just as colourful as ours. Even during difficult times, when nothing seemed to work out, you guys kept me going. You were such a big part of my life for five years; I'm really going to miss having you around every day. But mainly I'm just glad to be leaving the university having made two great friends.

The fantastic working environment at our research group, created by all the wonderful people working there, was pivotal during my time writing this thesis. Steven, thanks for being a great officemate. Sharing an office with you was a lot of fun, and I was always amazed with your general knowledge whenever we would quiz each other on random facts. Aisha, you were always there to help me with all sorts of small but very important issues and more importantly, to listen. Hopefully we can continue to have those nice virtual coffee or lunch moments in the future. Thus, it was really nice to be able to write a joined article, I've really enjoyed working with you. Thanks to all other amazing colleagues that played a vital part in making work, and especially

the lunch and coffee moments, enjoyable. Thanks to the original lunch group at the Van Unnik building, including Anne Sjoerd, Atse, Boudewijn (x2), Carina, Geert, Gert-Jan, Marc, Marlinde, Marnix, Martin, Meindert, Niels, Ric, Rosalien, Sierk and many others on occasion. Plus, a very special thanks to the person who supplied the tosti maker. A big thank you to many colleagues for sharing coffees, lunches and conversations with me, especially Ana, Anand, Bas, Blanca, Christian, Hu Jing, Ivan (x2), Jesus, Juraj, Marte, Ody, Panos, Sara, Steven, Tarek, Vincent and Wouter. Special thanks also to Ludo, for the coffee breaks and home-made cake. Birka, I've really enjoyed my teaching experience in the course that you supervised, thanks for this. Ernst, thank you for being the perfect neighbour, and for supervising me during my first period at the University. I really valued your feedback and guidance. Many thanks to Siham, Fiona, Ineke and Lisa, for taking care of so many issues and for always being available for a quick chat.

Special thanks also to Greg and Raju. Raju, thanks for letting me stay at your office during my trip to Moscow, Idaho. The way you included me in your life those few weeks really made my stay very pleasant. Thanks also for the snacks, tea and many great conversations. Greg, thanks for being willing to work together. From the moment I approached you with the research idea you quickly set everything in motion to make this happen. Thanks also for the great discussions and the social activities. I'm sorry I couldn't be of more help during the quiz night but at least I learned a lot about bourbon.

Giannis, we had the opportunity to make a great road trip throughout the southeast of the US, thanks for sharing this experience and for all the fun we had during this trip. Thanks also to all the BiologikNL project partners for the feedback and discussions. Special thanks to Hugo du Mez, Mark Bouwmeester and Thomas Chopin for supervising students and for providing important input data.

I'm very grateful to many friends for their moral support. To Alette, Gienke, Janneke, Jessie and Sanne, thanks for the Friday evenings. You were there to listen to me stressing over deadlines, and yet everytime I saw you guys, I forgot about my deadlines within minutes. Special thanks to Liza. I'm so happy to have you in my life. Thanks for all the fun, giggles, serious talks,

discussions and mischief. I look forward to sharing many milestones in the future. To my rugby family at DIOK, nothing works better for inspiration than a few hours of getting muddy on a rugby pitch. No matter what, going to DIOK always lifted my spirit. I'd like to specially mention As and Door - I can't wait to go to Ameland again. To Do, Cel, Kwint, Ilse, Maas, Machteld, Marije, Meike en Yv, thanks for all the wine and cheese, the ever-present but welcome distraction in the group chat, and occasionally the interesting books.

Most importantly, a huge thank you to my family. My parents-in-law, Elly and David, thanks for your love and support, and for always being so very interested in this thesis. My other Stolk relatives, Tanja en Janneke, en Annemarie, thanks for all the good moments, and for providing us the best holiday addresses. My parents, Siem and Marga, I really couldn't have wished for better parents. You have always intellectually challenged me, from a young age. Especially my mom who taught me how to read when I didn't want to wait for school to do so. You have always supported me in the things I wanted to do and have encouraged me to try things and take risks. When things didn't work out, you were the safety net I needed and when things did work out, you proudly celebrated my victories with me. To Rik and Evelyn, and Pleuni and Bas, you are the best siblings and in-laws. We got to grow up together and share bedrooms, clothes, stories and experiences. As we continue to grow in life, buy houses, build careers, get married and have babies, I'm so happy to always have you alongside me. Finally, to my partner Gijs, everything is so much better when I get to share it with you. Thank you for always supporting me. Thanks for actually listening to me explaining my research and for understanding when I had to work late. And however great this moment of having finished my thesis is, it pales in comparison to becoming parents together. To Finn, you are already the most amazing little boy and I can't wait to watch you grow up. Thanks for granting me a few moments in between all of the feeding, pooping, playing and crying to actually finish this thesis. Finally, thanks to my dad for babysitting at this very moment while I'm writing these acknowledgements.

ABOUT THE AUTHOR

Lotte Visser was born on the 9th of January 1988, in Hoorn, the Netherlands. She studied Molecular Science & Technology (BSc, 2006 – 2011) at Leiden University and the Technical University Delft and Sustainable Development, following the track Energy & Resources (2011 – 2013) at Utrecht University. Her master thesis was conducted at the Province of South-Holland, analysing the feasibility of reaching targets on the development of sustainable heating and cooling.

After graduating, Lotte started working as a junior researcher at Utrecht University. In this role, she worked on an EU project analysing the potential for circular economy initiatives, including a calculation of the potential energy savings resulting from re-use instead of recycling. Lotte started her PhD research at the Copernicus Institute at Utrecht University in 2015. Her research was focussed on analysing the potential for supply chain optimisation of wood pellets imported into the Netherlands, for both costs and greenhouse gas emissions, including literature research, techno-economic analyses and modelling of biomass availability and allocation. During her PhD, Lotte spent some time working at the University of Idaho in the United States. This research resulted in a number of presentations at international conferences, as well as multiple peer reviewed articles in international journals, which are presented in this dissertation.

Lotte is currently working as a policy maker at the Dutch Ministry of Economic Affairs and Climate. Her work there focusses on the development of sustainable heat production in the Netherlands, primarily on sources using bio-methane or biomass.