Jarno Föhr

RAW MATERIAL SUPPLY AND ITS INFLUENCE ON PROFITABILITY AND LIFE-CYCLE ASSESSMENT OF TORREFIED PELLET PRODUCTION IN FINLAND – EXPERIENCES FROM PILOT-SCALE PRODUCTION

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Dissertation for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium of the Mikkeli University Consortium at Mikkeli, Finland on the 5th of November 2021, at noon.

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Supervisor Professor Tapio Ranta
Department of Energy Technology
Lappeenranta-Lahti University of Technology LUT
Mikkeli, Finland

Reviewers Professor of Practice Tero Joronen
Materials Science and Environmental Engineering
Tampere University
Tampere, Finland

Associate Senior Lecturer David A. Agar
Department of Forest Biomaterials and Technology
Swedish University of Agricultural Sciences
Umeå, Sweden

Opponent PhD Lauri Sikanen
Department of Production Systems
Natural Resources Institute Finland (Luke)
Joensuu, Finland

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Abstract

Jarno Föhr
Raw Material Supply and its Influence on Profitability and Life-Cycle Assessment of Torrefied Pellet Production in Finland – Experiences from Pilot-Scale Production
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The European climate policy aims to move toward an environmentally friendly world, and it has been awakened by a strong will to find replacement fuel alternatives to fossil fuels, especially for coal. Torrefied pellets have emerged as a noteworthy alternative because their properties are more similar to coal. Because of this, it can be used in large quantities for co-combustion in coal-fired boilers. In this case, existing coal boilers do not need to be replaced by the new boilers. However, there have been problems with moving the technology of torrefaction forward and this dissertation has wanted to address this.

The purpose of this dissertation was to investigate the process technology and production costs of torrefied pellets, and the emissions of the supply chain in terms of research. The other purpose was to investigate the raw material differences in terms of heating value and to determine their effects on the profitability of a theoretical large-scale bio-coal pellet plant, and therefore on the production economy. The research environment was the region of South Savo, in Finland. At first, the focus of the studies was on the test runs in the pilot plant and base data for the dissertation was produced on these tests. At a later stage, the studies were expanded to the theoretical examinations dealing with the large-scale bio-coal pellet plant, and greenhouse gas emissions of the torrefied pellet supply chain.

The dissertation achieved the stated research objectives and provided accurate research information on the material properties of manufactured torrefied pellets. The work also achieved results on the costs of manufacturing the torrefied pellets and the cost of the entire supply chain. The total supply cost was €31.03–33.12/MWh for all pellet types in the large-scale plant. In addition, the work achieved economic calculations for the regional economy and determined the selling prices for the pellets. The highest final price (€37.02–42.92/MWh) was obtained for spruce pellets, but it caused the lowest annual economic impact for the region (€35.41–41.05 million). Finally, this work clarified the potential for reducing GHG emissions from the torrefied pellet supply chain. The GHG emissions were estimated by using a life cycle assessment. The reduction potential occurred in different sections of life cycle phases like using different chipping or crushing methods, using alternative supply chain paths, or using different materials like larger stems.

Based on the studies of this dissertation, more research is needed to explore differences in heating value between wood materials and the resulting economic impact. The supplementary research is also needed on the emission footprint of torrefied pellets over their entire life cycle. In addition, more research is needed for the technology aspect of the torrefaction and especially for solution based on a vertical reactor. This way ensures a smooth passage from the pilot phase to the launch of the continuously operated plant.

Keywords: pilot-scale, torrefaction, pellets, economics, profitability, LCA

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Jarno Föhr
October 2021
Mikkeli, Finland

To Annina,
my darling wife

Contents

List of Publications

This dissertation is based on the following papers. The rights have been granted by publishers to include the papers in dissertation.

I. Ranta, T., Föhr, J., and Soininen, H. (2016). Evaluation of a pilot-scale wood torrefcaction plant based on pellet properties and Finnish market economics. *International Journal of Energy and Environment*, 7(2), pp. 159–168.

II. Föhr, J., Ranta, T., Suikki, J., and Soininen, H. (2017). Manufacturing of Torrefied Pellets Without a Binder from Different Raw Wood Materials in the Pilot Plant. *Wood Research*, 62(3), pp. 481–494.

III. Föhr, J., KC, R., Karttunen, K., and Ranta, T. (2019). Impact of Alternative Raw Materials on the Profitability of a Large-Scale Bio-Coal Pellet Plant in Finland. *Journal of Sustainable Bioenergy Systems*, 9, pp. 1–15.

IV. KC, R., Föhr, J., Korpinen, O.-J., and Ranta, T. (2019). Feedstock and supply chain-oriented comparative cradle-to-gate life cycle assessment of torrefied pellets, case study: Finland. *International Journal of Energy and Environment*, 10(5), pp. 257–270.

Author's contribution

Jarno Föhr was the principal author and investigator in publications II and III. In Publication I, Jarno Föhr performed the experimental arrangements and post-processed the experimental data. In Publication IV, Jarno Föhr set the scenario inspection and participated in all stages of preparing the paper.

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Nomenclature

Abbreviations and symbols

BAU	Business as usual
C	Annual production capacity (MWh)
$c_{n/i}$	Annuity factor
CFB	Circulating fluidized bed
CHP	Combined heat and power
DBH	Diameter at breast height
E_c	Electricity (kWh/t)
E_p	Electricity price (€/MWh)
F_p	Freight (€/t)
EIA	Environmental impact assessment
GDP	Gross domestic product
GHG	Greenhouse gas
GWP	Global warming potential
H_c	Heat (kWh/t)
H_p	Heat cost (€/MWh)
HTC	Hydrothermal carbonization
IRR	Internal rate of return
I	Investment cost (M€)
ISO	International Organization for Standardisation
L_c	Workload (person year)
L_p	Labor cost (€/h)
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LHV	Lower heating value (MJ/kg or MWh/t)
m	Annual production amount of the plant (t)
M_a	Maintenance (%)
M_{ar}	Moisture content as received (w-%)
MC	Moisture content (w-%)
NPV	Net present value
P_{cost}	Production cost (€/MWh)
$Q_{net, ar}$	Lower heating value as received (MJ/kg or MWh/t)
$Q_{net, d}$	Lower heating value as dry basis (MJ/kg or MWh/t)
R	Required gross margin (€/MWh)
R_p	Raw material cost (€/MWh)
r	Discount rate
t	Number of years
TOP	Torrefaction and pelletizing
TRL	Technology readiness level
W	Annual energy production (MWh)

η	Raw material economy (%)

Conversion factors

1 Wh = 3600 J
1 m^3 solid wood = 2.5 m^3 loose wood
1 m^3 loose wood = 0.4 m^3 solid wood

Units

h	hour
kg	kilogram
m	meter
t	ton
W	watt
y	year

1 Introduction

1.1 Background and motivation

The positive will in the European climate policy wants to move toward an environmentally friendly world. The European Union's desire to increase the use of renewable fuels has inspired the author to continue the thesis until the end. In 2018, the European Commission published a long-term strategy aimed at an economy with net-zero greenhouse gas (GHG) emissions by 2050 (European Commission, 2018). The European Commission further specifies as follows: since 75% of emissions come from energy production, the EU must, among other things, disconnect from the fossil economy, improve energy efficiency, and increase the use of renewable energy. In particular, the need for biomass may increase by up to 80% of the current situation.

In northern conditions, winter coldness and dark polar nights have quite a different effect than in equatorial regions. The capacity of air heat pumps and solar cells is insufficient to achieve the necessary energy for heating properties. In this case, the biomass suitable for combustion must be transported to the site of use and produced for energy by burning. In Finland, wood fuels make up the largest share of biomasses and are mainly used to produce heat and electricity. Today, wood fuels are the single most important source of energy production, having had a higher proportion than oil, coal, or natural gas since 2012. In 2019, wood fuels accounted for 28% of Finland's total energy consumption (Ministry of Agriculture and Forestry of Finland, 2020). Overall, all renewable energy sources generated 37% of total energy consumption. Therefore, it is clear that wood fuels will continue to be used in Finland's energy production and the potential for its use will be increased.

Due to the cold climate and long winter season in Finland and the Nordic countries, heating is the sector that requires a significant part of energy consumption. A large portion of energy is supplied by power plants that are fueled by coal. In 2020, the consumption of hard coal as a fuel in the generation of electricity and heat amounted to 1.56 million tons, corresponding to 40 petajoule in energy content (Official Statistics of Finland, 2021). Replacing coal has been a challenge in Finland because of the lack of suitable material. Traditional white wood pellets can only substitute 5–7 % of the coal based on tests held at the Finnish capital's coal-fired power plants (Vuorinen, 2014). However, there has been a new development in the pellet production industry. A biomass product called torrefied pellets is thought to be capable of replacing coal in power plants.

In the torrefaction process, biomass is roasted in 200–300 °C temperatures in the absence of oxygen, which allows moisture and volatile organic compounds to evaporate. After that, the biomass is crushed and pelletized in order to achieve better bulk energy density, storability, and transportability. The final product, torrefied pellets, has larger heating value than traditional pellets and lower equilibrium moisture content in nature, meaning it has better storage quality. The properties of torrefied pellets are somewhat close to coal, so its replacement is possible in coal-fired power plants. (Bergman, 2005) Attempts have been made to commercialize the torrefaction technology across Europe currently and the new production plants of torrefaction are under development (Wilen et al., 2013). In order for a complete commercialization to be successful, the torrefaction reactors still need to be better optimized (Batidzirai et al., 2013).

Using woody biomass as a fuel is often driven by logistical considerations. Depending on the source of the woody biomass, the monetary value of the raw material is often quite low (Kusiima & Powers, 2010). However, the cost of harvesting, collection, processing, storage, and transportation from the forest site to end users can be quite expensive. It is also clear that all biomass is local and should be transported on short transport to the site of use (Kim & Dale, 2015). Therefore, it is important to intensify the biomass logistics, so they are more efficient and cost-effective. The fact is that the bulk density and calorific value of forest chips are low (Arkadiusz, 2016). In this case, the solution would naturally be biomass refining. Refining biomass can enable wood fuel to be used on a larger scale in energy production, and in this case, it can be delivered in long-distance transportations.

The main motivation for this dissertation has arisen from the problems above. Using biomass in energy production has been a much lesser value activity at the local level when compared to fossil fuel use. Here, the emphasis is specifically on long-distance transportation of fuels. Because of this, the desire is to develop the biomass supply chain and make it more operational and efficient. Biomass must be condensed to a smaller volume and have a higher calorific value, allowing it to compete with fossil fuels in logistics. This can be done through densification, e.g., the process of pelletizing. In addition, the equilibrium moisture content of biomass is notoriously high, which can be lowered by the process of torrefaction.

Often calorific values of different tree species are not directly associated with their respective monetary values. While the properties of the wood have been extensively analyzed in publications, the treatments of analyses have generally fallen short and the issue has not been addressed further in the theoretical extension studies (Günther et al., 2012, Telmo & Lousada, 2011). Otherwise, calorific analyses of woods have only been presented as supporting material. Because of this, it can be assumed that there is a research gap where the monetary value between the calorific values of woods in energy production has not been studied. This is an issue that will be raised later in this dissertation.

1.2 Objectives and research hypotheses

The main objective of this dissertation is to investigate the process technology and production costs of torrefied pellets, and emissions of the supply chain. At first, the main research was focused on the test runs in a pilot plant, wherein torrefied pellets were manufactured from different raw wood materials. The main research data was produced on the pilot plant and its test runs. In that case, the first two research papers have been produced from the test runs. The latter two research papers were based on results from the pilot plant analyses. These papers were expanded to deal with the profitability of a large-scale bio-coal pellet plant and the GHG emissions of a torrefied pellet supply chain.

This dissertation also aims to promote the use of forest-based biomass and reduce the use of imported fuel by replacing it with a domestic renewable alternative. The final results of this dissertation can show the potential of torrefied pellets for the large-scale energy production in terms of quality, as long as its use becomes more affordable at the plants. At the same time, this development requires the support mechanisms from the state, so that the pellets could really start to move on the markets.

The aim of the dissertation is to answer the following research hypotheses:

1. In Finland, the purchase cost of raw material accounts for most of the cost structure of the overall supply chain of torrefied pellets.
2. The final price of torrefied pellets is not completely correlated with the direct regional economic impact it produces, since it is also affected by the heating value of the pellets.
3. Depending on the supply chain alternative, upgraded biomass has a positive effect on the reduction of GHG emissions from the entire logistics of biomass.

1.3 Research contribution according to research papers

This dissertation comprises four scientific articles and covers extensively and determinedly the field of research on torrefied pellets. The dissertation will look at torrefied pellets from three different aspects, which are broad perspectives: biomass upgrading, economic aspect, and environmental aspect. Figure 1 shows the placement of publications on torrefied pellet studies. Publications I and II are ranked under biomass upgrading, where the study was intended to manufacture torrefied pellets on a pilot plant scale. Publication I also looked at an economic aspect that studied the production cost of the pilot plant in terms of pellet manufacturing. This economic aspect was extended in Publication III, which inspected the profitability of a large-scale bio-coal pellet plant. Finally, Publication IV studied an environmental aspect, which further considered the emission reduction potential of GHG emissions in the torrefied pellet supply chain.

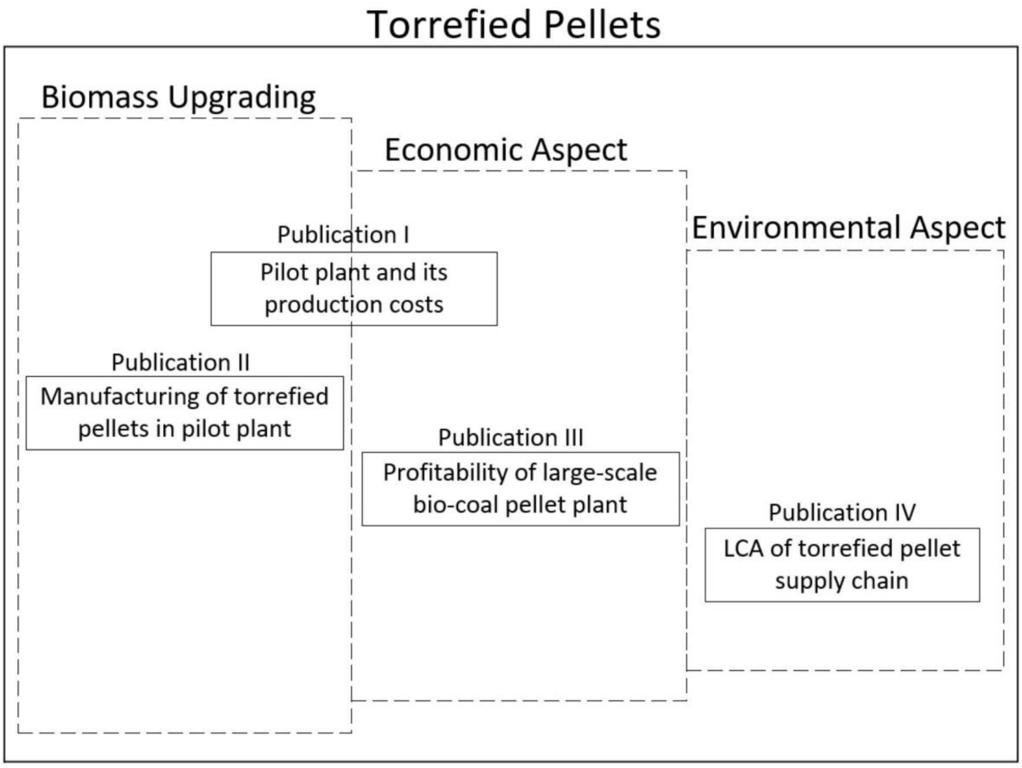


Figure 1: The framework of the dissertation.

Paper I presented a pilot plant located in Mikkeli, eastern Finland. The pilot plant began production in 2014 with a nominal capacity of 10,000 t/y. The study also carried out quality analyses of wood chips and torrefied pellets. Finally, the paper carried out the theoretical production cost analysis of a torrefied pellet plant with a nominal capacity of 50,000 t/y. In the paper, the size and costs were scaled from the existing pilot plant operation in Mikkeli, at Finnish cost and price levels.

Paper II carried out test runs at the same pilot plant as in paper I, but the focus of the study was on the implementation of test runs. The test used raw wood materials such as wood chips made from coniferous trees (spruce, pine), broadleaf (birch), mixed broadleaf (birch and aspen), and as well as by-products such as veneer chips. The test runs focused on making torrefied pellets without binders, and the pelletizing process only exploited condensation water that came about from the torrefaction process. The main purpose of this paper was to analyze the properties of torrefied pellets manufactured from different raw wood materials and in different conditions. The temperature and the retention time were varied, regarding the driving parameters. In addition, the purpose of this paper was to obtain accurate quality information on torrefied pellets and its raw materials.

Paper III expanded on papers I and II. The main purpose of paper III was to determine the regional added value of a theoretical large-scale bio-coal pellet plant for the region of South Savo, eastern Finland. The total production volume of the plant was modellet at 200,000 t/y and the raw wood materials used were birch pulpwood, spruce pulpwood, pine pulpwood, and energy wood. The aim was to investigate the impact of alternative raw materials on the heating value of torrefied pellets and their effect on the bio-coal pellet plant's profitability. Calculations included the annual raw material demand of the plant, the total supply costs, the required gross margin for each pellet type, and the final price for each pellet type.

Finally, emissions from the supply chain were investigated for torrefied pellets in paper IV. This paper assessed the impact of alternative supply chains on greenhouse gas emissions. Life cycle assessment (LCA) was used as the main tool. The assessment was divided into raw materials for different species of wood, and alternative routes were also considered in terms of the supply chain. The supply chain always started with forest side operations, continuing through chipping and torrefaction to final use. The assessment modelled a theoretical torrefaction plant with a capacity of 200,000 t/y located in the region of South Savo, eastern Finland. The final use of torrefied pellets was assumed to be in Helsinki, southern Finland. The purpose of the paper was to analyze GHG emissions from the entire logistics of torrefied pellets and to compare different logistics scenario options with each other.

1.4 Scope and limitations

The scope of this dissertation was to generate conclusions systematically through the methods and results. The purpose was to produce reliable research data on torrefied pellets that had been produced at the pilot plant. This was achieved by analyzing test batches of pellets with laboratory measurements. The profound scope of the dissertation was to compare the effects of differences in the calorific values of wood against the production cost of torrefied pellets and the economic benefit from the sale of pellets. This was achieved in the thesis by calculating the cost of the entire supply chain per wood species and eventually, by determining a price for the torrefied pellets along with the sales margin. With the help of these, deeper analysis was also achieved in terms of the regional economic impact of a theoretical large-scale bio-coal pellet plant. Finally, the dissertation examined the reduction potential of GHG emissions from the torrefied pellet supply chain. Emissions were determined by using the LCA method as an aid.

The dissertation involves the manufacture of torrefied pellets at a pilot plant, making it possible to manufacture on a large-scale with only a few different species of wood. In this case, the study did not have the opportunity to manufacture several different pellets at a small scale, e.g., in a laboratory. Also, the pilot plant process is limited to temperatures in the range of 240–260 °C. The process temperature could be higher when making top-quality pellets.

In literary sources, there are also limitations to finding cost information on pilot plants or supply chains. However, there are few publications concerned with biomass supply chains in the Nordic countries (Agar, 2017, Svanberg & Halldorsson, 2013). There is also a scarcity of suppliers and builders in the pilot stage, and the majority are still mostly in the pilot test stage in terms of their technologies. In addition, when the environmental impact is assessed and an LCA is used, then there can be the misrepresentation of life cycle inputs and outputs due to the lack of variability in assessments. In the torrefied pellet supply chain, multiple variables can have a direct impact, such as raw material availability in the region, harvested time of wood, capacity of storage facilities, and the transportation route.

2 State of the Art

This chapter's focus is to provide a literature review of the relevant topics and issues in relation to the work of this dissertation. The chapter starts with the introduction of the forest-based biomass supply chain and its handling of environmental issues. The chapter then continues with the introduction of torrefied pellets as a fuel for energy production, among other things detailing wood as a material, the process and technology of torrefaction, the pelletizing, and the market potential of torrefaction. Finally, chapter introduces other options for upgrading biomass and finalizing the process with the pelletizing phase.

2.1 Forest-based biomass supply chain

This section mainly covers the forest biomass supply chain and its environmental aspect, as these topics have been studied a great deal. Up to the torrefaction plant, the supply chain of forest-based raw material is based on the existing typical forest biomass supply chain. From the torrefaction plant onward, the supply chain of the finished product is focused on efficient distribution of the torrefied pellets, and this logistics area will not be addressed in detail in this dissertation.

2.1.1 Biomass supply chain

A supply chain generally refers to the delivery of products or services from suppliers to consumers (Santos et al., 2019). When looking at the biomass supply chain in the bioenergy sector, biomass is delivered from its point of origin to its final destination, where it is converted into final products, such as transport fuels, heat, and power (Santos et al., 2019). The supply chain normally consists of a number of different stakeholders that operate independently but are nevertheless interconnected. The supply chain for energy use of forest biomass typically consists of the following steps: harvesting, forwarding, storage, transportation, pre-processing, conversion, and distribution (Cambero & Sowlati, 2014). This supply chain based on forest biomass is shown in Figure 2.

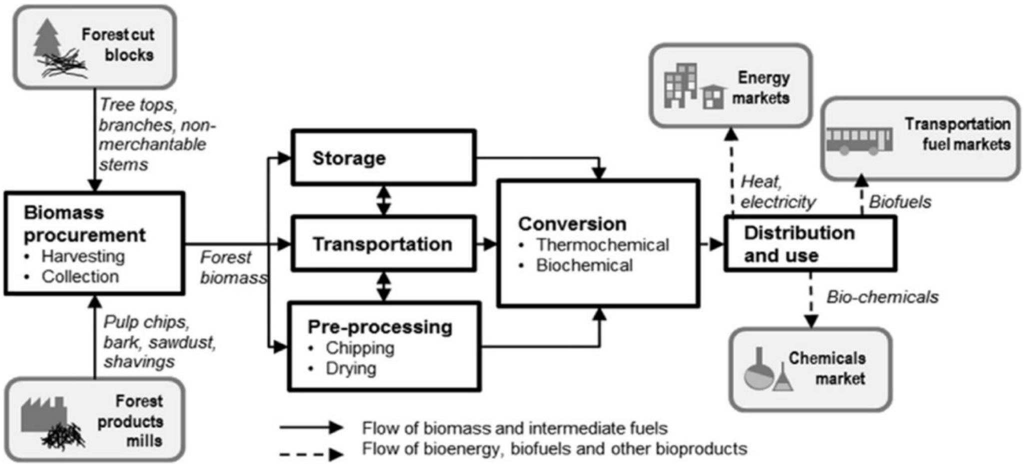


Figure 2: Chart showing forest biomass flow in the supply chain (Cambero & Sowlati, 2014).

It is better to refine biomass into an energy-intensive form in order to make logistics more efficient (Agar et al., 2020). Biomass is assumed to be a fuel used mostly locally or regionally close to its origin. Research into the energy use of biomass has dealt with the design of local and regional supply systems design, including the selection of transportation and handling equipment, network design, the decision whether to transport via a terminal or not, and the location of terminals (Gunnarsson et al., 2004, Kanzian et al., 2009). In addition, Svanberg and Halldorsson (2013) have mentioned that the increase in the use of biomass implies that transportation distances and hence transportation costs will increase further. They are caused mainly by the high moisture content (MC) and bulk density of the biomass logistics.

2.1.2 Environmental impact

Transportation of biomass is one of the factors affecting to the environment, including anthropogenic greenhouse gas emissions, in particular using fossil fuels in forest operations, material handling and transportation (Jäppinen, 2013, Abbas & Handler, 2018). Due to this, emissions from the biomass supply chain cause one negative aspect for the use of bioenergy (Abbas & Handler, 2018). On the other hand, the proportion of supply chain emissions is much lower than the main factors associated with bioenergy balance, such as disturbances related to forest carbon balance (Vanhala et al., 2013).

Sustainability issues must also be raised when dealing with an environmentally friendly supply chain. The European Commission has set sustainability and greenhouse gas emissions criteria for 2030, which also apply to transport, for biofuels. In this case, we will talk about the latest renewable energy directives, RED II. Sustainability criteria have set transport biofuels as a savings target of at least 65% of greenhouse gas emissions. Similarly, renewable electricity, heating, and cooling systems have a savings target of at least 70% of greenhouse gas emissions after 2021 and 80% after 2026. (European Commission, 2019)

Sustainability should also be addressed from the forest-side sector, as it is also strongly linked to emissions from the entire biomass supply chain. The sustainability of the forest sector and forest management in particular has been raised in many publications over the last few years. According to Schweier et al. (2019), strategies for forest management are continuously being developed and implemented on a worldwide basis. In addition, there have been dissenting opinions between the sustainability of forest management and the costs associated with it. For example, according to Marchi et al. (2018) sustainability of forest management depends on the efficient implementation of forest operations in a sustainable manner. In contrast, De Meyer et al. (2014) state the focus is on economic sustainability and cost optimization in terms of logistics. They also note that environmental sustainability is losing its position, even though the cost of environmental sustainability and logistics is interdependent. Their solution would therefore be to include the environmental sustainability for the cost optimization on the part of biomass supply chains.

2.2 Torrefied pellets for energy production

Torrefaction technology is a wood biomass processing method, which has attracted great interest since the 1990s. Partial pyrolysis of wood biomass at temperatures of 200 to 300 °C and under oxygen-free conditions is called torrefaction (Bergman, 2005, Wang et al., 2019). Biomass dries completely during torrefaction, and subsequent absorption of water back into the final product is limited. To facilitate transportability and handling, the torrefied biomass is crushed and pelletized. This final product has also been referred to as bio-coal pellets or TOP Pellet (Flyktman et al., 2011). Torrefied product material can be made from different types of biomasses. However, the same treatment conditions do not automatically produce a similar final product from all biomass materials (Bergman et al., 2005). The properties of torrefied pellets are somewhat close to coal due to the increase in consistency of product quality, so they can be used for co-combustion in coal-fired boilers (Arias et al., 2007). In this case, existing coal boilers do not need to be replaced by other types of boilers. A positive aspect of biomass torrefaction and pelletizing is material condensation, which reduces the costs in further pellet distribution.

2.2.1 Wood as a material and the torrefaction process

Torrefaction is designed to alter the structure and properties of a carbonaceous material to better fit fuel use. Torrefaction removes moisture and some of the volatile substances, and attempts to break down hemicellulose (Strezov & Evans, 2015). Most of the structure of the wood consists of a dead cell and its only function is to support the tree. Wood is composed of cellulose, hemicellulose, and lignin (Sjöström, 1993). The main function of cellulose is to be a building material for the cells of the tree and provide mechanical support to the cells. Hemicellulose occurs in cells as a medium, and forms cross-bonds with lignin, affecting the flexibility of cell wall structure. Fresh wood has MC averaging about 40–60 % on wet basis. Both drying and torrefaction processes change the chemical structure of wood, and both processes also affect the mechanical properties (Li et al., 2016). During the heat treatment, the largest changes in wood matter occur due to the degradation of hemicellulose (Acharya et al., 2012).

Typically, about 40–50% of the dry mass of wood consists of cellulose. Coniferous wood contains less hemicellulose (25–30 w-%) than deciduous wood (37–40 w-%). Lignin can be described as a binder that binds individual cells together and gives them mechanical strength. In turn, lignin content is higher in coniferous wood (27–30 w%) than in deciduous wood (20–25 w-%). Lignin is largely composed of carbon and hydrogen, which are the main elements of energy production. Wood also contains extractives (<5 w-%) such as terpin, lipid, and phenol. (Alakangas et al., 2016, McKendry, 2002)

The important temperatures and mechanisms of thermal decay for the torrefaction process are shown in more detail in Figure 3.

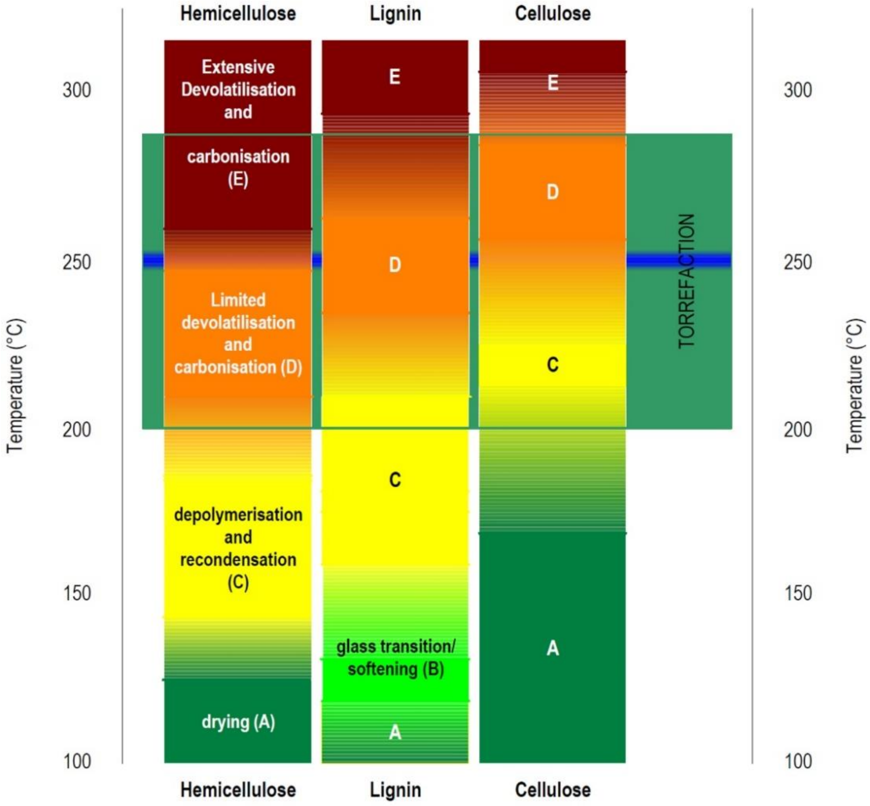


Figure 3: Thermal changes in biomass during torrefaction (Bergman et al., 2005).

At first, the vaporization of the water begins, and the water exits the wood at about 110 °C. As the temperature rises to 200–280 °C, the hemicellulose begins to break down and the water that had been in the chemical bonds of the wood is eliminated (Gaur & Reed, 1998). In addition, the most easily volatile substances are released. Hemicellulose is the most sensitive of the wood's structural components to thermal degradation when the temperature rises to more than 230 °C (Prins et al., 2006, Chen & Kuo, 2011). Cellulose is more heat-resistant and begins to decompose significantly as temperatures rise to 260 °C (Nada & Hassan, 2000). When the temperature rises above 290 °C, then about 45% of the cellulose has broken down (Bergman et al., 2005). Lignin is the main component of the most heat-tolerant wood and the reduction in mass of lignin is only minimal at less than 230 °C (Windeisen & Wegener, 2008). The greatest changes in mass of lignin begin to occur only when the temperature rises to 300 °C.

The torrefaction process mainly disposes of water from wood. During torrefaction, the wood dries almost completely, and its equilibrium MC varies between 1 and 5% after the process (Acharya et al., 2012). Torrefaction typically increases the higher heating value of the wood from 10–17 MJ/kg to 19–22 MJ/kg (Clark & Deswarte, 2015). According to data found in the literature, the end product of torrefaction contains 70–80% of the original mass and 80–90% of the original energy content. Consequently, the heating value increases by 10 to 22% with torrefaction (Flyktman et al., 2011). The end product is quite brittle and is easy to grind, and is commonly referred to as torrefied wood (Van der Stelt et al., 2011).

2.2.2 Torrefaction technology

In principle, heating methods are classified broadly under two generic groups: indirect heating and direct heating (Dhungana et al., 2012). In direct heating, an inert heat carrier is heated by torrefaction gases, in which case the heating medium is in direct contact with the feedstock (Kaltschmitt et al., 2016). In the indirect heating, the heat is transmitted for the feedstock through the reactor wall (Panchuk et al., 2019). In addition, torrefaction processes can be divided into two different types: single-phase and continuous operation processes. The main difference between these is that the capacity of the single-phase process remains low compared to the continuous operation process. An example of a single-phase process type is a common vertical reactor (moving bed), where wood chips flow downwards by gravity (Ranta et al., 2015). The moving bed reactor does not entail any moving parts and process conditions are similar to many other technologies as the residence time is 30–40 minutes and process temperature is approximately 300 ºC (Cremers et al., 2015). In an oscillating belt reactor, wood particles are transported using a moving and porous belt, and particles are directly heated using a hot gaseous medium. The residence time for wood particles inside the reactor can be well controlled by adjusting the belt speed.

Continuous operation torrefaction is carried out, studied, and developed in several different reactors, which were originally designed for other uses (Kleinschmidt, 2011).

Such reactors include a rotary drum reactor, a screw conveyor reactor, and a microwave reactor (see Figure 4).

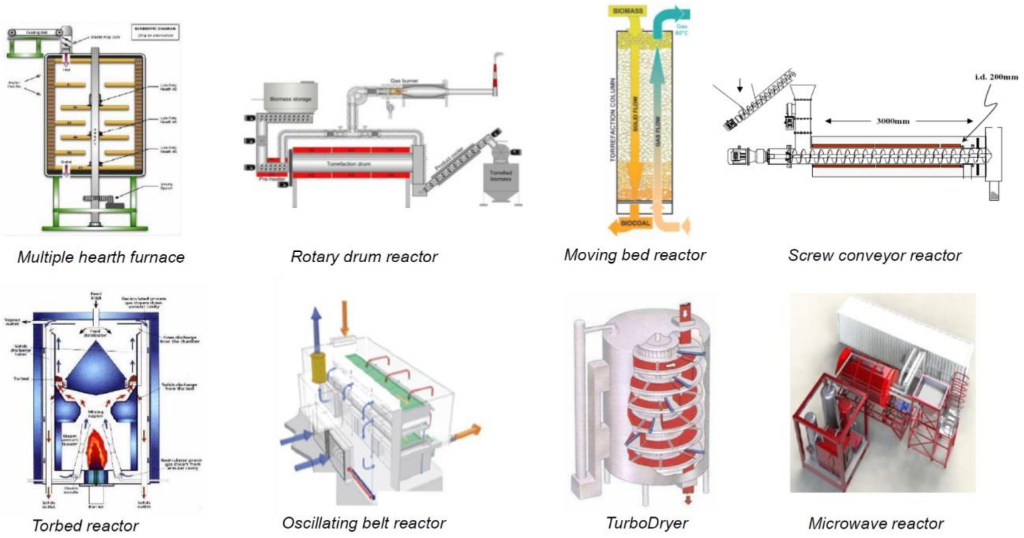


Figure 4: Reactor types for torrefaction (Kleinschmidt, 2011).

The process of rotary drum reactor can be controlled by varying the torrefaction temperature, length and slope angle of the drum, and rotation speed. In the bed, the rotation movement of drum causes heat variation in wood particles and to mix properly. The screw conveyor reactor consists of one or multiple auger screws that transport the wood particles through the reactor. This reactor technology can be placed both horizontally as well as vertically. A multiple hearth furnace is also the continuous reactor, consisting of multiple layers. On each individual layer, a single phase takes place in the process. In the upper layers of reactor, the wood particles are dried in lower temperatures, while in the lower layers torrefaction takes place. Totally different technology for heating wood particles is based on the use of microwave energy. In the microwave reactor, the wood particle heats homogeneously from the inside, which enable it to use a wider range feedstock particle sizes. However, the process is not energy efficient because of the need for electricity that is not easily generated from torrefaction gases. (Cremers et al., 2015)

However, proprietary reactor types such as the Torbed reactor have been developed for torrefaction. In the Torbed reactor, the heat is blown from the bottom of the bed with high speed (50–80 m/s) and this gives the wood particles inside the reactor both a horizontal and a vertical movement, resulting in swirls (Cremers et al., 2015). Post van den Burg (2012) has stated that the Torbed fluidized bed reactor has a short retention time and high heat transfer efficiency. Topell Energy built its own first industrial scale Torbed reactor with a production capacity of 60,000 t/year in the early 2010s in Duiven, the Netherlands. Along with this reactor, different manufacturers offer different patented models, among which one option is a bubbling bed reactor.

Table 1 shows different types of reactors and their manufacturers. The table also indicates technology readiness levels (TRL) and capacities until 2018. In Europe, several torrefaction reactor manufacturers claim that they have reached commercial production (Wilén et al., 2013). In North America there are also a few interesting initiatives under development, which claim that they are at least in a commercial demonstration phase. Steam exploded bio-coal pellets are a parallel technology option alongside torrefied pellets, and plants have been built for that as well. As an example, Valmet's bio-coal pellet plant is a complete production facility with an integrated CHP, from biomass infeed to bio-coal pellet outfeed (Valmet Oyj, 2018). The plant is located in the region of Champagne-Ardenne, France.

Table 1: Manufacturers of different reactor types by country (Scarlat & Fahl, 2020, Cremers et al., 2015).

Country	Developer	Technology	TRL	Capacity (tonnes/year)
Austria	Andritz	Rotary drum	TRL 6-7	8,000
Belgium	Torr-Coal B.V.	Rotary drum	TRL 9	30,000
Belgium	CMI NESA	Multiple hearth	TRL 6-7	Undefined
Canada	Airex	Cyclonic bed	TRL 6-7	16,000
Canada	Airex	Cyclonic bed	TRL 4-5	Undefined
Canada	Airex	Cyclonic bed	TRL 4-5	Undefined
Denmark	Andritz / ECN	Moving bed	TRL 6-7	10,000
Finland	Torrec	Moving bed	TRL 6-7	10,000
France	LMK Energy	Moving bed	TRL 6-7	20,000
France	CEA	Multiple hearth	TRL 1-3	Undefined
Indonesia	Hip Lik Green Energy	N/A	TRL 9	100,000
Ireland	Arigna Fuels	Screw reactor	TRL 9	20,000
Netherlands	Horizon Bioenergy	Oscillating belt conveyor	TRL 9	45,000
Netherlands	Topell Energy	Fluidised bed	TRL 9	60,000
Netherlands	Konza Renewable Fuels	Rotary drum	TRL 6-7	5,000
Spain	Grupo Lantec	Moving bed	TRL 6-7	20,000
Spain	CENER	Rotary drum	TRL 4-5	Undefined
Sweden	BioEndev	Screw reactor	TRL 6-7	16,000
UK	Clean Electricity Generation	Oscillating bed	TRL 9	30,000
UK	Rotawave	Microwave	TRL 1-3	Undefined
US	Solvay/New Biomass Energy	Screw reactor	TRL 9	80,000
US	Agri-Tech Producers LLC	Screw reactor	TRL 6-7	13,000
US	Earth Care Products	Rotary drum	TRL 6-7	20,000
US	Integro Earth Fuels, LLC	Multiple hearth	TRL 6-7	11,000
US	River Basin Energy	Fluidised bed	TRL 6-7	7,000
US	Teal Sales Inc	Rotary drum	TRL 9	20,000
US	Agri-Tech Producers LLC	Screw reactor	TRL 4-5	Undefined
US	Terra Green Energy	Multiple hearth	TRL 4-5	Undefined
US	Wyssmont	Multiple hearth	TRL 4-5	Undefined

TRL 1–3 = research, TRL 4–5 = pilot, TRL 6–7 = demonstration, TRL 8 = first-of-a-kind commercial, and TLR 9 = commercial

Nevertheless, varying data on different operating and process conditions are available for these reactor types of torrefaction. Choosing between different torrefaction technologies is difficult because there has been little comparative evaluation between different types of reactors. Further, alternative torrefaction techniques and their varying requirements in terms of raw material characteristics, heat transfer, process control, investment, and operating costs pose development challenges. Direct commercialization of technology without a pilot phase is problematic. (Acharya et al., 2012, Bergman et al., 2005)

2.2.3 Pelletizing process for torrefied material

In the actual pelletizing, the crushed wood mass is forced by pressurization through a perforated steel matrix. The most essential component of the matrix is the compression channel, into which wood mass is continuously fed during the pelletizing. The temperature of the wood mass rises in the channel under the influence of compression. On the other hand, torrefied wood mass is harder to press into a solid pellet than raw biomass. According to Stelte et al. (2012), the energy consumption of the pelletizing process itself is higher per ton of torrefied wood mass when compared to corresponding wood pellets (about 80–210 kWh/t vs. 50–60 kWh/t for wood pellets). Finally, the bulk energy density of the finished product increases, resulting in its energy density close to coal. After pelleting, the pellets are transferred to storage, depending on the plant size, either to a silo or large packs. In addition, the pelletized product can be transported pneumatically to intermediate storages or the coal pulverizers or hammer mills and is less sensitive to degradation and moisture uptake when compared to wood chips or pulverized fuels (Cremers et al., 2015).

Standard ISO 17225-2:2021 (2021) determines the fuel quality classes and specifications of graded wood pellets for non-industrial and industrial use. In the pelletizing phase, the torrefied wood chips are crushed and condensed with a condensate water of torrefaction process or other additional binders to reduce friction in the process and bind the material. The binders normally used in wood pellet production are lignin, glycerin, paraffin, molasses, bioplastic, and condensable fractions of torrefaction gases. The use of water as an aid to pelletizing has also recently been the subject of intensive research. Both the lignin and the MC play an important role in the internal binding of the pellet. During the torrefaction process lignin partially degrades, depending on the process conditions. Therefore, preparing a strong pellet requires optimization of both processes: torrefaction and pelletizing. (Koppejan et al., 2012) It is important to optimize process temperature in torrefaction and moisture in pelletizing.

By pelletizing torrefied biomass, several advantages can be achieved in transport, handling, and storage in comparison to torrefied biomass chips as the intermediate product (Cremers et al., 2015). The actual pelletizing phase requires special knowledge of changes in the structure of wood mass from the effects of high pressure and temperature. However, the formation of the pellet is heavily dependent on the raw material being fed and favorable control over the torrefaction condition. However, production without additional binders may limit the fine-tuning of the product to meet the logistical and end-user requirements. (Kiel, 2013) Requirements refer to the standard ISO 17225-2:2021 (2021).

2.2.4 Market potential of torrefied pellet

The IEA (2020) has estimated that around 7.9 billion tons of coal per year were used in the world in 2019 and its use appears to continue to grow. EU countries are committed to reducing carbon emissions and replacing coal with renewable fuels is the main factor in achieving the climate targets. Big energy companies generally view torrefied biomass as a significant opportunity to replace coal use (Helen Ltd, 2015, RWE, 2021). The most likely applications of torrefied pellets are co-firing with coal at pulverized-coal-fired power plants and in cement kilns, distributed combustion in small-scale pellet-burners, and gasification in entrained-flow gasifiers (Wild et al., 2016). In the future, the use on the industry side may be much smaller than the energy side regarding the volumes of torrefied pellets used.

The main market for torrefied pellets may be linked to pulverized coal-fired power plants in Europe. This would involve the co-firing of pellets together with coal. Other markets could relate to reported entrained flow gasification and small-scale combustion using pellets (Van der Stelt, 2011). Pulverized coal-fired power plants are located in almost every European country. They have a combined total capacity of about 200 GW_e, comprising about 1,200 power stations (Wilén et al., 2014). However, most of these facilities are located in Germany, the United Kingdom and Poland. The number of plants has decreased in recent years in an effort to reduce dioxide emissions.

The technology of torrefaction can provide a cost-effective way to enable large-scale replacement of fossil coal by renewable biomass. Torrefied pellets have been successfully tested and co-fired with coal in European power plants, such as the Amer power plant of RWE AG in the Netherlands and the Hanasaari and Salmisaari power plants of Helen in Finland (Blackwood Technology, 2021). The Amer power plant in Geertruidenberg, the Netherlands, has already been converted into a biomass power plant. Over 50% of the hard coal is being replaced by biomass on a daily basis. The company promised that this percentage would be increased to 80% or more by the end of 2020 (RWE, 2021). In addition, torrefaction technology developer Clean Electricity Generation (CEG) has announced a 200-ton shipment of bio-coal pellets in bulk from its storage facility in the UK to the end-user in France (Sherrard, 2019). The pellets exhibited the heating value advantages of torrefied bio-coal pellets over white wood pellets, when they were combusted in a circulating fluidized bed (CFB) boiler. This transaction was carried out by Cleantek Trade, which was the first trader to successfully market bio-coal pellets to utility companies (Bioenergy Insight, 2019).

In the future, the market for torrefied pellets is expected to develop, but the available public information is very limited, especially concerning the technologies used and volumes produced (Thrän et al., 2017). Most of the pilot plants have had technical problems that have caused postponements to starting their commercial operation

(Cremers et al., 2015). Several smaller pilot installations covering a wide range of different technologies are available at universities and research institutes. These include the Energy Research Centre of the Netherlands (ECN), the Spanish National Renewable Energy Centre (CENER), BioEndev (Sweden), and Lappeenranta-Lahti University of Technology LUT (Finland) (Wilén et al., 2013, Ranta et al., 2015). Currently, efforts have been made to accelerate the development and implementation of the technology through various research and pilot projects, mainly in the European Union and North America (Thrän et al., 2016). From European countries, the Netherlands, Belgium and France have been pioneered. However, when also taking into account the technology based on steam explosion, there are now at least seven commercial-scale plants under construction and due to start up in 2020–2021 (Hawkins Wright, 2021). A further eight projects are planned or are seeking permits, and this pipeline of projects amounts to about 2 Mt of annual capacity.

2.3 Other options for upgrading biomass

Along with the torrefaction process, other options for upgrading biomass and finalizing the process with the pelletizing phase include conventional pelletizing, steam explosion, and wet pyrolysis, which is also known as hydrothermal carbonization (HTC). The following are presented more broadly the alternative conversion methods.

2.3.1 Conventional pelletizing

Conventional pelletizing with white wood is the most common method of upgrading biomass and its equipment is the simplest compared to other alternative processes. In most cases, the raw material consists of dry sawdust, grinding dust, and cutter shavings (Alakangas et al., 2016). The conventional pelletizing process usually starts with the drying phase, in which the MC of sawmill residues is reduced from approximately 50% to around 8–12%. After the drying phase, the wood material is transferred to a ball or hammer mill where it is grounded. When making pellets, the rollers press the material through holes that are hot due to the process. When coming out, the wood material forms 6–8 mm in diameter and 20–40 mm long pellets. In addition, the material continues to dry during compression and pressure. Finally, the material is allowed to cool. (Arshadi et al., 2008)

The MC of the wood material determines much the success of the pelletizing phase, whereby the material is condensed into a more energy-dense state. In particular, the MC facilitates the friction and heat transfer (Back, 1987). Power consumption and friction in the die may increase due to too low MC of the material, and the holes in the die may become clogged (Resch, 1982). The MC of material also affects the thermal softening and self-bonding of individual particles in the wood pellet (Arshadi et al., 2008, Rhen et al., 2005). The durability of the wood pellets can be improved by using a mixture of fresh and stored (matured) sawdust, and it also reduces the energy consumption of the pelletizing equipment (Lehtikangas, 2001). The origin of the wood raw material can also have an effect on the success of the pelletizing. In this case, the moisture distribution and the differences in extractant content can lead to the difficulty of pelletizing, especially in the case of fresh Norway spruce sawdust, if the success is compared with pine sawdust (Lehtikangas, 2001).

2.3.2 Steam explosion

Alternatively, as for separate heat treatments, one option is steam explosion. It is a process where biomass is treated in steam at elevated pressure from 1 to 35 bar and temperatures of 180–240 °C (Ballesteros et al., 2000). The intention of the process is to cause the explosive decompression of the biomass. The high-pressure saturated steam heats up biomass rapidly and with or without rapid decompression (explosion) to rupture the rigid structure of the biomass. Better fermentation and enzymatic hydrolysis are achieved for cellulose when the cellulose bundles are defibrillated by a sudden release of pressure (Stelte, 2013). Steam explosion can achieve small cracks in the wood structure and also complete defibrillation of the wood fibers depending on the residence time and temperature (Stelte, 2013, Tanahashi, 1990).

Normally, the steam detonated wood material is transported on the production line directly to the pellet mill, where the material is again subjected to high temperature and pressure (Stelte, 2013). The wood pellets made from steam explosion processes are dark brown in color. Overall, the steam explosion is a pre-treatment process that can increase the calorific value of biomass and improve its properties at a later pelletizing phase (Stelte, 2013). Both continuous- and batch-type processes are available for steam explosion. Batch-type processes are usually used in set-ups of experimental laboratory scale. The continuous process offers a robust and steady operation in industrial applications and is thus a preferred solution offered, e.g., by Valmet (Björklund et al., 2016).

2.3.3 Wet pyrolysis

As for wet pyrolysis, it is also a thermochemical treatment of biomass-based materials taking place in the presence of water at moderate temperatures ranging from 180 °C to 260 °C (Román et al., 2012). However, wet pyrolysis may be more suitable for raw materials with varying MC, as the reaction takes place in wet circumstances and eliminates a pre-drying phase (Hoekman et al., 2011). Wet pyrolysis is significantly different process than the process of dry torrefaction described in this dissertation where biomass is pre-dried and then torrefied in the dry and oxygen-free conditions. In wet pyrolysis, biomass is processed in a pressurized reaction environment and saturated water (KC et al., 2017).

The final product of the treatment process is a hydrochar, and it is very similar in properties to torrefied biomass and is also homogeneous compared to the raw material

(Liu & Balasubramanian, 2012, Sermyagina et al., 2015). No additional binders are required for pelletizing the hydrochar. The bulk energy density of these pellets is higher if it is compared to conventional wood pellets. This is true both on a mass basis and volumetric basis. The pellets produced as a final product do not absorb moisture very much and are more weather-resistant compared to conventional wood pellets. (Yan et al., 2014)

2.3.4 Comparison of conversion methods

Alternative biomass conversion methods that exist alongside torrefaction were discussed above. These conversion methods had the principle that the finished product was a pellet. Table 2 shows typical properties for alternative upgrading products after pelletizing, and they are compared with torrefied pellets.

Table 2: Comparison of properties of alternative pellets.

Properties of pellets	**Conventional**[1]	**Torrefied**[2]	**Steam explosion**[1]	**Wet pyrolysis**[3]
Moisture (w-%)	5.0	6.4	5.0	8.5
Bulk density (kg/m^3)	617	678	739	685
Mechanical durability (w-%)	98.0	97.4	98.0	93.1
Ash (w-%)	0.4	1.2	0.5	0.9
Bulk energy density (MWh/m^3)	3.0	3.4	3.7	3.4

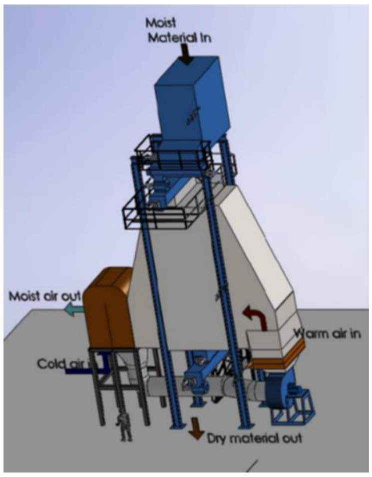
[1](Björklund, 2014: softwood)
[2](Publication II: birch)
[3](KC et al., 2017: grey alder)

A separate heat treatment is an additional process phase that brings additional costs compared to conventional white pellets. However, there are numerous benefits in the properties of heat treatment pellets when compared to conventional pellets. Heat treatment pellets have a high bulk energy density and their handling and transportation are economical in the next steps of the supply chain (Pöyry Management Consulting Ltd., 2011). GHG emissions are also reduced in the supply chain when the issue is considered in terms of heating value. In addition, important physical properties such as higher heating value and grindability make the heat treatment pellets more suitable for co-firing with coal, reducing the need for new capital investment of current coal-boilers (Wolfgang, 2012). A particular property is also the low moisture absorption ability of heat-treated pellets, allowing them to be stored better in outdoor storages, for example under the roof (Li et al., 2012).

3 Materials and Methods

3.1 Pilot-scale torrefaction

This dissertation was intended to showcase the general operation of the pilot plant. The pilot plant was set up in Mikkeli by Torrec Ltd in 2014 and it had a nominal capacity of 10,000 t/y (Figure 5) (Torrec Ltd, 2021). The pilot plant was related to a power plant of Etelä-Savon Energia Oy (South-Savo Energy), in eastern Finland, and its operations included the whole process, including drying, torrefaction, and pelletizing. The process of the unit was a single-phase. In practice, 9 to 10 bulk-m^3 of wood chips (approx. >300 kg/bulk-m^3) were fed into the reactor at one time and 1.5 to 2.0 tons of torrefied pellets were completed from the process. The torrefaction solution was based on a vertical reactor, where wood chips flowed by gravity and torrefaction occurs by steam inertization and accurate process control (see Figure 6). The plant received steam from a large-scale combined heat and powerplant (CHP) located right next to the pilot plant.



Figures 5 and 6: On the left is the pilot plant of Torrec Ltd in Mikkeli, eastern Finland (Publication I). On the right is a single-phase process in which both drying and torrefaction occurs (Publication I).

As the process temperature for main torrefaction, temperature was in the range of 240–260 °C due to the temperature of the steam obtained. All phases related to torrefaction were performed in the torrefaction unit, and these phases included pre-drying, post-drying, torrefaction, and cooling (see Figure 7). In the drying of the initial stages, the temperature was kept between 100–200 °C. The torrefaction unit was airtight and anoxic conditions were kept inside, and water vapor was also used to displace oxygen. After actual torrefaction, the material was moved to a storage silo (orange colored) to cool, after which the material was moved to a pelletizing hall. In the pelletizing process, the material was crushed, and moistening with tar liquid obtained from the torrefaction process was injected. The used amount of tar liquid in one pilot run varied between 100–150 liters, depending on the success of the pelletizing. After pelletizing, the pellets were packed into flexible intermediate bulk containers, which were large bags with a volume of 1 m^3.

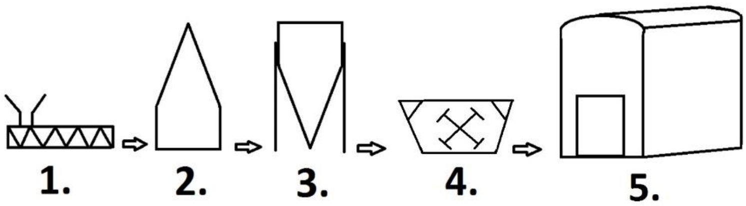


Figure 7: A schematic diagram of process: 1. screw conveyor, 2. torrefaction unit, 3. storage silo, 4. hammer mill, and 5. pelletizing hall (Publication II).

3.1.1 Manufacturing of torrefied pellets

In this thesis, the one goal was to analyze the properties of torrefied pellets manufactured from different raw wood materials and in varying process conditions. The studies of this dissertation are based on the results of the test runs at the pilot plant and the results are utilized in the whole dissertation. The test results serve as empirical data, which is later utilized in the use of research hypotheses for the dissertation. The purpose of this study was to obtain accurate quality information on torrefied pellets and its raw materials.

All pellets were produced in the pilot plant, and they were manufactured without an additional binder, such as tall oil. However, Kiel (2013) has reported quality problems with torrefied pellets when made without a binder. The manufacturing process only used condensation water in the pelletizing, which was obtained by torrefaction as a result of the process. The condensation water was brown in color due to process temperature, pressure, and feedstock.

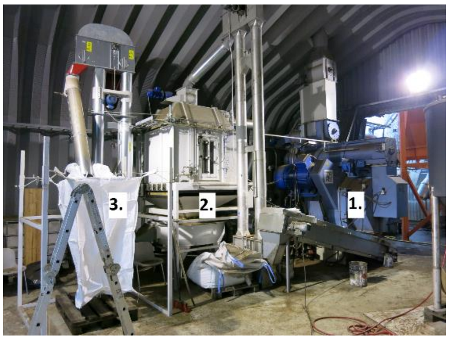
Six different wood chip materials were used in the study. The wood chips used in the pilot test consisted mostly of pulp wood-sized trees, which had been felled in spring, two months before torrefaction. The trees were chipped by a drum chipper with a sieve size class 50x60 mm. The tests used a variety of wood chip materials, which included birch, spruce, and pine. The mixed chips imported from Russia consisted mostly of birch and aspen. In addition, by-products of local plywood mill were used, which were birch and spruce veneer chips. The veneer chips did not contain any bark like the other previous chip materials. At the beginning of the test pilot runs, it was noted that a large share of fine fraction (F20–F25, <3.15mm) caused problems for the quality of the torrefied pellets. Due to this, it was decided to screen the wood chip material from the finest fraction. The screening was performed with the mobile Keestrack Combo (Keestrack Croup, 2021). After screening, the amount of fine material reached an acceptable level (F5–F15).

Next in turn was the torrefaction process. Table 3 shows the main process times and temperatures of torrefaction. Peng et al. (2013) reported in their study that a weight loss of about 30% was achieved with a torrefaction temperature of 250 to 300 °C. The actual torrefaction run was always started from about 160 °C, when the steam valve was fully opened. The length of each torrefaction run was approx. 40–50 minutes, so in some cases the test had to run three runs instead of two.

Table 3: Process times and temperatures of torrefaction.

Wood chip material	**Torrefaction time (h:min)**	**Max. temperature of reactor (°C)**	**Max. temperature of biomass bed (°C)**
Mixed hardwood	1:36	254	247
Birch	1:36	259	250
Spruce	2:08	249	240
Pine	1:42	259	252
Spruce veneer	1:51	255	246
Birch veneer	2:13	257	250

The first stage of the torrefied chip material is fining with a hammer mill, which had a 5 mm screen mesh. The crushed material was slightly moistened with condensation water before pelletizing, and the used amount varied between 100–150 liters, depending on the success of the pelletizing. The used pellet squeezer was a Munch RMP 650 and its capacity was 220 kW (Figure 8). The crushed material was pushed through a perforated iron matrix, which had the 65 mm press channel length (Figure 9). After compression, the pellets were screened of most of the fine particles and packed into large bags. All equipment was powered by electricity.



Figures 8 and 9: On the left is 1. the pelletizing unit, 2. screening unit, and 3. bagging unit (Publication II). On the right is a closer look at the iron matrix (Publication II).

Sampling and laboratory tests of samples followed the instructions in accordance with current standards and were performed on both wood chips and torrefied pellets (see Table 4). All samples were taken and placed in a lidded bucket, and they were stored in a cold room at 5 °C before the laboratory tests.

Table 4: Sampling and laboratory tests used for solid biofuels.

Method/analyze	**Reference**
Sampling	(SFS-EN 14778:en, 2012)
Storing	(SFS-EN 14780:en, 2012)
Particle size distribution	(SFS-EN ISO 17827-1:en, 2015)
Bulk density	(SFS-EN ISO 17828:en, 2015)
MC	(SFS-EN ISO 18134-1:en, 2015)
Ash content	(SFS-EN ISO 18122:en, 2015)
Length and diameter of pellets	(SFS-EN ISO 17829:en, 2015)
Mechanical durability of pellets	(SFS-EN ISO 17831-1:en, 2015)
Calorific values	(SFS-EN ISO 1716:en, 2011)
Energy density per volume	(Alakangas et al., 2016)

3.1.2 Production costs

In this study, the theoretical production cost analysis of a torrefied pellet plant was carried out. In addition, the analysis carried out sensitivity analysis with changing cost parameters. The purpose of this study was to look at the first research hypothesis and provide answers to it. The cost of purchasing the raw material is strongly related to the production costs. The production cost analysis of scaled pilot plant was based on the assumption that it had a production capacity of 50,000 t/y and the plant was a stand-alone plant.

The theoretical plant was located inland, and the assumed pellet end user was in a coastal area. The pellets were supposed to be transported in bulk by trucks, resulting in no cost from extra packaging. In addition, both the logistics and storage were based on covered solutions throughout the whole supply chain. In the analysis, the production and distribution costs were divided into three sections: raw material, torrefaction/pelletizing, and storing/transportation to the end user. The plant's fixed cost parameters comprised investment and annual maintenance, and variable cost parameters such as electricity consumption, heat consumption, and workload. Production cost P_{cost} (€/MWh) was calculated using Equation 3.1, where costs were divided into the above-mentioned feedstock, fixed, and variable torrefaction and freight costs. Annuity factor $c_{n/i}$ was defined using a lifetime of 20 years (n) and an interest rate of 10% (i). The lower heating value as received ($Q_{net,\,ar}$) of the pellets was assumed to be 5.1 MWh/t. Table 5 shows the starting values of the analysis based on the presented pilot plant's technology and Finnish price levels.

$$P_{cost} = R_p/\eta + (c_{n/i} * I + M_a * I + L_p * L_c)/C + \left(E_p * E_c + H_p * H_c + F_p\right)/Q_{net,ar} \tag{3.1}$$

Where:

$c_{n/i}$ is the annuity factor (0.1175)
C is the annual production capacity (50,000 t × $Q_{net, ar}$).

Table 5: Parameters for the production cost analysis.

Parameter	Value	Unit
Raw material cost, R_p	20	€/MWh
Raw material economy, η	90	%
Investment cost, I	6.7	M€
Maintenance, M_a	4	%
Electricity, E_c	240	kWh/t
Electricity price, E_p	100	€/MWh
Heat, H_c	615	kWh/t
Heat cost, H_p	25	€/MWh
Workload, L_c	8	person year
Labor cost, L_p	25	€/h
Freight, F_p	20	€/t
Lower heating value as received, $Q_{net, ar}$	5.1	MWh/t

Lastly, the sensitivity analysis carried out cost sensitivity analysis for raw material prices, investments, electricity, heat, labor, and freight. Previous parameters were varied in the range of ±10–20–30%.

3.2 Economy of production in bio-coal pellet plant

In this thesis, the regional added value of a theoretical large-scale bio-coal pellet plant (capacity of 200,000 t/y) was determined for the region of South Savo, in eastern Finland. The idea was to compare the differences in economic impact arising from differing heating value of the raw wood material used. In addition, the following points were also clarified in the study: the annual raw material demand of the plant, the total supply costs, the required gross margin for each pellet type, and the final price for each pellet type. In this study, the raw wood materials used in the plant production were birch, spruce, pine, and energy wood (mixed hardwood) that were the size class of pulpwood with a diameter at breast height (DBH) of 5–15 cm and a length of 2.7–5.0 m (Petty & Kärhä, 2014).

The annual energy production W (MWh) was determined using Equation 3.2 individually for all four wood materials (SFS-EN ISO 1716:en, 2011).

$$W = \frac{Q_{net,d} \times \left(\frac{100-M_{ar}}{100}\right) - 0.02443 \times M_{ar}}{3.6} \times m \tag{3.2}$$

Where:
$Q_{net,d}$ is lower heating value on a dry basis, MJ/kg
M_{ar} is MC as received, w-%
0.02443 is a correction factor for the enthalpy of vaporization for water (moisture) at a temperature of 25 °C, MJ/kg per 1 w-% of moisture
3.6 converts the unit MJ/kg into the MWh/t
m is annual production amount of the plant, t.

The Equation 3.2 can also be represented in a simpler form in Equation 3.3 (SFS-EN ISO 1716:en, 2011).

$$W = Q_{net,ar} \times m \tag{3.3}$$

Where:

$Q_{net,ar}$ is the lower heating value as received, MWh/t.

The lower heating value as received $Q_{net,ar}$ was obtained by dividing the annual energy production *W* by the annual production amount of the plant *m*. The MC of all pellets (M_{ar}) was set at 6.0% in the initial calculations. Both the MC and the heating value were taken as average values from the analysis results of Publication II.

Next, the plant's annual raw material need was determined. It was assumed that the plant's energy efficiency ran at 90% and the raw material demand was calculated on that premise. Many researchers have shown that with a 30% loss of mass, a 10% loss of energy has been achieved (Chin et al., 2013, Lee et al., 2012, Asadullah et al., 2014). In the case, the factor *m* was solved using Equation 3.2, and the factor *W* is already known from pellet calculations. The factor $Q_{net,d}$ was assumed to be the same as the end product itself. The MC (M_{ar} = 51.5%) and the bulk density (331 kg/m^3) were the average values from Publication II. The volume of woodchips was calculated by multiplying the weight of woodchips (*m*) by the average bulk density. In addition, the plant's raw material demand in cubic meter volume was obtained by multiplying the volume of woodchips by a conversion factor of 0.4. The conversion factor of 0.4 for the change from loose cubic meters to solid cubic meters is commonly presented in the literature (Alakangas et al., 2016, Petty & Kärhä, 2011). Finally, the calculation also required the energy density of the solid wood, and it was obtained by dividing the raw material need of the plant by the volume of solid wood.

The cost of the torrefied pellet supply chain was defined next. The supply chain always starts with felling and the delimbed stems are forwarded to the roadside. The stems are then transported to the plant by a full-trailer log truck. Next, the stems are chipped in a transferable medium-sized chipper, and the woodchips are then transferred to torrefaction and pellet production. Finally, the bio-coal pellets are distributed worldwide. All supply cost data was allocated for 2017, and they were collected from various sources (see Table 6).

Table 6: Cost data for supply chain of torrefied pellets.

Cost phase	Description	Reference
Average stumpage prices in South Savo	Birch pulpwood €10.95/m^3* Spruce pulpwood €10.60/m^3* Pine pulpwood €11.29/m^3* Delimbed energy wood €5.75/m^3¶	*(Natural Resources Institute Finland, 2018a) ¶(Natural Resources Institute Finland, 2018b)
Felling and forest transportation	Birch pulpwood €14.44/m^3 Spruce pulpwood €12.75/m^3 Pine pulpwood €12.44/m^3 Delimbed energy wood €16.81/m^3	(Strandström, 2018b)
Long-distance transportation	Average unit cost 7.1 cents/m^3/km, average transport distance 80 km average transportation cost €5.68/m^3	(Strandström, 2018b)
Chipping	A medium-sized chipper €6.8/m^3	(Rinne, 2010)
Torrefaction and pelletizing	Production costs €9.86/MWh	(Svanberg et al., 2013)
Pellet distribution	€3.01/MWh	(Svanberg et al., 2013)

The net present value (NPV) and internal rate of return (IRR) were used to calculate the required gross margin for each pellet type (Equation 3.4). IRR is the rate of interest that calculates NPV of all cash flows from the bio-coal pellet plant as equal to zero. The annual cash flow consists of the annual energy production *W* and the required gross margin of the bio-coal pellet *R* (€/MWh).

$$NPV = \sum_{t=1}^{T} \frac{W \times R}{(1+r)^t} - I \tag{3.4}$$

Where:

T is number of years; the payback period was set at 20 years
t is time of the cash flow, yearly
r is discount rate
I is investment cost, 45.5 M€ (Svanberg et al., 2013).

The factor *R* was solved from Equation 3.4, and the NPV was equal to zero. The factor *R* was sensitivity analyzed by different discount rates of 5%, 10%, 15%, and 20%. The final price of each produced pellet type was obtained by adding the total supply costs and the factor *R*. Finally, the annual economic impact of the bio-coal pellet plant was obtained by multiplying the final price of the pellet by the factor *W*.

3.3 Environmental impact from the supply chain

3.3.1 Life cycle assessment

An LCA means that it can be used to evaluate the environmental consequences of a product or service. It is a tool to evaluate and identify potential bottlenecks with regard to their environmental performance as well as potential opportunities to improve them. It is considered one of the best methods to identify environmental impacts for the bioenergy industry and it gives the opportunity to reduce them (Cherubini and Strømman, 2011). Other possible methods include Environmental impact assessment (EIA), and GHG Protocol, which is only related to greenhouse gas (Garcia & Freire, 2014). LCA method is valid and has been standardized by the International Organization for Standardization (ISO) (SFS-EN ISO 14040:en, 2006). In accordance with the standard ISO 14040, the LCA study has four phases:

a) The goal and scope definition
b) The inventory analysis (LCI)
c) The impact assessment (LCIA)
d) Interpretation.

The first and at the same time the most important stage of the method, the defining phase of goal and scope, describes the environmental impact and limits of the product system for study. The inventory analysis phase (LCI) takes into account the input and output of the product system in quantitative form. In the life cycle impact assessment (LCIA), the results of the previous phase are evaluated in such a way as to understand and evaluate the extent and significance of the potential environmental impacts of the product system throughout the life cycle of the product. Finally, the interpretation phase of the results compares the impact assessment or inventory analysis or both results with the stated goals and scope. To internalize the matter, the entire process is iterative within and between these four phases. (SFS-EN ISO 14040:en, 2006) The framework for the LCA is presented in Figure 10.

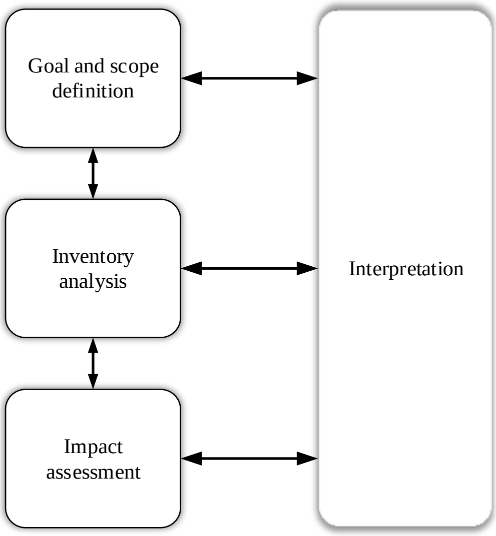


Figure 10: The framework of LCA (SFS-EN ISO 14040:en, 2006).

The LCA is generally case specific and may differ from other studies, even with respect to minor details. Thus, the LCA makes a comprehensive description of the chosen materials, methods, and scope of the study.

3.3.2 LCA of torrefied pellet supply chain

The study had the following wide-eyed assumption: Coal-fired power plants in Helsinki and surrounding regions would soon need a replacement fuel since the authorities are looking for an alternative source of renewable energy. This is where torrefied pellets could be a potential candidate to replace usable fuel in the metropolitan area. The fact is that the Finnish metropolitan area is already facing strict competition for renewable fuel and is also having to be sourced from other regions. On top of that, the South Savo region owns substantial bioenergy resources, but the region lacks a high processing industry of forest biomass, especially with regard to pulpwood processing.

In this study, an LCA was performed comparing GHG emissions from supply chains of torrefied wood pellets made from different tree species. Comparisons were made of the most common tree species in Finland, which were energy wood from birch and pulpwood from birch, pine, and spruce. In this study, energy wood and pulpwood had different diameters measured from breast height: energy wood had 4–6 cm and pulpwood had 6–16 cm (Karttunen et al., 2016). The goal of this assessment was to investigate the impact of using energy wood to make torrefied pellets and to compare them with torrefied pellets made of pulpwood. In order to elaborate the research further, five different logistics alternatives for each feedstock type were assessed.

It was assumed that all the biomass for feedstock originated from the region of South Savo, Finland, and the biomass were torrefied in a hypothetical torrefaction plant (with a capacity of 200,000 tons of pellets/year). After manufacturing, the torrefied pellets transported to a large-scale power plant in Helsinki, Finland, where the pellets were used for co-firing with a coal. In order to compare the difference between the transport of raw biomass and torrefied pellets, one scenario was assessed as the raw material was transported to Helsinki and torrefied in a similar hypothetical plant there. The corresponding locations between Helsinki and South Savo are presented in Figure 11.

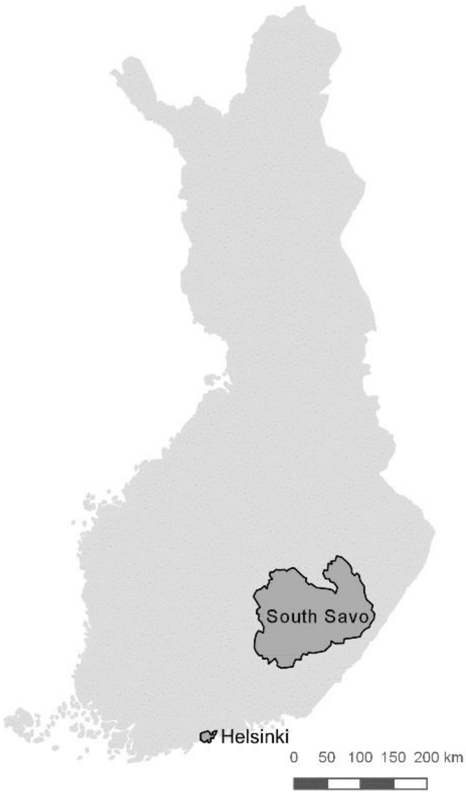


Figure 11: Locations of biomass origin (South Savo) and end use (Helsinki) (Publication IV).

The system boundary started with logging of biomass and forwarding it to a roadside storage. After that, work phases consistent with different scenarios occurred and eventually the torrefied pellet ended up in the power plant's yard. In this assessment, it was assumed that the average truck transport distance was 100 km. However, the biomass logistic scenario through the biomass terminal resulted in a surplus of 20 km for transport. In addition, in the last scenario, where the torrefaction plant was assumed to be in Helsinki, the torrefaction plant and biomass storage were assumed to be located 20 km away from the power plant. A rail transporter was pulled by an electric locomotive and the distance was 300 km in all scenarios. All the supply chain scenarios of the assessment are presented in Table 7. In addition, the schematic flow diagram and the system boundary for each scenario are presented in Appendix A.

Table 7: Supply chain scenarios and their description.

Scenarios	Description
Roadside chipping (RSC)	Harvested wood was chipped at a forest roadside storage point with a mobile drum chipper (diesel-powered) and transported to a torrefaction plant.
Terminal crushing (CRT)	Harvested wood was transported to a biomass terminal and crushed (diesel-powered) there before transporting it to the torrefaction plant.
Crushing at the plant (CRP)	Harvested wood was transported straight to the torrefaction plant and crushed (diesel-powered) there.
Chipping at the plant (CHP)	The same as for the CRP, but the wood was chipped with an electric chipper.
Torrefaction plant in Helsinki (TPH)	Harvested wood was transported to a railway storage point and left there to dry. Then, it was transported to a torrefaction plant in Helsinki and crushed (diesel-powered) at the plant yard.

This study used cradle-to-gate LCA, described as a system that includes beginning inputs and effects resulting from the origin of the raw material and the production phase. It also includes inputs and effects on the gate of the final destination of product usage. In addition, diesel and electricity production emissions were included in the LCA. Similarly, emissions from forest machinery, trucks, crushers, and wheel loaders were included. However, the GHG emissions resulting from the infrastructure such as powerplant production were beyond the scope of the study. Potential emissions resulting from the period of biomass storage were also excluded.

It was assumed that the biomass always dried naturally to 30% MC before the torrefaction process and the ready-made torrefied pellet had 6% MC. The calorific properties of torrefied pellets (see Table 8) were obtained from the results of Publication I. The lower heating values as received ($Q_{net, ar}$) were calculated based on their 6% MC according to Equation 3.5 (SFS-EN ISO 1716:en, 2011).

$$Q_{net,ar} = Q_{net,d} \times \left(\frac{100-M_{ar}}{100}\right) - 0.02443 \times M_{ar} \tag{3.5}$$

Where:

$Q_{net, ar}$ is the lower heating value as received, MJ/kg

$Q_{net, d}$ is the lower heating value as dry basis, MJ/kg

M_{ar} is the MC as received, w-%

0.02443 is the coefficient for the enthalpy of vaporization at a constant pressure and 25˚C, MJ/kg per 1% moisture.

Table 8: Characteristics of torrefied pellets.

Tree Species	**$Q_{net, d}$ (MJ/kg)**	**MC (w-%)**	**$Q_{net, ar}$ (MJ/kg)**	**$Q_{net, ar}$ (MWh/t)**	**Energy production (MWh/y)**	**Bulk density (kg/m^3)**
Birch	19.37	6	18.06	5.02	1,003,401	678
Spruce	18.47	6	17.22	4.78	956,401	699
Pine	19.96	6	18.62	5.17	1,034,212	682
Energy wood	19.15	6	17.85	4.96	991,912	696

The amount of raw biomass needed was calculated based on the assumption that 10% of the initial energy was lost during the torrefaction process. The volumetric ratio of loose to solid biomass was assumed to be 2.5. The detailed LCI is presented in Appendix B. The LCA modeling utilized GaBi Professional (version 8) software with the integrated databases GaBi International and Ecoinvent v3.1. The LCIA was conducted for a sole impact category: the *Global warming potential (GWP) 100 years excl. biogenic carbon dioxide*, based on the CML 2001 (2016) methodology (CML, 2016). The results are presented in the functional unit *kg $CO_{2\text{-}eq}$ per MWh* and *t $CO_{2\text{-}eq.}$ per year.*

4 Results

4.1 Quality analyses of torrefied pellets

The laboratory screenings were carried out on wood chip materials to determine the particle size distribution (see Table 9). The results were determined as an average of three screening tests. The main fraction was classed as P16 for all wood chip materials, and correspondingly, the main fraction was 3.15<P ≤16. In this case, at least 60% of the weight has remained in this screening interval (mm). The fine fraction (< 3.15) was F5–F15, and it was an acceptable result for the success of the torrefaction process. F means the percentage of fine material weight.

Table 9: Particle size distribution of wood chips.

Wood chip material	**Fine fraction**	**Main fraction**	**Coarse fraction**	**Median of distribution (mm)**	**Longest piece (mm)**
Mixed hardwood	F15	P16	-	5.3	80
Birch	F10	P16	-	6.3	70
Spruce	F5	P16	P16	7.1	60
Pine	F10	P16	-	5.5	80
Spruce veneer	F5	P16	P16	7.6	220
Birch veneer	F5	P16	P16	10.3	210

The quality results of wood chips are shown in Table 10. Unfortunately, the study did not get the proper measurements from mixed hardwood chips, because the company had already torrefied all the raw materials of the first chip batch. It is noted in Table 10 that the MC of the wood chips made of coniferous tree species was high. The ash content was low for spruce veneer and birch veneer chips because they did not contain any bark.

Table 10: Quality results of wood chips.

Wood chip material	**MC (w-%)**	**Bulk density (kg/m^3)**	**Ash content (w-%)**	**$Q_{net, d}$ (MJ/kg)**	**$Q_{net, ar}$ (MJ/kg)**	**Bulk energy density, E_{ar} (MWh/m^3)**
Mixed hardwood						
Birch	42.7	312	1.53	19.84	10.33	0.89
Spruce	51.3	310	1.79	18.77	7.89	0.68
Pine	60.5	371	1.37	18.54	5.84	0.60
Spruce veneer	57.4	348	0.29	18.87	6.65	0.64
Birch veneer	45.9	322	0.45	18.91	9.10	0.81

Analyses were also performed similarly for torrefied pellets. The analysis results of the pellet length, diameter, share of fine fraction, and mechanical durability are shown in Table 11. It is noted that the average length of hardwood pellets was the largest. The compression channel had a diameter of 8 mm, and the average diameter of each pellet was close to that value. In addition, pine and spruce veneer pellets had the largest share of fine fractions, up more than 0.8 w-%. Also, the mechanical durability of these pellets was the poorest, at 91.8–92.6 w-%.

Table 11: Analysis of results of torrefied pellets.

Torrefied pellet	**Length (mm)**	**Diameter (mm)**	**Fine fraction (w-%)**	**Mechanical durability (w-%)**
Mixed hardwood	17.06	7.99	0.16	96.6
Birch	10.79	7.95	0.57	97.4
Spruce	10.33	7.99	0.10	96.8
Pine	9.07	7.93	0.85	91.8
Spruce veneer	7.97	7.99	0.81	92.6
Birch veneer	13.11	8.08	0.24	96.8

The visual differences of torrefied pellets are presented in Figure 12. It is noted that pellets made of hardwood were, on average, longer than pellets made of coniferous wood. However, the spruce pellets also were longer than pine and spruce veneer pellets.

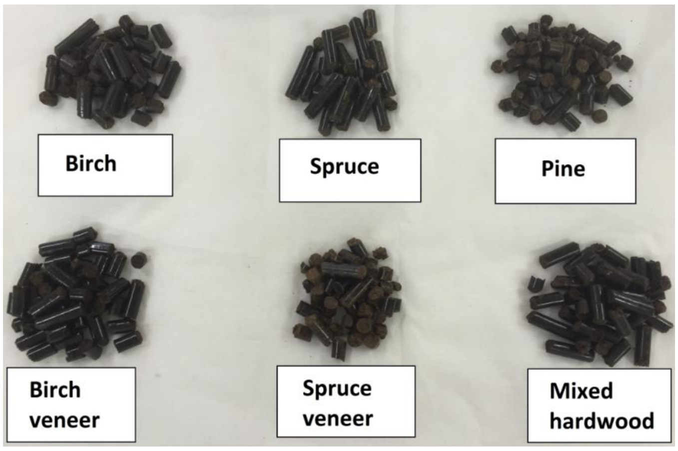


Figure 12: Visual differences of torrefied pellets. Birch pellets had the highest mechanical durability (97.4 w-%) and pine pellets had the lowest (91.8 w-%) (Publication II).

The quality results of torrefied pellets (see Table 12) showed that the MC of torrefied pellets varied between 4.4–8.6 w-%, and the bulk density was close to 700 kg/m^3. In terms of ash content, spruce veneer and birch veneer pellets had the lowest contents due to the absence of bark. Spruce veneer's lower heating value as a dry basis ($Q_{net,\ d}$) was the highest, but the highest MC (8.60 w-%) somewhat decreased its lower heating value as received ($Q_{net,ar}$) relative to other pellets. Mixed hardwood and birch veneer pellets had the highest energy densities (E_{ar}), at 3.61–3.64 MWh/m^3 (bulk).

Table 12: Quality results of torrefied pellets.

Torrefied pellet	MC (w-%)	Bulk density (kg/m^3)	Ash content (w-%)	$Q_{net,d}$ (MJ/kg)	$Q_{net,ar}$ (MJ/kg)	Bulk energy density, E_{ar} (MWh/m^3)
Mixed hardwood	6.57	704	1.31	19.91	18.44	3.61
Birch	6.40	678	1.23	19.37	17.96	3.38
Spruce	4.40	699	1.43	18.47	17.53	3.40
Pine	6.80	682	1.30	19.96	18.43	3.49
Spruce veneer	8.60	649	0.87	20.53	18.56	3.34
Birch veneer	4.98	699	1.16	19.88	18.77	3.64

4.2 Production costs

The production cost analysis was performed for a torrefied pellet plant with a production capacity of 50,000 t/y. The cost structure of torrefied pellets is shown in Figure 13. Raw material was the main cost component, accounting for 56%. After that came variable torrefaction costs (20%), fixed torrefaction costs (14%), and outbound logistics costs (10%). Using Equation 3.1, the average production cost levels of €202/t and €39.5/MWh were obtained with the pellet's lower heating value of 5.1 MWh/t.

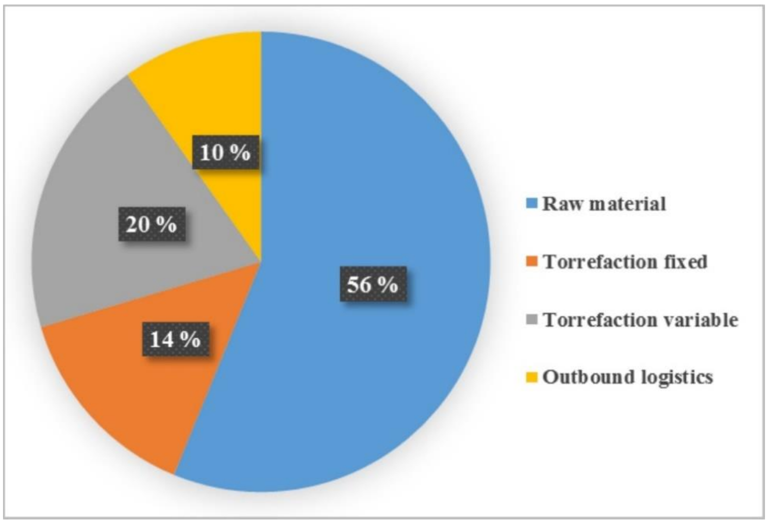


Figure 13: Cost structure of torrefied pellets includes raw material, torrefaction fixed, torrefaction variable, and outbound logistics (Publication I).

The sensitivity analysis of production cost of torrefied pellets with a ±30% variation in cost parameters was performed. Based on a sensitivity analysis, the raw material price had the highest effect on cost competitiveness (Figure 14). Within this broad ±30% variation, the final production cost of the pellets varied by 17% in line with the price of the raw material. However, in accordance with other cost parameters, the production cost of the pellets varied by only 3%. The production cost range was €32.9–46.2/MWh according to the raw material price.

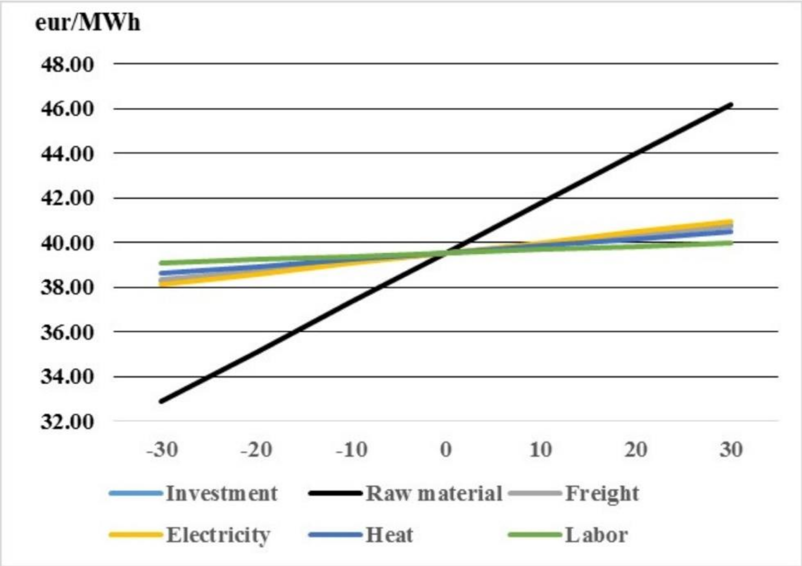


Figure 14: Sensitivity analysis of cost parameters (Publication I).

4.3 Economy of production in bio-coal pellet plant

The study determined on a pellet-by-pellet basis their lower heating values, annual energy production, and raw material need when the plant's production efficiency was 90% (see Table 13).

Table 13: Production information of the torrefied pellets.

Torrefied pellet	**$Q_{net, d}$* (MJ/kg)**	**$Q_{net, ar}$ (MWh/t)**	**Annual energy production (GWh)**	**Raw material need (GWh)**
Birch	19.37	5.02	1,003	1,115
Spruce	18.47	4.78	956	1,063
Pine	19.96	5.17	1,034	1,149
Energy wood	19.91	5.16	1,032	1,146
Average	**19.43**	**5.03**	**1,006**	**1,118**

*MC of pellets (6.0%)

The volumes of raw materials needed from the forest side are listed in Table 14. Table 14 shows the results for the mass and volume of woodchips, and the volume and energy density of solid wood. The annual needed average volume was 596 000 m^3, and the energy density of solid wood was 1.77–1.94 MWh/m^3.

Table 14: The demands of the plant on different raw material types.

Raw material of pellet*	**Mass of woodchips (t)**	**Volume of woodchips (bulk-m^3)**	**Volume of solid wood (m^3)**	**Energy density of solid wood (MWh/m^3)**
Birch	493 000	1 490 000	596 000	1.87
Spruce	497 000	1 501 000	600 000	1.77
Pine	491 000	1 484 000	594 000	1.94
Energy wood	491 000	1 484 000	594 000	1.93
Average	**493 000**	**1 490 000**	**596 000**	**1.88**

*MC as received (51.5%)

Figure 15 shows the total supply costs for different raw wood materials. The cost per cubic meter was converted to megawatt hours by dividing unit cost €/m^3 with the energy density of the solid wood (MWh/m^3). The total supply cost was €33.12/MWh for the birch and spruce pulpwood, €31.54/MWh for the pine pulpwood, and €31.03/MWh for the energy wood.

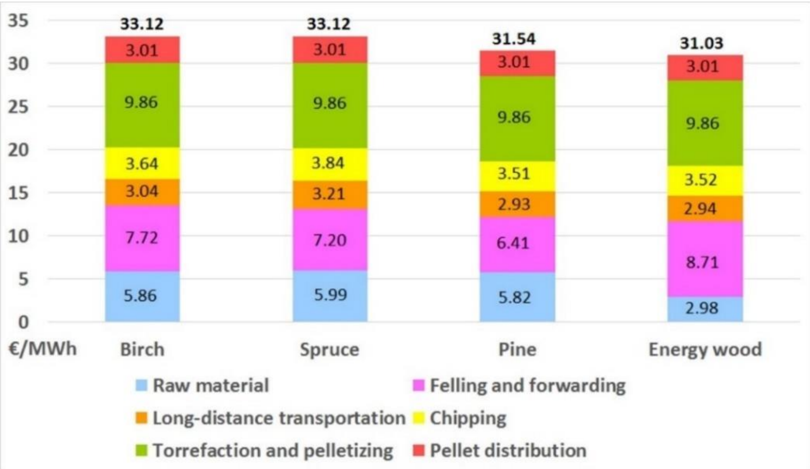


Figure 15: Total supply costs in accordance with raw wood materials (Publication III).

Next, the required gross margins of each produced pellet type were determined, and the results are shown in Figure 16. The plant investment was profitable when NPV ≥ zero euro and IRR ≥ discount rate. These were met, e.g., with a discount rate of 10%, when the gross margin was €5.2/MWh for pine and the energy wood pellets, €5.4/MWh for birch pellets, and €5.6/MWh for spruce pellets.

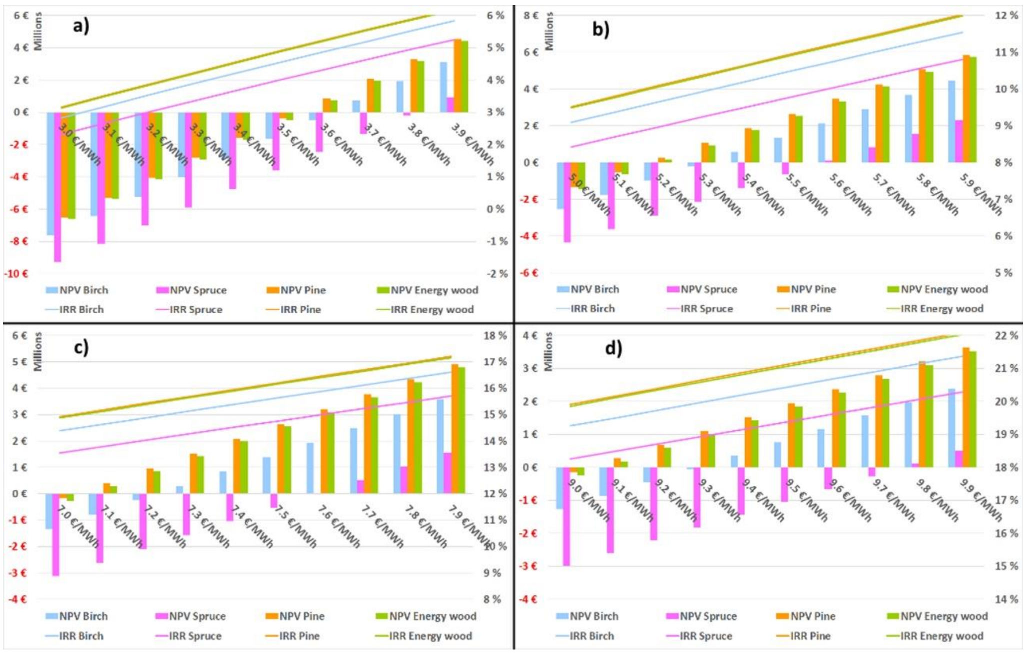


Figure 16: The gross margin at discount rates of a) 5%, b) 10%, c) 15%, and d) 20% (Publication III).

The final prices of each pellet type and the annual economic impact of the plant for the region of South Savo were determined, and the results are shown in Figure 17. Also, these results were presented at the desired discount rates of 5–20%. The results showed that at a certain discount rate the spruce pellets had the highest price and the energy wood pellets had the lowest. A completely different situation was achieved in the annual economic impact, where birch pellets had the highest impact on the region, but spruce pellets had the lowest impact.

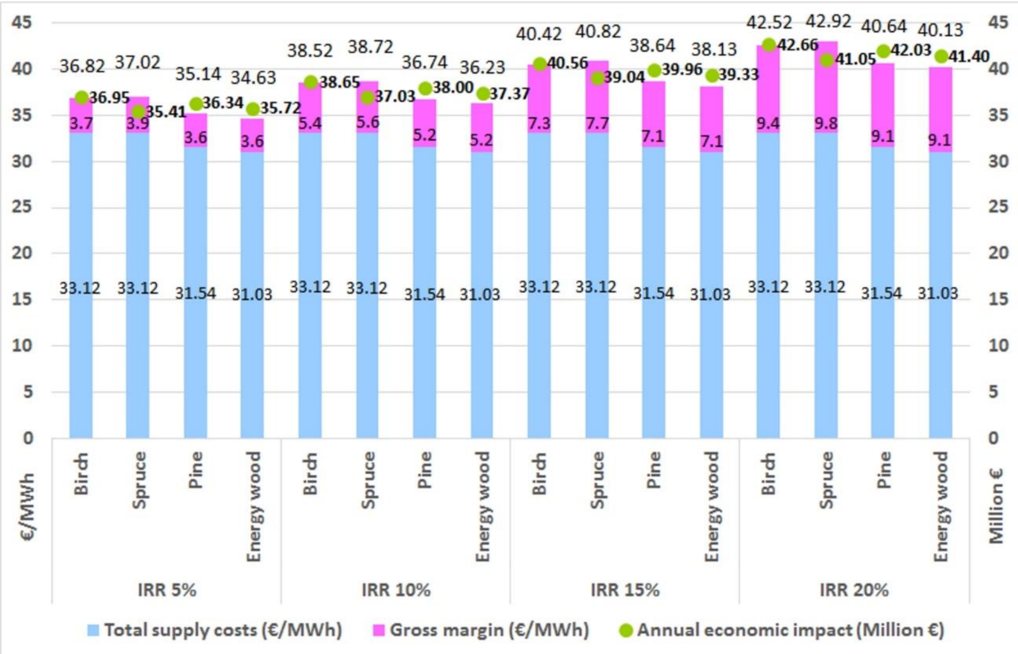


Figure 17: Final prices of the pellet types and the annual economic impact for South Savo (Publication III).

4.4 Emissions from the torrefied pellets supply chain

The last goal of this dissertation was to conduct a comparative LCA. The purpose was to estimate the impact of the heating value of different torrefied pellets on GHG emissions from their supply chains. The comparison included pulpwood from different tree species and also energy wood. The energy wood was included mainly because of comparing emissions as a result of the varying productivity of the output machines. The total GHG emissions from the torrefaction supply chain with respect to the functional units described in section 3.3.2 are presented in Figures 18 and 19.

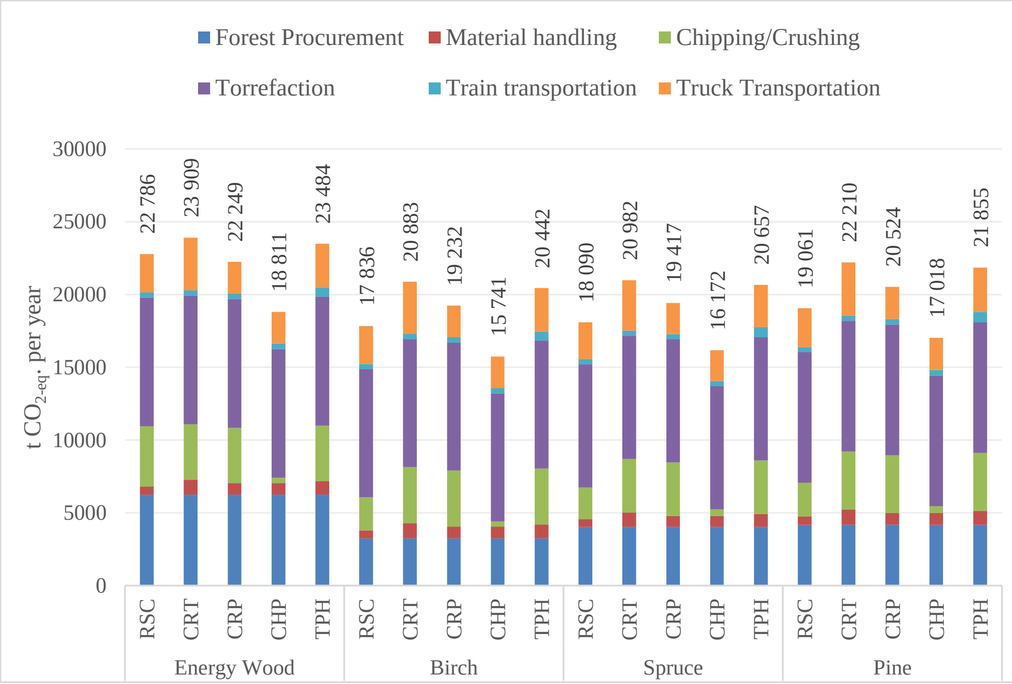


Figure 18: GHG emissions per year for different tree species and supply chain alternatives (Publication IV).

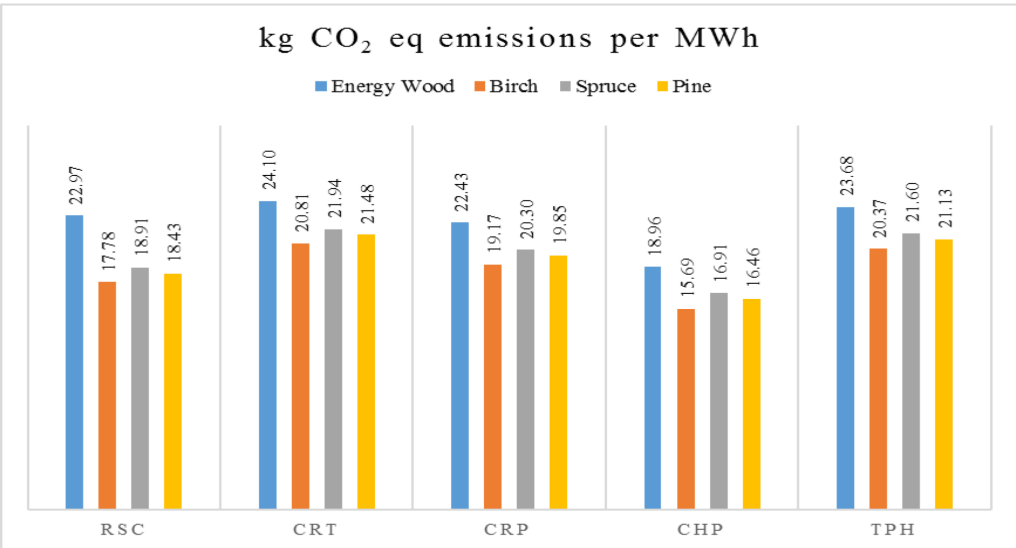


Figure 19: GHG emissions with respect to the heating value of torrefied pellets (Publication IV).

It is noted from Figure 18 that the lowest GHG emissions were caused by the production and supply chain of torrefied birch pellets. Correspondingly, energy wood had the highest GHG emissions. On the other hand, it is noted from Figure 19 that the CHP scenario had the lowest overall emissions per MWh of all the supply chains to be compared. CHP was the scenario, where the wood was chipped in the power plant yard and the chipper was powered by electricity. The lower emissions were caused by the fact that Finland's electricity grid has a relatively lower carbon footprint than, for example, diesel.

The overall results of GHG emissions per year were completely proportional to those of per MWh. The torrefied pellets of birch pulpwood chipped in the plant yard with an electric chipper had the lowest emissions (15.69 kg $CO_{2\text{-eq}}$ emissions per MWh). Correspondingly, torrefied pellets of energy wood crushed at the biomass terminal had the highest GHG emissions (24.1 kg $CO_{2\text{-eq}}$ emissions per MWh). The reasons for the relatively high emissions were additional transport and the use of diesel for the crushing of biomass at the terminal. The distribution of emissions for each phase of all supply chain alternatives and feedstock types are presented in Figure 20.

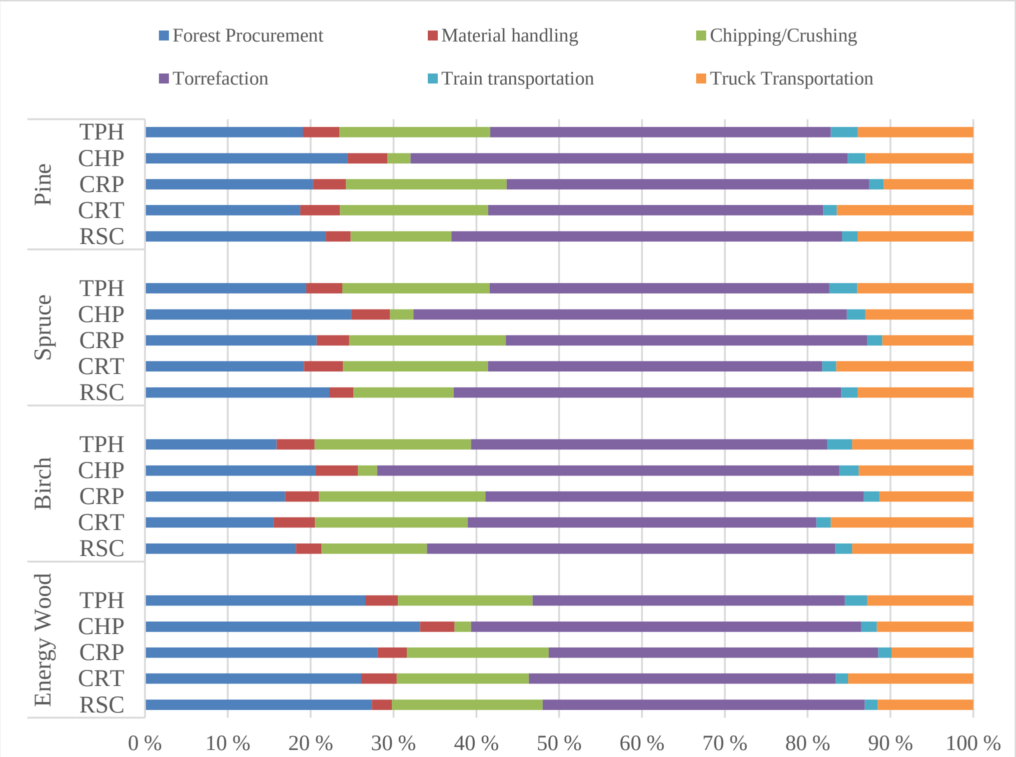


Figure 20: The distribution of emissions from each phase of the life cycle (Publication IV).

The distribution of emissions showed that the torrefaction phase caused the most emissions of all during the work stages in the supply chain. On the other hand, transporting by train caused the lowest share of emissions during the life cycle phases. Nevertheless, the distance of the rail transport was 300 kilometers and it caused minor emissions. This was due to the trains operating on electricity with a low carbon footprint relative to diesel. When the emissions of train transportation were looked at more closely, the TPH scenario had slightly higher emissions for this compared to other scenarios. This was the result of transporting the material as moist raw material to Helsinki instead of torrefied pellets. In addition, the weight of the raw material (MC of 30%) was much higher than that of pellets (MC of 6%). Finally, it is noted that the GHG emissions from forest procurement of energy wood were higher than pulpwood, and it also affected to the total GHG emissions.

5 Discussion

In this dissertation, the main idea was to help increase the potential of a new alternative wood fuel, torrefied pellets, in energy production. Three research hypotheses were presented at the beginning of the dissertation and the purpose of this chapter is to discuss them and offer some answers to them. The first two research hypotheses related to the purchase costs of raw material, and the possible incomplete correlation with the direct regional economy impact and the final price of the torrefied pellet. The last research hypothesis related to the positive effect of upgraded biomass on the reduction of GHG emissions from the entire logistics of biomass. In addition, the purpose of the chapter is to address the reliability of the results and their effectiveness on existing information. Finally, it considers those which remain open questions and which remain unexamined.

5.1 Quality of torrefied pellets

Dissertation examined the production of torrefied pellets in the batches of the ton-scale. Torrefied pellets were manufactured in the pilot plant, which offered the possibility to run the practical tests instead of the small-scale laboratory tests. However, minor problems (moving the mass on the mattress, heat leaks in the process) occurred during the torrefaction phases and were always worked out step by step. An example of one problem was the excessive amount of fine fractions in a torrefaction batch, which was solved by screening the whole material batch. The results of test runs established the whole basis for this dissertation. The properties of torrefied pellets and their raw materials were measured, and their quality properties were classified accordance with the standard “Graded thermally treated and densified biomass fuels” (ISO/TS 17225-8:2016, 2016).

In previous years, higher heating value levels were measured in other studies (Wolfgang, 2012, Kiel, 2013) than in the tests results of section 4.1. For example, Kiel (2013) had measured a heating value as received of 18–24 MJ/kg (MC of 1–5%) and the measurements in this dissertation achieved only 17.5–18.8 MJ/kg (MC of 4.4–8.6%). One explanatory point is the performance of the pelletizing phase in the pilot plant without binders, whereby fluid from the torrefaction phase was used proportionally more abundantly for pelletizing. However, the biggest explanatory point has certainly been the low torrefaction temperature of the pilot plant, from 240 °C to 260 °C, compared to previous studies. In practice, the near-site biomass CHP plant defined the maximum torrefaction temperature, from which the necessary steam was supplied to produce temperature energy in the torrefaction process.

5.2 Production costs

Based on the results of production costs, it can be stated that the raw material purchase for the plant is the largest contributing factor in the cost structure of torrefied pellets. However, the production costs are affected by factors such as the heating value of the wood, the scale of the plant and its location. Wood of less heating value must be purchased more in quantity in order to achieve a certain weight target. In addition, costs are influenced by many other factors in the supply chain, plant operations and pellet distribution, and should always be viewed on a case-by-case basis.

As already noted from the results of the analysis, the raw material was the main cost factor for the total production costs, accounting for 56%. The subsequent costs were variable torrefaction costs (20%), fixed torrefaction costs (14%), and outbound logistics costs (10%). This brings reader to the first research hypothesis that the purchase cost of raw material accounts for the largest share of the cost structure of the torrefied pellet supply chain. In this case, the cost of purchase means the total cost of the raw material acquired for the plant and chipped in advance. The calculation of the production cost analysis had been carried out in line with the conditions in Finland, in which case, the cost basis of the analysis was allocated only for this country. Svanberg et al. (2013) reached similar estimates for the cost structure in their own analysis, but in that case, the purchase share of raw material to the plant was up to 60%. In their study, the production cost of the plant was 31% and the distribution of pellets was 9%, but it should be remembered that their theoretical plant was located in Sweden and had a production capacity of 200,000 t.

The total average cost level was €39.5/MWh with the heating value of 5.1 MWh/t. Of this whole, the share of the raw material purchase to the plant was approximately €22/MWh (56%). On the other hand, in the section 4.3, the total supply chain cost for the torrefied pellets was also determined, resulting in €31.03–33.12/MWh. In this case, the share of the raw material purchase to the plant was approximately €19–20/MWh (approx. 60%) depending on the wood material alternative. Total production costs of various torrefaction plants were also determined in the SECTOR project with results of €34/MWh for an existing sawmill, €38/MWh for a new sawmill, and €33/MWh for a modern pulp mill, alternatively compared to a stand-alone plant at €43/MWh (Arpiainen & Wilén, 2014). Additionally, Svanberg et al. (2013) defined a total production cost of €32/MWh for a large-scale torrefaction plant.

5.3 Economy of production in bio-coal pellet plant

The total capital investment of the bio-coal pellet plant was supposed to be 45.5 million euros based on the study by Svanberg et al. (2013). The plant used young delimbed wood from early thinning as the raw wood material, which is best known as pulpwood. Based on the calculations of this study, the required average pulpwood need was about 596,000 m^3/year. In addition, initial results showed that there were differences in the heating value of pellet products. The heating value was 4.78 MWh/t for spruce, 5.02 MWh/t for birch, 5.16 MWh/t for energy wood, and 5.17 MWh/t for pine. The same internal order remained in the results of the fresh pulpwood (MWh/m^3).

It appeared from the results (Figure 17) that the highest final price was obtained for spruce pellets and the lowest for energy wood pellets, depending on discount rate. The final price was €37.02–42.92/MWh for spruce pellets and €34.63–40.13/MWh for energy wood pellets. Completely different results were provided for the annual economic impact of the region, as the direct effect was highest for the birch pellets (€36.95–42.66 million) and lowest for the spruce pellets (€35.41–41.05 million). A conclusion can be drawn that sold energy volumes were seen to have a great influence on the annual economic impact on the region. These results lead directly to the second research hypothesis that the direct economic impact does not correlate fully with the final price of the pellet. For the most part, the incomplete correlation is due to the different heating value of the pellets. In addition, the energy density of the solid wood (MWh/m^3) affected similarly the overall profitability of the bio-coal pellet plant and its annual economic impact on the region.

It can be concluded from the results that pellet material differences can directly impact the regional economy by up to millions of euros annually. The effect of differences in raw wood materials has remained a somewhat neglected topic, which is somewhat surprising as the heating value of the raw material decisively influences the profitability of bio-coal pellet plants. Previous studies have hardly considered the economic significance of bio-coal pellet plants on the inspection area in which they are located. However, Karttunen et al. (2018) had studied the total regional socio-economic benefits of sawmill and bio-coal plant investments, which were considered from a forest management perspective in the same study region of South Savo. As a result of the study of Karttunen et al., the regional benefits could be 2.8% (€150 million) annually for GDP more than in the BAU scenario (no plant investments at all) by 2030 including multiplier effects. In this case, the results of the direct regional economy will reach the same economic level with the previous study, if they are proportioned with each other.

5.4 Potential for reducing emissions in the supply chain

The results of dissertation showed that torrefied pellets made of small-diameter energy wood (diameter of 4–6 cm) caused considerably higher emissions of GHG (~20%) compared to pulpwood (diameter of 6–16 cm). From a long-distance (300 km) perspective of torrefied pellets, approximately 6% of GHG emissions can be saved by setting up a torrefaction plant close to the raw material source compared to torrefaction near the end users. In this case, rail transport does not need to carry heavy and moist raw material, but alternatively it can transport lighter torrefied pellets.

It is necessary to be careful when inspecting electric trains for long-distance transport, in particular, if raw material crushing or chipping is carried out in the plant yard. Chipping with electric chippers seems to be the most environment-friendly supply chain solution, but in Finland only 11% of biomass is chipped with electric chippers (Strandström, 2018a). Correspondingly, crushing in the biomass terminal before transporting the chips to the torrefaction plant had the highest GHG emissions. The crushing at the terminal caused 17% more emissions compared to the usual roadside chipping solution, depending on the wood material. However, it should be taken into account that there were a limited number of delivery options considered and these results were only indicative.

The amounts of wood chipping at the terminal have increased in popularity in recent years and in this case the proportion of terminal chips compared to chips produced at the roadside has been increasing. Korpinen et al. (2019) had thought that very often the primary motives for using a biomass terminal are other than environmental benefits, such as buffer storage that drives security of supply. Economical motives also encourage the use of the biomass terminal because of the challenging handling of chips at the roadside and the possibility of contamination increases. The previous observations already agree with the latest research hypothesis. Based on the findings presented in the section 4.4, it was possible to assume that the potential for reducing emissions in the torrefied pellet supply chain certainly exists. Potential occurs in different sections of life cycle phases like using different chipping or crushing methods, using alternative supply chain paths, or just using different materials (larger stems). However, the main focus must be on the environmental aspect, which can be verified by using the LCA tool, and better and reliable results will be achieved this way.

5.5 Challenges and limitations

The limiting factor of this dissertation was the production of research results in a batch principled reactor type. Research results were obtained only from a few pilot runs and the entire dissertation was based on these results. The problem may be the number of repetitions in terms of tests in the work. The number of repetitions also has an effect on the reliability of the work. The repetition of the test procedures is an important thing because researchers often faithfully follow the original methods and procedures as closely as possible (Nosek & Errington, 2020). Now in this work, the number of repetitions was not reached, due to the arrangements of pilot tests. The arrangements for the pilot test were difficult to implement and they took a lot of time. Above all, the organization of the pilot tests was quite costly and at each time the wood chip material was purchased through the local forest management association.

When dealing with the torrefaction process, its process temperature was perhaps too low to produce a fully top-quality pellet. The main torrefaction stage was performed between 240 °C and 260 °C and it was not enough to produce a pellet with high heating value. In this work, the torrefied pellets achieved heating value from 17.5 to 18.8 MJ/kg. The limiting factor was the temperature of steam obtained from a nearby biomass CHP plant. In addition, the final MC of torrefied pellets (4.4–8.6%) increased to a surprising degree because the torrefied material had to be moistened with the condensation liquid obtained from the torrefaction process. In the pelleting phase, a large amount of liquid was used, especially for materials that were going to crumble when compressing pellets at high pressure and temperature.

A little more can be speculated with the temperature of the torrefaction process. Wei-Hsin et al. (2011) studied the effect of process temperature on pellet properties. Their conclusion was that the process temperature of 280 °C increased the calorific value of the wood by 40%, but at the same time, the weight loss of the wood was over 50%. Wei-Hsin et al. suggested that a process temperature of 250 °C should be the preferred temperature in combination with sufficient torrefaction time to improve heating value and grindability while avoiding excessive weight loss of wood. In addition, if the process temperatures of torrefaction increase, then there are difficulties in producing a quality pellet in the pelletizing phase that would not crumble sensitively (Stelte et al., 2012). In this case, it is necessary to use more binders or condensation fluids. However, based on the results of dissertation, the pelletizing process will not need an additional binder, but if the pelletizing does not succeed as expected, then binders can be added.

Finally, LCA method was used as a tool in this thesis and there were also some limitations. The LCA includes the goal and scope of a particular study. Besides, determining environmental impacts requires a combination of multiple life cycle phases and it requires many assumptions over the entire life cycle of the product (Cherubini & Strømman, 2011). In addition, it is good to ensure that the collected data is true because the results of the LCA could easily be influenced by manipulating the scope and system boundary (O'Rourke et al., 1996). It may also follow that the problem always moves to the next phase of the life cycle, and in this case the whole of the analysis will not represent reality. The effects would be multiple and could change the results radically. Lastly, the assessment of dissertation was heavily dependent on the Finnish environment, and therefore the results should be interpreted carefully.

5.6 Future work

This dissertation focused on researching the manufacture of torrefied pellets in the pilot plant and the material results extended the subsequent studies to theoretical examinations. Torrefied pellets manufactured at the pilot plant did not quite achieve the expected results in terms of heating value. It might be good to look at a further torrefaction process at higher temperatures that could be implemented on a laboratory scale, for example. Optimization and parametric modeling could also be solutions in the future. In the future, the target temperature for the process could be, e.g., 280 °C, but when temperatures rise, it is important to balance the mass loss of the wood material (Wei-Hsin et al., 2011). Typically, as the process temperature of torrefaction rises close to 300 °C, mass loss also begins to increase rapidly. This issue should be studied even more in order to achieve the right driving parameters for the torrefaction process in the future.

The pilot plant provided important information on the manufacture of larger batches of torrefied pellets. Besides, working at the pilot plant was the key to achieving experiential knowledge from torrefaction and pelletizing processes, and developing process formulas further. Generally, for production plants, the next stage in technology is a continuously operating plant. Moving to this stage still requires further research in the process of continuous operation itself, and the searching of optimal pellet quality.

The results sections 4.3 and 4.4 guaranteed a more theoretical examination in the dissertation and further research also needs to be carried out on their basis. In brief, based on result section 4.3, more research is needed on the basis of differences in heating value between wood materials and the resulting economic impact. In addition, the result section 4.4 addressed only the emissions in the torrefied pellet supply chain, but other alternative supply chains with other materials were excluded from the review. Even more steps could include LCA, such as the use phase, when the effect of combustion could be considered. This would show the bigger picture of the entire supply chain and a more complete analysis can be done.

6 Conclusions

The main aim of this dissertation was to investigate the process technology and production costs of torrefied pellets, and emissions of the supply chain in terms of research. The other goal was to support the increase in bioenergy production based on the forest-based biomass and replacing the imported fossil fuels with a domestic alternative, which is wood-based biomass. This will be achieved when the extent of the results of this thesis is brought forward in the scientific community and public awareness is raised concerning torrefied pellets. At first, the focus was on the test runs in the pilot plant, resulting in the manufacture of various pellets from different raw wood materials. Because of this, the dissertation's base data for the studies was produced at the pilot plant and its test runs. At a later stage, the studies of the dissertation were expanded to deal with the profitability of a theoretical large-scale bio-coal pellet plant and, finally, inspecting the GHG emissions of a torrefied pellet supply chain.

Specific research information on the process of manufacturing torrefied pellets and its costs were achieved through the dissertation work. In addition to this, the costs of the entire torrefied pellet supply chain were also considered, and its results were also obtained. Studies also provided wood-specific information on differences in the calorific values and their effects on the cost of supply and the profitability of the received pellet sales. This dissertation also identified the economic impact of a theoretical large-scale bio-coal pellet plant for the local region. Finally, this dissertation clarified the potential for reducing emissions from the torrefied pellet supply chain.

In this dissertation, the following conclusions can be made based on the results obtained from the studies:

1. At the Finnish cost level, the purchase of raw materials accounts for more than half of the cost of the torrefied pellet supply chain when it includes the raw material price, felling and forwarding, long-distance transportation, and chipping.
2. The highest final price of the torrefied pellets does not guarantee the largest direct economic impact, as one of the main contributing factors is the heating value of the pellets as megawatt-hours.
3. Upgraded biomass has a positive effect on the reduction of GHG emissions from the entire logistic chain, but it depends, among other things, on the chipping and crushing methods, the alternative supply chain paths, and the size class of pulpwood.

The dissertation also had its own main limitations. Research results were obtained only from a few pilot runs, so the difficulty may be the number of repetitions in terms of tests in the work. In addition, the temperature of steam obtained for the torrefaction process was perhaps too low for manufacturing torrefied pellets with a high heating value. A solution to both of these limitations could be the continuation of further research in laboratory tests using a small-scale torrefaction reactor. Finally, based on the dissertation's theoretical studies, more specific research is needed on the basis of differences in heating value between wood materials and the resulting economic impact. In addition, supplementary research is needed on the GHG emissions from the biomass supply chains.

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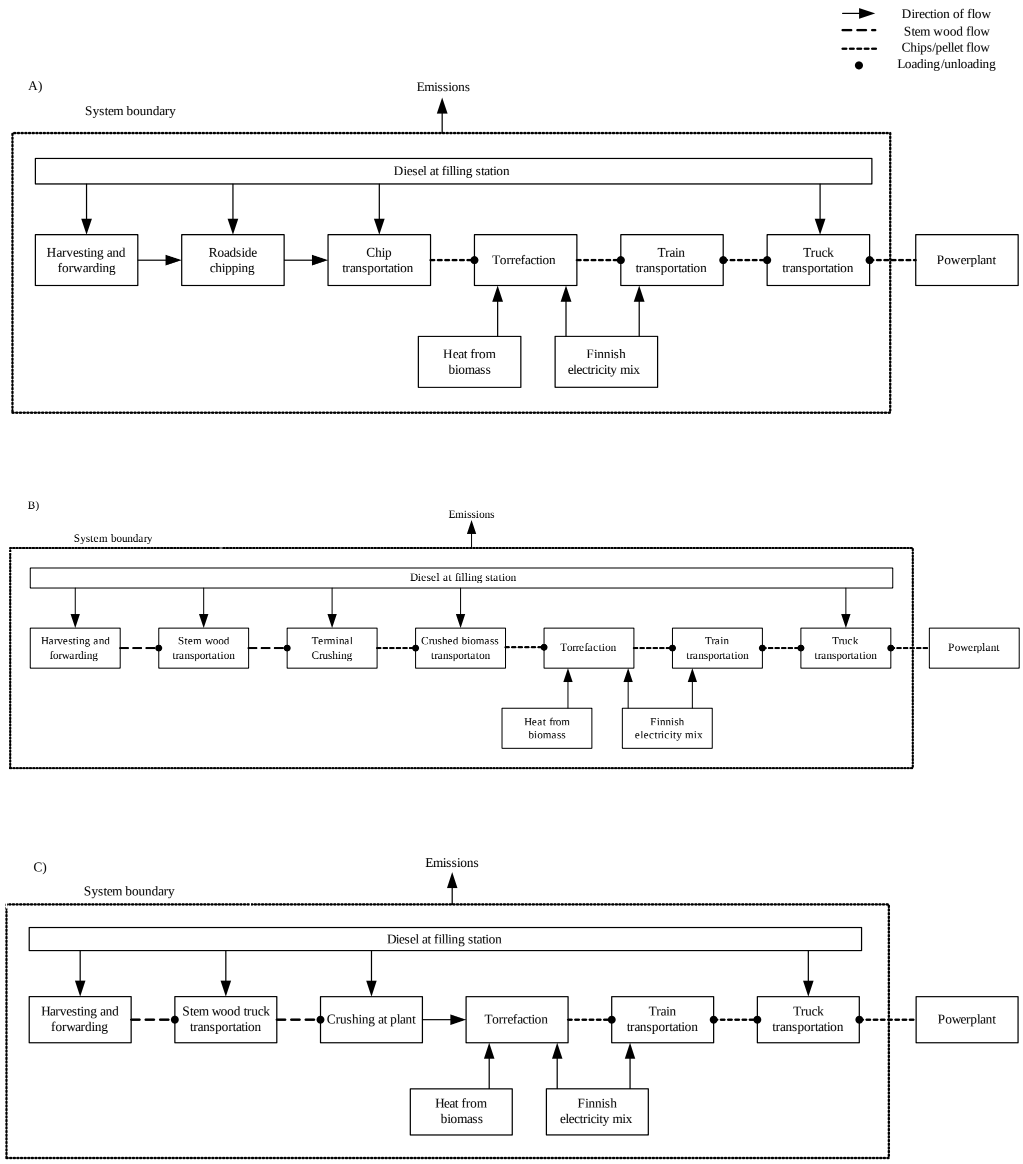
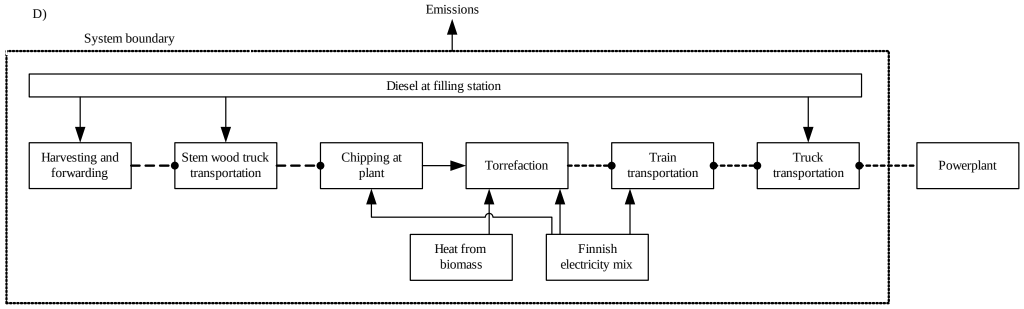
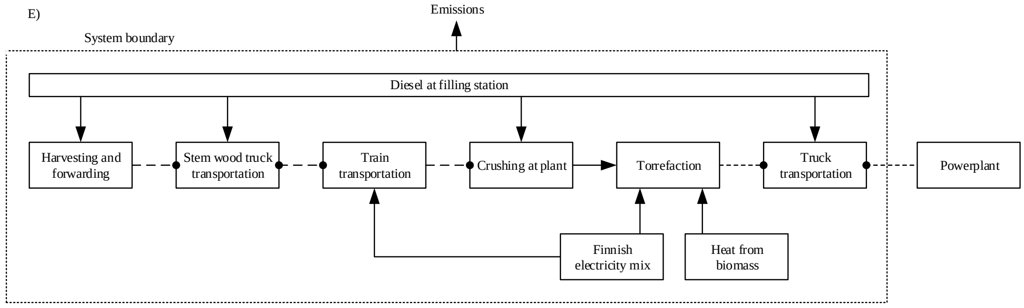
Appendix A: System boundaries for the dissertation




D)
Emissions
System boundary
Diesel at filling station
Harvesting and forwarding
Stem wood truck transportation
Chipping at plant
Torrefaction
Train transportation
Truck transportation
Powerplant
Heat from biomass
Finnish electricity mix


E)
Emissions
System boundary
Diesel at filling station
Harvesting and forwarding
Stem wood truck transportation
Train transportation
Crushing at plant
Torrefaction
Truck transportation
Powerplant
Finnish electricity mix
Heat from biomass

Appendix B: LCI for the dissertation

Unit processes	Description	Reference
Harvesting	Engine size 100 kW * Total weight 14t * Productivities • Energy wood 5.4 solid-m^3/h ¶ • Birch 10.4 solid-m^3/h * • Spruce, Pine 10.45 solid-m^3/h *	* (Werner, 2012b) ¶ (Ovaskainen, 2017)
Forwarding	Engine size 110 kW * Total weight 11t * Productivities • Energy wood 6.8 solid-m^3/h ¶ • Birch 12.3 solid-m^3/h * • Spruce, Pine 12.27 solid-m^3/h *	* (Werner, 2012a) ¶ (Ovaskainen, 2017)
Trucks	EURO 6 Empty return considered Payloads capacity (utilization) • Full trailer-truck 40.6t (100%) • Semi-trailer 24.7t (80–85%)	(GaBi Database, 2011)
Chipping/Crushing	Roadside energy woodchipper * • Weight 19.2 t • Power 475 kW • Productivities ▪ Energy wood 30 solid-m^3/h ¶ High(diesel)-powered conventional roadside pulpwood chipper, emission factor • 9.38 kg CO_2/ton biomass (oven dry) § Stationary electric chipper ∞ • Electricity consumption 1.1 kWh/loose-m^3 of chips Crushing ¶ • GHG emissions 3.46 kg CO_2 eq/MWh	* (Werner, 2012c) ¶ (Ovaskainen, 2017) ∞ (Laitila, Asikainen & Pasanen, 2012) § (Prinz et al. 2019)

Loading/unloading	Logs (grab truck) • Loading 0.05 g CO_2 per $MJ_{biomass}$ • Unloading 0.04 g CO_2 per $MJ_{biomass}$ Chips and pellets (assumed to be same as chips) Loading/Unloading (wheel loaders) 0.03 g per $MJ_{biomass}$	(Jäppinen, Korpinen & Ranta, 2013)
Torrefaction	Energy consumption per kg (dry) • Electricity 0.128 kWh • Process heat 0.339 kWh	(Thrän et al., 2016)
Train transport	• Payload capacity 1,452t • Volumetric capacity $60m^3$/wagon • 24 wagons	(GaBi Database, 2011)
Electricity mix	Electricity production mix (Finland) • Nuclear energy 33.26% • Hydropower 18.1% • Biomass 16.15% • Coal 15.07% • Natural gas 9.57% • Others 7.85%	(GaBi Database, 2011)
Diesel at filling station	GHG emissions • 534g CO_2 per kg of diesel at filling station (EU-28 average)	(GaBi Database, 2011)

Publication I

Ranta, T., Föhr, J., and Soininen, H.

Evaluation of a pilot-scale wood torrefcaction plant based on pellet properties and Finnish market economics

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Evaluation of a pilot-scale wood torrefcaction plant based on pellet properties and Finnish market economics

Tapio Ranta[1], Jarno Föhr[1], Hanne Soininen[2]

[1] Lappeenranta University of Technology, Lönnrotinkatu 7 50100, Mikkeli, Finland.
[2] Mikkeli University of Applied Sciences, Patteristonkatu 3 D, 50100 Mikkeli, Finland.

Abstract
In this study torrefaction was demonstrated at a Torrec Ltd. pilot plant located in Mikkeli, eastern Finland. The pilot plant with a nominal capacity of 10,000 tonnes/year began operation in August 2014. The torrefaction solution was a batch type process based on a vertical reactor, where biomass material flows by gravity without drives or actuators and torrefaction happens by steam inertization and accurate process control. Steam was supplied from the local biomass combined heat and power (CHP) plant next to the pilot plant. The product quality of torrefied pellets was analysed by testing alternative local woody biomass sources, such as forest chips made from coniferous trees (spruce, pine) and broadleaf (birch), as well as by-products such as veneer chips. Lower heating value as dry basis varied 18.47–20.53 MJ/kg with a moisture content of 4.41-8.60% for torrefied pellets. All raw materials were suitable for torrefied pellet production without binder addition. Noteworthy was good results also with hardwood species. The potential Finnish customers are CHP plants aiming to replace coal with pellets. In 2013 coal use was 31.2 TWh, where condensing was 15.3 TWh, CHP 14.2 TWh, and separate heat 1.6 TWh in Finland. If half of the current coal use in CHP would be replaced by biocoal, then Finnish potential bio-coal markets would be 7 TWh or 1.2 million tonnes of pellets/year. Aided by the results of this demonstration study and modelling of logistics it is possible to evaluate the competitiveness of torrefied pellets based on the local circumstances.

Keywords: Torrefaction; Demonstration; Wood chips; Cost analysis.

1. Introduction

1.1 Torrefaction technologies

Torrefaction technology is near the commercialization phase at the moment and there are some 60 companies with technology development and testing programs in process. However, most of the demonstration plants have had technical problems that have delayed their commercial operation [1]. Torrefaction developers are typically small enterprises which are strongly dependent on private investors and public subsidies, but some large process technology companies also have activities in this sector. Several thermal treatment technologies for wood with high-temperature (200–300 ºC) absence of oxygen have been developed and piloted especially in Central Europe. Every reactor technology has specific advantages and disadvantages [2]. There are some 10 demo units and first commercial units, and units in operation and under construction [3]. Thermal treatment of biomass will be executed either by direct or indirect heating. Overall efficiency also depends on heat integration design, in which different options are possible. The nearest commercialization stage among thermal treatment methods are torrefaction and steam explosion processes. Torrefaction can be done either by batch or continuous method, according to torrefaction volumes and space solutions.

Torrefaction technologies vary according to the demands for raw material characteristics, heat transfer, process control, investment and operating costs, and possibilities for dimensioning [4]. Therefore, direct technology commercialization without a piloting stage may be problematic, when the selected method should be adopted and applied to local circumstances and needs. Piloting periods with varying technologies have proven how the feedstock characteristics affect the maintenance of the process control and end-product quality [5]. Naturally, homogenous feedstock with uniform particle size distribution is desirable with most technologies. Feedstock of different type particle size distribution and volume weight needs varying residence times and temperatures in processing and thus customized technology choices [6].

The essential part of the process is pelletizing of torrefied material, since the potential customers are mostly far away and transport economy and material handling efficiency can be optimized [7]. Therefore, torrefied material must be crushed and pelletized immediately after torrefaction. Transport cost will not become such a dominant cost component for pelletized material as with forest chips or other biomass fuels. So far, there are few reports of handling and end-use experiments with torrefied pellets in the public, since there is only a limited amount of material available on the market and operators have not reported all results. However, thousand tonnes of torrefied pellets have been tested and demonstrated by US and European companies, mainly for large scale co-firing with coal. Experiments in Finland have been based on pellet shipments (pellet sacks) abroad or small-scale laboratory testing.

Vattenfall has reported experiments at Reuter's power plant (2x300 MW_e) in Berlin in 2011 and at Buggaeum's power plant (253 MW_e) in The Netherlands in 2013. In addition, pellets made via steam explosion method have been tested at several plants but not reported in public. Experiments with torrefied pellets indicated the challenges of dust during handling, potential problems with smell, durability (non-hydrophobic) and leachate problems (COD) with open storages. Combustion experiments have succeeded very well with high co-combustion shares with coal [8-11]. Additionally, Andriz has reported experiments performed at demo plants in Denmark and Austria (1 t/h), and called for additional research needed to verify pellets as fully marketable [12]. However, uncertainty still exists regarding large-scale production costs, durability, and the necessity of external binding agents.

1.2 Market situation in Finland

So far Finnish biocoal business models are targeted on local markets, not on export on global markets [13]. The primary market for biocoal in Finland is comprised of combined heat and power (CHP) plants aiming to replace coal with pellets. Only this kind of biocoal produced either by torrefaction or steam explosion process offers the possibility to use high mixing percentages (< 50%) with minor investments. Conventional wood pellets can be mixed with 5–7% shares [14]. The readiness to pay from biocoal is dependent on the market price of coal, price of emission allowances, fuel taxes (must be paid only for heating) and other potential incentives such as feed-in tariffs or production subsidies. The incentives vary greatly between countries and there are many exemptions and temporal variation with them. The coal price has decreased during the last years because of recession and decreased energy demand. At the moment, coal is the cheapest fuel in power production (Figure 1).

At the moment only wood fuel used with large-scale CHP-boilers is forest chips. They receive an energy subsidy for power production which is dependent on the price of emission allowances and excise tax on peat. When the price of emission allowances is lower than 10 €/t CO_2, the subsidy is at the maximum of 16 €//MWh and 0 €/MWh when they are higher than 22.7 €/t CO_2. The effect of the energy subsidy on the readiness to pay from fuels depends on boiler efficiency and power-to-heat ratio. Due to this subsidy system the readiness to pay for milled peat and forest chips are slightly better than for coal. But this is targeted at CHP plants (fluidized bed boilers suitable for co-combustion) where all these fuels can be used. At the moment there is no such subsidy system for coal plants (pulverized fuel boilers), because so far there has not been a biocoal market in Finland. This system could resemble the system made for forest chips, but including the excise tax for coal instead of peat in the calculation formula.

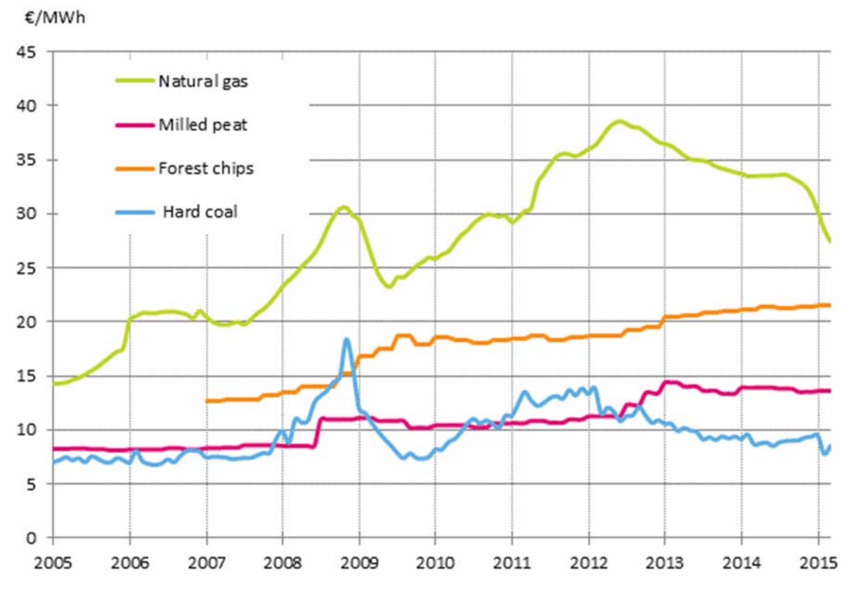

Figure 1. Fuel prices in electricity production in Finland, fuels labelled in descending order (Statistics Finland)

There are no excise taxes for fuels in electricity production, whereas in heat production they have excise taxes which are divided into energy content tax, carbon dioxide tax, and strategic stockpile fee, which is used for imported fuels as coal. The carbon dioxide tax is half for CHP production (Table 1). In 3/2015 the coal price for heat production was 30.31 €/MWh, while the price in power production was 8.50 €/MWh (see Figure 1). It is assumed that the coal market price will decrease to some extent according to futures set on coming months in 2015. The price of emission allowances was 7.50 €/t CO_2 (EUA Spot December 2015, EEX). The emission factor for coal is 94.6 gCO_2/MJ (0.34056 tCO_2/MWh). Thus, the current price of emission allowances constitutes 2.55 €/MWh of additional cost for coal combustion. At CHP plants the magnitude of excise taxes depends on the share of heat produced, since only that part of each fuel from the whole fuel consumption is liable to taxation. Therefore, the higher the share of power is the lower the energy taxation.

Table 1. Energy taxes and stockpile fees for coal (Statistics Finland, Energy prices)

Production mode	Energy content [€/MWh]		Carbon dioxide [€/MWh]		Stockpile fee [€/MWh]		In total [€/MWh]	
	2014	2015	2014	2015	2014	2015	2014	2015
Condensing power	0	0	0	0	0.00	0.00	0.00	0.00
CHP	6.65	6.65	5.96	7.50	0.17	0.17	12.78	14.31
Heat	6.65	6.65	11.93	14.99	0.17	0.17	18.74	21.81

The import of coal depends on rainfall and potential hydro power in Nordic countries, since a lot of rainfall means more electricity import instead of own condensing with coal power plants. Coal consumption has varied during the last decade, being at the maximum level of 9 million tonnes in the dry year of 2003 and lowest in the rainy year of 1999. However, there is a decreasing trend. Almost half of the coal is imported from Russia, while other export countries are South Africa, Indonesia, China, Colombia, Poland and United States.

In 2013 coal use was 31.2 TWh (4.4 million ton), where condensing 15.3 TWh, CHP 14.3 TWh, and separate heat 1.6 TWh in Finland. If half of the current coal use in CHP were replaced by torrefied pellets, the potential annual market would be 7 TWh or 1.2 million tonnes. There are 8 CHP plants, where the biggest user, Helen (energy company of Helsinki), could use 0.5 million tonnes of torrefied pellets on its own, comprising about 40% of the company's current coal use. In 2014 the coal use in Finland was dropped till 26.9 TWh (3.8 million ton).

2. Materials and methods

The target of this study was to evaluate the quality and characteristics of torrefied pellets produced at the Torrec pilot plant. The idea of the pilot plant was that the technologies and operations could be tested before launching the large-scale unit. This information is valuable for the latter stages in the supply chain (storing, handling, transporting, and milling). Co-combustion is beyond the scope in this study. The potential co-combustion market in Finland was also evaluated, as well as preliminary production cost level at full-scale production.

2.1 Pilot plant

Torrec Ltd constructed a pilot plant for torrefaction technology in Mikkeli, eastern Finland, in 2014 (Figure 2). This pilot site contains the whole process, including drying, torrefaction, and pelletizing. The nominal capacity is 10,000 t/a. In practice, the units utilize some 9–10 bulk-m³ of woodchips (approx. >300 kg/bulk-m³) to produce 1.5–2.0 tonnes of torrefied pellets allowing small scale testing by laboratories, and the actual capacity is lower. The torrefaction solution is based on a vertical reactor, where biomass material flows by gravity without drives or actuators and torrefaction occurs by steam inertization and accurate process control. Steam was supplied from the local biomass combined heat and power (CHP) plant next to the pilot plant.

Wood chips were conveyed from chip silo to the torrefaction unit, in which all the phases of torrefaction took place: pre-drying, post-drying, torrefaction, and cooling of solids. The pre-drying stage was performed between 100 °C and 200 °C, eliminating the need for a separate drying unit in the process. The torrefaction unit was dense when in progress in order to keep up the anoxic conditions, but it can be opened when maintaining the equipment. Both processes were run by electricity, and the anoxic conditions were achieved by introducing water vapor into the process to replace oxygen. Water vapor was also used in cooling the biomass after torrefaction to 100° C. After the torrefaction process, the torrefied mass was conveyed to the pelletizing unit, in which water vapor was taken into process in order to control the flammability and explosion risks. It also constrained the dusting of the material. There was a storage silo between the torrefaction and pelletizing unit. In the pelletizing process, torrefied material was crushed, and some moistening with tar liquid obtained from the torrefaction process were injected before pelletizing. After pelletizing, the pellets were packed into flexible intermediate bulk containers, which were big bags (1m^3). At the commercial scale the process is intended to be continuous, with separate drying and torrefaction units.

Figure 2. The pilot plant of Torrec Ltd. in Mikkeli, eastern Finland, which is a batch process where drying and torrefaction occurs inside the same reactor

2.2 Quality analysis of raw material

Forest chips were made of pulp-wood-sized trees felled in March, two months before torrefaction period. The trees were chipped at the roadside by a drum chipper with a sieve (50x60 mm). Each truck shipment consisted of 30 bulk-m^3 assorted wood selection (pine, spruce, birch). The characteristics of chipped and sieved material are presented in table 2. By-products were from the local plywood mills consisting both birch and spruce veneer chips (marked ve in Table 2). The trees were stored to some extent during spring, but still the moisture content was high, especially for pine. The mixed lot were imported from Russia, and consisted mainly of broadleaves such as birch and aspen, but the exact mixture of them was unknown. The ash content was low for spruce veneer and birch veneer chips, because they did not contain any bark. The energy content as a dry and wet basis of both birch assortment were the highest.

Table 2. Properties of chipped feedstock material

Tree assortment	Moisture content (%)	Ash content (%)	Bulk density (kg m^3)	Heating value (MJ kg_{dry})	Heating value (MJ kg_{ar})
Birch	42.7	1.53	312	19.8	10.3
Spruce	51.3	1.79	310	18.8	7.9
Pine	60.5	1.37	371	18.5	5.8
Mixed	52.2	1.44	327	15.5	na
Birch ve	45.9	0.45	322	18.9	9.1
Spruce ve	57.4	0.29	348	18.9	6.7

The particle size distribution was calculated as an average value from three sieving tests (EN ISO 17827-1). The main fraction was classed in P16, when the main fraction was $3.15<P \leq 16$. The fine fraction (< 3.15) was rather high, F15-F25, without separate sieving. There was no difference between tree assortments, since they all were chipped with the same chipper. The reason for a higher fine fraction might be blunt edges. This share of fines was too high for this torrefaction process and all lots were sieved separately after chipping. After sieving the fine fraction dropped to F5-F15 and the share of the main fraction P16 was 90–95% (Table 3).

Table 3. Particle size distribution of raw materials after separate sieving, the size of chips is the median value of the whole fraction.

Tree assortment	Fines	Main	Coarse	Size, mm
Birch	F10	P16	-	6.3
Spruce	F5	P16	P16	7.1
Pine	F10	P16	-	5.5
Mixed	F15	P16	-	5.3
Birch ve	F5	P16	P16	10.3
Spruce ve	F5	P16	P16	7.6

2.3 Quality analysis of torrefied pellets

The product quality of torrefied pellets was analyzed by testing alternative local woody biomass sources, such as forest chips made from coniferous trees (spruce, pine) and broadleaf (birch) and local by-products as birch and spruce veneer chips. The effect of particle-size distribution before torrefaction was analyzed by testing normally drum chipped material versus separately sieved material (EN 15149-1). Energy density, moisture and ash content, and alkalis were verified. In addition, the durability of pellets was verified by means of laboratory tests (EN 15210-1). All tests were done without any additional binder, which provides additional interest as many previous challenges are reported with torrefied pellet quality without binder [1]. Measured quality properties were evaluated according to the EN 17225-8 standards for “Graded thermally treated and densified biomass fuels” [15].

2.4 Production cost analysis

Cost calculation was based on a torrefaction plant annual capacity of 50,000 t. This was a scale-up form the existing pilot-plant. The production and distribution costs of torrefied pellets were divided into three sections: raw material, torrefaction and pelletizing, and storing and transportation to the power plant. Fixed cost parameters to torrefaction comprised investment and annual maintenance and variable cost parameters such as electricity consumption, heat consumption, work load, and binder consumption, if needed. The plant was a stand-alone plant where the biomass boiler was fuelled with the same raw material base as used for torrefaction. The fine and coarse fraction were sieved out and used for heating. Plant location dictated the transport costs of raw material to the torrefaction site and torrefied pellet material to the end-users. It also dictated possible transport modes (road, rail, and waterway) and storing needs between supply and demand sites. Here the potential plant was located inland and the potential pellet customer (co-combustion with coal at a CHP plant) was located in a coastal area and transportation was based on trucks.

Torrefied biomass must be pelletized and pellets are intended for bulk delivery by trucks, reducing the handling, packaging, and consumables utilization in the facility. Storage as torrefied pellets should be less vulnerable to wetting, but outdoor storage should be avoided so the logistics was based on covered solutions during the whole supply chain.

The initial values for calculations were listed in Table 4 and were based on demonstrated torrefaction technology and local circumstances and price levels. Since there were many uncertainties among cost parameters, there was a need for cost sensitivity analysis (raw material price, investment, electricity, heat, workforce, freight). Each parameter was varied using the range of ±10–20–30%. Additionally, the energy content of torrefied pellet was varied from the base value of 5.1 MWh/t using the target value of 5.7 MWh/t.

Table 4. Cost parameters for torrefcaction

Raw material, R_p	20 €/MWh
Raw material economy, η	90 %
Investment, I	6.7 Million €
Maintenance, m	4 %
Electricity, E_c	240 kWh/t
Electricity price, E_p	100 €/MWh
Heat, H_c	615 kWh/t
Heat cost, H_p	25 €/MWh
Work load, L_c	8 person year
Labor cost, L_p	25 €/h
Freight, F_p	20 €/t

Production cost (€/MWh), was calculated by using the equation 1, where costs were divided into above mentioned feedstock, fixed and variable torrefcaction and freight costs. Annuity factor $c_{n/i}$ was defined using lifetime of 20 years and interest rate of 10%.

$$P_{cost} = \left(R_p/\eta + (c_{n/i} * I + m * I + L_p * L_c)/C + (E_p * E_c + H_p * H_c + F_p\right)/Q_{net} \quad (1)$$

where annuity factor, $c_{20/10}$ = 0.1175 and annual production capacity, C = 50 000 t x 5.1 MWh/t

3. Results

3.1 Torrefied pellet quality analysis

According to results of torrefaction test runs done during 28.4-9.6 2015 the lower heating value (as received) varied 17.57–18.77 MJ/kg (4.87–5.12 kWh/kg) with a moisture content of 4.41-8.60%. Lower heating value as dry basis varied 18.47–20.53 MJ/kg (5.13–5.54 kWh/kg) (Table 5). The heating value was a result of raw material characteristic, the torrefaction reactor max temperature, 249-259 °C where max temperature of raw material mattress varied 240-250 °C and residence time 1h36min–2h13min, which typically contained 2-3 separate torrefaction period. Even the weather conditions had an effect to the torrefaction process which was possible only outside the winter period with this pilot facility construction. Now the temperatures varied between 5-9 °C with a windy weather in May and 13-18 °C with a windy and rainy weather in June. Additionally, moistening of the pelletizing process had an effect on torrefied pellet moisture content and heating value. There was no specific differences in heating values between local woody biomass sources used in this study. All raw materials were suitable for torrefied pellet production without binder addition. Noteworthy was good results also with hardwood species like birch and aspen, which offer vast unused resources in Russia. They also offered best mechanical durability among tested samples. The delivered steam from the near-site power plant defined the maximum torrefaction temperature.

According to EN 17225-8, these pellets should belong to property class TW1. Origin and source are stemwood, moisture M8≤8, Ash A2.0 ≤2.0, net calorific value dry Q19≥19, and bulk density BD BD650≥650, diameter D08, (8±1), length L (3.15≤L≤40), fines F1.0≤1.0, mechanical durability DU97.5≥97.5, where numbers define threshold values [15]. Fines and mechanical durability (DU) were measured as w-%. Only the mechanical durability was lower than threshold value. The mechanical durability according to EN 15210-1 was tested also for conventional wood pellets made from pine and spruce sawdust, being 97.9.

Table 5. Characteristics of torrefied pellets

Sample	MC-%	Ash-%	kg/m^3	MJ/kg d	MJ/kg ar	MWh/m^3	L, mm	D, mm	Fines, %	DU, %
Birch	6.40	1.23	678	19.37	17.96	3.38	10.79	7.95	0.57	97.4
Spruce	4.41	1.43	699	18.47	17.53	3.40	10.33	7.99	0.10	96.8
Pine	6.80	1.30	682	19.96	18.43	3.49	9.07	7.93	0.85	91.8
Mixed	6.52	1.41	696	19.15	17.80	3.44	17.06	7.99	0.16	96.6
Birch ve.	4.98	1.16	699	19.88	18.77	3.64	13.11	8.08	0.24	96.8
Spruce ve.	8.60	0.87	649	20.53	18.56	3.34	7.97	7.99	0.81	92.6

3.2 Torrefied pellet production cost analysis

Raw material was the main cost component, at 56%, variable torrefaction 20%, fixed torrefaction cost 14%, and outbound logistics 10% (Figure 3). The average cost level was 202 €/t and 39.5 €/MWh with the energy content of 5.1 MWh/t. The price level was clearly higher compared to the current coal price for heating part in CHP production, 25 €/MWh. If the price of emission allowances were 20 €/t CO_2 instead of the current 7.5 €/t CO_2, then the coal price would rise to 30 €/MWh.

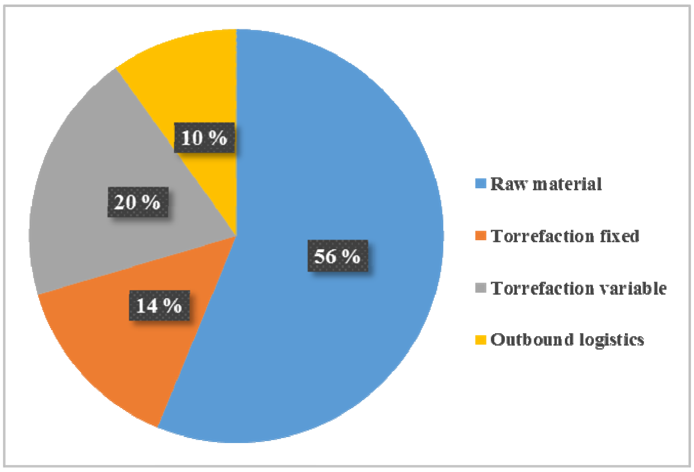

Figure 3. Cost structure of torrefied pellets, %

According to the sensitivity analysis, the raw material price had the highest effect on cost competitiveness. The torrefied pellet price varied ±17% in relation to raw material cost at ±30%, whereas with other parameters the variation was ±3% (Figure 4). The cost range was 32.9-46.2 €/MWh according to the raw material prize. In simultaneous variation with all cost parameters the range was 27.7-51.5 €/MWh.

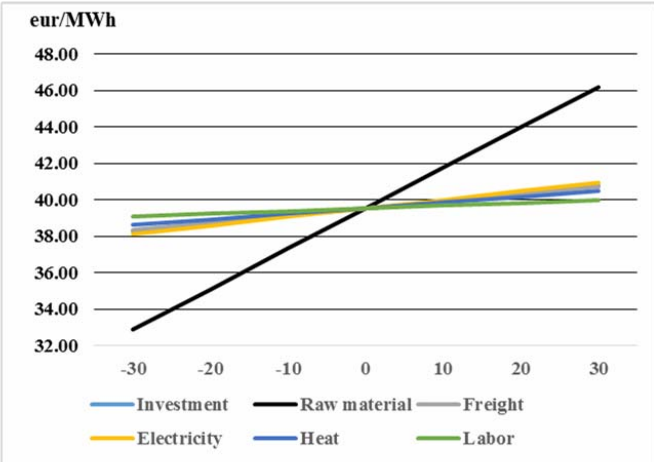

Figure 4. Sensitivity analysis of torrefaction cost parameters

4. Discussion and conclusion

Previous studies have proven higher energy content of torrefied pellets than in the preliminary results of this piloting unit [1]. The reasons for this might be the lower torrefaction temperature, 240-260 °C and torrefied wood moistening practice before pelletizing in the piloting unit. Energy research Centre Netherlands (ECN) reported MC 1–5% and LHV 18–24 MJ/kg [1]. Here the respective values were MC 4–9% and LHV 18–19 MJ/kg. In addition, this study pointed out that the quality of torrefied pellets depends to a large extent on the quality of raw material, and in this case the particle size distribution should be as homogenous as possible and fine particles avoided. The absence of binder was noteworthy, as it typically represents an additional cost with torrefaction. Here, conditioning by steam added to the biomass seemed more adequate for the rather mild torrefaction treatment. However, changes in torrefaction parameters (medium and/or dark torrefaction) may require the utilization of a different binder. Also technological solutions matters, for example the lower durability than expected might be result of the unoptimized feed screw for pellet press because of pilot facility construction and pelletizing without a binder like starch.

The production cost would decrease only to the level of 37 €/MWh with the target value on LHV 20 MJ/kg of torrefied pellets. In this study a sensitivity analysis was made, since torrefaction of biomass on a large scale is a recent concept; there is still a lack of reliable sources for cost estimates. Suppliers of this type of equipment are scarce, and the majority is still mostly in the pilot test stage for their technologies. Depending on the range (± 30%) of cost parameters, the cost can vary between 27–50 €/MWh, where the raw material costs were the most crucial cost parameter in the sensitivity analysis. In previous studies lower cost level has also been reported, e.g. for a 200, 000 t plant, the total supply cost accounts to 32 €/MWh [16]. There the economy of scale could lower the cost level whereas the stand alone plant capacity in this analysis was 50, 000 t. A drawback of higher capacity is the increasing raw material costs if supply areas and transport costs are increased. Another way to decrease cost level is the integration of torrefaction with the forest industry. There the benefits are related to by-product utilization at sawmills or plywood mills, but also to general wood procurement logistics at forest industry plants [17]. In the SECTOR programme the production cost of torrefied pellet was evaluated at the existing sawmill to 34 €/MWh, at a new sawmill 38 €/MWh or at modern pulp mill 33 €/MWh, compared to a stand-alone plant at 43 €/MWh [18].

The cost structure of torrefied pellets got in this study is a rather typical also with larger capacity, as in the 200,000 t study, in which the supply system accounts for 60%, the production cost 31%, and the distribution system 9% of the total cost [16]. With larger capacity the raw material supply costs will be emphasized if material supply is outsourced. It has been also shown that in spite of the fact that economy of scale plays an important role in costs of pre-treatment, there are capacity limits after it won't bring more economical advantage [17].

The main market for torrefied pellets would be pulverized coal-fired power plants, but also other markets as entrained flow gasification and small scale combustion using pellets have been reported [19]. In Finland the main market would be CHP plants, due to better readiness to pay and more even work load compared to condensing plants. The market potential of 1.2 million tonnes would need 6 large-scale 200, 000 t torrefaction units or several smaller ones. Pulverized coal-fired power plants are found in nearly all European countries, with a total capacity of around 200 GW_e or some 1,200 plants. The great majority of these plants are, however, located in Germany, the UK and Poland [17]. This European market is practically unlimited for torrefied pellets, since one 350 MW_e plant needs some 6 TWh of fuel annually when operating full-time at 40% efficiency.

The current fuel costs with coal at CHP plants is 25 €/MWh for heat and condensing plants 11 €/MWh in Finland. If the price of emission allowances rose to 20 €/t CO_2, then the fuel cost for heat would be 30 €/MWh at CHP plants. This is at the same level as the wood-pellet market price of 30 €/MWh, which represents the PIX index price of pellets in the Baltic Sea region. However, wood pellets need additional investments at power plants to be suitable for co-combustion. Due to the price difference, the attractiveness of co-firing torrefied pellets with coal is heavily dependent on national support schemes for renewable electricity generation. This could be a feed-in tariff or similar support mechanism for torrefied pellets to guarantee paying capability for coal-fired power plants above 35 €/MWh so as to make the investments viable. The level of feed-in tariff could be 40–50 €/MWh, depending on the price of emission allowances and excise tax for coal. However, problems with support schemes are posed by possible market disturbances between alternative end-users for the same raw material base.

Finnish new government has decided in 2015 to leave off coal use in energy production by 2030. One practical action would be higher excise taxes and also full carbon dioxide tax instead current half value for CHP production. This may lead to investment trend to pure heat capacity instead of more resource efficient CHP capacity and pure electricity capacity based on carbon free production based on nuclear, wind and solar. Helen (energy company of Helsinki) has already announced this kind of plan to invest pellet boilers and geothermal energy for heat production and solar panels for electricity production. This will increase the share of renewables in Helsinki from the current 7% till 20% by 2020 but still leave a high share of gas and coal based CHP capacity.

Due to promising market prospects in Finland, the next stage in the piloting would be a continuous process with a separate drying and torrefaction unit and own biomass boiler where the torrefaction temperature could be increased. The target value for the LHV would in this case be the before mentioned 20 MJ/kg, which would be nearer the reported literature values [1].

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Publication II

Föhr, J., Ranta, T., Suikki, J., and Soininen, H.
Manufacturing of Torrefied Pellets Without a Binder from Different Raw Wood Materials in the Pilot Plant

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MANUFACTURING OF TORREFIED PELLETS WITHOUT A BINDER FROM DIFFERENT RAW WOOD MATERIALS IN THE PILOT PLANT

Jarno Föhr, Tapio Ranta
Lappeenranta University of Technology
Laboratory of Bioenergy
Mikkeli, Finland

Jemina Suikki, Hanne Soininen
South-Eastern Finland University of Applied Sciences
Department of energy and Environmental Technology
Mikkeli, Finland

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ABSTRACT

This paper concentrated on the production of torrefied without an additional binder from different raw wood materials. The torrefaction and pelletizing was carried out at the Torrec Ltd. pilot plant located in Eastern Finland and its effective capacity was 2,200 tonnes per year. Six different woodchips lots were tested in the pilot runs. The test was to identify whether the pelletizing process requires an additional sealant as a binder. The pelletizing process only exploited condensation water that came about from the torrefaction process. The temperature control range and the holding time were varied, regarding the driving parameters. Finally, quality factors were analysed from torrefied pellets and its raw wood materials after each pilot run. The maximum temperature of the reactor, 260°C, was perhaps too low to manufacture pellets of high energy content. Based on the study, the pelletizing process will not require an additional binder in the future.

KEYWORDS: Torrefaction, pellet, binder, quality, biomass, woodchips.

INTRODUCTION

Torrefaction means a thermo chemical treatment of wood at 200 to 320°C and the process takes place in oxygen free circumstances. At this point, the temperature is high enough to evaporate the water from inside the wood, and then the moisture content (MC) of the wood achieves an almost zero point. Wood is completely dried during the torrefaction and the absorption of water is very minor, when the process is over. The MC varies from 1 to 6 w-%, depending on the torrefaction conditions and the treatment of the product afterwards (Bergman 2005). A torrefied wood pellet is an effortless end product, as the handling and transportation of pellets is economical, whilst, it also has a high energy density of>3.9 $MWh.m^{-3}$ (bulk) (Pöyry 2011). Energy density for regular wood pellet remains significantly less, at only 2.8 – 3.3 $MWh.m^{-3}$ (bulk). As a consequence of these values, the energy content per volume is 20 – 40% higher for torrefied wood pellets than for regular wood pellets. In addition to the high energy density of torrefied pellets, they have a high calorific value of between 20 - 23 $MJ.kg^{-1}$. It is noteworthy that the properties of charcoal are almost the same as the chemical and physical features of torrefied material. Co-firing with torrefied pellets offers the significant additional advantages of using existing coal-fired power facilities, reducing the need for new capital investment, and diminishing greenhouse gas emissions (Wolfgang 2012).

The high temperature of the torrefaction process improves the heating charcoal value of wood. Tab. 1 shows the effect of the torrefaction temperatures on the heating values of wood (Baltic Bioenergy). Wei-Hsin et al. (2011) demonstrated in the study that the process temperature of 280°C increased the calorific value of the wood by 40%. On the other hand, the mass loss of the wood was over 50%. The study proved that a process temperature of 250°C, along with a torrefaction time longer than one hour, was the recommended procedure to improve the value and grindability, at the same time as avoiding too high a mass loss of the wood.

Tab. 1: Typical calorific values for untreated wood, torrefied wood and coal (Baltic Bioenergy 2016).

Material	Processing temperature (°C)	Heating value ($MJ.kg^{-1}$)
Untreated wood		18.0
Torrefied wood	230	18.5
	250	19.0
	280	22.0
Coal		15.0 - 31.0

There is a desire to increase the use of torrefied pellets and to standardize the variable methods, and because of this, there are plans to draft a new product standard in Europe, as well as a worldwide standard in the sector project. The European and International Standard will be developed parallel to each other and the European torrefied pellet will belong, according to the quality criterion, to the EN ISO 17225-8 standard for "Graded thermally treated and densified biomass fuels" (Alakangas 2014a). Tab. 2 shows the quality criterion of torrefied pellets, according to the new product standard. Thermal treatment contains the following processes: torrefaction, charring, steam explosion, and hydrothermal carbonization. All of these processes are more or less contacted to oxygen, heat, water and steam. According to the ISO 16559:2014 standard, a thermally woody treated biomass is defined as a biomass, whose chemical composition has been changed by the effect of heat.

Tab. 2: Quality criterion of torrefied pellets under the new EN ISO 17225-8 standard (Alakangas 2014a). The pellets are divided into three different quality classes.

Property class	Unit	TW1	TW2	TW3
Diameter, D	(mm)	D06, 6 ± 1 D08, 8 ± 1	D06, 6 ± 1 D08, 8 ± 1	D06, 6 ± 1 D08, 8 ± 1
Length, L	(mm)	3.15 ≤ L ≤ 40	3.15 ≤ L ≤ 40	3.15 ≤ L ≤ 40
Moisture, M	(%), as received, wet basis	M08 ≤ 8	M08 ≤ 8	M08 ≤ 8
Ash, A	(%), dry	A2.0 ≤ 2,0	A5.0 ≤ 5,0	A7.0 ≤ 7,0
Mechanical durability, DU	(%), as received	DU97.5 ≥ 97.5	DU96.5 ≥ 96.5	DU95.0 ≥ 95.0
Fines, F	(%), as received	F1.0 ≤ 1,0	F2.0 ≤ 2,0	F2.0 ≤ 2,0
Additives	W(%) dry	≤10, Type and amount to be stated	Type and amount to be stated	Type and amount to be stated
Net calorific value, Q	$MJ.kg^{-1}$, dry	Q19, Q ≥ 19	Q19, Q ≥ 19	Q18, Q ≥ 18
Bulk density, BD	$kg.m^{-3}$, as received	BD650 ≥ 650	BD650 ≥ 650	BD650 ≥ 650

High quality pellets can be produced without an additional binder. Pelletizing after torrefaction requires specialist know-how of the densification of wood mass under high pressure. However, the pelletizing performance is strongly dependent on biomass feedstock and good control of the torrefaction conditions. Without an additional binder, the window for tuning the product quality to logistics and end-use requirements may be small (Kiel 2013).

The mechanical durability of the torrefiedpellets can be similar to traditional wood pellets, depending on the process circumstances and the raw materials. Wood also contains its own natural binder, which is called lignin and can be activated under high temperature. However, the wood's own lignin is not always enough to produce good quality and sustainable pellets. Lignin acts as an important factor in the internal binding of the pellet. Lignin slightly degrades during the torrefaction process, depending on the conditions of process. Manufacturing of the torrefied pellets will require optimization of both the torrefaction and pelletizing processes, when temperatures are increased and high pressures are exerted. Many companies in the field of torrefaction technology are considered to use binders, such as lignin, glycerine, paraffin, molasses, bio-plastics and condensable fractions of torrefaction gas. An injection of water mist prior to the pelletizing process also seems to improve the binding characteristics of the torrefied material. The use of water is subject to intensive research these days (Koppejan et al. 2012).

Finland's most important tree species are Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), as regards to softwoods, and downy birch (*Betula pubescens*) and silver birch (*Betula pendula*), as regards to hardwoods. Most of a tree trunk is comprised of dead woody tissues and they only serve to support the weight of the crown. The actual building materials of wood are cellulose, hemicelluloses and lignin (Vanninen 2009).

A normal wood is typically comprised of 40 – 50% cellulose of the dry weight. Softwood contain less (25 - 30 w-%) hemicelluloses than hardwood (37- 40 w-%). Lignin is often called the cementing agent that binds the individual cells together and gives the mechanical strength. It is known that the lignin content is higher in softwood (27- 30 w-%) than in hardwood (20-25 w-%). Lignin largely consists of carbon, oxygen and hydrogen, which are elements of heat generation. In addition to the main building materials, wood also includes extract substances (<5 w-%), such as phenols, lipids, and terpenes (Alakangas 2000, McKendry 2002).

In this study, torrefied pellets were manufactured in a pilot plant, which was established by the company Torrec Ltd. located in Eastern Finland (Torrec Ltd. 2016). The pellet plant began pilot operations since August 2014. This one tonne-scale pilot plant of torrefied pellet offered the possibility to run a practical test, based on local biomass resources, for the first time in Finland. So far, the examinations have been based on small-scale laboratory tests or imported material batches from abroad. The pilot plant was a key factor in order to plot the properties of the raw wood materials and torrefied pellets. In addition, the suitability of the pellets to parallel firing in a coal plant was an encouraging issue for the establishing of the pilot plant. Because of this, the technologies and process control were possible to test in the pilot plant before launching the large-scale unit. Torrefaction technology has not yet been commercialized in a large-scale. The results will be very important for Finland, as there are plans to set up a commercial-scale (200 000 tonnes/year) bio-coal production plant in Eastern Finland (Nurminen 2012). Prospective Finnish customers are regional combined heat and power (CHP) plants who mean to replace a certain share of fossil coal with bio-coal pellets. The potential bio-coal market in Finland could be about 7 TWh or 1.2 million tonnes of pellets per year (Ranta et al. 2016).

The main purpose of this paper was to analyse the properties of torrefied pellets manufactured from different raw wood materials and in different conditions. All of the pellets were produced without an additional binder in the pilot runs, which was the main theme of this paper. The pelletizing process only used condensation water, which came through the torrefaction process. The qualities of the manufactured pellets were compared, when they were produced from different raw wood materials, and the temperature and the retention time were varied, regarding the driving parameters. In this case, the quality factors of the pellets meant the bulk density, moisture content, ash content, pellet length and diameter, mechanical durability, calorific values, and energy density per volume. In addition, some other quality factors, such as the particle-size distribution, were analysed from the beginning by using moist woodchips. Other purpose of this paper was to obtain accurate quality information on torrefiedpellets and its raw materials. This paper highlights the novelty of the present process and its profitability for the bio-fuel industry in general and specifically for the pellet producers.

MATERIAL AND METHODS

Material

The production plant of the study solely used wood chips as a raw material, which was suitable for the torrefaction process. Six different wood chip materials were used in the study. The wood materials used in the pilot runs were obtained from hardwood species as birch and softwoods as spruce and pine. These wood chips were made of pulp-wood-sized trees felled in March, two months before the pilot runs. The fourth lot of mixed hardwood chips were imported from Russia, and consisted mainly of hardwood species, such as birch and aspen. Also, birch veneer chips and spruce veneer chips from a plywood plant were tested. The particle-size of those veneer chips was slightly higher than the previous wood chip materials and they did not contain any other bark, like woodchips.

It was found that a large share, F20 – F25, of fine fraction (<3.15mm) caused problems for the torrefaction process at the beginning of the pilot runs. Fine fraction caused a varying of the quality of the pellets and, therefore, the calorific values and other values may remain low. The reason for a high share of fine fraction might be the blunt edges of a mobile chipper. A decision was made to screen the pulp-woodchip material from fine fraction, which helped to improve the quality of the pellets before the pilot runs. The mobile screening with Keestrack Combo (Keestrack Croup 2016) was a key factor in obtaining a good quality pellet in a pilot plant of this size. Also, other woodchip materials were screened before deliveries from the starting point to the pilot plant.

All of the torrefied pellets were done without any additional binder, like a tall oil, which ensures an additional advantage, as many previous challenges (Kiel 2013) were reported concerning the torrefied pellets quality without a binder. The pelletizing process always requires some moistening liquid to facilitate the producing of pellets. The pelletizing process now utilised condensation water obtained from the torrefaction process.

Methods

Pilot plant

The pilot plant for torrefaction technology was constructed by the company Torrec Ltd. The plant was located in Mikkeli, Eastern Finland and started operations since August 2014. This pilot site contains the entire process, including the drying, torrefaction, and pelletizing. The effective capacity was 2,200 tonnes per year. In practice, the units produce tonnes cale batches, allowing representative logistics and end-use performance testing by industry, and the actual capacity was lower. The entire pilot plant was a batch principled production plant. Normally, about 9 – 10 m^3 (bulk) of woodchips (approx. >300 $kg{\cdot}m^{-3}$) were input into the process, resulting about 1.5 – 2.0 tonnes of torrefied pellets. This pellet amount was always similar to the pilot plant runs in this study. The technology of torrefaction was based on a vertical reactor. In the process, woodchips flow due to the influence of gravity without drives or actuators. Torrefaction occurs through steam conduction to a steam radiator and by exact process control. The torrefaction process received its heating power from steam, which was directly conveyed from the regional CHP plant, which was located next to the pilot plant.

Process

At the beginning of the process, woodchips are moved from a raw material pit to the torrefaction unit via a screw conveyor (Fig. 1). The phases of the torrefaction process take place in the torrefaction unit: pre-drying, post-drying, torrefaction, and the cooling of solids. The pre-drying stage was carried out between 100°C and 200°C, therefore, there was no need for separate drying unit in the process. The pre-drying stage was performed for woodchips in order to remove the free water (above 30%) from the wood. Thereafter, the main torrefaction stage was performed between 240°C and 260°C. The time for the torrefaction stage varied normally between 1.5 – 2.0 hours. Due to the high torrefaction temperatures, the pulling out of wood from the torrefaction unit required a cooling of the wood before pelletizing. There was a storage silo between the torrefaction and pelletizing unit, where in the final cooling takes place.

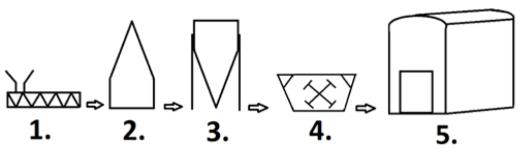

Fig. 1: The process sketch: screw conveyor (1.), torrefaction unit (2.), storage silo (3.), hammer mill (4.) and pelletizing hall (5.).

The torrefied wood mass was conveyed to the hammer mill, wherein the wood was crushed after the torrefaction process. The hammer mill had a 5 mm of screen mesh, but a part of the fraction was of a very small particle size, due to torrefaction. Finally, the crushed wood mass was conveyed to the pelletizing hall (Fig. 2). The crushed wood was slightly moistened with condensation water obtained from the torrefaction process before pelletizing. The used amount of water in one pilot run varied between 100 – 150 litres, depending on the success of the pelletizing. The purpose of moistening was to reduce the friction in the pelletizing process and to bind the material. A pellet squeezer was Munch RMP 650 and its capacity was 220 kW. The squeezer always operated at full power and the used amps were twice 145 – 165A. The crushed wood mass was pushed through a perforated iron matrix (Fig. 3). The essential part of the matrix was the 65 mm length compression channel, into which the wood mass was fed continuously more during the pelletizing. After pelletizing the pellets was screened of most of the fine particles and packed into large flexible bags (1 m^3), which had been made of polyethylene.

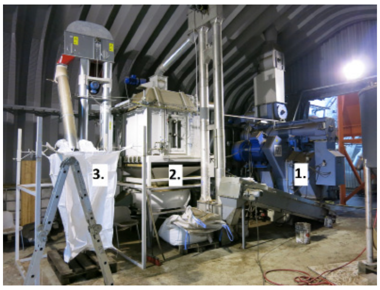

Fig. 2: The pelletizing hall, wherein were the pelletizing unit (1.), screening unit (2.) and bagging unit (3.).

Fig. 3: Iron matrix, which was used in the pelletizing process.

The torrefaction reactor was airproof during the process, in which case there were anoxic conditions. On the other hand, hatches can be opened for maintenance purposes. The water vapour was used to achieve the anoxic conditions in the heating process with the intention of replacing the oxygen. In addition, the torrefied wood material cools to the low temperature of approx. 100°C, by water vapour after torrefaction. After this process, the torrefiedwood material was moved to the crushing and pelletizing process. The pelletizing phase contains flammability and explosion risks, when the water vapour is also put into operation. The water vapour also prevents the dusting of the wood. All processes received their motion power from electricity. The next step of this technology is a commercial scale, in which the process will be continuous. The entire process is then built of separate drying and torrefaction units.

Pilotplant runs and schedule

All of the pilot plant runs were carried out during May and June 2015 and only the mixed hardwood chips lot imported from Russia was carried out during November 2014 of the previous year. The final laboratory analysis was finished in July 2015. All of the important process times and temperatures are presented in the Tab. 3. Peng et al. (2013) reported in their own study that a suitable torrefaction condition is a temperature of 250 to 300°C, with a mass loss of about 30%.

Tab. 3: Torrefaction process times and temperatures.

Woodchip material	Total time (h:min)	Max. temperature of reactor (°C)	Max. temperature of biomass bed (°C)
Mixed hardwood	1:36	254	247
Birch	1:36	259	250
Spruce	2:08	249	240
Pine	1:42	259	252
Spruce veneer	1:51	255	246
Birch veneer	2:13	257	250

It can be said that the torrefaction process was always started from a temperature of 160°C during the pilot runs. The torrefaction time was, in practice, the time interval, when a steam valve was fully opened and closed. A length of less than two torrefaction hours were carried out on two separate runs and these higher times called for three runs. The length of each run was approx. 40 – 50 minutes. The maximum temperature of the reactor was measured with a temperature sensor, which was located between the steam radiator and the chips mattress. The maximum temperature of the biomass bed was measured on the upper surface of the bed.

Sampling and laboratory tests

Sampling was performed in the same manner for both moist woodchips and final pellets. Sampling followed the general standards: SFS-EN 14778: en (2012) and SFS-EN 14780:en (2012). Every sample was taken and placed in a lidded bucket from each batch during the pilot runs. All of the buckets were stored in a cold room at 5°C before the laboratory tests.

The particle size distribution, bulk density, MC, ash content, length and diameter of pellets, mechanical durability of pellets, calorific values, and energy density per volume were tested from each sample material within the laboratory. However, not all of the above mentioned analyses were performed for the test materials, depending on the suitability of the material and the test.

The test materials were analysed, according to the following standards of solid bio-fuels: SFS-EN ISO 17827-1:en (2015), SFS-EN ISO 17828:en (2015), SFS-EN ISO 17829:en (2015), SFS-EN ISO 17831-1:en (2015), SFS-EN ISO 18134-1:en (2015),SFS-EN ISO 18122:en (2015).

The calorific values (SFS-EN ISO 1716: en 2011) and energy density per volume (Alakangas 2014b) were estimated values.

RESULTS

Woodchips

The share of fine fraction was rather high with the pulpwood chips at F20 – F25 before mobile screening. After screening, the fine fraction dropped to F5 – F10 (Tab. 4). The share of fine fraction was also small in other pre-screened woodchip materials at F5 – F15. The main fraction was classed in P16 for all woodchip materials, when the main fraction was $3.15 < P \leq 16$.

Tab. 4: Particle size distribution of woodchips.

Woodchip material	Fine fraction	Main fraction	Coarse fraction	Median of distribution (mm)	Longest piece (mm)
Mixed hardwood	F15	P16	-	5.3	80
Birch	F10	P16	-	6.3	70
Spruce	F5	P16	P16	7.1	60
Pine	F10	P16	-	5.5	80
Spruce veneer	F5	P16	P16	7.6	220
Birch veneer	F5	P16	P16	10.3	210

The quality results of woodchips are presented in the Tab. 5. The woodchips would have now been too old to be analysed after the entire pilot runs. The enclosed Tab. 5 shows that the MC was high, especially for coniferous tree species. The ash content was low for spruce veneer and birch veneer chips, because they did not contain any bark. The energy content (Qnet, d), as a dry basis of both birch species, was the highest.

Tab. 5: Quality results of woodchips.

Woodchip material	Moisture content (w-%)	Bulk density ($kg.m^{-3}$)	Ash content (w-%)	LHVa Qnet,d ($MJ.kg^{-1}$)	Qnet, ar[b] ($MJ.kg^{-1}$)	Ear ($MWh.m^{-3}$) (bulk)
Mixed hardwood						
Birch	42.7	312	1.53	19.84	10.33	0.89
Spruce	51.3	310	1.79	18.77	7.89	0.68
Pine	60.5	371	1.37	18.54	5.84	0.60
Spruce veneer	57.4	348	0.29	18.87	6.65	0.64
Birch veneer	45.9	322	0.45	18.91	9.10	0.81

[a]Lower heating value (low)

[b]Net calorific value as received, contains moisture

Torrefiedpellets

The measurement results of the pellet length, diameter, and share of fine fraction and mechanical durability are presented in the Tab. 6. Tab. 6 shows that the average length of hardwood pellets, as mixed hardwood and both birches was the largest. The screen of the pellet unit had a diameter of 8 mm, so all the pellets were close to that value. Pellets made of pine woodchips and spruce veneer chips had the largest share of fine fractions, at more than 0.8 w-%. Also, the mechanical durability of these pellets was the poorest, less than 92.6 w-%. Rudolfsson et al. (2015) indicated that the process window to optimize the pellet strength was narrow and, surprisingly, somewhat higher MC at higher degrees of torrefaction increased the strength of crush of the pellets. On the other hand, Shang et al. (2013) reported that a negative influence was found for the pellet strength when the MC was beyond 5%. The pellets are shown in the Fig. 4.

Tab. 6: Results of pellet length, diameter, and the share of fine fraction and mechanical durability.

Woodchips material	Length (mm)	Diameter (mm)	Fine fraction (w-%)	Mechanical durability (w-%)
Mixed hardwood	17.06	7.99	0.16	96.6
Birch	10.79	7.95	0.57	97.4
Spruce	10.33	7.99	0.10	96.8
Pine	9.07	7.93	0.85	91.8
Spruce veneer	7.97	7.99	0.81	92.6
Birch veneer	13.11	8.08	0.24	96.8

Fig. 4: The pellets which were made of different wood species.

The quality results of torrefied pellets are presented in the Tab. 7. The enclosed table shows that the MC of pellets varied between 4.4 – 8.6 %. The bulk density of all pellets was close to 700 kg.m^{-3}. Spruce veneer had the lowest bulk density 649 kg.m^{-3}.

In the case of pellets and also woodchip materials, the ash content was low for spruce and birch veneer chips, because they did not contain any bark. The energy content as a dry basis (Qnet, d) was the highest for spruce veneer, but the highest MC (8.60 w-%) decreased some its energy content as received (Qnet, ar). The energy content as received was the highest for spruce and birch veneers. However, the low bulk density decreased the spruce veneer towards the worst, as regards the energy density (Ear). Mixed hardwood and birch veneer had the highest energy densities, more than 3.6 MWh.m^{-3} (bulk).

Tab. 7: Quality results of torrefied pellets.

Woodchip material	Moisture content (w-%)	Bulk density (kg.m^{-3})	Ash content (w-%)	LHVa Qnet,d (MJ.kg^{-1})	Qnet,ar^{b} (MJ.kg^{-1})	Ear (MWh.m^{-3}) (bulk)
Mixed hardwood	6.57	704	1.31	19.91	18.44	3.61
Birch	6.40	678	1.23	19.37	17.96	3.38
Spruce	4.40	699	1.43	18.47	17.53	3.40
Pine	6.80	682	1.30	19.96	18.43	3.49
Spruce veneer	8.60	649	0.87	20.53	18.56	3.34
Birch veneer	4.98	699	1.16	19.88	18.77	3.64

^{a}Lower heating value (low)

^{b}Net heating value as received, contains moisture

DISCUSSION

The whole plant was a batch principled production plant and it solely used woodchips as a raw material or feedstock. The pilot project runs were performed with various raw wood materials and some altered driving parameters in the study. After each test run, quality factors were defined from woodchips of beginning and final products.

The studies of the previous years (Wolfgang 2012, Kiel 2013) have proven a higher energy content of torrefied pellets than in the analyse results of these pilot project runs. Kiel (2013) has reported a MC of 1 – 5% and energy content as received of 18 – 24 MJ kg·m^{-3}. In this study, the respective values were 4.4 – 8.6% and 17.5 – 18.8 MJ kg·m^{-3}. The main torrefaction stage was performed between 240°C and 260°C. That temperature range was perhaps too low to manufacture pellets, in which would have extremely high energy content. The delivered steam from the near-site biomass CHP-plant defined the maximum torrefaction temperature. An additional reason for the lower energy content of pellets may have been the moistening of pellets with condensation water during the pelletizing process.

The raw material chips had energy content as received from 5.8 to 10.3 kg·m^{-3} at the beginning of the torrefaction process, so the energy content of pellets had obtained a huge improvement. All woodchip materials were classed in the P16 category, as regards the main fraction. The share of fine fraction was small in woodchip materials at F5 – F15 after the separate screening. The small share of fine fraction was an important issue in the production of top quality pellets in this pilot plant. Otherwise, the fine fraction can form obstructions to the chips mattress and cause a varying quality of pellets. The quality issue will not be a problem in a continuously operating plant, where all the entire fine fraction will be burned during the process.

The average length of hardwood pellets as mixed hardwood and birch veneer was the largest. Also, these pellets had the highest bulk and energy densities at more than 3.6 MWh·m^{-3} (bulk). The energy density is the main numerical value, which best describes the energy quality of pellets. So, it can be concluded that hardwood was the best raw wood material to produce torrefied pellets at this pilot plant. In addition, the experiences of pelletizing process indicated that hardwood material pelletized better than softwood material. All torrefied pellets were done without any additional binder, like a tall oil, which ensures the special advantage of avoiding the additional costs of a binder in the future. Condensation water obtained from the torrefaction process was the only binder in the pelletizing process. So, basically, the pilot plant was a closed circulation system.

Based on the study, the pelletizing process will not need an additional binder in the future. Only the mechanical durability of pellets made from softwoods was low, less than 92.6 w-%, in which case the pellets fail to reach the minimum requirement (≥95 w-%) of the prospective EN ISO 17225-8 standard (Alakangas 2014a). It would be necessary to use an additional binder to manufacture durable torrefiedpellets from softwood. Otherwise, all the quality requirements regarding the above-mentioned standard were achieved under all woodchip materials. If there is a need to use the additional binders, then sawdust could be a brilliant raw material as a binder. Peng et al. (2015) indicated, that since raw sawdust is abundantly available and much cheaper than lignin and starch, it is recommended as a low-cost and effective binder.

CONCLUSIONS

The manufacture of torrefiedpellets without an additional binder should be tested more in order to learn new aspects about the difficulty of pelletizing and the durability of pellets in the long term. Normally, as the temperatures of reactor are increased, the quality of pellet may then weaken. When considering test runs in the future, the small-scale laboratory runs with a small reactor could be somewhat suitable for testing the benefit of the manufacture of torrefied pellets without a binder. By this procedure, the study would achieve both various test repetitions and be more dependable. The weakness of this study was the repeatability of pilot runs, which was difficult to realize. The arrangements for the pilot project runs were difficult to implement, time-consuming and costly. Additionally, it would have been useful to carry out pilot production runs at higher process temperatures. The maximum temperature was now only 260°C, due to the steam of the CHP-plant.

The pilot plant was the key to achieve experiential knowledge from torrefaction and pelletizing processes. In addition, the small problems that occurred in the process during the pilot runs can be solved, when the next step towards the continuously operating plant is taken. This step will be the next move, whilst the correct formulas for producing a top quality pellet are now known better. The best energy quality pellet will be formed when the woodchips are torrefied at close to 280°C at first. Then, the consisting pellet will receive high energy content as received, as well as a low MC. In addition, the pellet requires a high bulk density, when it has a high energy density. Of course, the torrefied pellet must be produced from a raw wood material, such as hardwood.

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Jarno Föhr, Tapio Ranta
Lappeenranta University of Technology
Laboratory of Bioenergy
Lönnrotinkatu 7
Fi-50100 Mikkeli
Finland
Correspondig author: jarno.fohr@lut.fi

Jemina Suikki, Hanne Soininen
South-Eastern Finland University of Applied Sciences
Department of energy and Environmental Technology
Patteristonkatu 3 D
Fi-50100 Mikkeli
Finland

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Impact of Alternative Raw Materials on the Profitability of a Large-Scale Bio-Coal Pellet Plant in Finland

Jarno Föhr*, Raghu KC, Kalle Karttunen, Tapio Ranta

Laboratory of Bioenergy, Lappeenranta-Lahti University of Technology LUT, Mikkeli, Finland
Email: *jarno.fohr@lut.fi

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Abstract

The aim of this paper was to compare the annual economic impact of a large-scale bio-coal pellet plant by raw material specifically for the Finnish Lakeland region. In this study, the total production volume of the theoretical plant was 200,000 tons per year and the raw wood materials used were birch pulpwood, spruce pulpwood, pine pulpwood, and energy wood. These wood materials were young delimbed wood from early thinnings. The main goal of the paper was to illustrate that the energy content differences of raw wood materials affect the economic profitability of a bio-coal pellet plant at regional level. In this case, wood type also has a regional economic impact, which the pellet plant can influence through its raw wood material choices. The raw material comparison was based on measured data and not computational or literary data alone. The study found that lower solid wood energy densities caused higher relative costs for the total supply chain. A parallel phenomenon occurred with the required gross margin of the pellets, where lower energy content caused higher required gross margin for pellet sales. The gross margin was also sensitivity analyzed at different discount rates from 5% to 20%. At each required discount rate, the highest annual economic impact on the region was found for birch pellets, with values of 36.95 - 42.66 million €. Spruce pellets had the smallest annual economic impact, although it had the highest final pellet price in the same cases. The different economic effects were caused by the energy volumes sold.

Keywords

Bio-Coal, Pellet, Plant, Profitability, Raw Material, Region

1. Introduction

The use of fossil fuels is still high in the world, causing global warming as a result of greenhouse gas emissions, thereby reducing the global balance of nature, not to mention rising sea levels, melting glaciers, and increasing extreme weather phenomena. A lot of new technologies are being developed to replace or at least reduce the use of fossil fuels. The world's most used non-fossil raw material is produced for fuel production in three different thermo-chemical conversion ways—torrefaction, pyrolysis, and gasification—to achieve solids, liquid, and gas respectively from biomass [1]. Biomass is widely considered as an ideal energy resource for replacement of fossil fuels due to the zero carbon emission and renewable characteristics [2]. Nevertheless, biomass has a low energy density, which causes high transportation and handling costs. The key to resolving this problem is locating the energy conversion process close to a concentrated source of biomass [3].

A bio-coal pellet plant is a modern and effective solution to increase the degree of local processing of biomass by pre-treatment and pelletization. Torrefaction was the principal pre-treatment process in this paper [4]. Torrefaction is a thermochemical treatment of biomass in the low-temperature range of 200˚C - 300˚C [5] [6]. The aim of the treatment is to refine the biomass to a high-quality solid biofuel of high energy density that can be used for combustion purposes. Biomass loses relatively more oxygen and hydrogen than carbon during the torrefaction process when the calorific value of the raw material increases [7]. The lower heating value (LHV) of torrefied biomass is typically around 18 - 23 MJ/kg [8]. The end product is a torrefied wood pellet with a high energy density whose handling and transportation are economical in the next steps of the supply chain [9]. The significant improvement in the energy density of the wood biomass can mean that transportation-related costs can be halved following torrefaction [10].

The physical properties such as higher energy content and grindability make torrefied pellets suitable for co-firing with coal. A study by Ndibe *et al.* [11] suggests that torrefied pellets can be mixed with coal in pulverized coal furnace with high share up to 100% full conversion. An increasing number of industrialized nations have committed themselves to increase renewable energy source to lower their CO_2 emissions and bioenergy is a potential mid-term solution. Furthermore, since torrefied pellets could potentially replace the coal, the investment for the retrofit would be significantly lower than building a completely new energy system [12]. Thus, ultimately, torrefied pellets could be the potential solution to the energy transition towards low-carbon energy system.

The main aim of this paper was to determine the regional added value of a theoretical large-scale bio-coal pellet plant for the region of South Savo. The regional added value is the direct economic effects on the region from operation of the plant. A further goal was to compare the differences in economic impact arising from differing energy content of the raw wood material used. The total production volume of the plant was assumed to be 200,000 tons per year and the total capital investment of the plant was assumed to be 45.5 million euros based on the study by Svanberg *et al.* [13]. Karttunen *et al.* [14] studied the total regional socio-economic benefits of sawmill and bio-coal investments, which were supported by the intensive forest management at the South Savo region. As a result, the regional benefits could be annually 2.8% (150 M€) for GDP more than in BAU scenario by 2030 including multiplier effects [14].

In the first part of the work, the annual raw material demand of the plant was calculated in solid cubic meters. Material demand was calculated for the four different raw wood materials studied based on their calorific values. In the second phase, the total supply costs were calculated by work stage for each raw material. In the third phase, the net present value (NPV) and internal rate of return (IRR) were used to determine the required gross margin for the pellet types produced. The gross margin was then examined more closely by sensitivity analysis for discount rates of 5%, 10%, 15%, and 20%. In the last phase, the final price for each pellet type was determined when the total supply costs were added to the required gross margin. The approach used enables comparison of the direct annual economic impact of the plant by raw material for the specific Finnish region studied.

This paper extends earlier work by Föhr *et al.* [15], which investigated manufacturing of torrefied pellets in a ton-scale pilot plant and determination of the energy content of pellets made from different wood species. This paper contributes to literature in the field because previous studies have not specifically considered the economic significance of bio-coal pellet plants on the region in which they are located. In addition, the effect of differences in raw wood materials on bio-coal pellet plants has remained a somewhat neglected topic, which is somewhat surprising as the energy content of the raw material decisively influences the profitability of pellet plants.

2. Regional Source Information

There is a lack of large-scale processing industries in many regions in Finland, particularly in northern and eastern areas, and this is also true for the region of South Savo, located in south-eastern Finland (**Figure 1**). The surface area of the region is 19,130 km^2 and it has a population of more than 147,000 people [16]. South Savo is the most forested area in Finland and the economic importance of forests and forestry is significant. For example, in 2017, forest owners of South Savo had gross stumpage earnings of 261.2 million euros [16]. Currently, the region's pulpwood is not processed in South Savo but sold as raw wood for the pulp mills of neighboring regions.

The total wood supply of the region of South Savo is shown in **Figure 2**. In the figure, the total forest biomass supply is divided into different wood product groups. The total supply volume in 2017 was 7.44 million cubic meters. The total timber share was 3.66 million cubic meters and total pulpwood share 3.31 million cubic meters, respectively. Energy wood had the lowest share of 0.47 million cubic meters [17].

The most interesting wood product groups from the perspective of this study are the pulpwood groups and energy wood, because they are potential raw materials for bio-coal pellet production as regard price and quality. According to statistics from the state Natural Resources Institute Finland, pine pulpwood in South Savo consists of Scots pine (*Pinus sylvestris*) and spruce pulpwood is Norway spruce (*Picea abies*). Hardwood pulpwood comprises only young birchwood

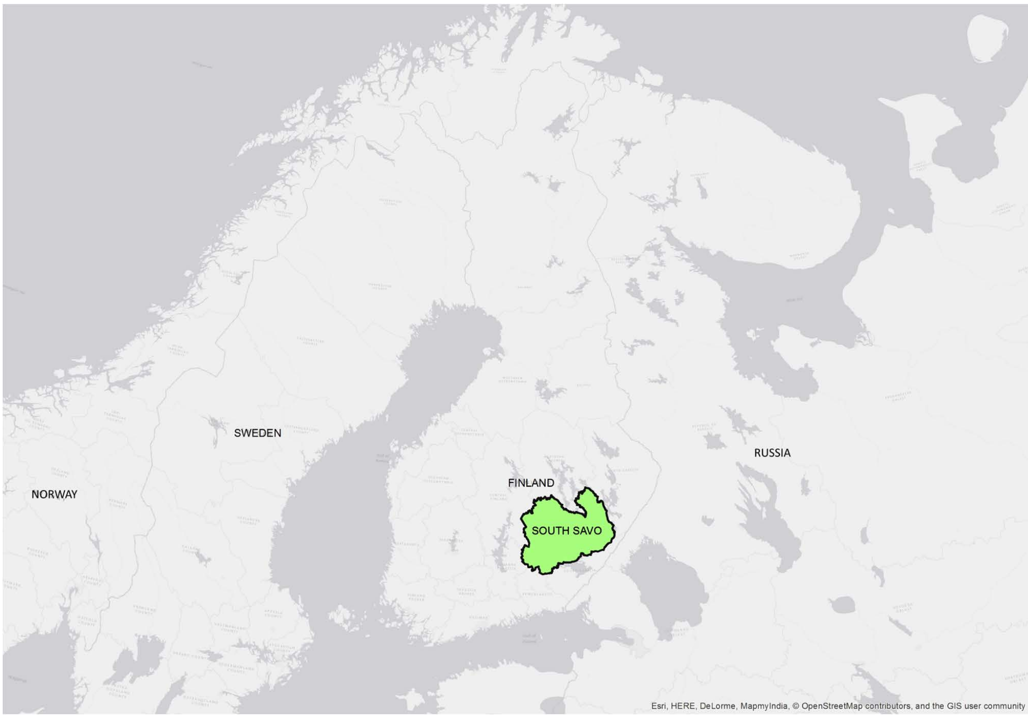

Figure 1. Region of South Savo in Finland.

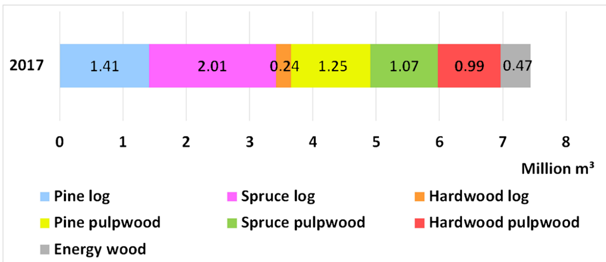

Figure 2. Total wood supply of South Savo in 2017 [17].

species like downy birch (*Betula pubescens*) and silver birch (*Betula pendula*). Energy wood contains mixed wood species and, usually, most of it is hardwood. Energy wood consists of different parts of the tree such as young delimbed stems, small whole trees and logging residues that are not suitable for industrial production [18].

3. Material and Methods

3.1. Material

Young delimbed wood of early thinnings was used as the raw wood material of the plant. It is best known as pulpwood, which has a diameter at breast height (DBH) of 5 - 15 cm and a length of 2.7 - 5.0 m [19]. This kind of wood is not suitable for sawing due to its size and quality. The different raw wood materials used in the plant production modeling in this study were birch, spruce, pine and energy wood. They were chosen because they are the most common wood species in Finland. The energy wood is composed of mixed hardwood. The plant's raw wood material flow did not contain logging residues.

The bio-coal pellet plant's raw material supply chain starts from the forest. First, trees of pulpwood size are felled by a felling machine in thinning operations and the delimbed stems are forwarded to a stack on the roadside (**Figure 3**). The delimbed stems are then transported to the plant by a full-trailer log truck. Next, the delimbed stems are chipped in a transferable medium sized chipper at the plant. The produced woodchips are then transferred to torrefaction and pellet production. Finally, the finished bio-coal pellet products are distributed worldwide.

3.2. Methods

3.2.1. Energy Volume of Annual Production

The energy volume of annual production at the plant was determined individually for all three puplwoods and the energy wood. The plant's energy volume of annual production in megawatt-hours was calculated with Equation (1), which is taken from the publication of Alakangas *et al.* [20]:

$$W = \frac{Q_{net,d} \times \left(\frac{100 - M_{ar}}{100}\right) - 0.02443 \times M_{ar}}{3.6} \times m \qquad (1)$$

where

W is energy volume of annual production, MWh,

$Q_{net,d}$ is net calorific value on a dry basis, is also known as LHV, MJ/kg,

M_{ar} is moisture content as received, w-%,

0.02443 is a correction factor for the enthalpy of vaporization for water (moisture) at a temperature of 25˚C, MJ/kg per 1 w-% of moisture,

3.6 converts the unit MJ/kg into the MWh/t,

m is annual production volume of the plant, in tons.

Equation (1) includes also the energy content calculation, which is shown in Equation (2).

$$E = \frac{Q_{net,d} \times \left(\frac{100 - M_{ar}}{100}\right) - 0.02443 \times M_{ar}}{3.6} \qquad (2)$$

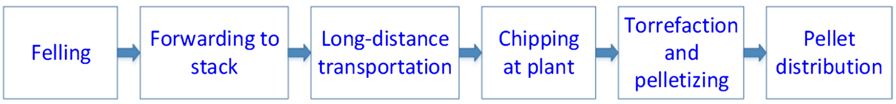

Figure 3. Raw material flow from forest to end users.

where E is energy content, MWh/t.

The moisture content of all pellet products (M_{ar}) was set at 6.0% in the initial calculations. The selected moisture content is an average value of the torrefied pellets from the study of Föhr *et al.* [15], which considered the same wood species as this study. LHV values are also taken from the same study [15]. The annual production volume of the bio-coal pellet plant (m) was assumed to be 200,000 tons and the same production volume was used for each wood product group. The study examined four alternative cases for raw material sources of the bio-coal pellet plant.

3.2.2. Raw Material Demand

The raw material demand of the bio-coal pellet plant was calculated at a plant energy efficiency of 90%. The energy efficiency of the plant was set based on the assumption of many researchers that mass loss of around 30% provides the best bio-coal pellet product in terms of calorific value [21] [22]. The energy loss for this mass loss is usually around 10% [23].

The weight of the woodchips used annually was calculated when the factor m (annual production volume of the plant in tons) was solved from Equation (1). The factor W (energy volume of annual production) is already known from previous calculations. In the weight calculations, the LHV of the woodchips ($Q_{net,d}$) was assumed to be the same as that of the end product itself, because total moisture content does not affect this value. The as-received moisture content of the woodchips (M_{ar} = 51.5%) was the average value from the study of Föhr *et al.* [15]. The volume of woodchips was calculated by multiplying the weight of woodchips (m) by the average bulk density of 331 kg/m^3 [15]. Subsequently, the plant's raw material demand in cubic meter volume was obtained by multiplying the volume of woodchips by a factor of 0.4, which is a conversion value from the bulk volume to the cubic meter volume [20] [24]. Finally, the energy density of the solid wood was obtained by dividing the raw material need of the plant by the volume of solid wood.

3.2.3. Total Supply Costs

All supply cost data was allocated to the year 2017 in this study. Since young delimbed pulpwoods and delimbed energy wood were the cheapest source at market prices in the region of South Savo, they were chosen to be the raw wood materials for the bio-coal pellet plant. In 2017, the average stumpage price was 10.95 €/m^3 for birch pulpwood, 10.60 €/m^3 for spruce pulpwood, 11.29 €/m^3 for pine pulpwood, and 5.75 €/m^3 for delimbed energy wood. The stumpage prices of the woods were taken from the price statistics for South Savo compiled by the Natural Resources Institute Finland [25] [26].

The total costs of felling and forest transportation were taken from data for 2017 presented by Metsäteho Oy, a R&D organization owned by leading Finnish forest industry actors which has maintained annual statistics in this area [27]. The above-mentioned costs formed the total stack cost at the roadside, which was 14.44 €/m^3 for birch pulpwood, 12.75 €/m^3 for spruce pulpwood, 12.44 €/m^3 for pine pulpwood and 16.81 €/m^3 for delimbed energy wood.

The average unit cost was 7.1 cent/m^3/km for long-distance transportation (>100 km), which was also taken from the statistics of Metsäteho Oy [27]. The required raw wood material was assumed to be available in the surrounding area of the plant within a radius of 160 km. The average transport distance for all raw wood materials was set at 80 kilometers [28]. Hence, the average transportation cost was 5.68 €/m^3 for all raw wood materials.

The average chipping cost was 6.8 €/m^3 for all raw wood materials, based on the study by Rinne [29]. Rinne assessed the costs of wood fuel chipping and crushing and this average chipping cost was for a medium-sized chipper at intermediate storage, which can be equated to the situation at the bio-coal pellet plant in this study.

The whole production costs of the bio-coal pellet plant were 9.86 €/MWh and the cost of pellet distribution was 3.01 €/MWh [13]. These costs were selected from the base scenario study of Svanberg *et al.* [13], which also focused on torrefaction technology. The research of supply chain cost evaluation of a bio-coal pellet plant study can be considered in line with this study because the same scale was investigated at the plant level. In addition, the research used data for Sweden, whose costs and cost structure can be considered to correspond to those of the Finnish region studied in this work.

3.2.4. Required Gross Margin of Pellet

In this study, NPV and IRR were used to determine the required gross margins of each produced pellet type (Equation (3)). IRR is a rate of interest that calculates NPV of all cash flows from the project of the bio-coal pellet plant as equal to zero. The IRR calculations rely on the same equations as NPV.

$$\text{NPV} = \sum\nolimits_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \tag{3}$$

where

NPV is net present value, is equal to zero,

C_t is annual cash flow, €,

r is discount rate,

t is number of years,

C_0 is total investment cost, €.

The annual cash flow (C_t) consists of two different factors: cash flow from the energy volume of annual production (W) and the required gross margin of the bio-coal pellet. Thus, Equation (4) can be written:

$$\text{NPV} = \sum\nolimits_{t=1}^{T} \frac{W \times R}{(1+r)^t} - C_0 \tag{4}$$

where R is required gross margin, €/MWh

The required gross margin of the bio-coal pellet (R) was solved from Equation 4 for when the NPV was equal to zero. The gross margin (R) was sensitivity analyzed by different discount rates of 5%, 10%, 15%, and 20%. The plant's repayment period (t) was set at 20 years. The total investment cost of the plant (C_0) was 45.5 million euros. Using the model developed by the study of Svanberg *et al.* [13], the total personnel requirement for the size of plant studied was 23 staff working on a full-time basis.

3.2.5. Final Price of Pellet and Annual Economic Impact

The final price of each produced pellet type was obtained by adding the total supply costs and the required gross margin (R). Finally, the annual economic impact of the bio-coal pellet plant was obtained by multiplying the final price of the pellet by the energy volume of annual production (W). These calculations were made by raw material specifically.

4. Results

4.1. Energy Volume of Annual Production

Production information of the bio-coal pellets is presented in Table 1. The LHV of the bio-coal pellets (torrefied) was taken from the study of Föhr *et al.* [15]. The energy contents of the pellets were calculated using Equation (2). Equation (1) was used in calculation of the energy volume of annual production. The raw material need of the plant was calculated with a production efficiency of 90%. Thus, the calculated average raw material need of the plant was 1118 GWh annually.

4.2. Raw Material Demand

The raw material demand of the plant was calculated from the forest side for fresh wood. The calculation results of the weight and volume of woodchips, and the volume and energy density of solid wood are shown in Table 2. Based on these values, the required average cubic meter volume to meet the plant's annual need was 596,000 m^3. The energy density of solid wood varied between 1.77 MWh/m^3 and 1.94 MWh/m^3 by raw material.

4.3. Total Supply Costs

Total supply costs for the different raw wood materials are shown in Figure 4.

Table 1. Production information of the bio-coal pellets.

Bio-coal pellet[a]	LHV[b] (MJ/kg)	Energy content (MWh/t)	Energy volume of annual production (GWh)	Raw material need (GWh)
Birch	19.37	5.02	1003	1115
Spruce	18.47	4.78	956	1063
Pine	19.96	5.17	1034	1149
Energy wood	19.91	5.16	1032	1146
Average	**19.43**	**5.03**	**1006**	**1118**

[a]Moisture content of pellet (6.0%); [b]Lower heating value (low).

Table 2. Required weights and volumes by raw material. The table also presents the energy densities of solid wood for the materials studied.

Raw material of pellet[a]	Weight of woodchips (t)	Volume of woodchips (bulk-m^3)	Volume of solid wood (m^3)	Energy density of solid wood (MWh/m^3)
Birch	493,000	1,490,000	596,000	1.87
Spruce	497,000	1,501,000	600,000	1.77
Pine	491,000	1,484,000	594,000	1.94
Energy wood	491,000	1,484,000	594,000	1.93
Average	**493,000**	**1,490,000**	**596,000**	**1.88**

[a]Moisture content as received (51.5%).

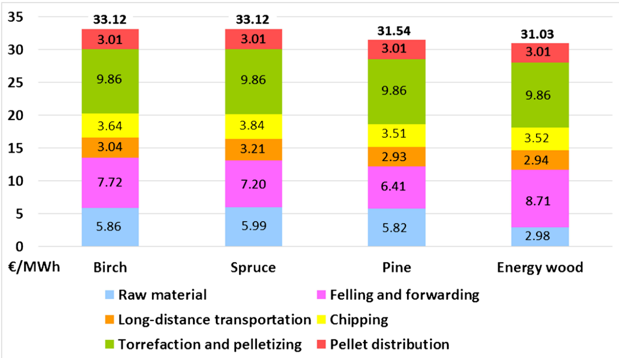

Figure 4. Total supply costs for different raw wood materials.

The costs were distributed by cost category. The unit cost €/m^3 was converted to unit cost €/MWh by dividing unit cost €/m^3 with the energy density of the solid wood. The total supply cost was 33.12 €/MWh for the birch and spruce pulpwood, 31.54 €/MWh for the pine pulpwood, and 31.03 €/MWh for the energy wood.

4.4. Required Gross Margin of Pellet

The required gross margins of each produced pellet type are shown in Figure 5. The gross margin was sensitivity analyzed at discount rates of 5% (a), 10% (b), 15% (c) and 20% (d). The principle was that the plant investment is profitable when NPV ≥ 0 € and IRR ≥ discount rate. Figure 5 shows in the case of a discount rate of 5% that these financial circumstances were fulfilled when the gross margin was 3.6 €/MWh for pine and the energy wood pellets, 3.7 €/MWh for birch pellets, and 3.9 €/MWh for spruce pellets. In the case of a discount rate of 20%, the corresponding values were 9.1 €/MWh for pine and energy wood pellets, 9.4 €/MWh for birch pellets and 9.8 €/MWh for spruce pellets.

4.5. Final Pellet Price and Annual Economic Impact

The final prices of each produced pellet type and the annual economic impact of the plant for the Finnish region studied are shown in Figure 6. The results of

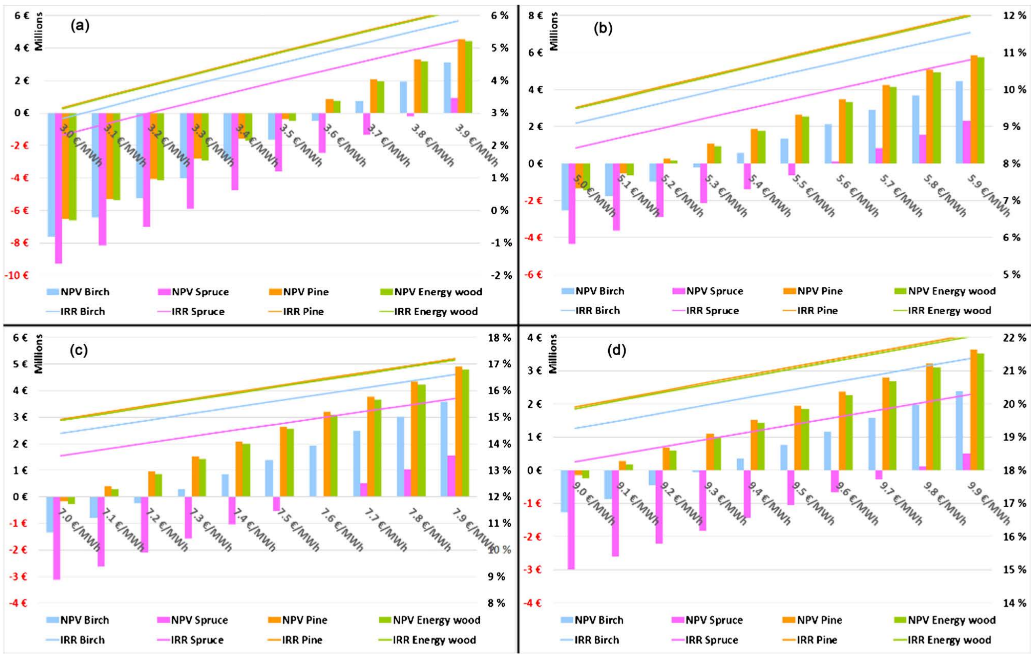

Figure 5. Results of NPV and IRR for each produced pellet type at discount rates of 5% (a), 10% (b), 15% (c) and 20% (d).

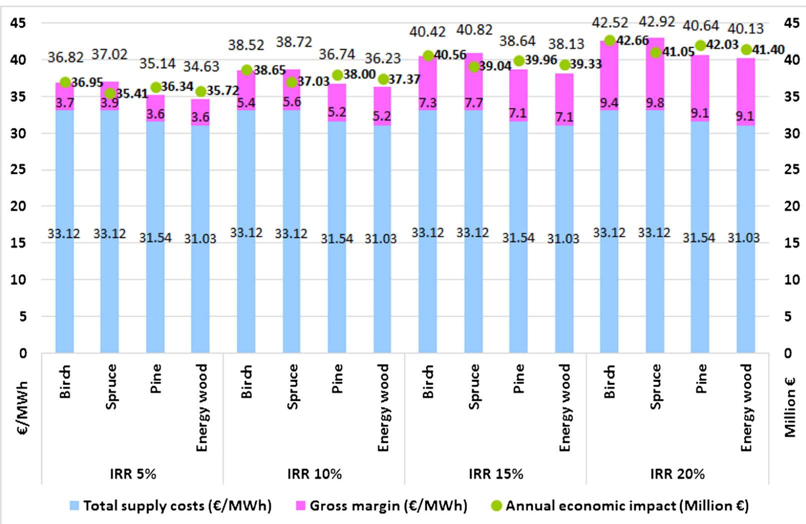

Figure 6. Final prices of the pellets and the annual economic impact for the studied Finnish region. Gross margin of the pellets varied depending on the desired discount rate.

Figure 6 are raw wood-specific and the gross margin of the pellets varied due to the desired discount rate from 5% to 20%. Figure 6 shows that, at each discount rate, the highest final price was obtained for spruce pellets and the lowest for energy wood pellets. However, at each discount rate, the annual economic impact was highest for the birch pellets and lowest for the spruce pellets.

5. Discussion

The main aim of the paper was to determine the direct annual economic impact of a large-scale bio-coal pellet plant on the Finnish region of South Savo and to analyze variation in economic impact resulting from differences in the energy content of the raw wood materials used. The theoretical total production volume of the plant was 200,000 tons per year and production efficiency of the plant was 90%. For this case scenario, the required average raw material need was about 596,000 m^3 based on the calculations of this study. This volume of raw material demand would increase annual felling capacity by 8% in the region of South Savo. It is also possible that the effect of the increased demand would be to increase the price of raw wood supply, which would cut into the rate of return, assuming no increase in pellet price. If the pellet price increased, then the plant would become less competitive relative to other pellet suppliers and other energy forms. It was also assumed that the raw wood material arrives at the plant at a moisture content of 51.5% and the plant produces bio-coal pellets of a moisture content of 6.0%.

In this study, the results for the bio-coal pellets showed that the energy content was 4.78 MWh/t for spruce, 5.02 MWh/t for birch, 5.16 MWh/t for energy wood, and 5.17 MWh/t for pine. The same internal order of raw materials remained in the results of the fresh solid woods. Correspondingly, the energy density was 1.77 MWh/m^3 for spruce, 1.87 MWh/m^3 for birch, 1.93 MWh/m^3 for energy wood, and 1.94 MWh/m^3 for pine. Both the energy content of the pellets and the energy density of the solid woods were lowest for spruce and highest for pine. These numerical values are greatly influenced by the LHVs measured in the previous study of Föhr *et al.* [15], so the starting values had a research base.

The study noted that lower energy densities of solid wood caused higher relative costs for the total supply chain. A particularly strong effect was seen in the costs of the work stages from the forest to the bio-coal pellet plant. Spruce wood had the highest relative unit costs, and the costs were greatly affected by energy density. The calculations showed that the same volume of wood passed through the supply chain for all the wood species, but differences in the energy density of the wood species caused changes in the relative unit costs. The same phenomenon was also noticed for the gross margin of the pellets. At each studied discount rate from 5% to 20%, the required gross margin was lowest for pine and energy wood pellets and highest for spruce pellets. The higher energy content allowed a lower required gross margin. The gross margin of the pellets was examined at varying discount rates in order to obtain a more nuanced picture of the effects and better reliability.

Depending on the raw material, the total supply costs of the bio-coal pellets were 31.03 - 33.12 €/MWh. This study did not examine pellet production costs and distribution costs in detail since Svandberg *et al.* [13] had previously determined reliable values for Nordic conditions. In the work by Svandberg *et al.*, total supply cost of 31.8 €/MWh was determined in a base scenario, but differences between different raw materials were not examined. In another study, the European Framework Programme 7 Sector Project, the total supply cost was evaluated for a stand-alone plant at 43 €/MWh [30]. In the same work, the corresponding cost for an existing sawmill was 34 €/MWh, for a new sawmill 38 €/MWh, and for a modern pulp mill 33 €/MWh [30]. On the other hand, the total supply cost was 39.5 €/MWh according to the study of Ranta *et al.* [31], who inspected a Finnish bio-coal pellet plant with an annual production volume of 50,000 tons. It should be noted that in these studies the size of the bio-coal pellet plant has a strong impact on the total supply costs.

The calculations in this paper show that the final price of bringing the bio-coal pellets to the market is greatly affected by the raw wood material used. In this study, the lowest pellet price was obtained for energy wood and the highest for spruce at all studied discount rates. An interesting finding was that spruce pellets had the lowest direct annual economic impact on the region when taking into account the energy volumes of annual pellet sales. Sold energy volumes were seen to have a great influence on the annual economic impact on the region. For example, at a discount rate of 10%, the largest annual economic impact was found for birch pellets at 38.65 million €, followed by pine pellets at 38.00 million €, energy wood pellets at 37.37 million €, and spruce pellets at 37.03 million €.

6. Conclusion

This study investigated the direct annual economic impact of a large-scale bio-coal pellet plant by raw material for a specific Finnish region. It was found that the raw wood material had a major impact on the total supply costs of bio-coal pellets and the resulting profit. Both the energy content of the pellets and the energy density of the solid wood affected the overall profitability of the bio-coal pellet plant and its annual economic impact on the region. It is often assumed in published literature that one solid cubic meter of fresh wood contains two-megawatt hours of energy. This is only an assumption and different raw wood materials have energy content differences, which are mainly affected by the calorific value and moisture content of the wood. In this study, certain moisture content values were fixed in order to make the calculation results comparable. The study demonstrated that the differences in the raw wood material greatly affected the profitability of the bio-coal pellet plant and thus the economic benefit for the whole region.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

C_t	is annual cash flow, €
C_0	is total investment cost, €
E	is energy content, MWh/t
M_{ar}	is moisture content as received, w-%
m	is annual production volume of the plant, in tons
NPV	is net present value, is equal to zero
$Q_{net,d}$	is net calorific value on a dry basis, is also known as LHV, MJ/kg
R	is required gross margin, €/MWh
r	is discount rate
t	is number of years
W	is energy volume of annual production, MWh
0.02443	is a correction factor for the enthalpy of vaporization for water (moisture) at a temperature of 25˚C, MJ/kg per 1 w-% of moisture
3.6	converts the unit MJ/kg into the MWh/t

Publication IV

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Feedstock and supply chain-oriented comparative cradle-to-gate life cycle assessment of torrefied pellets, case study: Finland

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Feedstock and supply chain-oriented comparative cradle-to-gate life cycle assessment of torrefied pellets, case study: Finland

Raghu KC, Jarno Föhr, Olli-Jussi Korpinen, Tapio Ranta

Lappeenranta-Lahti University of Technology LUT, Laboratory of Bioenergy, Lönnrotinkatu 7, 50100 Mikkeli, Finland.

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Abstract
Life cycle assessment (LCA) is used to compare global warming potential of torrefied pellets made of different feedstock materials, namely energy wood of birch and pulpwood of birch, pine and spruce. In addition, five different supply chain alternatives for each feedstock type are also evaluated. It is assumed that all of the biomass originates in the South Savo region of Finland and the pellets are used for co-firing with coal in a large-scale power plant in Helsinki, Finland. The results show that the torrefied pellets made of pulpwood of birch have the lowest global warming potential, whereas energy wood of birch impose the greatest environmental burden. Of the supply chain alternatives considered, biomass chipped with an electrical chipper in the torrefaction plant yard in South Savo has the lowest global warming potential. Consequently, torrefied pellets of birch chipped in an electric chipper in the torrefaction plant yard have the lowest environmental impact of all feedstock material and logistics alternatives. On the other hand, energy wood torrefied on-site in Helsinki results in the greatest environmental impact of all the raw material and logistics alternatives assessed. Furthermore, logistics with roadside mobile chipping generates 5-17% lower greenhouse gas (GHG) emissions than terminal crushing. Similarly, moving the torrefaction plant from South Savo to Helsinki would cause up to 6.5% additional GHG emissions depending on the raw material. Alternatively, chipping at the plant yard in a stationary electric chipper instead of crushing with a diesel-powered crusher would cause up to 18% fewer GHG emissions depending on the raw material.

Keywords: Biomass; Bioenergy; Torrefaction, pellets; Logistics; LCA.

1. Introduction
Bioenergy is considered a key element of efforts to meet the mandated Paris climate agreement target of keeping global warming to less than 2˚C above pre-industrial levels [1]. If grown sustainably, bioenergy has zero net CO_2 emissions to the atmosphere as the CO_2 released during the energy production is from carbon that the biomass absorbed in the first place [2-4]. Biomass, the source of bioenergy, is challenging as a source of renewable energy due to unfavorable physical and chemical properties such as low heating value, high moisture content, low energy density and hygroscopicity [5, 6]. These properties have a great impact on the logistics of biomass use for energy production. Treatment of the biomass prior to its

utilization is thus required to address limitations arising out of the intrinsic characteristics of biomass and to enable large-scale use of biomass for energy production. One of the many ways to improve biomass quality is torrefaction [7].

Torrefaction is a thermochemical treatment of biomass in which the biomass is heated at 200-300° C in an oxygen deficient environment. During the treatment, the biomass partly decomposes releasing different types of volatiles.

Torrefied biomass contains up to 90% of the initial energy content while reducing weight to about 30% of the initial weight [2, 3, 5, 7] The torrefaction process also enhances physical and chemical properties such as calorific value, grindability, and hydrophobicity. Pelletization of the torrefied biomass further improves the volumetric energy density, which plays an important role in reducing logistics cost as well as energy use during transportation [8]. A further benefit arising from the high-energy content and grindability of torrefied pellets is that they can be co-fired with other fuels in existing power plants, for example, with coal in a coal-fired power plant [7]. Moreover, pulverized coal furnaces can be converted to 100% torrefied pellets mode, which provides an opportunity for coal-fired power plants to reduce their emissions [9].

About 50% of the energy used in Helsinki, Finland is met from coal and about one-third of total energy comes from natural gas. The remaining energy demand is produced by nuclear and renewables with hydropower covering the majority of renewable energy. As a part of efforts to reduce fossil fuel use, the combined head and power (CHP) plants in Salmisaari (160MW_e, 300MW_{th}) and Hanasaari (220 MW_e, 420 MW_{th}) have started to blend white wood pellets with coal, thus increasing the share of renewables in the energy system [10]. Additionally, there are plans for the construction of more heat plants firing biomass after the eventual closure of the Hanasaari facility [11]. However, the energy use of forest biomass is already high in areas in the vicinity of Helsinki (i.e. Uusimaa region), leading to intense competition for resources and potentially higher biomass feedstock prices [12]. On the other hand, approximately 200–300 km from Helsinki, the South Savo region has abundant forest biomass [13]. In 2017, a greater amount (~7 solid-m^3 out of total 62.9 solid-m^3) of industrial round wood was harvested from this region than any other region in Finland [14], and since the area lacks biomass-processing industries, the harvest potential could be considered higher than the current energy wood use in the region. Circumstances such as these make South Savo a possible location for biomass processing industries and Helsinki a possible location for large-scale final biomass use.

The aim of this research is to evaluate the environmental performance of torrefied pellets originating from four different feedstock types using life cycle assessment (LCA). In order to refine the research further, five different logistics alternatives for each feedstock type are evaluated. It is assumed that the delimbed stem wood biomass originates in the South-Savo region and that the power plants in which the pellets are used are located in Helsinki. Different feedstocks (energy wood of birch and pulpwood of birch, spruce and pine) are compared because dissimilar properties such as energy density, volumetric density and forest machine productivity play an important role in determining the environmental performance of the supply chain. Similarly, different supply chains are evaluated because biomass fuel terminal concepts are evolving and terminal type and processing method affect costs and production efficiency [15]. Thus, it is worthwhile to evaluate traditional and innovative logistics solutions in terms of environmental performance. This study will highlight the different elements of biomass supply chain in terms of GHG emissions related to bioenergy and help understand the hotspots along the supply chain. In addition, the study will also identify the better alternative of biomass supply chains that are currently in practice.

2. Materials and methods

2.1 Life cycle assessment (LCA)

According to SFS-EN ISO 14040 [16], life cycle assessment (LCA) is an environmental management technique that helps identify the possible environmental impacts of a product or service through its various life cycle phases. It can assist in identifying improvement possibilities and inform decision makers in industries as well as governing bodies. There are four phases of LCA:

- Goal and scope definition
- Life cycle inventory analysis (LCI)
- Life cycle impact assessment (LCIA)
- Interpretation.

The purpose of the study, intended application and audience are defined in the goal and scope definition phase. Additionally, the product system to be studied is clarified as well as the system boundaries and functional units. LCI comprises collection and validation of the input/output flows in each process as per the defined goal and scope definition. In the LCIA phase, LCI results are assigned to impact categories such as global warming potential (GWP), acidification etc. Finally, in the interpretation phase, the LCI and LCIA results are evaluated and interpreted in terms of the scope of the study. As illustrated in Figure 1, LCA is an iterative process where information is exchanged and modified throughout the process.

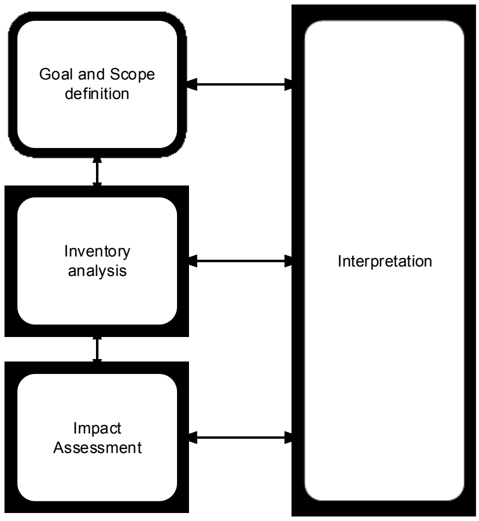

Figure 1. Life cycle assessment framework [16].

In this study, the LCA modelling is done using GaBi Professional (version 8) software with the integrated databases GaBi International and Ecoinvent v3.1. Concerning impact assessment, a sole impact category *global warming potential (GWP) with 100 years of time frame* is presented based on the methodology developed in CML 2001 (2016 version). The characterization factor for two major GHGs, methane and nitrous oxides are 28 kg CO_2 eq. and 265 CO_2 eq., respectively. In addition, the biogenic carbon emissions are excluded from the evaluation. Finally, sensitivity analysis is done for different moisture content of the raw material and different energy content of the torrefied pellets.

2.2 Goal and scope of the study

The aim of this research is to analyze comparative cradle-to-gate LCA of torrefied pellet production including supply chain alternatives for different feedstock biomasses. Four types of feedstock, namely, energy wood of birch (a mix of *Betula pendula* and *Betula pubescens*) and pulpwood of three tree species, i.e., birch (mix of *Betula pendula* and *Betula pubescens*), spruce (*Picea abies*) and pine (*Pinus sylvestris*) are studied. The primary location of the torrefaction plant is assumed to be in the South-Savo region of Finland and the torrefied pellets are assumed to be co-fired with coal in a large-sized power plant in Helsinki, Finland. The corresponding locations are shown in Figure 2. For the sake of comparison, one of the scenarios assesses location of the torrefaction plant in Helsinki. The functional unit of the study is identified as: *kg CO_2 eq. per 1 MWh of torrefied pellets*

2.3 System boundary

A typical cradle-to-gate LCA describes a system that includes upstream inputs and effects resulting from the origin of the raw material and the production phase, and downstream inputs and effects to the gate of the final destination of product usage, which in this case is the power plant where the pellets are co-fired with coal. Furthermore, emissions from diesel and electricity production are taken into account. Similarly, emissions from forest machinery, trucks, biomass crushers and wheel loaders are included in the analysis but the infrastructure and production of vehicles, trains and machinery are excluded from the system. Potential GHG emissions from biomass decay during storage are outside the boundaries of the system. The system boundaries are illustrated in Figure 3.

2.4 LCI

2.4.1 Biomass properties

In this study, it is assumed that the production of torrefied pellets occurs in a hypothetical torrefaction plant with a production capacity of 200,000 t per year. In terms of feedstock, biomass from delimbed stems of various tree species is compared. For the sake of consistency, it is assumed that the biomass is dried naturally to 30% moisture content. Further explanation of the assumption of moisture content and its impact on transportation are given in Section 2.5.1. The moisture content of the torrefied pellets is kept constant at 6% for the sake of comparability. The major difference between energy wood and pulpwood is that energy wood (4-6cm) generally has a smaller top diameter than pulpwood (6-16cm) [17]. The purpose of using pulpwood as a feedstock is to analyze whether it has the same environmental impact as energy wood from a logistics point of view. The properties of the biomass and torrefied pellets are presented in Tables 1 and 2. The heating value of the torrefied pellets of the pulpwood of different species and energy wood is taken from Ranta et al. [18]. The heating value of the torrefied pellets as received (Q_{ar}) is calculated based on dry-basis lower heating value (Q_d) and moisture content (m) using Equation 1 from Alakangas et al. [19]:

$$Qar = \mathrm{Qd} \times \left(\frac{100-\mathrm{m}}{100}\right) - 0.02443 \times m, \tag{1}$$

where: Q_{ar} is heating value (as received), Q_d is lower heating value (dry basis), m is moisture content % and 0.02443 is the coefficient for enthalpy of vaporization at constant pressure and 25˚C, MJ/kg per 1 % moisture.

The total mass of fresh biomass required is calculated based on the moisture content and Q_d of the fresh biomass, as shown in Table 2. Once the total energy in the torrefied pellet ($Q_{ar,pellet}$) has been calculated, the required amount of energy in the feedstock is calculated based on the assumption that 10% of the energy is lost during the torrefaction process [20]. The calculation is shown in Equation 2:

$$Q_{ar,raw} = \frac{Q_{ar,\ pellet}}{0.9} \tag{2}$$

The moisture content of pulpwood is assumed to be 51.5% as in Föhr et al. [21]. The values of $Q_{d,\ raw}$ of birch, spruce and pine are taken from Alakangas et al. [19], the $Q_{d,raw}$ of energy wood is assumed to be the same as that of the birch pulpwood, and the moisture content is assumed to be 52.2 % [18]. The volumetric ratio of loose to solid biomass is assumed to be 2.5 [22].

Figure 2. Locations of biomass origin and use.

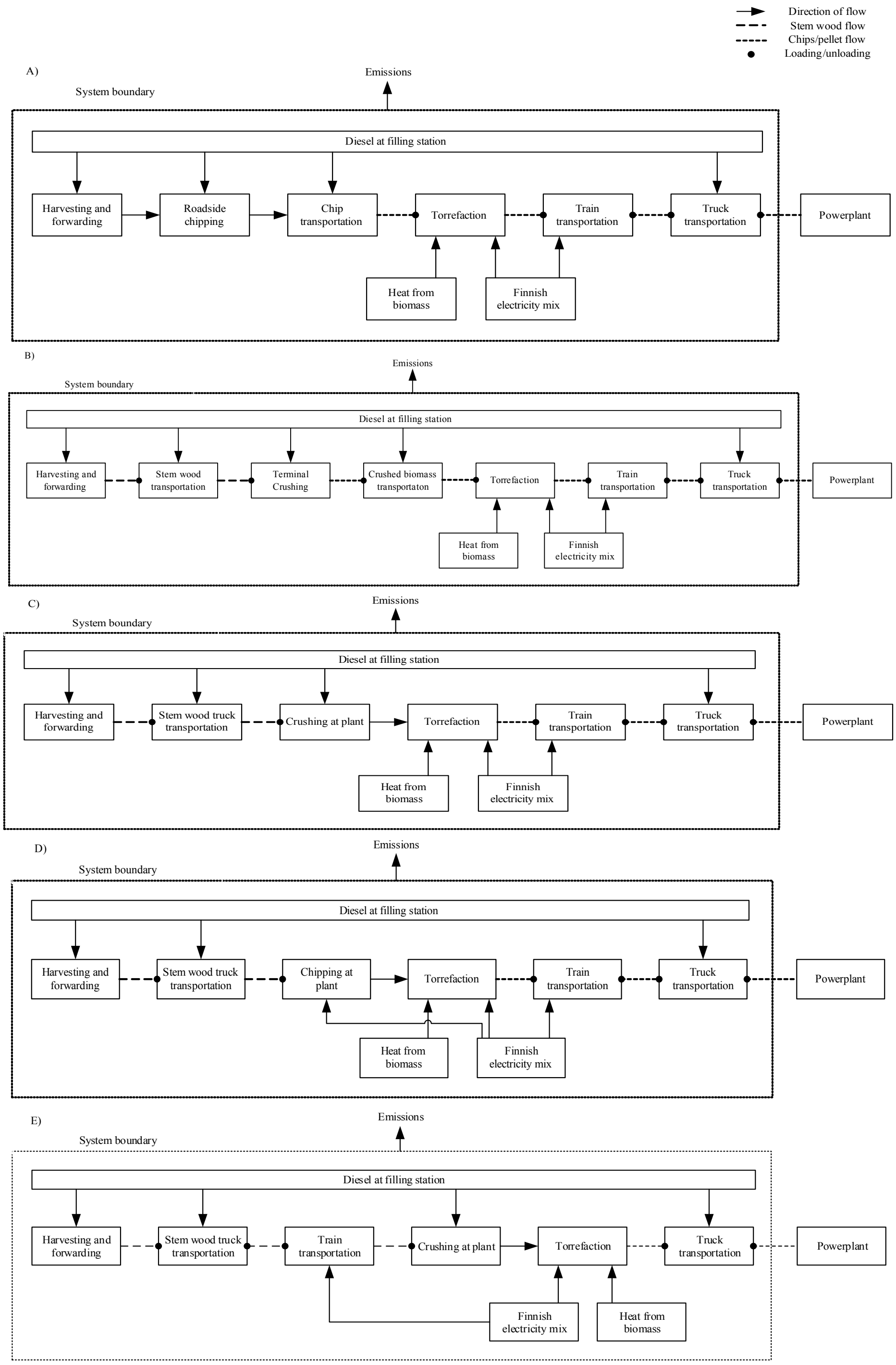

Figure 3. System boundary with supply chain scenarios depicted as Scenario (A): Roadside Chipping (RSC), Scenario (B): Terminal Crushing (CRT), Scenario (C): Crushing at the Plant (CRP), Scenario (D): Chipping at plant (CHP), Scenario (E): Torrefaction plant in Helsinki (TPH).

Table 1. Properties of the torrefied pellets [18].

Species	$Q_{d. pellet}$ MJ/kg	Moisture (m) %	$Q_{ar, pellet}$ MJ/kg	$Q_{ar, pellet}$ MWh/t	Total $Q_{ar, pellet}$ MWh/yr	Density kg/m^3
Birch	19.37	6	18.06	5.02	1,003,401	678
Spruce	18.47	6	17.22	4.78	956,401	699
Pine	19.96	6	18.62	5.17	1,034,212	682
Energy wood	19.15	6	17.85	4.96	991,912	696

Table 2. Properties of raw materials.

Species	$Q_{d, raw}$ MJ/kg	Moisture (m) %	$Q_{ar, raw}$ MJ/kg	$Q_{ar, raw}$ MWh/t	$Q_{ar, raw}$ MWh/yr	Fresh Mass t/yr
Birch	19.19	51.5	8.05	2.24	1114890	498656
Spruce	19.02	51.5	7.97	2.21	1062668	480217
Pine	19.33	51.5	8.12	2.25	1149125	509668
Energy wood	19.19	52.2	7.90	2.19	1102125	502398

2.4.2 Supply chain alternatives

A flow chart of the five different supply chain alternatives for each feedstock type is shown in Figure 3. In this study, it is assumed that the average truck transport distance is 100km. However, in scenario CRT where biomass is stored and comminuted at the biomass terminal, a surplus of 20km from the terminal to torrefaction plant is added. Similarly, in scenario TPH, where the torrefaction plant is assumed to be in Helsinki, the torrefaction plant is considered to be 20km from the power plant. The process heat required in the torrefaction process is assumed to be produced from biomass. However, electricity is an average Finnish grid mix, shown in Table 3. Long-distance transport is modeled as freight train transportation pulled by an electric locomotive and the distance is set as 300km in all scenarios. Currently, power plants in Helsinki have no railway access so biomass is considered to be handled at a harbor rail-yard 20 km from the powerplant. A brief outline of the scenarios is given below.

Roadside chipping (RSC): Delimbed stem wood is harvested and then forwarded to the roadside storage for natural drying. After drying, it is chipped with a diesel-powered mobile chipper straight to chip trucks (full truck-trailer). The chips are transported to the torrefaction plant. After torrefaction, the torrefied pellets are loaded into an electric freight train for transport to Helsinki and unloaded at the biomass handling harbor rail yard and transported to a power plant in a semitrailer.

Terminal crushing (CRT): After the forest procurement, the delimbed stem wood is immediately transported in trailer-trucks to the biomass terminal. After drying at the terminal, the delimbed stems are crushed with a diesel-powered terminal crusher. The crushed biomass is then loaded into chip trucks for transport to the torrefaction plant. After torrefaction, the torrefied pellets are loaded into the electric freight train for transport to the harbor rail yard, where the pellets are unloaded. The pellets are then loaded onto semi-trailer trucks and transported to the powerplant.

Crushing at the plant (CRP): Similar to RSC, harvested logs are left at the roadside storage for drying. The dried stems are then transported directly to the torrefaction plant and crushed at the plant yard in a diesel-powered crusher. The crushed biomass is torrefied and the finished product delivered to the biomass handling harbor yard, where it is unloaded. The pellets are then transported to the power plant in a semi-trailer truck.

Chipping at the plant (CHP): The scenario is similar to CRP but the delimbed stems are chipped in a stationary electric chipper.

Torrefaction plant in Helsinki (TPH): In this scenario, unlike previous scenarios, the torrefaction plant is assumed to be located in Helsinki, 20 km from the power plant. After the forest procurement, the logs are immediately transported on a truck-trailer to train loading site, where they are left to dry. The delimbed stems are then loaded onto the freight train and unloaded at the torrefaction plant, where the wood is crushed with a diesel-powered crusher. The torrefied pellets are then transported to the power plant in semi-trailer trucks.

2.4.3 Unit processes

Table 3 presents the various phases of the LCA (unit processes) and input data for the LCI calculations. The corresponding references are attributed accordingly.

Table 3. Unit processes and their description.

Unit processes	Description	Reference
Harvesting	Engine size 100 kW * Total weight 14t * Productivities • Energy wood 5.4 solid-m^3/h ¶ • Birch 10.4 solid-m^3/h * • Spruce, Pine 10.45 solid-m^3/h*	*[23] ¶ [24]
Forwarding	Engine size 110 kW * Total weight 11t * Productivities • Energy wood 6.8 solid-m3/h ¶ • Birch 12.3 solid-m^3/h * • Spruce, Pine 12.27 solid-m^3/h *	¶[24] *[25]
Trucks	EURO 6 Empty return considered Payloads capacity (utilization) • Full trailer-truck 40.6t (100%) • Semi-trailer 24.7t (80-85%)	[26]
Chipping/Crushing	Roadside energy wood chipper* • Drum chipper • Weight 19.2 t • Power 475 kW • Productivities ▪ Energy wood 30 solid-m^3/h ¶ High(diesel)-powered conventional roadside pulpwood chipper, emission factor • 9.38 kg CO_2/ton biomass (oven dry) § Stationary electric chipper ∞ • Electricity consumption 1.1 kWh/loose-m^3 of chips Crushing ¶ • GHG emissions 3.46 kg CO_2 eq/MWh	*[27] ¶[24] § [28] ∞ [29]
Loading/unloading	Logs (grab truck) • Loading 0.05 g CO2 per $MJ_{biomass}$ • Unloading 0.04 g CO2 per $MJ_{biomass}$ Chips and pellets (assumed to be same as chips) Loading/Unloading (wheel loaders) 0.03 g per $MJ_{biomass}$	[22]
Torrefaction	Energy consumption per kg (dry) • Electricity 0.128 kWh • Process heat 0.339 kWh	[30]
Train transport	• Payload capacity 1,452t • Volumetric capacity 60m^3/wagon • 24 wagon	[26]
Electricity mix	Electricity production mix (Finland) • Nuclear energy 33.26% • Hydropower 18.1% • Biomass 16.15% • Coal 15.07% • Natural gas 9.57% • Others 7.85%	[26]
Diesel at filling station	GHG emissions • 534g CO_2 per kg of diesel at filling station (EU-28 average)	[26]

2.5 Sensitivity analysis

2.5.1 Moisture content

In this study, the moisture content of the raw biomass is kept constant at 30% in all scenarios. However, according to [31], the moisture content of delimbed stems depends on the duration of natural drying at the temporary storage facility and the weather conditions during the storage period. Thus, in order to address the uncertainty of moisture content in naturally dried stems, a sensitivity analysis is done assuming that the moisture content of the raw biomass after drying at temporary storage is 40%.

2.5.2 Heating value of pellets

The heating values of torrefied pellets are taken from Ranta et al. [18] and are constant in all scenarios. However, heating values of torrefied pellets depend on the production process parameters and the values can be higher than the values assumed [32]. In order to assess the impact of the heating value of the pellets, a sensitivity analysis is done assuming torrefied pellets with 10% higher heating values for each biomass type.

3. Results

3.1 LCIA

The total annual GHG emissions from the production of torrefied pellets for the different feedstock material and supply chain alternatives are shown in Figure 4. The results show that pellets produced in South Savo from energy wood crushed in a biomass terminal have the highest GHG emissions (23,909t/y), whereas pellets produced in South Savo from birch pulpwood after comminution in an electric chipper (CHP) have the lowest GHG emissions (15,741t/y). Moreover, torrefied pellets of energy wood were found to have significantly higher GHG emissions compared to pulpwood in all respective scenarios.

The GHG emission results of torrefied pellets of all feedstock types and supply chain alternatives with respect to the functional unit are presented in Figure 5. Of the four types of feedstock, the production chain of torrefied pellets of birch is found to emit the least amount of GHG gases in all five scenarios. In contrast, torrefied pellets made of energy wood have the highest GHG emissions. Furthermore, of the five scenarios studied, scenario CHP is found to have the lowest GHG emissions. Consequently, torrefied pellets of birch in scenario CHP, where the biomass is comminuted in an electric stationary chipper at the torrefaction plant located in South Savo, is found to have the lowest GHG emissions of 15.69 kg CO_2 eq. per MWh. In contrast, scenario CRT, where biomass is comminuted at the biomass terminal and torrefied in South Savo, has the highest GHG emissions. Thus, torrefied pellets made of energy wood produced in South Savo have the highest GHG emissions of 24.1 kg CO_2 eq. per MWh.

3.2 Emissions in life cycle phases

The contributions of the different phases in the supply chains to total GHG emissions for different types of feedstock are presented in Figure 6. Of the different life cycle phases, the torrefaction phase is found to be the largest contributor to total GHG emissions in all scenarios and for all feedstock types. In addition, forest procurement, comminution, and truck transportation are other major phases that contribute to total GHG emissions. In contrast, the comminution of biomass in a stationary electric chipper (assessed in scenario CHP of all type of feedstock) has ~3% GHG emissions compared to comminution in diesel-powered crushers (~18%). Even though the longer distance is covered, train transportation has a significantly lower share of emissions (~2%) than truck transportation (~10%–17%). The reason for the lower GHG emissions is that electricity-powered transport is significantly cleaner than transport with diesel-powered trucks.

As shown in Table 4, changing the supply chain alternative from roadside chipping to terminal chipping (from scenario RSC to scenario CRT) causes 4.7–17.1% additional GHG emissions depending on the feedstock material. Similarly, moving the torrefaction plant from South Savo to Helsinki (from scenario CRP to scenario TPH) will cause 5.5–6.5% additional GHG emissions. In contrast, chipping at the torrefaction plant yard with an electric stationary chipper instead of a diesel-powered crusher can reduce GHG emissions by 15.5–18.2%, depending on the raw material. As presented in Table 5, the results show that pulpwood of birch (13.7%-22.6%), spruce (8.8%-17.7) and pine (10.7%-19.8%) cause lower GHG emissions than energy wood. The size of the reduction depends on logistics alternatives.

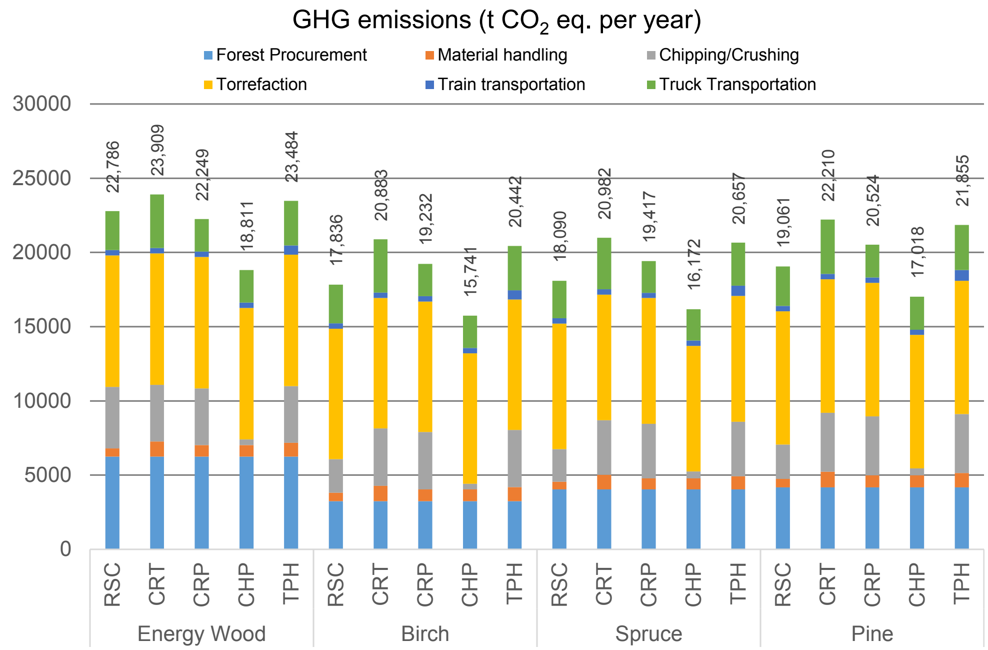

Figure 4. Total GHG emissions in a year from different feedstock scenarios and their supply chain alternatives.

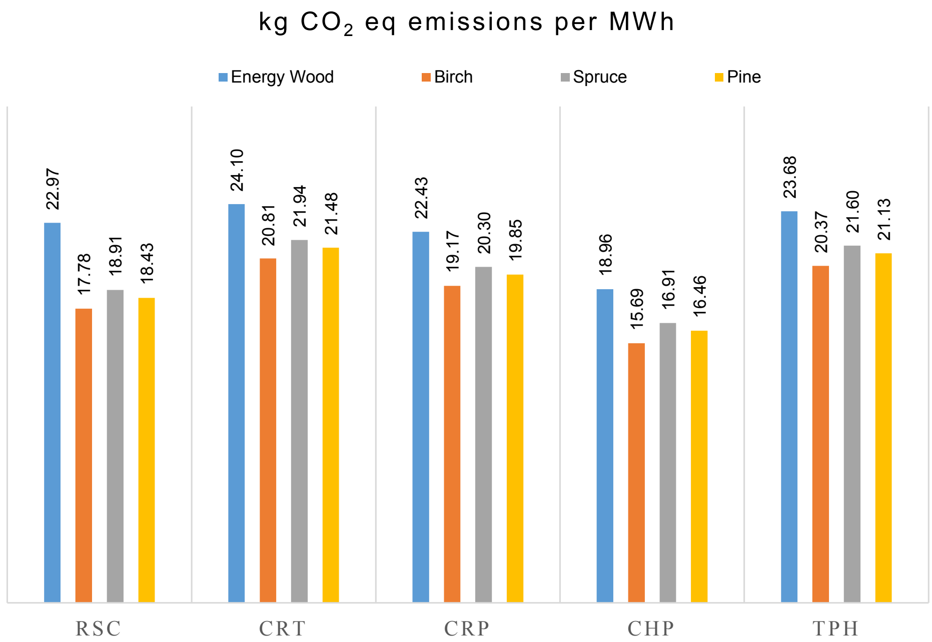

Figure 5. GHG emissions of different supply chain alternatives for each feedstock type.

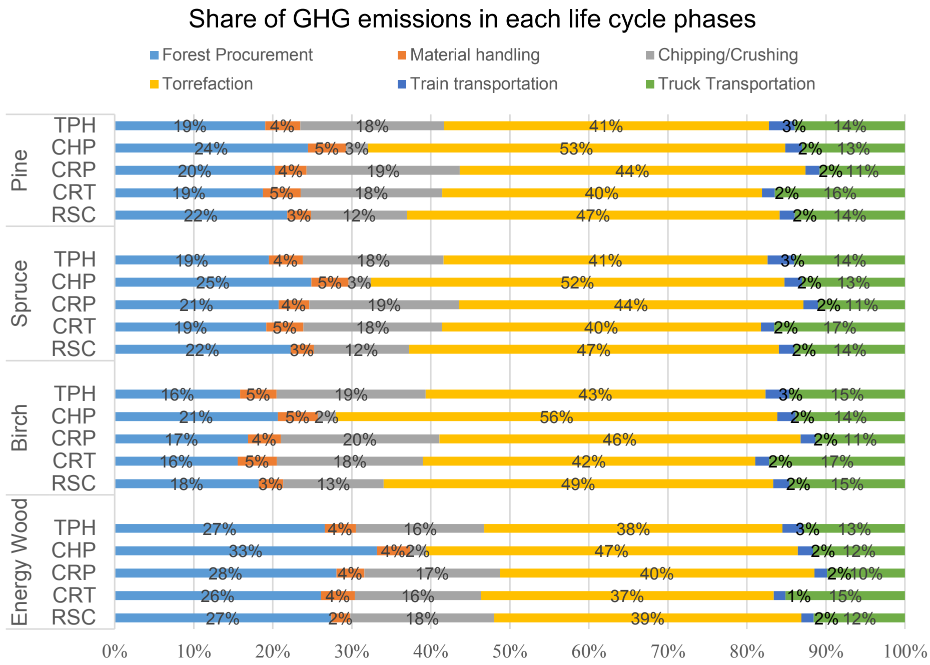

Figure 6. Share of GHG emission of different life cycle phases in each scenario for each feedstock type.

Table 4. Difference in GHG emissions in corresponding scenarios.

Scenarios	Energy Wood	Birch	Spruce	Pine
RSC→CRT	+4.7%	+17.1%	+16%	+16.5%
CRP→TPH	+5.5%	+6.3%	+6.4%	+6.5%
CRP→CHP	-15.5%	-18.2%	-16.7%	-17.1%

Table 5. GHG emissions of torrefied pellets of pulpwood compared to energy wood for each logistics alternative.

Logistics alternatives	Birch	Spruce	Pine
RSC	-22.6%	-17.7 %	-19.8 %
CRT	-13.7 %	-9.0 %	-10.9 %
CRP	-14.6 %	-9.5 %	-11.5 %
CHP	-17.3 %	-10.8 %	-13.2 %
TPH	-13.9 %	-8.8 %	-10.7 %

3.3 Sensitivity analysis

In this study, the moisture content of the dried biomass and the heating values of the pellets were kept constant. However, these two areas were highlighted in the sensitivity analysis, the results of which are presented in Figure 7. The upper and lower values of the error bars indicate sensitivity results of 10% higher moisture content in delimbed stems and 10% higher energy content in pellets, respectively. Based on the assessment, removal of biomass from forest roadside storage when the moisture content is 40% rather than 30% can cause up to 2% additional GHG emissions from transportation. However, it should be noted that emissions from storage and the effect of moisture on torrefaction are not studied in this assessment. On the other hand, 10% higher energy content in torrefied pellets causes <1% less emissions compared to the main study. However, it should be mentioned that energy yield is kept constant at 90%, as in the main study.

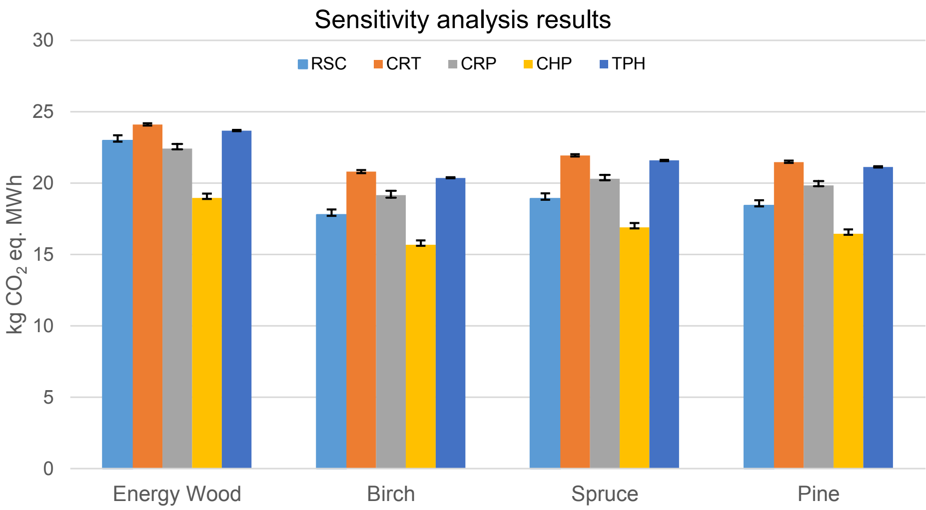

Figure 7. Sensitivity analysis results compared to the main results. The upper values of the error bars represent results from 10% additional moisture content in delimbed stems after natural drying, whereas lower values represent 10% higher energy yields in torrefied pellets.

4. Discussion

The results of this paper show that there is a real opportunity to lighten the environmental burden of bioenergy by adopting a suitable logistics alternative and using appropriate raw material for torrefaction. In particular, using an electric chipper instead of a diesel-powered crusher can help avert up to 18% of total emissions. A key factor is that the majority of the electricity mix in Finland consists of clean energy; a little over two-thirds of electricity is produced in the form of nuclear energy, hydropower, and bioenergy. However, in Finland, only about 11% of the energy biomass is chipped with electric chippers [33]. Thus, there is an opportunity to reduce the carbon footprint of comminution operation. Similarly, producing torrefied pellets from birch pulpwood instead of energy wood can help decrease GHG emissions by about 23% because of the higher productivity of the forest machinery and chipper with pulpwood than energy wood. According to the sensitivity analysis results, the location of the storage for natural drying, either at the forest roadside or in the plant yard, has no significant impact (~2%) on overall global warming potential of torrefied pellets. However, it is observable that the impact of higher moisture content is greater in the RSC, CRP and CHP scenarios, due to the biomass only being dried at the forest roadside before long-distance transportation.

The sensitivity analysis showed that the moisture content in the raw material is one of the important factors in GHG emissions of torrefied pellets. Transportation of biomass with 10% higher moisture contributed about 2% more GHG emissions from the overall supply chain. However, due to lack of inventory data, moisture content before comminution and torrefaction is assumed to be the same throughout the study which may not be the case in actual practice. Moreover, the natural drying process at forest roadside or biomass terminal is a crucial element for GHG emission reduction from torrefied pellets supply chain.

This is case-specific research dealing with a certain Finnish bioenergy scenario such as availability of forest biomass, transportation distance, and means of transportation. However, this research can also serve as a benchmark for other areas as more use of biomass and transportation distance is anticipated in the future. One of the drawbacks of case-specific studies, on the other hand, is that some of the key factors may drastically affect the results for one region, and the same factor may not be as effective in others. For example, in scenarios CRP and CHP where biomass is either crushed with a diesel-powered crusher or chipped with an electric chipper, the impact of the electricity mix was significant. However, the electricity mix may not have the same effect in any other region depending on the proportion of the source of electricity in those regions.

To our knowledge, no comparative LCA studies of torrefied pellets that investigate pulpwood and energy wood of different tree species as a raw material and supply chain alternatives have been presented. A study by Thrän et al. [30] examined GHG emissions of torrefied pellets made from straw, logging residues and short-rotation coppice (willow). In addition, the study compared GHG emissions for biomass originating from different countries such as Spain, Canada, USA, and Tanzania. It would be impractical to compare the results of this study with torrefied pellets of straw; however, results for logging residues and short-rotation coppice are somewhat comparable to this study. Thrän et al. [30] found that torrefied pellets of logging residues and short-rotation coppice from Spain generated GHG emissions of 39.9kg and 47.7kg CO_2 eq. per MWh of pellets, respectively. However, the results are very parameter-dependent because, as seen in this study, biomass supply alone contributes about 45% of total GHG emissions.

McNamee et al. [32] studied LCA of torrefied pellets of pine round wood produced in North America and shipped to the UK for final use. Their analysis indicated that GHG emissions varied from 27.9g CO_2 eq to 43g CO_2 eq per MJ of electricity produced depending on the torrefaction parameters (temperature and residence time) and utility fuel used during torrefaction (natural gas or wood chips). The study assumed 40% electric efficiency of the plant, thus, tentative comparable results would be 251 kg to 387 kg CO_2 eq per MWh of pellets. In cases where biomass is used as a utility fuel, transportation (including shipping) contributes over 80% of total GHG emissions.

Adams et al. [3] studied GHG emissions of torrefied pellets of Scots Pine (*Pinus sylvestris*). Their results showed GHG emissions varied from 17.5 g to 40.5 g per MJ of pellets depending on the energy demand for drying. The tentative comparable range of results would be 63 kg to 145 kg per MWh. However, in their study, 15% of the heat required was sourced from natural gas as utility fuel. In addition, the results included transportation of torrefied pellets from Norway to a power station in the UK.

Pergola et al. [34] studied the LCA of packaged traditional white pellets. According to their study, production of one ton of white pellets emitted 38 kg CO_2 eq. According to Alakangas et al. [20], one ton of white pellets equals 4.7-5 MWh of energy. With this assumption, the results would be 7.6-8 kg CO_2 eq per MWh of white pellets. It should be noted that wood chips are considered as a main fuel in the pelletization process as in our study. Similarly, Magelli et al. [35] studied the LCA of white pellets produced in Canada and imported to Sweden. It was found that production of one ton of white pellets from wood residues emitted 532 kg CO_2 eq., of which 422 kg was generated by ocean transportation. Thus, GHG emissions from forest procurement to production and delivery to the seaport is only about 110 kg CO_2 eq per ton, which is roughly 23 kg CO_2 per MWh pellets. It should be noted that land transportation in the study by Magelli et al. [35] included 763 km of train transportation.

Currently, it may be unrealistic to consider pulpwood as a feedstock for torrefied pellet production because of stiff competition from other industries such as the pulp and paper industry and biorefineries [36]. For instance, in the third quarter of 2018, the average price of delimbed stem (energy wood) was 23.3 EUR/solid-m^3 as delivery sales. On the other hand, the average price of birch pulpwood at the roadside was 32.8 EUR/solid-m^3 [14]. The significantly higher price of the raw material may prove to be an obstacle to pellet production for power plant usage. However, coal-fired power plants may look to use more biomass in energy production, since growing numbers of countries have pledged to phase out coal from the energy sector by 2030, including Finland, and other benefits of torrefied pellets such as being a potential replacement of fossil coal could play a role in wider adoption. According to Helen Oy [37], an energy firm owned by Helsinki city, utilizing biomass is the easiest way to replace coal and furthermore there is a lack of biofuel availability in the Helsinki area. In addition, as Helsinki is a coastal urban city with a less forested environment than commonly found in Finland, it is inevitable that biomass feedstock will need long-distance transportation, either from other parts of Finland or from neighboring countries such as Russia or the Baltic countries. Thus, biomass from areas such as South Savo could provide a timely solution for power industries in Helsinki. This study provides valuable information regarding the environmental performance of torrefied pellets originating several hundred kilometers inland from the power plant and transported using land transportation. However, biomass originating in Finland is not the only possible source and research is required on the environmental performance of biomass imported using marine transportation.

5. Conclusion

This study assessed GHG emissions associated with different supply chain alternatives and a range of raw biomass material for torrefied pellets. GaBi software tool was used for the LCA modeling and different databases and previous literature were used for the lifecycle inventory. The findings of this study were evaluated based on the CML (2001) 2016 version methodology and global warming potential (GWP) was chosen as a sole impact category. Finally, the results were interpreted as kg CO_2 eq. per MWh of pellets delivered to a power plant in Helsinki. The results show that GHG emissions are greatly impacted by the choice of supply chain and raw material. The torrefied pellets of energy wood were found to have significantly higher GHG emissions compared to pulpwood. On the other hand, torrefied pellets of birch (pulpwood) produced in South Savo contribute the lowest GHG emissions in respective supply chain method. Similarly, chipping at plant yard with an electric chipper contributes a lowest GHG burden among the supply chain alternatives. Thus, a significant amount of GHG emissions can be averted by choosing the right raw material for torrefaction. However, the high demand for pulpwood and consequent higher price as compared to energy wood is a major hindrance for pulpwood based pellets in Finland.

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Conflicts of interest
On behalf of all authors, the corresponding author states that there is no conflict of interest.

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