Torrefied wood pellets as an alternative fuel to coal:

Climate benefits and social desirability of production and use

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Abstract

The objective of this thesis is to study the climate impacts and the social returns and social desirability of torrefied wood pellet production and use as an alternative fuel to coal. The raw material of torrefied pellets is forest chips and production and use are assumed to take place in Finland. Climate impacts are assessed with focus on the full fuel chain, or the torrefied pellet life cycle. A brief review of other environmental impacts of the fuel chain is also provided. A socio-economic model is then developed for analyzing how desirable torrefied pellet production and use would be from society's viewpoint when both private profits and climate benefits are taken into account. The model is applied to a hypothetical case where torrefied pellets are produced in Northern Finland and co-fired with coal at Helsingin Energia's cogeneration plant. The purpose of this study is thus to analyze whether co-firing torrefied pellets with coal in combined heat and power production generates social surplus and is socially desirable when both net climate benefits and the private revenue and costs of torrefied pellet production and use are taken into account.

Results show that co-firing torrefied pellets and coal in combined heat and power production leads to a reduction in greenhouse gas emissions compared to a coal-only situation when the life cycle of both fuels is taken into account. In the case studied, torrefied pellet production and use also generates positive social returns. The energy producer's private profits proved to have the greatest impact on net social benefits.

Keywords
Torrefied pellets, torrefaction, climate benefits, life cycle, social desirability, net social benefits

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Tiivistelmä

Tutkielman tavoitteena on arvioida biohiilen eli torrefioidun ja pelletöidyn biomassan tuotannon ja käytön ilmastovaikutuksia ja yhteiskuntataloudellista kannattavuutta, kun sillä korvataan kivihiiltä. Biohiilen raaka-aineena on metsähake, ja tuotannon ja käytön oletetaan tapahtuvan Suomessa. Ilmastovaikutusten tarkastelussa otetaan huomioon koko polttoaineketju eli biohiilen elinkaari. Käsittelen lyhyesti myös ketjun muita ympäristövaikutuksia. Työssä kehitellään yhteiskuntataloudellinen malli, jonka avulla voi tutkia biohiilen tuotannon ja käytön yhteiskuntataloudellista kannattavuutta tilanteessa, jossa sekä ilmastohyödyt että yksityiset tuotot ja kustannukset otetaan huomioon. Mallia sovelletaan hypoteettiseen case-tapaukseen, jossa biohiiltä tuotetaan Pohjois-Suomessa ja poltetaan yhdessä hiilen kanssa Helsingin Energian Salmisaaren yhteistuotantolaitoksella. Työn tarkoituksena on siis tutkia, tuottaako biohiilen ja kivihiilen seospoltto sähkön ja lämmön yhteistuotannossa hyötyä yhteiskunnalle, kun sekä ilmastohyödyt että yksityiset tuotot ja kustannukset biohiilen tuotannosta ja käytöstä otetaan huomioon.

Tulokset osoittavat, että kivihiilen osittainen korvaaminen biohiilellä yhdistetyssä sähkön ja lämmön tuotannossa vähentää kasvihuonekaasupäästöjä, kun molempien polttoaineiden elinkaari otetaan huomioon. Tarkastellussa case-tapauksessa biohiilen tuotanto ja käyttö tuottaa positiivisen hyödyn yhteiskunnalle. Energiantuottajan yksityiset voitot osoittautuivat suurimmaksi yhteiskunnallisiin nettohyötyihin vaikuttavaksi tekijäksi.

Avainsanat
Biohiili, torrefiointi, ilmastohyöty, elinkaari, yhteiskuntataloudellinen kannattavuus

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Muita tietoja

Foreword

This master's thesis has been conducted in co-operation with Helsingin Energia and is related to the company's development projects in the area of renewable energy.

I would like to thank Jussi Kukkonen, Martti Hyvönen, Ari Joona and Jukka Rouhiainen from Helsingin Energia for all their ideas, comments and advice and for providing me important background information. I also wish to thank professor Markku Ollikainen from my department for his help and valuable comments during the process. Last but not least I would like to thank my nearest and dearest for their support and encouragement both in this project as well as in life in general.

Helsinki, December 29, 2011

Kiira Happonen

Abbreviations

CHP	Combined heat and power
CH4	Methane
CO	Carbon monoxide
CO2	Carbon dioxide
CO2-eq.	Carbon dioxide equivalent
EC	European Commission
ECN	Energy research Centre of the Netherlands
EUA	EU Allowance; CO2 emission allowance
GHG	Greenhouse gas
GWP	Global Warming Potential
IEA	International Energy Agency
LCA	Life Cycle Assessment
LHV	Lower heating value
NOx	Nitrogen oxides
N2O	Nitrous oxide
PAH	Poly-aromatic hydrocarbon
RES	Refers to an EU directive on promoting the use of energy from renewable energy sources
SO2	Sulphur dioxide
VOC	Volatile organic compound

Units

MJ	Megajoule
GJ	Gigajoule
PJ	Petajoule
kWh	Kilowatt hour
MWh	Megawatt hour
TWh	Terawatt hour
m3	Cubic metre
% wt.	Weight percent

Contents

1 Introduction

1.1 Background

Global warming is one of the most severe environmental problems of our time. It is a consequence of increased concentrations of greenhouse gases (GHGs) in the atmosphere. The most prevalent of these gases is carbon dioxide (CO2), which is mainly emitted into the air through combustion of fossil fuels (see e.g. Wihersaari 2005a, 435). In 2010, the world's energy-related CO2 emissions hit an all time high, totaling 30,6 billion tonnes and rising by 5,9 % from the previous year (International Energy Agency 2011).

In order to slow down global warming and fight climate change, greenhouse gas emissions must be reduced. Replacing fossil fuels like coal and oil with renewable energy sources could be one part of the solution. Renewable energy options include solar energy, wind energy and fuels made from biomass, among others.

The European Union (EU) has set ambitious targets for reducing GHG emissions and increasing the production of energy from renewable energy sources. The EU is committed to cutting GHG emissions by 20 % from 1990 levels and increasing the share of renewable energy to 20 % of final energy consumption by year 2020. The responsibility for achieving the targets has been divided among member states, and country-specific targets may differ. Finland, for example, is required to raise its renewable energy share to 38 % of final energy consumption, while it is currently around 30 %. The 38 % target also forms the basis of Finland's national climate and energy strategy. Meeting the target requires curbing energy consumption and improving energy efficiency, but also a strong increase in renewable energy production. Finland is, for example, planning to increase the energy use of forest chips from 7,2 TWh in 2006 to 21TWh in 2020. (Ministry of Employment and the Economy 2008.)

To take part in helping meet national emission reduction and renewable energy targets, the city of Helsinki has set climate targets with the objective to reduce GHG emissions by 20 % and increase the share of renewables in energy production to 20 % by year 2020. As a response to this, the city-owned energy company Helsingin Energia formulated a development programme, which presents ways for reducing emissions and increasing renewable energy production. One of the most important means for achieving the targets is co-firing biomass fuels with coal at Helsingin Energia's coal-fired cogeneration plants. Helsingin Energia's biomass fuel options include wood chips, wood pellets and torrefied biomass. (Helsingin Energia 2010.)[1]

1.2 Definition and objectives of the study

The objective of this master's thesis is to study the environmental impacts and social desirability of the production and use of torrefied wood pellets in Finland. Out of environmental impacts, my focus is on climate effects, which are valued and incorporated into the socio-economic analysis.

Torrefaction is a biomass pre-treatment method that involves heating or ”roasting” wood chips or other forms of biomass at a temperature of 200-300 °C. During the process, biomass is completely dried, becomes easily grindable and develops other coal-like properties. The most essential outcome of the torrefaction process is an increase in the calorific value (MWh/t) of the biomass. (Uslu, Faaij & Bergman 2008, 1207; Bergman 2005.) Biomass can be pressed into pellet form after torrefaction. Pelletising increases both the density and energy density (MWh/m3) of the torrefied material. This facilitates transport and storage, as the same amount of energy now fits into a smaller space. (Uslu et al. 2008, 1208; Bergman 2005.). In this thesis, torrefied wood biomass that is in pellet form is referred to as torrefied pellets.

Torrefied pellets could be co-fired with coal for example in combined heat and power production in coal-fired power plants. In Finland, their combustion alongiside coal would require little or no modifications to existing coal boilers, which is a significant advantage over other biomass fuels like wood chips. When it comes to co-firing with coal, torrefied pellets are also a more promising fuel than conventional wood pellets, because the share of the former in the fuel mix could be as high as 50-60 % while the maximum share of conventional pellets in the fuel mix has typically been in the range of 10-20 % (see e.g. Wilen 2011; Flyktman, Kärki, Hurskainen, Helynen & Sipilä 2011, 46).

Biomass fuels are considered to be carbon neutral, because the carbon released upon combustion of these fuels is soon taken up again by growing plants. However, biofuel production generates direct and indirect emissions of CO2 and other GHGs, which

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[1] This study has been carried out in co-operation with Helsingin Energia.

means it is crucial to look at the entire fuel life-cycle when estimating how beneficial replacing fossil fuels with biofuels would be for the climate. (Wihersaari 2005a; Repo, Tuomi & Liski 2010.) In the case of torrefied wood pellets, one should thus look at the whole fuel production chain from forest to power plant. In this study, I define this chain i.e. the torrefied pellet life cycle and assess the climate effects of different stages of the chain in order to determine the potential of torrefied pellets to reduce GHG emissions when used in place of coal.

Biofuels are generally better for the climate than fossil fuels. Replacing coal with torrefied pellets is also likely to lead to GHG emission reductions and thus help mitigate climate change. This does not, however, mean that increasing torrefied pellet production and use would necessarily be optimal from society’s viewpoint. The purpose of this study is to analyze whether co-firing torrefied pellets with coal in combined heat and power production generates social surplus and is socially desirable, when both net climate benefits and the private revenue and costs of torrefied pellet production and use are taken into account. I approach this question through a hypothetical case study, that is by quantitatively analyzing the profitability and social desirability of torrefied pellet production and use in a hypothetical case in which torrefied pellets are produced somewhere in Finland and used in heat and power production at one of Helsingin Energia’s coal-fired cogeneration plants.

The commercial production of torrefied pellets has only recently begun, and no proper market yet exists. Despite this, many energy companies consider torrefied pellets to be one of the most promising wood fuels thanks to their high calorific value and superior properties. One objective of this study is to provide information on the climate effects of torrefied wood pellet production and use, which helps evaluate how ”good” this new fuel is for the climate when compared to other fuels such as coal. Another objective is to develop a model for analyzing the social desirability of torrefied pellet based heat and power production and, like mentioned earlier, to apply it to a hypothetical case. As far as I know, a similar study has not yet been carried out, at least not in Finland. There are other bioenergy-related studies that incorporate environmental effects and private profits into the same analysis, but they have either been conducted from a different point of view or focus on a different fuel. For example, Lankoski & Ollikainen (2008) assessed the social returns and private profitability of bioenergy crop production, but their focus was on agrobiomass and their model somewhat different from mine. Lankoski & Ollikainen (2011) examined whether climate benefits warrant biofuel production when nutrient runoff and changes in the quality of wildlife habitat are accounted for. There are some similarities in our methodology and models, but in addition to being more extensive, their study focused on agrobiomass-based liquid biofuels, which differ from torrefied pellets with regard to environmental and climate impacts.

1.3 Structure of the study

The study is structured as follows. In chapter 2, I take a more profound look at the torrefaction and pelletisation process and the fuel properties of torrefied pellets. I also describe the combined heat and power production process and briefly analyze the current market situation of torrefied pellets.

In chapter 3, I define the torrefied pellet life cycle i.e. the fuel production chain and take a look at the environmental and climate impacts associated with differents stages of the chain. The analysis has been restricted to only cover torrefied pellets made from forest chips.

In chapter 4, I review literature on greenhouse gas and energy balances of wood fuels and attempt to estimate the GHG balance of an average torrefied pellet chain. In the case of biomass fuels, a greenhouse gas balance refers to the GHG emissions produced over the biomass fuel life cycle compared to those of a reference fossil fuel, which in this case is coal. (Cherubini 2010; Wihersaari 2005a). An energy balance on the other hand reveals how much energy the production of a fuel requires.

In chapter 5, I briefly go through the basics of externalities theory, which forms the theoretical basis for my socio-economic analysis. I then develop a model with which I can calculate the social returns of torrefied pellet production and use in heat and power production. The model incorporates the private revenue and private costs of companies involved in torrefied pellet production and use, but also takes into account climate effects of the fuel chain, as both have an impact on social welfare i.e. on how much society as a whole benefits from torrefied pellet production and use. Climate effects are incorporated into the model by assigning them a monetary value.

In chapter 6, I apply the model developed in chapter 5 to a hypothetical case where torrefied pellets are produced in Northern Finland and transported to Helsinki to be co-fired with coal at Helsingin Energia’s coal-fired cogeneration plant. Through this hypothetical case I can get a more concrete estimate of the social desirability of torrefied pellet production and use in Finland.

In chapter 7, I present the results of the case study. I also perform a sensitivity analysis in order to evaluate how a change in the values of key parameters, such as in the prices of electricity and district heat, fuel prices or the monetary value of climate benefits, affects results. In my case study, the volume of torrefied pellet production and use is fixed on an annual level, so in chapter 7 I will also test whether it would be privately and/or socially optimal to increase (decrease) the production and use of torrefied pellets compared to base case volumes.

Finally, in chapter 8, I sum up my main findings, briefly discuss controversies related to the topic and present suggestions on further research in the area.

2 Torrefied wood pellets as an alternative fuel to coal

Torrefaction is a thermochemical treatment process that involves heating or ”roasting” biomass at temperatures of 200-300 °C in the absence of oxygen during which the biomass partly decomposes, giving off different types of volatiles. The final product of the process is the remaining solid, which is referred to as torrefied biomass – or torrefied wood, if produced from woody biomass. During torrefaction a considerable energy densification can be achieved, as the remaining solid typically contains up to 90 % of the initial energy content but only 70 % of the initial weight of the biomass feedstock (expressed on dry and ash-free basis). Biomass is completely dried during torrefaction and its hygroscopic nature changes to hydrophobic. Uptake of moisture after torrefaction is very limited. This implies that biological degradation does not occur anymore. Torrefaction also improves the grindability characteristics of biomass, which can be a great advantage when co-firing with coal in existing coal-fired power stations. (Bergman 2005, 12.) Indeed, due to the increased calorific value, hydrophobic nature and better grindability, the properties of torrefied biomass approach those of coal (Bergman & Kiel 2005, 3).

Torrefied biomass has a low volumetric density, so densification is usually required to facilitate transport and storage of the material. Densification is also desirable because it reduces dust formation and increases the mechanical strength of the product. (Uslu et al. 2008, 1208.) Densification of torrefied material is done through pelletisation. Combining the torrefaction and pelletisation steps results in torrefied pellets, a dense and energy dense biomass fuel with many coal-like properties, such as high bulk and energy density, high calorific value, hydrophobic nature and superior grindability compared to untreated biomass. These properties make torrefied pellets an attractive fuel especially for co-firing in coal-fired power stations. (Bergman 2005, Bergman & Kiel 2005, 3.)

This chapter focuses on the torrefaction process, the properties of torrefied pellets and co-firing of torrefied pellets with coal in combined heat and power (CHP) production. The raw material of torrefied pellets – in this study forest chips – is described in more detail in section 2.1.1. In section 2.4 I will take a look at the current market situation of torrefied biomass and its raw material, forest chips, focusing on the international market in the former and Finnish market in the latter case.

2.1 The torrefaction process

2.1.1. Raw material

Torrefied biomass can be produced from a wide variety of biomass while yielding similar product properties (Bergman & Kiel 2005, 5). Torrefaction can, at least in theory, be applied to all woody and herbaceous biomass i.e. lignocellulosic biomass such as sawdust, wood chips or energy crops. However, the applied technology limits the allowable variation in feedstock properties. This implies that if a torrefaction plant is based on only one type of feedstock, its design can be specific. (Bergman, Boersma, Zwart & Kiel 2005, 29-30.) The type of biomass used has, among other things, an impact on the mass and energy yield of torrefaction (Obernberger & Thek 2010, 104). Mass and energy yields are greater for woody biomass than for straw-based biomass, for example (Flyktman et al. 2011, 31).

In this study I focus on torrefied biomass produced from forest chips, which is a general term for chips made from woody material harvested from forests. There are several reasons behind this choice. First, unlike in the case of certain types of agrobiomass, energy use of forest chips does not cause conflict with food production. Second, use of forest chips does not create pressure to convert existing forest land into fields – land use change effects of this kind are thus avoided. The third and perhaps most important reason is, that in my case study, I assume torrefied pellet production to take place in Finland. Finland’s strategy to meet the renewable energy targets set by the EU RES directive relies heavily on the increasing use of forest chips (Ministry of Employment and the Economy 2008). Finland has large forest resources – it is the most forested country in Europe with over 70 % of the land being forest – so forest chips would be a very relevant raw material for torrefaction if it were to take place in Finland.

Forest chips can be and are currently used in energy production as such, but through torrefaction and pelletisation the properties of the fuel can be enhanced and a significant energy densification is achieved.

In Finland, the main sources of forest chips used in energy production are currently logging residue (branches, top refuse), stumps and small-diameter wood from young stands, which together are typically classified as energy wood (Metla 2011). Chips can also be made from stem wood that would be suitable for wood processing purposes, that is from industrial wood such as pulpwood and logs, but this is currently not encouraged, as the state wants to avoid competition between the energy and forest industries. However, according to some scenarios it is likely that pulpwood will also serve as a source of chips to some extent (see e.g. Elo 2009). Chips are already being made from stem wood, but part of it is imported and its significance as a source for chips has lately decreased (Metla 2011).

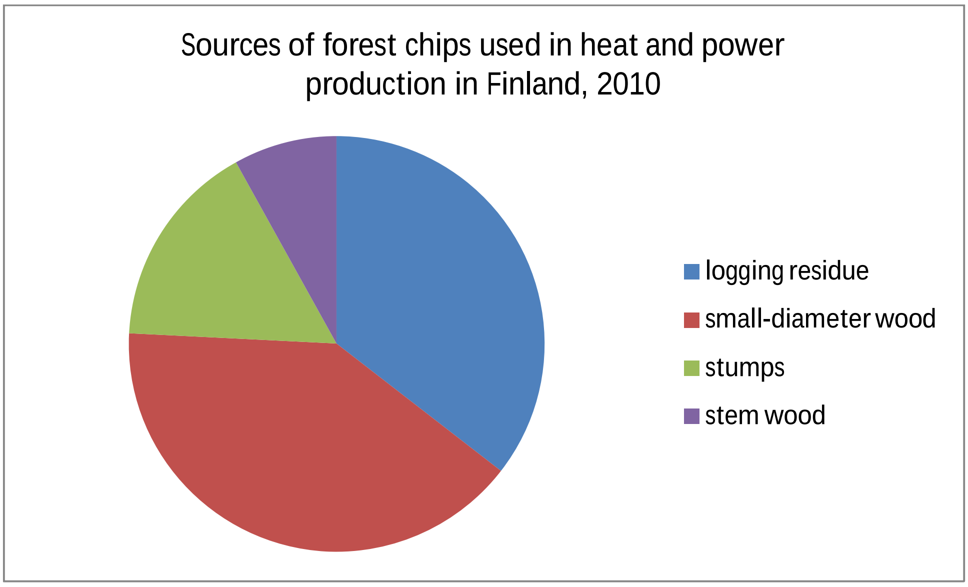

Figure 2.1. Sources of forest chips used in heat and power production in Finland, 2010. Based on Metla (2011).

Forest chips are produced by chipping or crushing woody material. In the process the wood is cut into short, thin wafers. The particle size of chips varies between 3 and 50 millimeters, depending on the raw material and the chipper (Alakangas 2000, 48-55). The moisture content of chips varies between 30-60 percent on weight basis, a typical moisture content being 40-50 %. The moisture content depends on the source of the chips – stumps have a lower moisture content than fresh logging residue – and especially on for how long the biomass has been left to dry on the harvesting site before chipping. The energy content of chips in turn depends on the moisture content: the higher the moisture content, the lower the lower heating value (LHV) which tells us how much energy can be obtained from the fuel upon combustion. The bulk density of chips also depends on their moisture content – the higher the moisture content, the higher the bulk density. Typical ranges for the moisture content, energy content, bulk density and energy density of forest chips are presented in table 2.1.

Table 2.1. Properties of forest chips. Values are based on multiple sources.

	Moisture content % wt.	Mass density, bulk kg/m3	Lower heating value* MJ/kg	Calorific value MWh/t	Energy density, bulk MWh/m3
Forest chips	30-60	250-400	6-13	1,7-3,6	0,7-0,9
Average values used in my study	45		9	2,5	0,8

* = expressed on as received basis

Energy use of forest chips in Finland has rapidly increased in the past 10 years, totaling 6,9 million m3 in 2010. Cogeneration plants and heating plants consume a lion's share of forest chips (6,2 million m3 in 2010), while the rest is used in domestic heating. (Metla 2011.)

There is plenty of energy wood harvest potential in Finland, although harvest potentials as well as the demand for chips differ across areas. Logging residues and stumps are side products of industrial wood fellings, which means the availability of these sources of chips is tied to the timber industry's demand for stem wood. Small-diameter wood is harvested from young stands during thinnings, so its availabilty is not as clearly linked to timber industry activity. Elo (2009, 13) estimated the theoretical harvest potential of logging residue and stumps from final harvests to total 40 TWh in 2020, assuming that industrial wood fellings stay close to current level. However, instead of theoretical potentials, it is better to look at more realistic techno-economic energy wood harvest potentials. The techno-economic harvest potential takes into account that less than 100 % of available forest residue is collected and that residue cannot be collected from all felling sites. The techno-economic forest residue harvest potential, including small-diameter wood, was estimated to be 43 TWh in 2020, which is only 3 TWh larger than the technical harvest potential for logging residue and stumps alone. (Elo 2009, 13.) Although energy wood harvest potentials are rather high, not all of this energy wood is available at reasonable costs. The higher the demand for chips, the higher the production costs tend to become as energy wood harvesting has to be extended further away from the user and to less favourable sites. (Hetemäki, Niinistö, Seppälä & Uusivuori 2011, 42.)

2.1.2 Combined torrefaction and pelletisation

Torrefaction of biomass is a promising pre-treatment technology and several torrefaction process concepts are currently being developed. In my study I will, however, focus on one concept in particular: the ECN approach. ECN (Energy research Centre of the Netherlands) is one of the pioneers in research and development of combined torrefaction and pelletisation (Obernberger & Thek 2010, 106). In this section I will describe the basic combined torrefaction and pelletisation process as developed by ECN, closely following the works of Bergman (2005) and Bergman et al. (2005).

Like mentioned earlier in this chapter, torrefaction is a thermal pre-treatment method that improves the fuel properties of biomass and makes it more suitable for e.g. co-firing with coal. When combined with pelletisation, torrefaction results in energy-dense pellets with a high calorific value and other desirable properties such as a hydrophobic nature and improved grindability characteristics compared to untreated biomass.

The torrefaction and pelletisation process consists of six steps: pre-drying, post drying and intermediate heating, torrefaction, size reduction, densification (pelletisation) and cooling. The process is outlined in figure 2.2.

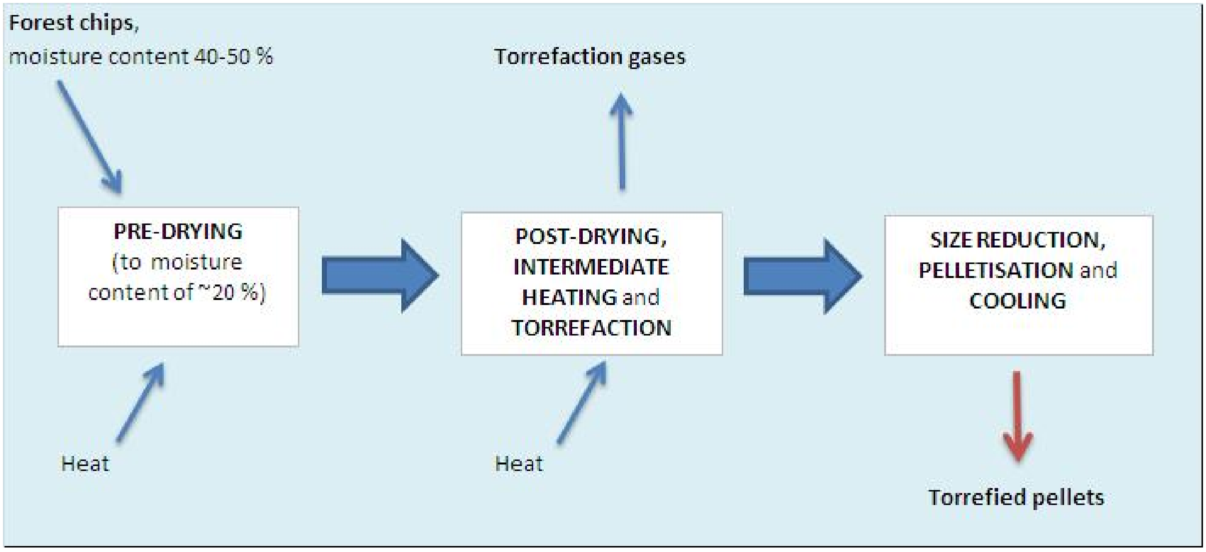

Figure 2.2 The combined torrefaction and pelletisation process.

Pre-drying is usually necessary for feedstocks with a high moisture content, such as forest chips. The purpose of pre-drying is to lower the moisture content of the feedstock to around 20 % before it is fed into the actual drying and torrefaction reactor (Novox

2010, 6). Of all process steps, pre-drying has the largest heat demand, unless the initial moisture content of the feedstock is low (Bergman et al. 2005, 17).

The next steps, intermediate heating, post-drying and torrefaction, take place in oxygen-free conditions. During intermediate heating and post-drying, the temperature of the biomass is steadily increased until it reaches the desired torrefaction temperature. During this step, physically bound water is released and the biomass completely dried. (Bergman et al. 2005, 17.) Torrefaction begins when the temperature exceeds 200 °C. It is the step where biomass is actually torrefied or ”roasted” at temperatures of 200-300 °C. During torrefaction the biomass partly decomposes, giving off various types of volatiles. It loses relatively more oxygen and hydrogen compared to carbon, which leads to an increase in calorific value on mass basis. (Bergman 2005, 12; Bergman et al. 2005, 17-20.) The remaining solid, referred to as torrefied biomass, contains up to 90 % of the initial energy content of the biomass but only 70-80 % of the initial mass. 20-30 % of the mass and roughly 10 % of the energy content of biomass are converted into torrefaction gases during the process. The higher the energy conversion to the final product, the lower is the energy content of torrefaction gas and vice versa. (Bergman 2005, 17; Flyktman et al. 2011, 31.) Ash is inert in the torrefaction process and thus remains in the produced solid (Bergman et al. 2005, 44). Figure 2.3 presents the typical mass and energy balance of the ECN torrefaction process.

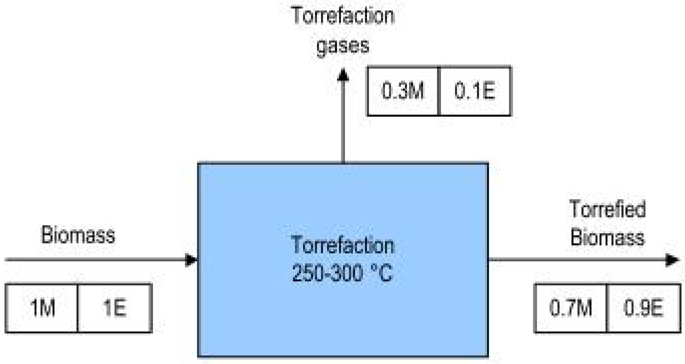

Figure 2.3 Typical mass and energy balance of the torrefaction process, expressed on a dry and ash-free basis. Source: Bergman (2005, 12).

Although torrefaction leads to a higher calorific value on mass basis, it does not increase the volumetric energy density of the biomass much. Combining torrefaction with a densification step, pelletisation, significantly increases the volumetric energy density of the torrefied product, which in turn facilitates transport and storage, leading to savings in logistics. Pelletisation also reduces dust formation and increases the mechanical strength of the product. (Bergman 2005, 13; Uslu et al. 2008, 1208.) Like in the process of conventional pelletisation, torrefied biomass undergoes size reduction before pelletisation. During the actual pelletisation step, biomass is pressed into pellets (see figure 2.4). After pelletisation, the produced torrefied pellets are cooled and stored or transported to the end user.

Figure 2.4. Torrefied pellets. Source of picture: ECN.

The heat demand of the drying and torrefaction processes can – at least partially – be met through combustion of the liberated torrefaction gas. The system is thus self-supporting at least to some degree. Torrefaction gases consist of organic compounds, water, CO and CO2. If the energy content of torrefaction gas is sufficient to balance the heat duty of drying and torrefaction and heat losses encountered elsewhere in the process, the process is autothermal and fully self-supporting. If autothermal operation is not possible, a utility fuel is required to produce the rest of the heat that the process requires. (Bergman et al. 2005, 26; Bergman 2005, 15.) Flyktman et al. (2011, 31) note that combustion of torrefaction gas produces enough energy to run the torrefaction process, but auxiliary energy is needed when pre-drying wet biomass. A utility fuel is also needed to get the process running. However, even in cases where auxiliary energy and a utility fuel are needed to thermally balance the whole process, torrefaction gases satisfy a major part of the total heat requirement. The possibility to utilize torrefaction gases for heating the process both greatly reduces the utility fuel consumption of the process and leads to high process efficiency. Bergman (2005) and Uslu et al. (2008, 1208) report high, over 90 % efficiencies for the ECN torrefaction process. Process energy efficiency is an important aspect when evaluating pre-treatment technologies.

Size reduction and pelletisation require electricity, so the energy demand of these process steps cannot be met through combustion of torrefaction gas. However, Bergman (2005, 16) observed that the power consumption of size reduction is dramatically reduced when the biomass is first torrefied compared to size reduction of untreated biomass. This reduction in power consumption can be as high as 70-90 %.

The torrefaction plant can either be a stand-alone facility or integrated to, for example, an existing power plant. Flyktman et al. (2011, 31) argue in favor of an integrated facility – this way the auxiliary energy needed for pre-drying can be taken from e.g. the combustion gases of energy production processes and torrefaction gas can in turn be used to fuel up these processes. Bergman et al. (2005, 27) also see the possibility to use heat from the power station for drying and torrefaction operations as an advantage. Moreover, this means that one does not need to build a separate boiler for burning the utility fuel and liberated torrefaction gas as would be the case with a stand-alone torrefaction plant (Novox 2010, 14). Integrating a torrefaction facility to a condensing power plant might be especially interesting, since the heat that usually goes to waste in condensing power production could then be used for running the torrefaction process – no extra heat would need to be produced. Despite potential benefits, not everyone is fully in favour of integrated torrefaction plants: Bergman et al. (2005, 27) argue that through heat integration, torrefaction and the power station become highly dependent on each other and perturbations in the operation of one could influence the operation of the other. Also, if the power plant supplies heat for torrefaction in the form of steam, it has a negative although minor impact on the plant’s steam capacity and thus electrical output.

2.2 Fuel properties

In the words of Bergman & Kiel (2005, 3), ”The application of torrefaction as a new pre-treatment technology is only interesting when it leads to a reduction of costs of the overall biomass-to-energy production chain.” In this section I will take a closer look at the fuel properties of torrefied pellets, which give insight into why torrefied pellets could potentially be a superior biomass fuel compared to e.g. wood pellets or forest chips and lead to cost savings in the biomass-to-energy chain on a per MWh basis.

The drawbacks of biomass as a fuel alternative to coal and other fossil fuels are mainly attributed to its low energy density, high moisture content and heterogeneity (Obernberger & Thek 2010, 1). Low energy density implies that transportation costs per energy unit are high and that more storage space is needed, making biomass logistics costly. A high moisture content decreases the calorific value of biomass and thus the amount of energy that can be obtained from it upon combustion. The wetter the biomass, the lower the calorific value and the fuel quality – combustion of such fuels adversely affects power plant efficiency (Bergman 2005, 24). The heterogeneity of biomass can also cause problems in the final conversion stage.

Wood pellets are often seen as a solution to some of the major drawbacks of using biomass as an alternative fuel. Wood pellets have a higher energy density, higher calorific value and lower moisture content than for example forest chips or untreated biomass. Like torrefied pellets, they are also uniform in size and more homogenous regarding fuel quality. Wood pellets are made up of small particles, and can, unlike biomass of larger particle size, be readily crushed in coal mills – the resulting particles can be fed into pulverised burners just like coal powder (Bergman 2005, 9).

However, there are also some drawbacks to pellets. Despite their lower moisture content, wood pellets retain the hygroscopic nature of wood and are thus still vulnerable to water, although to a lesser extent than chips and other untreated biomass. The possibility of biological degradation can cause storage issues and implies that special precautions need to be taken in the logistics chain in general. Another drawback is that pellet production has traditionally been limited to only few types of feedstock, mainly sawdust, cutter shavings and bark, which are by-products of the wood processing industry, although lower-quality industrial pellets that are suitable for large-scale use can also be made from forest chips and other types of wet biomass. The potential feedstock base for torrefied pellets is currently larger than that of wood pellets, and does not rely as heavily on the wood processing industry. (Bergman 2005, 11; Flyktman et al. 2011, 29.)

When it comes to biomass, one of the greatest drawbacks of both wood chips and conventional pellets is that their share in the fuel mix when co-firing with coal will remain small, up to around 10-15 % of the fuel mix, unless substantial modifications are made to the existing coal infrastructure (see e.g. Flyktman et al. 2011, 4). For torrefied pellets, the co-firing ratio could be as high as 50 % (see e.g. Flyktman et al. 2011, 46). Quoting Obernberger & Thek (2010, 105), ”If normal pellets are to be utilised for combustion or co-firing in coal power plants, substantial modifications have to be carried out, such as creating storage facilities and separate transport, milling and feeding lines, and these would be very expensive.” According to research such modifications might not be necessary for torrefied pellets, which can, at least in theory, be stored on the coal yard and milled and fed together with the coal (see e.g. Obernberger & Thek 2010, 105). Being able to use the plant’s existing coal infrastructure for torrefied pellets would be ideal, as it would enable the energy producer to reach a high biofuel share at low additional costs. Even though the on-site handling properties of torrefied pellets seem promising, more experience of how co-milling torrefied pellets affects the coal mill and of the storage behaviour of torrefied pellets is still needed to fully back up these assumptions. But, even if torrefied pellets were to require similar technology that is used for co-firing conventional pellets at higher ratios, the additional investments and operational costs would be roughly 30 % smaller due to lower volumes for the same thermal capacity (Bergman 2005, 24).

Table 2.2: A comparison of the fuel properties of forest chips, wood pellets, torrefied biomass, torrefied pellets and bituminous coal. Values are based on multiple sources. Values in italics are average values used in my case study.

	FOREST CHIPS	WOOD PELLETS	TORREFIED BIOMASS	TORREFIED PELLETS	BITUMINOUS COAL
Moisture content (% wt.)	30-60 *45*	7-10	3	1-5 *max 5*	5-10
Mass density, bulk (kg/m3)	250-400	600-650	230	750-850 *750*	800-1000
Lower Heating Value (as received, MJ/kg)	6-13 *9*	16,2	19,9	19-22 *21*	25+
Calorific value (as received, MWh/t)	1,7-3,6 *2,5*	4,5	5,5	5,2-6,2 *6*	7
Energy density, bulk (MWh/m3)	0,7-0,9 *0,8*	3	1,3	4,2-5 *4,8*	5,6-7
Hygroscopic nature	water uptake	swelling/ water uptake	hydrophobic	poor swelling/ hydrophobic	hydrophobic
Biological degradation	possible	possible	impossible	impossible	impossible

Table 2.2 compares the fuel properties of forest chips, conventional wood pellets, torrefied biomass, torrefied pellets and coal. As we can see from the table, torrefied pellets are a superior fuel compared to chips and wood pellets with regard to calorific

value, energy density, moisture content and degradability. The properties of torrefied pellets approach those of coal.

We have seen that combined torrefaction and pelletisation produces an energy dense biomass fuel with properties similar to those of coal. The high calorific value and high energy and bulk densities of torrefied pellets may lead to significant cost savings in the biomass-to-energy chain compared to state-of-the-art biofuel chains, especially in logistics (see e.g. Bergman 2005; Uslu et al. 2008). It is easy to see why: the higher the energy density of a fuel, the more energy a truckload, a trainload or a shipload of that fuel contains. At the same time less storage space is required, that too leading to cost savings. However, in practice the high bulk density of torrefied pellets limits utilisation of the full carrying capacity of a train or truck. A high energy density also brings along other benefits: it improves the functionality and decreases the energy use of conveyors and mills at the combustion plant (Flyktman et al. 2011, 33).

In addition to the possible savings in logistics that can be achieved when switching from untreated biomass or conventional pellets to torrefied pellets, superior grindability is often said to be one of the key properties that makes torrefied biomass and torrefied pellets so attractive for co-firing in existing coal-fired power stations. Section 2.3.2 explains the importance of good grindability characteristics.

The very low moisture content of torrefied pellets facilitates storage, as no or only limited uptake of water will occur. This also implies that storage periods can be longer than those of chips, for example, although potential spontaneous ignition properties of torrefied pellets might limit storage options. In addition to facilitating storage, the low moisture content of torrefied pellets is expected to lead to decreased stack losses and a higher power plant efficiency compared to wood pellet co-firing (Bergman 2005, 24).

Despite their many good fuel properties, torrefied pellets are still a new fuel, and, unlike in the case of chips and wood pellets, there is not yet much experience of their large-scale use, logistics et cetera. The future will show whether torrefied pellets prove to be as good a fuel in practice as on paper.

2.3 Biomass co-firing

Co-firing refers to the simultanious use of two or more fuels in the same furnace or boiler. Co-firing biomass with fossil fuels is one way to reduce the greenhouse gas emissions of existing power plants. This section describes the combined heat and power production process and explains how biomass co-firing can be carried out in a coal-fired power station. Cogeneration and direct or indirect biomass co-firing is also possible in for example peat- or gas-fired power plants, but as this study deals with torrefied pellets as an alternative to coal, I will solely focus on coal-fired power plants. Indeed, a great majority of biomass co-firing worldwide is carried out in pulverized coal power boilers (Van Loo & Koppejan 2008, 206).

2.3.1 The combined heat and power production process

Combined heat and power (CHP) refers to an energy production system that simultaneously or sequentially generates electric energy and utilizes the thermal energy that is normally wasted (International Energy Agency 2007). The thermal energy (heat) can be utilized in district heating or as process heat in industrial operations.

Combined heat and power production has many benefits over seperate heat generation and condensing power production. In CHP production, up to 90 % of the energy content of the fuel is converted into useful energy in the form of electricity and heat. In condensing power production this ratio would be as low as 40 %. When the energy content of the fuel is more fully utilized, the carbon dioxide and other emissions per unit of useful energy are smaller. According to the International Energy Agency, Finland is a world leader in combined heat and power with high levels of both district heating and industrial CHP (International Energy Agency 2008). In Finland, nearly 80 percent of district heating and roughly one third of electricity production is based on combined heat and power production (Finnish Energy Industries 2011).

Figure 2.5 illustrates the combined heat and power production process in a cogeneration plant using coal or other solid fuels. Fuel is fed into burners at the bottom of the boiler. There are pipes in the boiler that have water in them. Combustion of the fuel generates thermal energy that turns this water in to steam. The enthalpy of the steam then translates into mechanical energy of the turbine, which in turn turns the generator. The generator, located on the same axel with the turbine, converts energy into electricity. Electricity is transmitted to the electricity grid through transformers. After turning the turbine, the steam is further led into heat exchangers, where the thermal energy remaining in the steam warms up cool water that is returning from the district heating network. As a consequence, the steam condenses back to water and is ready to be used in the cogeneration process again. The water that was heated in the heat exchangers is led back to the district heating network.

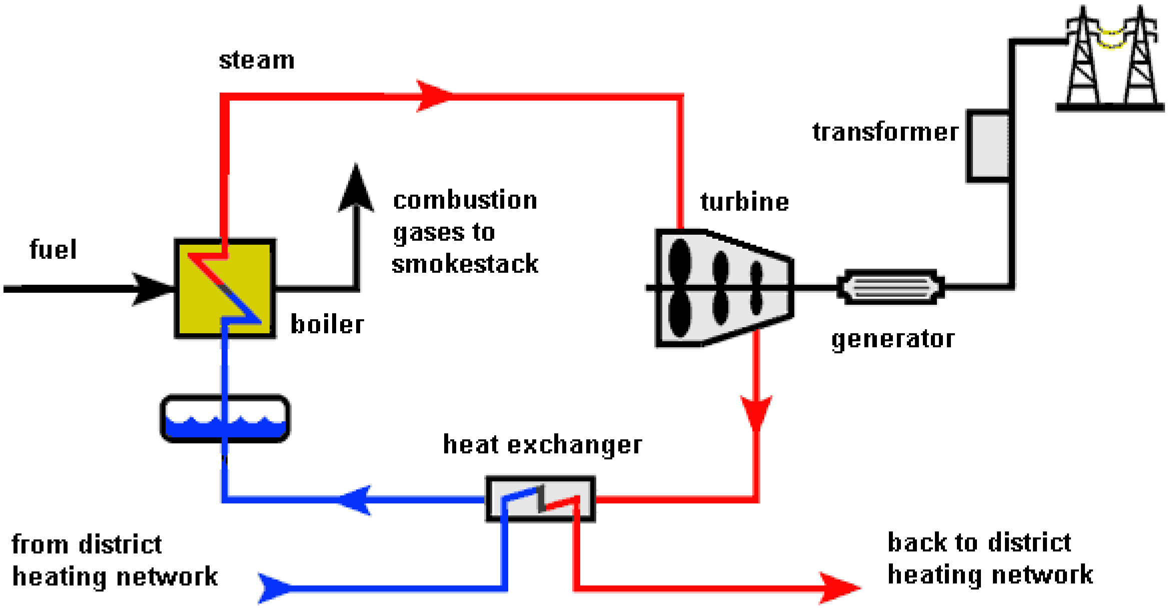

Figure 2.5. The combined heat and power production process.

2.3.2 Co-firing with coal

There are different coal combustion technologies. One common technology is pulverized coal combustion, which is in use in several coal-fired cogeneration plants in Finland as well as in the power plant that is the end user of torrefied pellets in my case study. In pulverized coal boilers, the coal is first ground into fine powder in coal mills. A mixture of air and pulverized coal is then blown into the burners at the bottom of the boiler. Combustion generates thermal energy which turns water into steam. The enthalpy of the steam then translates into mechanical energy of the turbine which turns the generator, and so on. (Flyktman et al. 2011, 37.) Knowing that combustion of solid fuels in pulverized coal burners requires the fuel to be ground into very fine particles, it is easy to understand why good grindability is a desirable property for a solid fuel that is co-fired with coal.

Biomass can be co-fired with coal either directly or indirectly. Direct co-firing involves direct feeding of biomass into the coal firing system whereas indirect co-firing involves gasification of the biomass and then combustion of the product fuel gas in the boiler. (Van Loo & Koppejan 2008, 206.)

The simplest option for direct co-firing is to mix the biomass fuel with coal before the fuel enters the coal feeders. The mixed fuel is then processed through the coal milling and feeding system. This approach has been applied when co-firing biomass that is in granular, pelletized or dust form. Co-firing ratios have generally remained relatively low. (Van Loo & Koppejan 2008, 207.) This simple and least costly form of direct co-firing could be applied to torrefied pellets as well, but at a relatively high co-firing ratio like 50 %. The so called design values of the boiler have an impact on the maximum amount of coal that can be replaced with torrefied pellets or other biofuels without major decreases in plant output and efficiency and the power-to-heat ratio (Flyktman et al. 2011, 46, 57). At very high torrefied pellet shares there is also potential for boiler slagging and corrosion, which may limit the maximum bio share in co-firing (Wilen 2011, 3; J. Kukkonen, personal notification 7.10.2011).

The biomass fuel can also be handled and comminuted seperately from the coal and injected into the pulverized fuel pipework upstream of or at the burners. This option can allow for higher shares of the biomass fuel in the fuel mix, but also requires some modifications to the system and thus raises costs when applied in existing coal power stations. (Van Loo & Koppejan 2008, 207.) This would be the co-firing option for torrefied pellets if it were to turn out that in practice they are not suitable for co-milling and co-feeding with coal.

The third and most expensive option for direct biomass co-firing involves seperate handling and comminution of the biomass but also combustion through a number of dedicated burners. This approach would require significant modifications to the combustion equipment and furnace. (Van Loo & Koppejan 2008, 207.)

The side product of solid fuel combustion is ash. When biomass and coal are co-fired directly, coal and biomass ashes mix together, resulting in so called mixed ash. Separate coal and biomass ashes can be re-used to a certain extent – coal ash, for example, can be used in cement production or for earthwork purposes. It is unclear whether mixed ash can be re-used to the same extent – this is a potential downside of direct co-firing.

Biomass can also be co-fired indirectly. This approach involves gasification of the biomass. The resulting product gas is then burned directly in the coal-fired furnace. The calorific value of the product gas depends on the moisture content of the biomass fuel, and pre-drying is usually necessary for wet biomasses with a 40-50 % moisture content. Gasification can be seen as a form of biomass fuel pre-treatment. Indeed, through gasification the otherwise low shares of biomass fuels such as wood chips or wood pellets in co-firing can be increased. The quality requirements for biomass are also lower in gasification than in direct co-firing. Another potential benefit is, that in indirect cofiring, the biomass and coal ashes remain partially separate. However, investing in a gasifier is costly. That is why direct cofiring is preferred at least in the case of torrefied pellets. (Flyktman et al. 2011, 41; J. Kukkonen, personal notification 7.10.2011.)

2.4 Current market situation and competing use

The demand for biomass-derived fuels is growing globally as countries try to find ways to curb greenhouse gas emissions and reduce fossil fuel dependency. In Europe, the RES directive and targets for renewable energy production and use are also expected to increase the demand for biofuels in both liquid, solid and gaseous form.

Torrefaction is a technology that has only recently begun to become commercially available. It is not yet applied in a large scale, although there are several demonstration plants in operation and commercial production is also starting with several full-scale torrefaction plants being built or planned on both sides of the Atlantic (see e.g. Jalonen 2011, 7). When torrefied pellets become commercially available, there is potential for high demand because of their attractive fuel properties, especially if experiences of their large-scale use are positive. It is, however, difficult to say what the market price will be, as a market for torrefied pellets does not yet exist. For example, Flyktman et al. (2011, 6) provide an indicative price estimate of 35 €/MWh, but note that there is still considerable uncertainty related to the price level. The torrefied pellet price is commonly expected to be close to the price of conventional pellets on a per MWh basis. For reference, pellet prices in Finland have been in the range of 35-36 €/MWh in 2011 (Pöyry 2011a). The relative prices of torrefied pellets and other fuels will naturally have an impact on torrefied pellet demand.

In Finland, the demand for forest chips has grown substantially in the past 10 years (Metla 2011). At the same time chip prices have increased from less than 10 €/MWh in 2000 to the current level of around 18 €/MWh (Pöyry 2011a). Chip demand is driven by users’ interest in renewable energy, the prices and availability of other fuels, especially peat, and the EU emission allowance price whereas supply is dependent for instance on the level of industrial fellings and forest owners’ willingness to sell energy wood (see e.g. Elo 2009).

Power, heat and cogeneration plants are not the only ones interested in torrefied pellets, forest chips or energy wood in general. For example, in Finland, several companies have either publicly presented plans for starting up a biorefinery that would refine forest-based biomass into liquid biofuels, or have at least been considering a biorefinery investment (see e.g. Seppälä 2011). When it comes to wood in general, another source of competing use is, of course, the traditional forest industry.

3 The fuel production chain and its environmental impacts

In this chapter I define the torrefied pellet production chain (life cycle) from the forest to the end user. I will then discuss the environmental impacts – both positive and negative – of the whole chain.

3.1 Definition of the chain

In this section I define the torrefied pellet fuel chain, or, in other words, the torrefied pellet life cycle. It is crucial to define the fuel chain properly in order to undestand at which stage costs, benefits and environmental impacts arise.

In this study, the torrefied pellet fuel chain is assumed to be based in Finland and the end user of the torrefied pellets is assumed to be a coal-fired power plant. Forest chips are assumed to be the raw material of torrefied pellets. Thus, the fuel chain begins in the forest. The term *forest chips* covers all kinds of chipped woody material that comes from the forest, such as branches, stumps and other forms of logging residue, small-sized trees and stem wood.

The first stage of the chain or life cycle depends on the source of chips. Logging residue and stumps are leftovers of industrial timber harvesting and small-diameter wood is usually cut down in thinnings whether or not it is used for energy. Thus, logging residue, stumps and small-diameter wood that is not suitable for industrial use are all forms of forest residue. (Soimakallio et al. 2010, 56.) For such residue, the fuel chain is thought to begin from the residue collection stage, or felling stage when speaking of small-sized trees. If chips are produced from something else than residue, i.e. from full-grown stem wood that is the main product of forestry, the fuel chain should also include the stem wood production stage i.e. cultivation, tree planting and forest management and the associated impacts (see e.g. Soimakallio et al. 2010, 21; Mäkinen, Soimakallio, Paappanen, Pahkala & Mikkola 2006, 25).

Felling and logging residue collection procedures depend on the type of wood being harvested. Small-diameter wood can be harvested either as whole trees or trimmed poles. Harvesting of small-diameter wood can be integrated to industrial wood felling processes. (Kärhä, Mutikainen, Keskinen & Petty 2010.) Removing stumps from the ground requires rather heavy machinery like a clamp that is attached to an excavator.

The next stage of the chain is usually the intermediate storage stage. One of the most challenging tasks in biomass harvesting is how to manage the storage of the material so that material losses due to degradation can be avoided. From a fuel properties point of view it would be optimal to cut the tree stands in early spring and let the residues dry naturally on the site or roadside until early autumn, and then use the fuel when its moisture content is lowest. In practice this is usually not possible due to structures of industrial wood and energy demand. This leads to a need to store forest residue either before or after chipping (or both). (Wihersaari 2005b, 445.) Biomass is usually stored in heaps at the roadside near the felling site. The heaps can be covered to protect them from snow, water and freezing. The conditions at the intermediate storage site, such as windiness and openness, also affect the moisture content of the heap. (Äijälä, Kuusinen & Koistinen 2010, 26.)

Chipping can be done at the roadside, in a terminal or at the end-use site. Chipping at the roadside, also called the intermediate storage site, can be done either using a seperate chipper and transportation truck or an integrated chipper and chip truck, the first approach being far more common. The chips are then transported to the end user. If chipping is done in a seperate terminal, the harvested forest residue or wood is first transported to the terminal, chipped, and then further transported to the end user. Depending on the location of the terminal, transportation to the end user can even be done by train or ship whereas in the roadside chipping chain long distance transport is generally done by truck. If the end user is not located very far from the harvesting site and is equipped with adequate storage space and chipping machinery, harvested wood and residue can also be transported straight to the end user who then takes care of the chipping. (Kärhä 2010.)

Out of the three chip production chains described above, the roadside chipping chain has been and still is the most common chain in Finland for logging residue and small-diameter wood. Stumps, on the other hand, usually undergo crushing either at the end use site or in a terminal. Earlier there existed also a fourth chip production chain, chipping at the harvesting site, but it is not used anymore in Finland. It is difficult to say which chip production chain is the best. Factors such as the source of chips, availability of roadside storage space, tranportation distances and the volume of chip production determine which chain is the most appropriate in each situation. (Kärhä 2011).

In the torrefied pellet production chain, the end user of the chips is the torrefaction plant. It is assumed in this study, that the torrefaction plant buys the chips from a chipping company that has in turn bought the energy wood or the right to harvest the energy wood from forest owners.

When chips are delivered to the torrefaction plant, they are stored in, for example, a silo. They then undergo the torrefaction and pelletisation process, which consists of pre-drying, drying, torrefaction, size reduction, pelletisation and cooling. A description of the torrefaction and pelletisation process was provided in section 2.1.2.

If the torrefaction plant is not integrated to a power plant that uses torrefied biomass as a fuel or if the power plant does not use the whole output of the torrefaction plant, the produced torrefied pellets need to be transported to the end user. Transportation can happen by truck, train or ship, depending on the location of the torrefaction plant and also on transportation distances. In Finland most coal-fired power plants (which are also potential users of torrefied pellets) are located on the coast, making sea transport an attractive option. Sea transport also allows to make the most of the high mass and energy density of torrefied pellets, whereas the maximum carrying capacities of trains and trucks are more restricted so that the full volume of the carrier cannot be utilized when transporting material with a very high mass density.

Depending on the volume of torrefied pellets that the energy producer uses, intermediate storage of torrefied pellets may be necessary somewhere along the chain – especially if the power plant’s own fuel storage space is limited. Torrefied pellets can be stored in silos, or, if they are hydrophobic enough, outdoors on a coal yard, for example.

At the end of the chain, the energy producer (power plant) co-combusts the torrefied pellets with coal. The effects of co-combustion on the GHG and other emissions of the power plant are discussed in more detail in the following chapters. The life cycle of torrefied pellets does not end at the combustion stage: ashes created in the combustion process are a side product that needs to be dealt with one way or another. Coal ash can either be re-used or delivered to a landfill. It is possible that mixed coal and biomass ash cannot be re-used the same way that pure coal ash can. This poses potential problems.

Figure 3.1 summarizes the key stages of the torrefied pellet fuel chain, or life cycle.

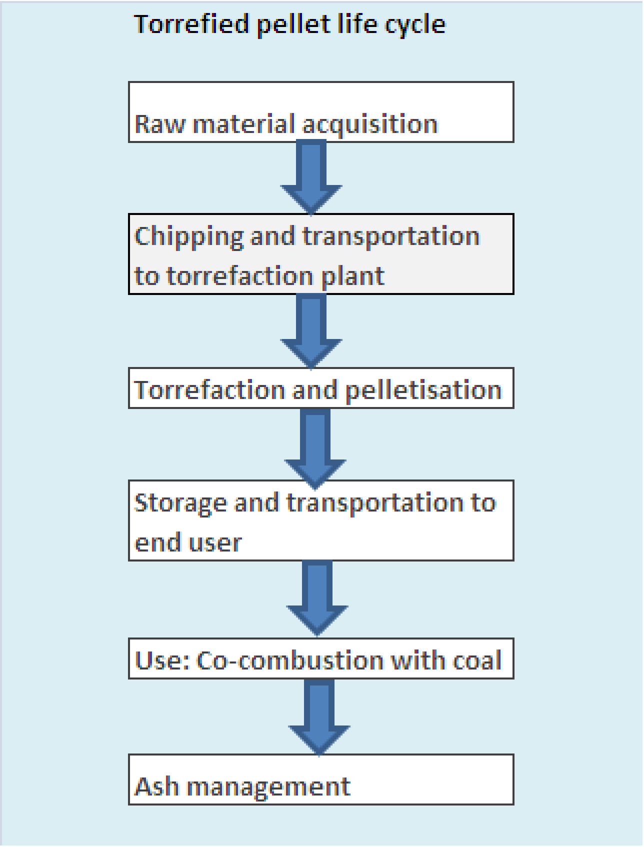

Figure 3.1. Torrefied pellet production and use chain with forest chips as the raw material of torrefied pellets.

3.2 Environmental impacts of torrefied pellet production and use

When assessing the environmental impacts of a fuel, it is important to look at the full fuel chain, also known as the life cycle of the fuel, instead of only parts of the chain like fuel processing or conversion to energy. Focusing on the full chain is the only way to understand the overall impact that the production and use of a fuel has on the environment. There are environmental impacts related to each stage of the torrefied pellet chain described in section 3.1. I will now discuss the environmental impacts of the chain stage by stage.

In Finland there has lately been lots of discussion about the environmental and climate impacts of forest residue[2] removal from forests. The increasing demand for energy

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[2] General term for logging residue, stumps and small-diameter wood from thinnings.

wood has raised concerns about the effects of residue removal on forest ecosystems and especially the forest carbon balance. Stump removal has become an particularly controversial subject. For these reasons, discussion about the environmental pros and cons of wood-based fuel use often focuses on what happens in the forest. The felling and residue collection stage will thus be a special area of interest in this chapter as well.

Production of raw material

If the source of forest chips is stem wood instead of forest residue, the environmental impacts of the raw material production stage, not only fellings, should be accounted for when assessing the fuel chain. Typical phases of raw material production in the case of wood are cultivation of forest land, planting the trees, managing the forest during its growth, thinnings and possible fertilisation. These activities require auxiliary energy and commodities, which leads to GHG and other emissions. They also affect the forest environment. (Soimakallio et al. 2010, 68.)

In this study, I assume that the raw material of forest chips is mainly forest residue, and thus I will focus more on the environmental impacts of residue removal than of stem wood production.

Felling stage: impacts of forest residue removal

Normally, when forest is cut down, logging residue is left at the felling site. Some fear that removal of logging residue will take valuable nutrients away from the forest, or disturb the nutrient balance of forest soil and weaken its productivity. This might lead to a need for fertilizer use or weaken the growth of the new generation of trees that grows on the site. (See e.g. Antikainen et al. 2007, 51.) Excessive nutrient loss can be effectively avoided if logging residue is left to dry on-site before use (Äijälä et al. 2010, 19). This way most of the needles and leaves that also contain most of the nutrients will drop and be left on the site to prevent nutrient loss.

According to Antikainen et al. (2007, 51) there is a possible risk of nutrient and particle matter leaching and erosion related to stump removal. This is due to the nature of the stump removal process, which leads to cultivation of forest soil. The risk of erosion and leaching is smaller for removal of other logging residue such as branches – actually logging residue removal from clear-cut sites might even reduce nutrient leaching from the site (Antikainen et al. 2007, 51).

Energy wood harvesting can have both positive and negative effects on species diversity. However, the overall impact on forest biodiversity may be slightly negative. There are concerns that energy wood harvesting further reduces the amount of decaying and dead wood, which are vital for certain forest species. Especially stump removal can be problematic from the biodiversity viewpoint as stumps make up a part of the already inadequate large-size rotten wood resource in Finnish forests. (Antikainen et al. 2007, 55.) In Finland, the decline in the amount of decaying and dead wood in forests is the most important single reason that causes forest species to become endangered. (Äijälä et al. 2010, 20). It is also possible that increased forest access disturbs wildlife or harms residual trees (Lattimore, Smith, Titus, Stupak & Egnell 2009, 1330).

The forest residue removal stage has both a direct and indirect effect on the climate. The machines used for collecting logging residue, removing stumps and cutting down small-diameter wood run on diesel fuel, and thus emit GHGs and other emissions to air. What about the indirect emissions then? When biomass is collected from the forest for energy use and burned, the forest soil carbon stock decreases by the amount of carbon that the removed residue would contain had it been left to decompose in the forest (Liski et al. 2011, 16). This decrease in forest soil carbon stock is, from the climate viewpoint, analogous to a carbon emission. When biomass is burned, the carbon it contains is immediately released into the atmosphere as carbon dioxide. The carbon would eventually be released through natural decomposition even if the biomass had been left in the forest, but this would happen gradually in the course of decades. For example, Liski et al. (2011, 15) note, that after 20 years of being left in the forest to decompose, 25-29 % of spruce branches, 47-56 % of small-diameter wood from thinnings and 66-74 % of stumps had not yet decayed.

The decrease in forest soil carbon stock that forest residue removal for energy use causes means, that, at least in a short time horizon, the use of wood-based fuels in place of fossil fuels does not reduce carbon dioxide emissions as much as one may think. It is, however, important to note, that the longer the time horizon, the smaller is the decrease in forest carbon stock as carbon would have been released through natural decomposition anyway. The magnitude of changes in forest soil carbon stocks and how they affect the life-cycle GHG emissions of forest chips is discussed in more detail in chapter 4.

Intermediate storage stage

Harvested forest residue is usually stored outside in heaps at some point either before or after chipping because the demand and supply of forest chips do not always coincide. Storage of chips is a potential source of GHG emissions because of decomposition reactions that take place in storage heaps. For example, Wihersaari (2005b, 444) found that rather great amounts of greenhouse gases, namely methane and nitrous oxide, may be released during storage of wood chips, especially if there is rapid decomposition in the heap and if storage times are long. Emissions from storage are, however, difficult to measure and monitor.

Decomposition during storage also leads to material and thus energy losses. The rate and speed of decomposition reactions depend on many factors, such as the moisture content of the stored material, chip size and circumstances inside the heap. The higher the moisture content of the stored material, the higher the material losses tend to be. In order to avoid material losses and emissions from storage, chipped forest residue should be used as soon as possible, preferably within a week. (Wihersaari 2005b, 447-451.)

One aspect that should be considered when storing forest residue on roadsides is the possibility of nutrient leaching. Sometimes residue storage heaps leave behind lots of needles and leaves and thus a considerable amount of nutrients. (Vanhatalo 2011, 10.)

Chip production and transport stage

Chip production and transport generates GHG and other emissions. These are both direct emissions from diesel fuel use in roadside and terminal chipping and transportation and indirect emissions from the production of electricity needed for crushing or chipping at the end use site. (Wihersaari 2005a, 439.)

Torrefaction and pelletisation stage

Although the heat demand of the torrefaction process (including the pre-drying phase) can be partially met through combustion of liberated torrefaction gas, an additional heat input is usually required to keep the process running. The pelletisation stage in turn consumes electricity. GHG and other emissions from auxiliary energy use depend on how the heat and electricity have been produced.

Bergman et al. (2005, 30) note that emissions to air may be encountered as a consequence of drying the biomass. They can also be a consequence of combustion of the torrefaction gas (e.g. NOx and VOCs), although this is likely to depend on the boiler in which the torrefaction gas is combusted. Like industrial activities often, it is possible that the torrefaction and pelletisation processes cause noise. Another potential adverse impact related to this stage is dust formation (Novox 2010, 24).

Long-distance transport of torrefied pellets

The environmental impacts of biofuel transport depend on the means of transport as well as on the transportation distance. Torrefied pellets can be transported to the end user by truck, train or ship. Antikainen et al. (2007, 60) argue that ship transport of biofuels in large units does not cause major environmental impacts per unit of biofuel even if the shipping distance is long, but if the fuel is transported by road in small units, the transport phase can have a bigger effect on the GHG and air emissions of the biofuel chain. Continuous truck transport can also be disturbing, especially if the end user is located in a densely populated area. Frequent truck transport also causes other adverse local impacts such as fine particulate matter emissions and dusting (Liski et al. 2011, 30).

Combustion stage

The CO2 emissions of biofuel combustion are generally not accounted for as a GHG, because the carbon released upon combustion is of biological origin and was captured by the plant during its growth (Cherubini 2010, 1570). CO2 emissions of biofuel combustion are thus calculatorily zero. However, this carbon neutrality principle only applies for sustainably grown biomass. Sustainability means that biomass is grown as much as used, or, in other words, that the biomass comes from a replenished source. (IPCC 1996, according to Soimakallio et al. 2009, 82). In the forest energy case, sustainability requires that new trees are planted in place of trees used for energy.

The combustion of biofuels produces other GHGs, namely methane and nitrous oxide, but the amount is small especially in modern combustion plants (Wihersaari 2005a, 438).

Wood fuels, including torrefied pellets, contain very little sulphur. This leads to lower sulphur dioxide emissions when replacing coal with torrefied pellets. Wood fuels also contain less nitrogen than coal, which will likely lead to a decrease in NOx emissions. (Flyktman et al. 2011, 34.) Karvosenoja et al. (2005) have in turn noted that replacing coal with wood fuels reduces mercury emissions (Antikainen et al. 2007, 52). The combustion of wood fuels in large CHP plants should not result in significant PAH or heavy metal emissions (Antikainen et al. 2007, 52).

Small-scale combustion of wood fuels in households is known to generate rather high levels of fine particulate matter emissions. These emissions can also be significant when wood fuels are used in small-scale combustion plants that do not effectively filter particulate matter from combustion gases. Fine particulate matter is bad for human health and causes premature deaths. These adverse effects on human health and mortality occur even at rather low concentrations of fine particulate matter in the air. When wood fuels are used in large combustion plants that have efficient filters, the fine particulate matter emissions are small and not significantly different from those of solid fossil fuels. (Antikainen et al. 2007, 48.) Thus, fine particulate matter emissions from combustion of torrefied pellets are likely to be small if the pellets are used in large CHP plants with proper filters. However, if the combustion plant is located in a densely populated area, the adverse impacts of fine particulate matter emissions are more significant than in a sparsely populated area, even if these emissions from wood fuel combustion are small or if wood fuels only cause a minor increase in these emissions. Producing district heat with wood fuels is still definitely a better option than producing the same amount of heat in wood-fuelled house-specific heating applications, especially in densely populated areas – in the latter case the effect on the population’s exposure to fine particulate matter would be 100-800 times greater than in the former case. (Liski et al. 2011, 30.)

What is left over from combustion of solid fuels such as torrefied pellets and coal is ash. Ash is a side product that can either be re-used or must be disposed of properly. Wood fuels contain less ash than coal, but the composition of the ash is a bit different (see e.g. Flyktman et al. 2011, 34). This implies that co-combustion of torrefied pellets and coal generates less ash than coal combustion alone. However, it is unsure whether this mixed ash can be re-used to the same extent as seperate coal and bio ashes can. Pure bio ash could be recirculated back into forests, but mixed ash usually cannot because of the impurities it contains (Wihersaari 2005a, 442). Coal ash is currently re-used by the cement industry and in earthworks. It is not yet sure whether a mixture of bio and coal ash could be used for the same purposes. If not, it would have to be disposed of as waste and taken to some form of landfill.

4 Greenhouse gas and energy balances

In this chapter, I look at the greenhouse gas (GHG) balance of the torrefied pellet production chain i.e. the fuel life cycle. My aim is to provide information on the climate impact and GHG emissions of the full fuel chain. In section 4.1 I briefly look into the theory behind defining the GHG balance of a fuel and explain why it is important to look at the full life cycle of a fuel instead of solely focusing on what happens during combustion. I will also introduce the concept of energy balance, because it is a relevant tool in bioenergy assessments. In the subsequent sections I roughly estimate a GHG balance for a torrefied pellet production chain, focusing, like throughout this study, on a Finland-based chain where torrefied pellets are made from forest chips. I will review existing studies on GHG emissions of different parts of the chain and finally build an estimate of the GHG balance of the whole chain based on this review. I will also present estimates of the energy consumption of forest chip production, although the energy balance of a full torrefied pellet chain is not calculated here.

It is important to note that I will not to carry out an extensive, full-scale assessment of the GHG balance of the torrefied pellet life cycle. Neither do I follow all the rules of the Life Cycle Assessment (LCA) methodology, although I use its main principles as a guideline in this chapter. The aim of this chapter is to highlight the relevance of different stages of the life cycle on results and to stress the role of GHG and energy balance assessments in deciding whether a certain biofuel is ”good” or ”bad” compared to a reference fuel or scenario. Also, even if the estimate of life cycle GHG emissions of the torrefied pellet chain presented here is a rough estimate, it still helps understand the magnitude of effects and to see the big picture.

4.1 Definition and principles of calculation

GHG balance

The combustion of biomass fuels is considered to be carbon neutral, because combustion releases the same amount of CO2 as was captured by the plant during its growth. The burning of fossil fuels, on the other hand, releases CO2 that has been locked up and out of the carbon cycle for millions of years. However, the production chain of a biomass fuel is rarely carbon neutral. External (fossil) fuel inputs are required when harvesting the feedstock, processing and handling the biomass and transporting both the feedstock and the fuel. The harvesting of biomass may also lead to a change in the amount of carbon stored above or in the ground. Then there are also the emissions of other greenhouse gases along the fuel chain and even upon combustion, that cannot be ignored based on carbon neutrality. (Cherubini, Bird, Cowie, Jungmeier, Schlamadinger & Woess-Gallasch 2009, 436.)

The reasons presented above give rise to the importance to assess the GHG emissions of the full biofuel life-cycle in order to define how big a reduction in GHGs can really be achieved when substituting a fossil fuel with a biofuel.

In a GHG balance calculated following the LCA methodology, emissions of the three most important greenhouse gases (CO2, CH4 and N2O) must be accounted for over the entire life cycle of a bioenergy system. The gases can be emitted either directly or indirectly and are responsible for increasing temperature in the atmosphere. The effect is then quantified using the global warming potentials (GWPs) of the different gases, which are expressed as CO2-equivalents (CO2-eq.)[3]. The global warming potentials of the bioenergy and its fossil reference system are estimated by calculating the total GHG emissions of the production chains, multiplying them with the relevant GWP factors and then summing up. The GHG savings of the bioenergy system can then be estimated by subtracting the total GHG emissions of the biofuel chain from the total emissions of the fossil fuel chain. (Cherubini 2010, 1567.)

The results of GHG balance calculations should be related to a defined functional unit, for example one MWh of fuel or one kWh of energy produced from the fuel. When comparing fuels, it is important that results have been expressed in terms of the same functional unit, so that comparison is based on delivery of the same service (Cherubini 2010, 1567).

When calculating the GHG balance of a bioenergy system, special attention should also be paid to the definition of system boundaries, as they have a significant impact on the results of GHG balance calculations as well as on the validity of the results. As Soimakallio et al. (2009, 81) put it, ”defining system boundaries and selection of the reference case are one of the most crucial phases of energy and greenhouse gas balance analysis”. If the system boundaries are too narrow, it is possible that the analysis does not cover life-cycle GHGs to a necessary extent and thus the validity of the results suffers. On the other hand, system boundaries that are too wide turn the assessment into a huge task but do not necessarily bring any additional value to it.

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[3] The GWP of methane (CH4) is 23 times that of the GWP of CO2 on a 100 year time horizon. The GWP of nitrous oxide (N2O) is 296 times greater than that of CO2. (Cherubini 2010, 1567.)

Bioenergy systems can be complex, generating co-products in addition to the main product, the biofuel itself. In order to attribute shares of the total GHG emissions to the different products of a system, allocation procedures are sometimes needed (Cherubini 2010, 1568). Let's assume, for example, that a co-product of the biomass conversion stage is utilized outside the bioenergy system to replace another product. The processes needed to produce the original product and the GHG emissions from doing so are then avoided. The utilization of co-products in place of something else should thus enhance the GHG balance of the bioenergy system. (Antikainen et al. 2007, 25.) According to LCA guidelines, allocation should be avoided if possible by expanding system boundaries. Different allocation methods exist, but it is unclear which one is the best. (Cherubini 2010, 1568.)

Energy balance

Bioenergy systems usually require non-renewable energy inputs in the production, conversion and transportation stages. The same is of course true for the fossil reference system. The greater (fossil) energy input the bioenergy chain (or any fuel chain) requires, the less desirable it is energy-wise. (Cherubini et al. 2009, 441.) For example, if the production chain of a certain biomass fuel consumes nearly as much fossil energy as the biofuel contains, the production of this fuel is neither very reasonable nor leads to significant – if any – GHG savings.

The energy balance of a bioenergy system can be expressed in different ways. Wihersaari (2005a, 436) expresses it as the fossil energy consumption per energy unit of bioenergy produced. Mäkinen et al. (2006, 31) and Soimakallio et al. (2009, 82) define it as the primary energy consumption of the biofuel production chain and express it as primary energy demand per energy unit of the produced fuel. Primary energy includes both renewable and non-renewable energy inputs but not the amount of energy that is transferred into the studied biofuel, meaning only auxiliary energy inputs converted into primary energy are considered. Cherubini et al. (2009, 441) present energy balances of biofuels both as the ratio of non-renewable energy input per energy output and as a cumulative primary energy requirement, expressed per unit of energy output.

Definition of system boundaries, selection of the reference case and allocation are crucial phases also in the case of energy balance analysis.

4.2 Estimates of GHG and energy balances of wood fuels

The energy and GHG balances of bioenergy systems differ depending on the type of feedstock, conversion and end-use technologies, system boundaries and the chosen reference system. Regional differences can also be significant, as land use, biomass production patterns, end-use technologies and reference systems differ across countries. (Cherubini et al. 2009, 435.) This means that it is impossible to calculate universal and exact GHG and energy balances that would apply to a certain biofuel in all cases.

In this section I review a few estimates of GHG and energy balances of wood fuels that have been presented in literature. I have not found such estimates for torrefied pellet chains, but there are several studies that focus on the GHG and energy balances of forest chips, which are assumed to be the raw material of torrefied pellets in my study. The life-cycle GHG emissions and energy inputs of forest chip chains form a part of the torrefied pellet GHG and energy balances.

Wihersaari (2005a) calculated the direct and indirect emissions from final harvest fuel chip production chains in Finland. In her study the source of chips was logging residue from final harvests. She chose one MWh of chips as the functional unit and set system boundaries so that in addition to collecting, chipping and transporting the residue, the analysis covered emissions from storage, combustion, possible nitrogen fertilisation and changes in forest soil carbon pools. Emissions generated in the production of fossil fuels needed in the chain as well as in manufacturing of machines and facilities were excluded. Table 4.1 summarizes her findings. There are considerable uncertainties related to the emissions from storage and changes in forest soil carbon. Also, nitrogen loss compensation through forest fertilisation might not be necessary, at least not on all sites. Or, fertilisation might be necessary during the first rotation period, but not during subsequent periods (M. Ollikainen, personal notification 21.10.2011).

We can see that the emissions from residue collection, chipping and transporting are small. As noted before, biofuel combustion is considered carbon neutral, so CO2 emissions from combustion are zero. Combustion of wood chips in a modern CHP-plant generates only small amounts of CH4 and N2O, about 2 kg CO2-eq. per MWh$_{chip}$. Furthermore, this amount of other GHGs from combustion should be about the same for the biofuel and the fossil fuel, so it could be left out of the analyses. (Wihersaari 2005a, 438.) Emissions from chip storage and the decrease in forest soil carbon could have a significant impact on the GHG balance of chips, but as Wihersaari (2005a, 442) states, they are very hard to measure or verify through measurements.

Table 4.1: GHG emissions and the energy input of final harvest fuel chip production chains in Finland, based on Wihersaari (2005a).

Part of fuel chain	Emissions, kgCO2-eq. / MWhchip	Energy input / output, %
Collecting, chipping and transportation of residues	6,5 - 7,4	2,3 - 2,6
Storage of chips	5 - 10 ?	
Other GHGs from combustion	2	
Nitrogen fertilisation	7	1,4
Changes in forest soil	40 – 45 ?	

Wihersaari (2005b, 451) estimates that if chip storage periods are long (6 months), the GHG emissions from storage could in some cases be as high as 58-144 kg CO2-eq./ $\mathrm{MWh}_{\mathrm{chip}}$ taking material losses into account. Forest residue is, however, not always stored as chips let alone for such long times, so in reality emissions from storage are unlikely to be this remarkable.

To get an idea of the magnitude of the emissions of the chip chain, a comparison with a fossil fuel is useful. Wihersaari (2005a, 441) estimates the emissions from the production and combustion of an average coal fuel to be 375 kg CO2-eq. per MWh of fuel. Liski et al. (2011, 37) and Repo et al. (2010) use an estimate as high as 396 kg CO2-eq. per MWh of coal.

Wihersaari (2005a) expresses the energy balance of final harvest fuel chip systems as an input-output ratio, which is the ratio between external energy needed in the bioenergy chain and the energy content of the produced biofuel, chips. She obtains a value of 2,3 % for roadside chipping and 2,6 % for terminal chipping.

Mäkinen et al. (2006) assessed the energy and GHG balances of biomass-based fuels used in transportation and in combined heat and power (CHP) production. They calculated, among other things, the primary energy demand and GHG emissions of different Finnish forest chip production chains – this is the part of their study that I will discuss here.

Mäkinen et al. (2006, 73-76) chose one GJ of chips as their functional unit. This means that results are not dependent on final conversion technologies, such as the efficiency of the CHP plant that uses the chips. System boundaries of their analysis covered the felling / residue collection / stump removal stage, transportation (both from forest to roadside and long-distance), chipping and moving machinery around.[4] They also acknowledged the impact of changes in forest soil carbon stocks. Their results for three different chip chains – logging residue, stumps and small-diameter wood – are presented in table 4.2. The table has been modified so that energy inputs and emissions are expressed per megawatt hour (MWh) of fuel instead of on a per GJ basis. The energy demand and emissions of long-distance transportation have been calculated for a 60 km driving distance. Doubling the distance would increase transport fuel consumption by about 1 litre per MWh of chips and thus raise emissions by a bit more than 3 kg CO2-eq. per MWh. Values have been calculated for chips with a 45 % wt. moisture content. The table does not include indirect emissions from changes in forest soil carbon stocks or possible emissions from storage.

Table 4.2: Energy demand and GHG emissions of three Finnish forest chip production chains, based on Mäkinen et al. (2006).

Energy input and GHG emissions per fuel energy content	Logging residue, roadside chipping		Stumps		Small-diam. wood, roadside chipping	
	Energy, MWh /MWh	GHGs, kg CO2-eq /MWh	Energy, MWh /MWh	GHGs, kg CO2-eq /MWh	Energy, MWh /MWh	GHGs, kg CO2-eq /MWh
Felling	-	-	-	-	0,04	3,03
Stump removal	-	-	0,04	3,63	-	-
Forest transport	0,02	1,66	0,02	1,66	0,01	1,21
Chipping	0,03	2,69	0,00	0,14	0,03	2,41
Long-distance transport	0,04	2,95	0,06	4,93	0,04	2,95
Machinery transfers	0,01	0,93	0,01	0,93	0,02	1,39
Crushing (electricity)	-	-	0,00	0,11	-	-
Total	0,10	8,23	0,13	11,40	0,13	10,99

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[4] Mäkinen et al. assume forest residue (logging residue, stumps and small-diameter wood) to be leftovers from forest industry practices. The energy demand and emissions of planting and managing the forest are thus allocated to the harvested industrial wood and not the residue.

We can see that neither the required energy input nor emissions per MWh of chips are very large. There are differences between the values for logging residue, stumps and small-diameter wood. The stump chain has the highest energy requirement and emissions, although they are only slightly higher than for small-diameter wood. Stump removal and small-diameter wood felling consume more energy than residue collection, which explains most of the differences between chains.

Liski et al. (2011) focused on the indirect CO2 emissions from changes in forest soil carbon stocks but also estimated the GHG emissions from Finnish forest chip production chains based on previous literature. Their estimates of the emissions from chip production and transportation were slightly lower than those presented by Mäkinen et al. (2006) and Wihersaari (2005a). Their GHG emission estimates took into account the same steps as Mäkinen et alii's (2006), but ranged from 4,3 kg CO2-eq. per MWh$_{chip}$ (logging residue chips) to 6,5 kg CO2-eq. per MWh$_{chip}$ (small-diameter wood from thinnings) at a 95 kilometre transportation distance. According to Liski et al. (2011), the emissions from forest chip production and transportation are very small compared to the indirect CO2 emissions caused by the decrease in forest soil carbon.

The indirect carbon dioxide emissions from a decrease in forest soil carbon caused by the collection and combustion of forest residues seem to account for a major share of the GHG emissions of forest chip production and use, so it is worth to look more deeply into this matter. Like mentioned in chapter 3.2, these indirect CO2 emissions occur when the carbon that forest residue contains is emitted to the atmosphere at once through combustion, instead of being released little by little as a result of natural decomposition. If forest residue was not collected for energy use but was instead left in the forest, it would decompose in the course of decades, slowly releasing the carbon it contains into the atmosphere. When forest residue (or a product made of forest residue) is burned, this carbon is immediately released as carbon dioxide. This means that in the short run, energy use of forest chips increases the amount of atmospheric carbon compared to the situation where forest residue is left to decompose naturally. (Repo et al. 2010; Liski et al. 2011; Mäkinen et al. 2006; Wihersaari 2005a.)

There are several studies that assess the magnitude of these indirect carbon emissions. Repo et al. (2010) and Liski et al. (2011) simulated decomposition rates of forest residue in Finnish forests using a dynamic soil carbon model. The indirect CO2 emissions from using forest residue for bioenergy production were taken to be equal to the amount of carbon remaining in forest residues if they were left to decompose in the forest. These emissions were related to the cumulative amount of bioenergy produced, so that the cumulative indirect emissions caused by combusting forest residue until year *i* were calculated by summing up the amount of carbon left in forest residues until this year *i.* The studies found that decomposition rates and thus indirect emissions are dependent on the initial diameter of the residue, so for large stumps indirect emissions are higher than for more quickly decomposing branches. For example, Liski et al. (2011, 16-18) estimated that 20 years after the start of cumulative bioenergy production, the increase in atmospheric carbon caused by the decrease in forest soil carbon stocks was 55 % (branches), 30 % (small-diameter wood) and 20 % (stumps) smaller than the carbon emission from producing the same amount of energy with coal. In terms of radiative forcing i.e. actual climate warming effect, respective figures were 62 %, 44 % and 37 % lower than that of coal. The longer the time horizon, the lower the indirect emissions are. After 100 years of producing 1 PJ of energy from forest residue annually, the increase in atmospheric carbon caused by energy use of forest residues was as much as 82 % (branches) and 55-60 % (stumps) lower than the carbon emission from coal.

Palosuo, Wihersaari & Liski (2001) and Wihersaari (2005a) estimated the indirect CO2 emissions from decreasing soil carbon in the case of logging residue based on differences in soil carbon stocks between sites where residues are removed and sites where they are left to decay. The difference in carbon stocks was calculated to be 11 % of the total carbon in residues within a rotation length of 100 years. Depending on the energy yield per hectare and moisture content of residues, this leads to CO2 emissions of 40-45 kg per MWh of residues in a 100 year time period. Other studies have suggested slightly higher figures per MWh of logging residues for a 100 year period (Soimakallio et al. 2010, 66).

We can see that the indirect CO2 emissions from forest chip production are very strongly dependent on the chosen time horizon and that they decrease over time. It is also worth to note that they critically depend on estimated decomposition rates. Estimated decomposition rates vary between studies and thus lead to variation in the magnitude of indirect emissions especially at longer time periods such as 100 years. There is still considerable uncertainty related to the magnitude of indirect emissions but all studies in the area acknowledge the significance of indirect CO2 emissions from decreases in forest soil carbon stocks on the GHG balances of forest chip chains. Indirect emissions are an order of magnitude larger than GHG emissions from the rest of the chip production chain.

Although indirect CO2 emissions from changes in forest soil carbon balances weaken the capability of forest chips to reduce atmospheric carbon and thus mitigate climate change in the short run, one should keep in mind, that, from the climate viewpoint, forest chips are still better than fossil fuels. The carbon locked up in fossil fuels would not be naturally released over time like the carbon in forest residues and thus CO2 emissions from energy use of fossil fuels do not decrease over time unlike in the case of wood energy. (See e.g. Ilvesniemi, Asikainen & Hynynen 2011.) It is also likely that increasing energy use of forest residues will not threaten overall carbon balances of Finnish forests or their role as a carbon sink, although it slightly decreases the size of this sink (Ilvesniemi et al. 2011; Soimakallio et al. 2010, 65).

4.3 GHG balance of torrefied pellets

In this section I estimate the GHG balance of a torrefied pellet production chain as defined in chapter 3.1 and compare it to the emissions from coal production and combustion. Like before, the raw material of pellets is assumed to be forest chips and production of both the raw material and the fuel is assumed to take place in Finland.

When setting system boundaries for GHG balance analysis, I follow the example set by Soimakallio et al. (2009), who assessed GHG balances of biofuels and electricity and heat generation in Finland, and Wihersaari (2005a). Soimakallio et al. (2009, 81) excluded the energy input required and emissions output caused by the construction of infrastructure and the production of facilities, machinery and other equipment required in the fuel chains, because ”reliable data of such inputs and outputs is not available and the difference in these issues is not significant between fossil fuels and biofuels”. In addition to the factors mentioned above, Wihersaari (2005a, 437) excluded emissions from production of fossil fuels (mainly diesel fuel) needed in the biofuel chain. They, as well as the factors Soimakallio et al. excluded, should be of minor importance regarding the magnitude of results.

I have estimated the emissions of chip production and transportation based on Mäkinen et al. (2006), because their calculations have often been referred to in other studies and they thoroughly explain how emission estimates have been calculated. I assume that the torrefaction plant uses a mixture of chips made from logging residue, stumps and small-diameter wood, the respective shares being 40 %, 15 % and 45 %. The chosen shares reflect the distribution of sources of chips used in energy production in Finland (Metla 2011). I assume that chips are not made from stem wood or industrial wood, although this assumption might not be fully realistic if chip demand is high. The average emissions of producing and transporting one MWh of chips to the torrefaction plant are calculated as a weighted average of the emissions of the three different chip chains using the values in table 4.2. The average transportation distance of chips is assumed to be 100 km, which increases emissions per MWh of chips in each chain by 2-3 kg CO2-eq. compared to the values in the table. GHG emissions from possible nitrogen fertilisation are not included in Mäkinen et alii's figures, so I will leave them out at this point, because it is not fully certain, whether nitrogen compensation is needed or not. I will, however, include an estimate of GHG emissions from chip storage by adding it to the values in table 4.2. Emissions from chip storage are uncertain, hard to measure and strongly dependent on factors such as the length of the storage period and the initial moisture content of the chips. For these reasons, I will use a rather conservative estimate of 7,5 kg CO2-eq. per $\mathrm{MWh}_{\mathrm{chip}}$ based on Wihersaari & Palosuo's (2000) rough estimate (Wihersaari 2005a, 438).

In addition to the GHG emissions from forest chip production, storage and transport, I take into account the indirect CO2 emissions from a decrease in the forest soil carbon stock when calculating the weighted average of GHG emissions per MWh of chips. When evaluating these emissions, I use a 100-year time horizon and Wihersaari's (2005a) emissions estimate, 40-45 kg CO2 / MWh_{chip}. As Wihersaari's figure only applies to logging residue, I estimate the equivalent indirect emissions for small-diameter wood and stumps by taking into account their slower decomposition rates i.e. different climate impact within a 100-year period. Relative climate impacts were estimated based on Liski et al. (2011, 16-17) in order to get a rough estimate of what the indirect CO2 emissions of stumps and small-diameter wood would be within a time period of 100 years, if those of logging residue are 40-45 kg CO2 / MWh.

When defining the auxiliary energy requirement of the torrefaction plant, I take into account that part of the energy demand of the pre-drying and torrefaction processes can be met through combustion of liberated torrefaction gas. This does not of course change the amount of electricity needed in pelletisation. I assume the torrefaction plant to be a stand-alone facility that is designed according to the ECN torrefaction and pelletisation concept (see Bergman 2005; Bergman et al. 2005 & Uslu et al. 2008). Bergman (2005, 18-19) presented technical process characteristics for a torrefaction plant that produces 56 kilotonnes of torrefied pellets per year from 170 kilotonnes of green wood chips with a moisture content of 57 % wt. This amount of production corresponds to 40 MW_{th} of fuel output. The estimated utility fuel consumption of the torrefaction and pelletisation process was calculated to be 4,7 MW$_{th}$ and electricity consumption 1,01 MW$_{e}$. This means that the additional heat input and power input of the process are 12 % and 2,5 % of the energy content of torrefied pellets, respectively. Bergman reported the calorific value of torrefied pellets on an as received basis to be 5,8 MWh/t. Multiplying this with the amount of output, 56 kilotonnes, indicates that the torrefaction plant produces 325 000 MWh of torrefied pellets per year. The yearly additional heat and power inputs to a process producing 56 kilotonnes of torrefied pellets are thus 39 000 MWh and 8125 MWh, respectively.

The GHG emissions of auxiliary energy production depend on how the additional heat and electricity have been produced. When estimating the emissions of electricity production, I follow Mäkinen et al. (2006, 33) who estimate GHG emissions from electricity bought from the Finnish grid to typically range between 200 and 300 kg CO2-eq. per MWh of electricity. This range includes both direct and indirect emissions of electricity production. The emissions of heat production depend on the fuel and the heat production process (cogeneration versus separate generation). I stick to Bergman's (2005, 18-19) example of a stand-alone torrefaction plant with a furnace built exclusively for running the process, and, like him, assume the utility fuel to be natural gas. The CO2 emission factor for natural gas is 55,04 kg CO2/GJ (Statistics Finland 2011). The magnitude of GHG emissions from natural gas production and transport is estimated to be around 25 % of the emissions from combustion (see e.g. Wihersaari 2005a, 441). I will thus use a rough estimate, 69 kg CO2-eq/GJ, for the life-cycle emissions of natural gas. If heat is produced at a 85 % efficiency, emissions would be 292 kg CO2-eq per produced MWh of heat.

GHG emissions from transportation of torrefied pellets depend on transportation distances and the means of transport. In order to obtain some sort of emissions estimate, I assume torrefied pellets to be transported to the end user in ships. I use the GHG emissions of ship transportation of coal as a proxy for emissions from shipping torrefied pellets, because the two should not essentially differ on a per tonne basis.

Like in the case of other biofuels, combustion of torrefied pellets is considered carbon neutral. I will leave CH4 and N2O emissions from combustion out of the analysis, because they depend on combustion technology and are thus difficult to accurately estimate. Furthermore, they are usually low compared to overall emissions from combustion and expected to be of the same magnitude for both the biofuel and solid fossil fuel if combustion technologies are equal. (Mäkinen et al. 2006, 33; Wihersaari 2005a, 442.)

I have chosen one MWh of torrefied pellets to be the functional unit of my GHG balance analysis. This means that I express the emissions of the torrefied pellet chain in relation to the energy content of torrefied pellets. Usually it is recommended that GHG balances are calculated per unit of useful energy, such as one MWh of produced electricity and/or heat. This way possible changes in final conversion efficiencies are taken into account – for example, if a biofuel were to weaken the efficiency of a power plant, one MWh of biofuel would supply less useful energy than one MWh of fossil fuel and thus the GHG balance of the biofuel would be less favourable when calculated per MWh of useful energy than per MWh of fuel. According to current knowledge, the combustion of torrefied pellets alongside coal should not affect the efficiency of the coal-fired power plant much – only minimal reductions in efficiency are expected – so it should be OK to compare GHG balances of torrefied pellets and coal on a per MWh of fuel basis (J. Kukkonen, personal notification 16.6.2011). Also, this way the results of the analysis are not dependent on final conversion technologies.

Like mentioned before, the reference energy system is assumed to be coal use in CHP production. With their coal-like properties, torrefied pellets are an alternative fuel to coal. Emissions from coal production and transportation depend on the type of coal mine and transportation distances. I will use the same estimate for GHG emissions of the coal production and use cycle as Liski et al. (2011), which is 396 kg CO2-eq. per MWh of coal.

In table 4.3 I present an estimate of the GHG emissions of torrefied pellet production and use and compare them to the average emissions of coal production and use. Figure 4.1 provides the same information in graphic form. GHG emissions of torrefied pellet production have first been calculated on a yearly basis and then divided by the amount of torrefied pellets produced per year, which in this example is 56 kilotonnes and 325 000 MWh. According to Bergman (2005, 19), this amount of output requires a wood chip input of 170 kilotonnes, which corresponds to 295 000 MWh when the moisture content of chips is 57 % wt. In order to apply the values in table 4.2 (estimated for chips with a moisture content of 45 % wt.) when calculating the emissions of chip production and transport in this case, I adjusted the values so that they account for the higher moisture content.

The result for total GHG emissions of the torrefied pellet chain that I provide in table 4.3 is a rough estimate and dependent on assumptions related to the chain – the purpose of the table is to illustrate the magnitude of differences between the life cycle GHG emissions of torrefied pellets and coal, not to provide exact figures. In this example, the

GHG emissions of torrefied pellet production and use are an order of magnitude lower than the GHG emissions from the production and combustion of an average coal fuel, the difference in emissions over the life cycle being 262 kg CO2-eq / MWh of fuel. Replacing coal with torrefied pellets in energy generation would thus lead to substantial reductions in GHG emissions. For example, if 600 000 MWh of coal was to be replaced with 600 000 MWh of torrefied pellets, the total reduction in GHG emissions would be 157 200 t CO2-eq.

Table 4.3 Example of GHG balances of torrefied pellets and coal.

GHG BALANCE	
GHG emissions of torrefied pellet chain	kg CO2-eq. / MWh of torrefied pellets
Decrease in forest soil carbon stocks	69,0
Chip production and transport (truck)	16,1
Chip storage	6,8
Auxiliary energy production for torrefaction	
Electricity	6,3
Heat	35,0
Torrefied pellet transport (ship)	1,2
Combustion	0*
TOTAL	134
** = CH4 and N20 emissions excluded*	
	kg CO2-eq. / MWh of coal
GHG emissions of coal life cycle (production, transport & combustion)	396

The total life cycle GHG emissions of torrefied pellets presented here would be different if, for example, the emissions from decrease in forest soil carbon stocks were presented for a shorter time horizon than 100 years, if emissions from chip storage turned out to be higher, if the utility fuel used in torrefaction was something else than natural gas or if torrefied pellets were transported to the end user by some other means than by ship. GHG balances are always case-specific. Another even more case-specific calculation of the net climate effect of a torrefied pellet chain in a case where the raw material of pellets is Finnish forest chips is presented in chapter 6 of my study.

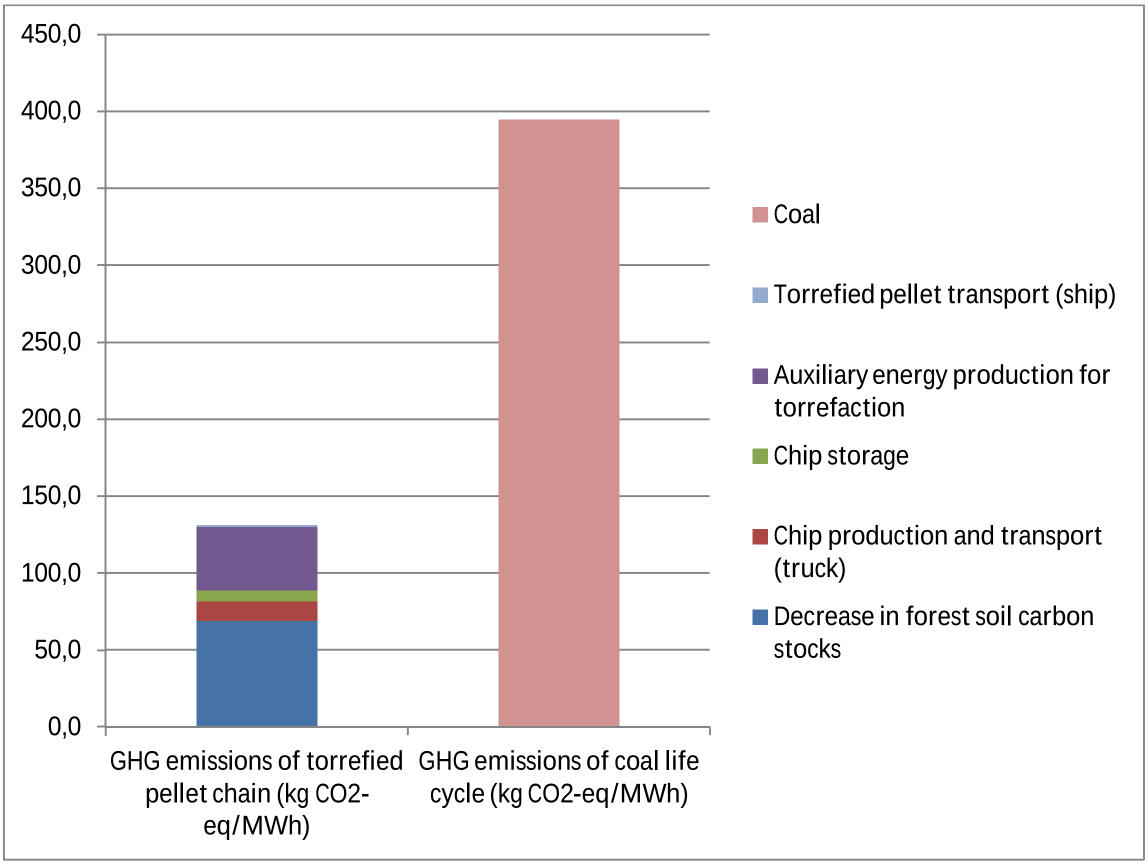


Figure 4.1: Example of GHG balances of torrefied pellets and coal.

5 Social desirability of the use of torrefied pellets: theory and the model

The purpose of this chapter is to develop a model for assessing the social desirability of the production and use of torrefied pellets as an alternative fuel to coal when both private profits and the value of net climate benefits to society are taken into account. I start by introducing the theoretical framework behind the model. I then discuss climate benefit and damage valuation in more detail. Finally, in section 5.2, I construct the parametric model, which is then applied to a hypothetical case in subsequent chapters.

5.1 Theoretical framework

The theoretical framework of my thesis relies on externalities theory. Externalities are consequences of a production process, that are not reflected in the product price. They emerge whenever production processes, or consumers' utility, are affected by variables not controlled by themselves, but by other economic agents. These effects may be positive (external benefits) or negative (external costs). The fact that these costs and benefits are not included in prices and thus not taken into account by the market produces a market failure, which in turn leads to an inefficient assignment of resources from the whole society's point of view. (Saez, Linaress & Leal 1998, 469.) The production and use of torrefied pellets creates both positive and negative climate externalities. For example, replacing coal with torrefied pellets reduces CO2 emissions and is thus beneficial for society and the climate. On the other hand, torrefied pellet production and transport generates harmful GHG emissions. These externalities are not accounted for in private decision making unless they are partially or fully internalized into private profit functions through climate policy instruments. The presence of externalities may cause the privately optimal levels of torrefied pellet production and use to differ from socially optimal levels.

The net social benefits, also referred to as social welfare, of torrefied pellet production and use are defined as the difference between social benefits and social costs of the chain. Net social benefits incorporate the monetary value of environmental impacts – only climate impacts in this case – and the private profits (without subsidies and taxes) of companies or agents involved in the chain (Lankoski & Ollikainen 2011, 682). If net social benefits are positive, torrefied pellet production and its use as an alternative fuel to coal generates social surplus and can be considered socially desirable.

In order to incorporate climate benefits and climate damage into social welfare calculation, they need to be assigned a monetary value (see e.g. Lankoski & Ollikainen 2011; Lankoski & Ollikainen 2008; Saez et al. 2009). The valuation of climate benefits and damage can be done in several ways. One option is to use an estimate of the mean marginal damage cost of GHG emissions that can be found in literature (see e.g. Fahlén & Ahlgren 2010; GES 2002; Tol 2005). The marginal damage cost is equivalent to the social cost of emitting one additional tonne of CO2 or equivalent GHGs or the social benefit of reducing one tonne of CO2 or CO2-eq. Another option would be to use the price of EU emission allowances (EUA) as a proxy for the value of climate damage caused by one tonne of CO2 or CO2 equivalent emissions. In my work, I am going to follow Lankoski & Ollikainen (2011) and rely on the first approach. It is hard to say how well EUA prices reflect the true value of marginal climate damage and climate benefits to society, because the price level of EUAs is dependent on e.g. the state of European economies. For example, an economic crisis reduces the output and thus emission allowance demand of European companies, which leads to a reduction in the EUA price – but that does not make climate change any less of a problem or decrease the social value of climate benefits and climate damage.

5.2 The model

In this section I develop a model for analyzing the net social benefits of torrefied pellet production and its use as an alternative fuel to coal. The torrefied pellet chain, presented in more detail in chapter 3.1, is divided into four stages:

1) The biomass production stage (chipping company)
2) The biomass conversion stage (torrefaction plant)
3) The torrefied pellet distribution stage (shipping company)
4) The torrefied pellet end use stage (energy producer)

It is assumed that a different company is involved in all four stages and each of them maximizes their profits. In this model, the chipping company is thought to be the biomass producer that harvests the biomass, chips it and delivers it to the torrefaction plant. Its cost function consists of the costs of harvesting, chipping and transportation activities as well as the stumpage price that it has to pay to forest owners for the wood or forest residue. The torrefaction plant buys the chips from the chipping company and uses them as the main input in the torrefaction process. Another key input of the torrefaction plant's production process is assumed to be the auxiliary energy – both electricity and heat – needed to run the process. Thus, the torrefaction plant's variable costs mainly consist of the costs of chips and auxiliary energy. A shipping company is responsible for transporting the torrefied pellets from the torrefaction plant to the end user. The shipping company is assumed to receive revenue for each unit (tonne or MWh) of torrefied pellets that it transports. Its variable cost function consists of, for example, fuel costs and labour costs. Finally, the energy producer buys the torrefied pellets at a certain gate price. It earns revenue from the electricity and heat it produces. In this simplified model, its cost function consists of the costs of buying coal and torrefied pellets as well as other operational costs.

It is worth to note that the model presented here has been restricted to only take into account the variable or operational costs of each company involved in the chain. Investment costs and other fixed costs have generally been excluded. This approach is typical especially when analyzing the short term and short-run profits. The model has been developed for analyzing the social desirability of torrefied pellet production and use assuming that all necessary investments to the chain have already been carried out. The focus is thus on the operational side, which means that the model as such cannot be used to define whether, for instance, investing in a torrefaction plant is socially desirable or not.

Next I will present the private profit functions of each of the four "companies" mentioned above.

Private profit functions

The energy producer's profit is denoted by Π_1:

$$\Pi_1 = p_e \alpha Q(k,t) + p_d (1-\alpha) Q(k,t) - w_k k - w_t t - \emptyset \tag{5.1}$$

where p_e is the market price of electricity, $Q(k,t)$ is the combined heat and power (CHP) production function, $\propto$ denotes the share of electricity generated in the CHP process and $(1-\alpha)$ the share of heat, p_d is the price of district heat, k the quantity of coal used, t the quantity of torrefied pellets used, and w_k and w_t are the unit gate prices of coal and torrefied pellets, respectively. $\emptyset$ denotes other operational costs related to power and heat production that the power plant faces, including the costs of ash handling.

The shipping company's (tranporter of torrefied pellets) profit is denoted by Π_2:

$$\Pi_2 = \delta t - c(t) \tag{5.2}$$

where δ is the price the company receives for transporting one unit of torrefied pellets t, and $c(t)$ are transportation costs as a function of t.

The torrefaction plant's profit is denoted by Π_3:

$$\Pi_3 = \hat{w}_t f\left(h, e_{e,} e_d\right) - w_h h - w_e e_e - w_d e_d - \lambda \tag{5.3}$$

where $\hat{w}_t$ is the net unit price the plant receives for torrefied pellets, $f(h, e_{e,} e_d)$ is the torrefied pellet production function, h is the forest chip input, w_h is the unit gate price of forest chips, e_e the electricity input, w_e the unit price of electricity, e_d the additional heat input, w_d the price of heat and λ denotes the other operational costs of the torrefaction plant.

Finally, the chip producer's profits are denoted by Π_4:

$$\Pi_4 = w_h h - \beta(h) \tag{5.4}$$

where w_h is the unit price the pellet producer pays for forest chips and $\beta(h)$ is the forest chip cost function that includes stumpage price paid for wood, harvesting and chipping costs and transportation costs to the torrefaction plant.

In a privately optimal situation, all these four companies involved in the torrefied pellet chain maximize their profits, which in turn determines output and input use. Prices are assumed to be taken as given, meaning that all four operate under perfect competition.

The amount of torrefied pellet production and use that maximizes private profits along the chain might not, however, maximize social welfare, as private profit maximization does not account for the value of environmental impacts, both benefits and costs, to society.

Private profit functions and current climate policy

The private profit functions presented above do not take current climate policy into account – they are so called theoretical profit functions. In Finland, for example, (large) electricity and heat producers belong to the EU Emissions Trading Scheme which internalizes the climate benefits of replacing coal with biomass fuels into company profit maximization functions. In Finland there is also an excise tax on certain fossil fuels used for heat generation, which means coal use in heat production is taxed while biomass use is not.

Thus, under current climate policy the energy producer's profit function would look more like this:

$$\Pi_1^{cp} = p_e \alpha Q(k,t) + p_d(1-\alpha)Q(k,t) - (w_k + b)k - (w_t - \varepsilon_c p_c)t - \emptyset \tag{5.5}$$

where b is the coal tax (calculated based on the fact that the excise tax only applies to coal used for heat generation), ε_c denotes the amount of carbon dioxide emissions from coal combustion that one unit of torrefied pellets offsets and p_c is the carbon credit price, i.e. the EUA price.

In the Finnish case, the chip producer could be entitled to certain subsidies that aim to increase forest chip production. These subsidies would lower the costs of the chip production chain. However, the effect of such subsidies is not modelled here.

Social welfare

Social welfare (SW) depicts the net social benefits of torrefied pellet production and use. SW incorporates the net profits of the companies involved in the chain as well as the monetary value of environmental impacts, in this case the monetary value of climate benefits and climate damage. Subsidies, taxes and other policy instruments such as emissions trading are not included in social welfare calculations.

The social welfare function is formed by combining the private profit functions (5.1) – (5.4) with the following net climate benefit function (5.6). The net climate benefits of torrefied pellet production and use are defined as the difference between CO2-equivalent offsets and emissions created in the production chain.

(5.6) $$NCB = q(\varepsilon t - \sum z_n)$$

where q is the monetary value of climate impacts, ε denotes the amount one unit of torrefied pellets offsets GHG emissions from coal (defined over the coal life cycle), and z_n refers to GHG emissions associated with the different production and transport stages along the chain (unit = t CO2 eq).

Social welfare along the whole torrefied pellet production chain can be calculated using formula (5.7). In economic terms, social welfare is defined as the sum of producers' and consumers' surplus. As prices are assumed to be exogenic, consumers' surplus in this model is represented by the net climate benefits while private profits represent producers' surplus.

(5.7) $$\begin{aligned} SW = \; & p_e \alpha Q(k,t) + p_d(1-\alpha)Q(k,t) - w_k k - (w_t - \varepsilon q)t - \emptyset \\ & + \delta t - (c(t) + z_1 q) \\ & + \hat{w_t} f(h,e) - w_h h - w_e e_e - w_d e_d - z_2 q - \lambda \\ & + w_h h - (\beta(h) + z_3 q) \end{aligned}$$

where z_1 denotes the GHG emissions from torrefied pellet transportation, z_2 the emissions from auxiliary energy production and z_3 the emissions from forest chip production and transportation.

As we can see, in addition to the theoretical private profit functions, the SW function contains terms that account for the cost of GHG emissions to society and the benefit of GHG reductions to society.

It is important to note two things. Firstly, in the SW function, ε is defined over the whole coal life cycle, i.e. from extraction to production and use. Secondly, as mentioned earlier in this chapter, q can be estimated either using a marginal damage cost estimate from literature or using the EUA price as a proxy.

The SW function can be further simplified. We can write:

(5.8) $$w_t = \hat{w_t} + \delta$$

This implies that the gate price the power plant pays for torrefied pellets consists of the net price the pellet producer receives and the unit transportation cost.

We can also write:

(5.9) $$f(h, e_{e,} e_d) = t$$

By substituting equations (5.8) and (5.9) into equation (5.7) and simplifying, we obtain the following function for social welfare:

(5.10) $$\begin{aligned} SW = \; & p_e \alpha Q(k,t) + p_d(1-\alpha)Q(k,t) - w_k k + \varepsilon q t - \emptyset \\ & - (c(t) + z_1 q) \\ & - (w_e e_e + w_d e_d + z_2 q + \lambda) \\ & - (\beta(h) + z_3 q) \end{aligned}$$

SW represents the net returns to society of the torrefied pellet production and use chain. By maximizing SW, one can calculate the socially optimal levels of torrefied pellet production and use. When these levels are compared with the levels of torrefied pellet production and use that maximize private profits (main focus being on the energy producer's and torrefaction plants profits), one can see whether society would benefit from an increase (or decrease) in torrefied pellet production and use.

If equation 5.10 is applied to an existing case, SW can be thought to represent the social desirability of torrefied pellet production and use in that specific situation: if SW is positive, it means the net benefits to society are positive and vice versa.

Forest residue removal decreases the forest soil carbon stock, which has the same effect on the climate as a carbon dioxide emission (see e.g. Liski et al. 2011). As noted in chapter 4, this decrease in forest soil carbon stocks can, although subject to uncertainties, account for a major part of the life-cycle emissions of torrefied pellets. This means it should definitely be included in the model.

In the model, the decrease in forest soil carbon stocks can be described as a carbon leakage and accounted for in the model through ε. This implies, that ε can be redefined as

(5.11) $\varepsilon^{\wedge} = (\varepsilon - \gamma)$

where ε is the amount of GHG emissions from coal that one unit of torrefied pellets replaces defined over the coal life cycle and γ represents the decrease in the forest carbon stock or the so called carbon leakage, calculated per unit of torrefied pellets. γ varies depending on the source of the chips and especially on the time horizon within which the climate effect of forest chip based torrefied pellets is studied. It is subject to a rather large degree of uncertainty.

By replacing the ε term in equation 5.10 with $\varepsilon^{\wedge}$ from equation 5.11, one has at hand a model that should account for all the major climate effects of the torrefied pellet chain while taking private costs and benefits into account at the same time.

The model presented here can be used in multiple ways. It can be used for calculating the privately and socially optimal levels of torrefied pellet production and use and for assessing whether the socially optimal level differs from the privately optimal level. Optimal levels of production and use are calculated by maximizing private profits and social welfare. The model can also be applied to an existing (or hypothetical) case to find out whether net benefits to society are positive or negative in that particular case. Instead of trying to determine the social welfare maximizing levels of torrefied pellet production and use through optimization, one simply assesses the social desirability and level of social returns of current (or hypothetical) production and use patterns. In my thesis I will stick to this latter approach, also referred to as normative analysis.

The model could be extended so that instead of being restricted to only climate externalities, it would also take into account other externalities, such as other emissions to air (e.g. SO2, NOx, fine particulate matter) and possible improvements in air quality, biodiversity effects or reduced fossil fuel dependency. These are all factors that affect social welfare, but are not accounted for in private decision making unless internalized through government policies. By valuating these externalities and adding them to the current model, one could more accurately assess the overall social desirability of replacing coal with torrefied pellets.

A summary table of parameter definitions can be found in Appendix 2.

6 Empirical application of the model: The case of Helsingin Energia

In this chapter I apply the model developed in section 5.2 to a hypothetical case in which torrefied pellets are produced in Northern Finland and delivered to Helsingin Energia's existing coal-fired cogeneration plant in Salmisaari, Helsinki, to be co-fired with coal at a fixed ratio. The analysis seeks to answer the question whether the use of torrefied pellets to partially replace coal in an existing coal-fired power station generates positive social returns, when both climate benefits and GHG emissions over the life cycle are taken into account.

It is worth to note that in this analysis I do not try to find the parameter values that maximize social welfare. Instead, I apply the model to a case where the torrefied pellet to coal blending ratio is fixed and thus determines the output of the torrefaction plant: it is assumed in this case study that Helsingin Energia buys all the torrefied pellets that the torrefaction plant produces and that the produced amount of torrefied pellets equals Helsingin Energia's demand. The output of the torrefaction plant in turn determines the demand for chips. Thus, the purpose of this analysis is merely to find out whether social welfare (SW) and the net climate benefits of torrefied pellet production and use in this particular case are positive or negative and which factors influence the results most.

6.1 Description of the case

In this hypothetical case study, the torrefaction plant is located in Northern Finland. The forest chip resource potential in Northern Finland is fairly large and exceeds current demand of chips in the area, which means chips could be available to the torrefaction plant within a modest transportation distance, and, if there are no other potential users nearby, at a lower cost too. Nowadays torrefaction research commonly focuses on production near the raw material resource and far from the end use site, because short raw material transportation distances and cost savings from transporting the torrefied product are key benefits of torrefaction technology (Flyktman et al. 2011, 31).

Forest chips are assumed to be delivered to the torrefaction plant from surrounding areas, the transportation distance ranging from 10–200 kilometres. In Finland, chips are usually transported to the user in trucks, as roadside chipping is currently the most common chip production chain. Truck transportation of chips is also assumed in this case and used as the basis for cost and GHG emission calculations of the chip production chain.

The torrefaction plant is assumed to be integrated to an existing peat and wood fuelled cogeneration plant, this plant also being hypothetical. Potential benefits of an integrated torrefaction plant have been discussed in chapter 2.1.2. I assume that the cogeneration plant, to which the torrefaction plant is integrated, produces surplus heat, meaning that its heat production exceeds consumers' district heat demand in the area. The surplus heat can then be used as an input in the torrefaction process. The technical details of the hypothetical torrefaction plant are presented in table 6.1 and those for the peat and wood fuelled cogeneration plant in Appendix 3.

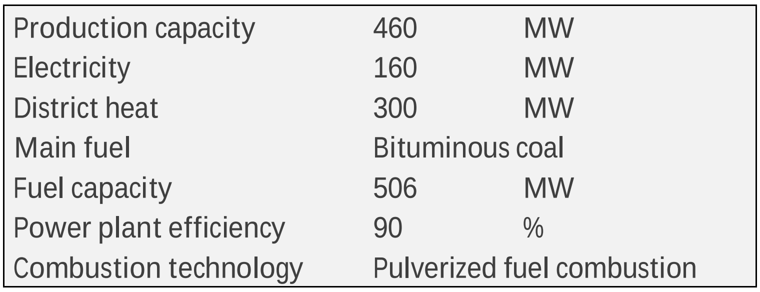
Table 6.1: Technical details of the hypothetical torrefaction plant that produces torrefied pellets.

Production capacity; output	100000	t/year
	600000	MWh/year
Forest chip input	255000	t/year
	644600	MWh/year

Torrefied pellets are assumed to be transported to the end user, the Salmisaari power plant in Helsinki, by sea. Salmisaari is located by the sea in southern Helsinki. Helsinki in turn is located on the south coast of Finland, so the transportation distance from the hypothetical torrefaction plant in the north to Salmisaari is long, approximately 600–800 kilometres by land. For such a long distance, truck transportation of large volumes of torrefied pellets would not be profitable. This limits the feasible options to railroad and sea transport. Since the power plant is located on the coast and the transported product has a high bulk density, the best option is likely to be sea transport in ships. Coal is also delivered to Salmisaari in ships, and the existing coal harbour infrastructure could probably serve torrefied pellet deliveries as well.

The Salmisaari power plant is a coal-fired cogeneration plant owned by Helsingin Energia. Its combustion technology relies on pulverized coal combustion. The technical details of the plant are given in table 6.2.

Table 6.2: Technical details of Helsingin Energia's Salmisaari B cogeneration plant.



Production capacity	460	MW
Electricity	160	MW
District heat	300	MW
Main fuel	Bituminous coal	
Fuel capacity	506	MW
Power plant efficiency	90	%
Combustion technology	Pulverized fuel combustion	

Helsingin Energia is one of the largest energy companies in Finland and is owned by the city of Helsinki. The city of Helsinki wants to reduce CO2 emissions by 20 % from 1990 levels and increase the share of renewables in energy production to 20 % by year 2020. As a response to this, Helsingin Energia formulated a ”Development programme towards a carbon-neutral future”, that presents ideas on how the reduction in emissions and increase in the renewables share can be achieved. Cofiring biomass-based fuels – chips, pellets or torrefied pellets – with coal is one of the suggested options. If the goals are to be met through co-firing alone, it would require the biomass share in the fuel mix to be roughly 40 % at Helsingin Energia's coal-fired power plants, Hanasaari and Salmisaari. (Helsingin Energia 2010.)

In this study, I assume torrefied pellets to be co-fired with coal at a fixed ratio – no optimization with regard to the torrefied pellet to coal ratio is performed. For simplicity, the torrefied pellet to coal ratio is set so that Salmisaari power plant uses the same amount of torrefied pellets, 100 000 tonnes per year, that the hypothetical torrefaction plant produces. This way the volume of torrefied pellets remains constant throughout the chain, which facilitates calculation of net climate benefits of the chain.

6.2 Data and parameter values

In this section I present the data and parameter values used in this specific case study. The parameters are the same as in the model developed in section 5.2. In addition to presenting a table of parameter values, I will briefly explain where the values have been derived from and how. I will also discuss possible uncertainties related to parameter values or the data behind them. This section has been grouped so that parameter values are discussed in relation to the stage of the torrefied pellet chain they belong to.

For economic parameters, such as prices and costs, I mainly use 2011 values. Many of them have been calculated as a mean value of monthly prices. As this study has been finished in late 2011, electricity and coal prices for the last one or two months of the year are estimates. Value-added taxes are not included in any of the prices.

Energy producer

The energy producer in this case study, Helsingin Energia's Salmisaari power plant, produces electricity and heat in a combined process. Roughly 1/3 of produced energy is electricity (α) and 2/3 district heat ($1-\alpha$). This is a rather typical ratio for coal-fired CHP plants. The electricity that Salmisaari produces is sold to the Nordic power exchange, Nord Pool. In this study, I have calculated the market price of electricity (p_e) as a weighted average of monthly 2011 Nord Pool spot prices (Finnish area prices). Weights are based on Salmisaari's monthly electricity generation volumes in an average year. Calculating a weighted average takes seasonal fluctuations of electricity production and the spot price into account.

District heat is sold to consumers in the Helsinki area. Helsingin Energia sets the price of district heat based on heat production costs. The price depends on the season, cold winter months being the most expensive. I have calculated the price of district heat (p_d) as a weighted average of Helsingin Energia's district heat prices for year 2011. Due to the nature of combined heat and power production, the monthly distribution of heat production and thus weights are the same as in the electricity case.

The power plant's electricity and heat output ($Q(k,t)$) as well as coal use (k) have been calculated for an average year and are based on information provided by Helsingin Energia. The amount of torrefied pellets (t) that the power plant uses is assumed to be equal to the torrefaction plant's output. The gate price of coal (w_k) is a mean value of 2011 monthly coal prices. Monthly coal price data is based on the h-value index maintained by Statistics Finland. H-values are weighted averages of monthly CIF prices: they include both the price of coal and the cost of (sea) freight to Finland. For torrefied pellets, no proper market or market price yet exists, so I use a price estimate provided by Flyktman et al. (2011). This estimate is roughly equal to the price of wood pellets on a per MWh basis, so it should be in the right range.

The other operational costs of the power plant (∅) include basic maintenance and reparation costs as well as all variable costs related to production, such as the costs of storage, chemicals, sulphur removal, filters and ash handling. These costs have been estimated for an average year based on information from Helsingin Energia. The default value for ∅ is assumed to be roughly the same in the current situation, when only coal is used, and in the case of co-firing. It is slightly unclear how co-firing would affect the variable costs. Maintenance and storage costs could rise but sulphur removal costs would decrease as torrefied pellets contain less sulphur than coal. The possible change in ash handling costs is a big question mark – torrefied pellets contain less ash than coal, but if co-firing limits the re-use of ashes, more ash would end up as waste to landfills at high costs. The default value of operational costs used here corresponds to a situation where roughly 50 % of ashes are re-used. Recent changes in the costs of delivering ash to a landfill are not accounted for in the cost figure.

When calculating the energy producer's profits under current climate policy, I need the European CO2 emission allowance price (p_c). Instead of using the average 2011 market price, I have roughly estimated what the current market price would be, if the carbon market had not been distorted by the economic crisis. The chosen value, 17 €/t CO2, is also equal to the mean value of EUA prices in the current emissions trading period (2008 – October 2011).

Shipping company

The unit price of transportation and storage of torrefied pellets (δ) has been estimated based on a quick survey to Finnish transport companies that was conducted at Helsingin Energia in 2010. The price includes short-distance truck transport from the torrefaction plant to the port, loading the ship and the cost of ship transport. I did not find adequate information on the shape or magnitude of an average shipping company's cost function, so I have simply assumed the shipping company's costs ($c(t)$) to be 70 % of the estimated revenue it earns. The shipping company's net profits do not play a major role in the chain, so a modest amount of inaccuracy in these parameter values should not have a large impact on final results.

Torrefaction plant

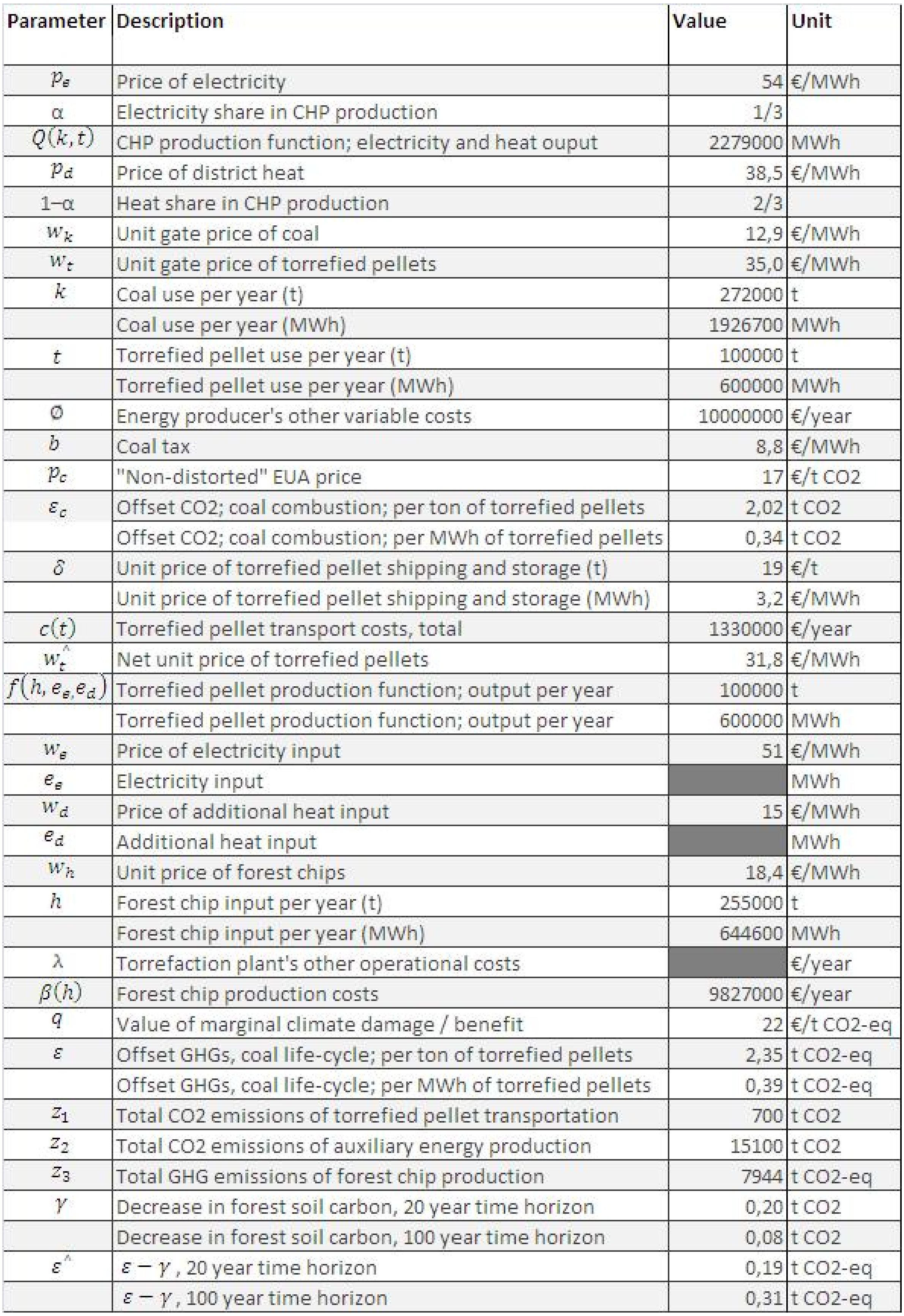
The torrefaction plant's output ($f\left(h, e_{e,} e_d\right) = t$) per year is assumed to be fixed. The production volume in turn determines input use. Input use calculations are based on the technical design of an integrated torrefaction plant with an output of 100 kilotonnes per year. I accessed this technical process data through Helsingin Energia. Based on this data as well as descriptions of the ECN combined torrefaction and pelletisation process, I have estimated that roughly 75 % of the heat demand of the whole torrefaction process can be met through combustion of torrefaction gases. The rest of the required heat has to be produced using a utility fuel and is referred to as the additional heat input (e_d). The additional heat input in this case does not greatly differ from that in the case of a torrefaction plant producing only 56 kilotonnes of torrefied pellets (Bergman 2005) that was referred to in chapter 4.3. In my case study, the moisture content of chips used as feedstock is assumed to be 45 % wt. instead of 57 % wt., which means pre-drying will require less thermal energy. I also assume the energy yield of torrefaction to be 85 % instead of 90 %, which means the energy content of torrefaction gas is higher and combustion of torrefaction gas thus produces more energy for the process, decreasing the required additional heat input.

In this case study, the torrefaction plant is assumed to be integrated to a peat and wood fuelled CHP plant. The plant's heat production is assumed to exceed consumers' heat demand in the area, so extra heat is available for the torrefaction process. I assume that the electricity and additional heat that the torrefaction plant uses is produced in this CHP plant. The plant can sell electricity either to the Nordic power exchange or to the torrefaction plant, so the price the torrefaction plant pays for electricity (w_e) is assumed to be equal to the average Nord Pool spot price. For simplicity, it is assumed that torrefaction is a year-round activity, and thus there is no need to calculate a weighted average of the electricity price. For the heat input, I use a price (w_d) that is lower than average district heat prices because the CHP plant is assumed to generate excess heat. The price of the forest chip input i.e. the price of forest chips (w_h) is taken from Finnish fuel price statistics (Pöyry 2011b). Here I used the average price for of the last 12 months. The other operational costs of the torrefaction plant (λ) include, among other, the costs of maintenance, labour and nitrogen that is needed for creating the oxygen-free conditions of the torrefaction process. This cost data was obtained from the same source as the technical process data for an integrated torrefaction plant.

Chipping company

The chipping company's production volume equals the torrefaction plant's demand for forest chips (h) and it gets the same price for forest chips (w_h) that the torrefaction plant pays for them. The chipping company's costs ($\beta(h)$), including the cost of transporting the chips to the torrefaction plant, have been evaluated based on Mäkinen et al. (2006), Pöyry (2009), Repola et al. (2009) and Ryymin et al. (2008). All of these sources present production costs for three different production chains: chips made from logging residue, small-diameter wood and stumps. I assumed the shares of these three types of residue in the forest chip ”mix” to be 40, 45 and 15 %, respectively. I first calculated the weighted average for this kind of forest chip ”mix” based on values from each of the four sources, and then calculated a mean value of the four values I had obtained. The values were calculated for a transportation distance of 100 km. In practice, the costs of chip production would likely depend on production volumes. Here I have, however, calculated a constant unit production cost and then multiplied it by the volume of supplied chips to get a numerical estimate of the chipping company's total costs.

Table 6.3 Parameter values.



Parameter	Description	Value	Unit
p_e	Price of electricity	54	€/MWh
α	Electricity share in CHP production	1/3	
$Q(k,t)$	CHP production function; electricity and heat ouput	2279000	MWh
p_d	Price of district heat	38,5	€/MWh
1–α	Heat share in CHP production	2/3	
w_k	Unit gate price of coal	12,9	€/MWh
w_t	Unit gate price of torrefied pellets	35,0	€/MWh
k	Coal use per year (t)	272000	t
	Coal use per year (MWh)	1926700	MWh
t	Torrefied pellet use per year (t)	100000	t
	Torrefied pellet use per year (MWh)	600000	MWh
$\varnothing$	Energy producer's other variable costs	10000000	€/year
b	Coal tax	8,8	€/MWh
p_c	"Non-distorted" EUA price	17	€/t CO2
ε_c	Offset CO2; coal combustion; per ton of torrefied pellets	2,02	t CO2
	Offset CO2; coal combustion; per MWh of torrefied pellets	0,34	t CO2
δ	Unit price of torrefied pellet shipping and storage (t)	19	€/t
	Unit price of torrefied pellet shipping and storage (MWh)	3,2	€/MWh
$c(t)$	Torrefied pellet transport costs, total	1330000	€/year
$w_t^{\wedge}$	Net unit price of torrefied pellets	31,8	€/MWh
$f(h, e_e, e_d)$	Torrefied pellet production function; output per year	100000	t
	Torrefied pellet production function; output per year	600000	MWh
w_e	Price of electricity input	51	€/MWh
e_e	Electricity input		MWh
w_d	Price of additional heat input	15	€/MWh
e_d	Additional heat input		MWh
w_h	Unit price of forest chips	18,4	€/MWh
h	Forest chip input per year (t)	255000	t
	Forest chip input per year (MWh)	644600	MWh
λ	Torrefaction plant's other operational costs		€/year
$\beta(h)$	Forest chip production costs	9827000	€/year
q	Value of marginal climate damage / benefit	22	€/t CO2-eq
ε	Offset GHGs, coal life-cycle; per ton of torrefied pellets	2,35	t CO2-eq
	Offset GHGs, coal life-cycle; per MWh of torrefied pellets	0,39	t CO2-eq
z_1	Total CO2 emissions of torrefied pellet transportation	700	t CO2
z_2	Total CO2 emissions of auxiliary energy production	15100	t CO2
z_3	Total GHG emissions of forest chip production	7944	t CO2-eq
γ	Decrease in forest soil carbon, 20 year time horizon	0,20	t CO2
	Decrease in forest soil carbon, 100 year time horizon	0,08	t CO2
$\varepsilon^{\wedge}$	$\varepsilon - \gamma$, 20 year time horizon	0,19	t CO2-eq
	$\varepsilon - \gamma$, 100 year time horizon	0,31	t CO2-eq

Climate parameters

In the energy producer's private profit function under current policy, ε denotes the amount of CO2 from coal combustion that one unit of torrefied pellets offsets. It was calculated using the official CO2 emission factor for coal combustion provided by Statistics Finland (2011).

In the social welfare function, ε is defined over the coal life-cycle, meaning it also takes into account emissions from the coal production chain. I used the same estimate for emissions from coal production and combustion as Liski et al. (2011). In total, these emissions are roughly 15 % higher than the emissions from combustion alone – ε is thus higher than in the first case. Coal life-cycle emissions depend on the origin of the coal and on the type of mine it comes from as well as on transportation distances. The coal Helsingin Energia uses mainly comes from underground mines in Russia, but as precise estimates of the GHG emissions of this specific coal production chain are not available, I have to rely on general estimates.

My estimate of the total emissions of shipping torrefied pellets (z_1) is based on coal transport emissions data obtained from Helsingin Energia (K. Kaija, personal notification 1.7.2011). The CO2 emission of transporting 1 tonne of torrefied pellets by sea was assumed to be the same order of magnitude as the CO2 emission of transporting 1 tonne of coal by sea. I then multiplied this unit CO2 emission by the quantity of torrefied pellets used.

The GHG emissions from the production of auxiliary energy for torrefaction were calculated assuming that the electricity and heat inputs are produced in the peat and wood fuelled CHP plant to which the torrefaction plant is integrated. The CO2 emissions of the CHP plant were calculated using the official CO2 emission factor of peat combustion (Statistics Finland 2011) and setting the CO2 emissions of wood fuel combustion to zero according to the carbon neutrality principle. Possible other GHGs from combustion and the GHG emissions of production and transport of the peat and wood fuels to the CHP plant were excluded from the calculations, as these should not have a major impact on final results. The CO2 emissions of the hypothetical CHP plant were allocated to electricity and heat using an allocation formula by the European Commission (European Commission 2011, 26). This EC formula is used in, for example, the process of determining the free emission allowance allocation for district heat produced in CHP applications. In my study, using this allocation formula made it possible to calculate CO2 emissions per unit of produced electricity and per unit of produced heat. Per unit emissions of electricity and heat were then multiplied by the total electricity and heat inputs, yielding the total CO2 emissions of auxiliary energy production.

For the GHG emissions of forest chip production and transportation (z_3), I decided to use estimates provided by Mäkinen et al. (2006), because their work in the area has been referred to in many subsequent studies. I calculated a weighted average of the emissions of three different chip production chains (logging residue, small-diameter wood and stump chains). The emissions of transportation were calculated for a distance of 100 km. The magnitude of emissions from chip storage is rather uncertain and strongly depends on the length of storage periods, so I did not include emissions from storage in the default value of z_3.

The temporary decrease in forest soil carbon stocks as a consequence of forest residue collection and energy use is a source of indirect carbon dioxide emissions, but instead of being accounted for in the emissions from forest chip production (z_3), they are accounted for through $\varepsilon^{\wedge}$, which describes the ability of torrefied pellets to offset GHG emissions from coal when carbon leakage is accounted for. These indirect CO2 emissions (γ) (expressed per MWh of torrefied pellets) strongly depend on the chosen time horizon, so I will study their effect on results using two time horizons: 20 years and 100 years. For comparison, I will also calculate net climate benefits and social welfare assuming that γ is zero. As the time horizon becomes longer, the calculatory indirect CO2 emissions approach zero because forest residue would undergo natural decomposition even if it had been left in the forest. When calculating the values for γ in the 20- and 100-year time horizons, I follow Repo et alii's (2010, 3) approach and assume the indirect CO2 emissions from using forest residues for bioenergy production to be equal to the amount of carbon remaining in the residue had it been left to decompose at the harvesting site. The relative amounts of carbon remaining in harvest residues, small-diameter wood and stumps 20 and 100 years after felling were calculated based on Liski et alii's (2011, 15) estimates of forest residue decomposition in Nothern Finland. In order to calculate indirect CO2 emissions per unit of chips, the relative amounts of carbon remaining in residues were converted into carbon dioxide by multiplying them by the official CO2 emission factor of wood fuel combustion (Statistics Finland 2011), an approach used also in other works such as Sorsa (2011, 45). I then calculated a weighted average of indirect CO2 emissions that corresponds to the forest chip mix[5] for both the 20- and 100-year time periods and finally expressed them on a per MWh of torrefied pellets basis in order to obtain a value for γ.

The climate benefits and climate damage caused by GHG offsets and emissions respectively have been assigned a value based on estimates found in literature. The range of marginal damage cost estimates is wide and there is still considerable uncertainty related to them. Damage costs are also assumed to increase over time (GES 2002, 6). After reviewing several studies in the field (e.g. Fahlén & Ahlgren 2010; GES 2002; Tol 2005), I have chosen to use 22 €/tCO2-eq. as the value of marginal climate damage and climate benefit to society. This value is close to that used by Lankoski & Ollikainen (2011), whose work also concentrated on the net social benefits of biofuels.

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[5] 40 % logging residue, 45 % small-diameter wood and 15 % stumps.

7 Results and sensitivity analysis

In this chapter I present the results of the case study. A sensitivity analysis is also performed in order to assess the effect of changes in key parameters on results. Calculations are based on the model developed in chapter 5.2 that is then applied to the hypothetical case presented in chapter 6.1. A table of parameter values was provided in chapter 6.2.

The reader should keep in mind, that in this case study, the volume of torrefied pellet production and use is fixed at 100 000 tonnes per year, which is equivalent to 600 000 MWh. Thus, unless stated otherwise, the presented results only apply for this level of torrefied pellet production and use in the chain.

7.1 Results

Theoretical case

I first calculate the results for the so called theoretical case, in which current climate policy (subsidies, taxes, emissions trading) and the effect of a decrease in forest soil carbon stocks on offsets and climate benefits are not taken into account. Results for this case are presented in table 7.1. and they correspond to torrefied pellet production and use volumes of 100 kilotonnes per year. Table 7.1 shows the private profits of each of the companies involved in the torrefied pellet chain, GHG emissions from torrefied pellet production, offsets i.e. GHG savings from replacing coal with torrefied pellets, net climate benefits and finally the ex-post social welfare i.e. net social benefits generated by torrefied pellet production and use. All figures have been calculated on a per year basis. It is also important to keep in mind, that fixed costs have not been included in private profit calculations and are thus neither accounted for in SW.

From table 7.1. we can see, that the private profits of all four companies are positive. Out of the companies involved in the torrefied pellet chain, the energy producer's profits are by far the largest and also make up a major part of social welfare. Using torrefied pellets in the place of coal offsets more GHG emissions (including emissions from burning, transporting and producing the coal) than torrefied pellet production generates, meaning net climate benefits are positive. When climate benefits are assigned a monetary value of 17 €/tCO2-eq., the value of climate benefits to society is over 5 million euros. Ex-post social welfare, which is the sum of private profits and net climate benefits, is also positive. Since investment costs and other fixed costs were not included in the private profit and social welfare functions, the calculated level of net social benefits only applies to the operational side of the chain. In other words, in this specific case, torrefied pellet production and use generates 55,7 million euros of social revenue if we assume necessary investments have already been made and if fixed costs are not taken into account.

Table 7.1 Revenue, costs, private profits, CO2-eq. emissions and offsets, net climate benefits and ex-post social welfare in a case where current climate policy and the effect of decreases in forest soil carbon stocks are not taken into account.

	Revenue (M€)	Costs (M€)	Private profits (M€)	Emissions (t CO2-eq)	Offsets * (t CO2-eq)	Net climate benefit (M€)	Social Welfare (M€)
Energy producer	99,3	55,9	43,4	-	234754	5,16	48,6
Shipping company	1,9	1,3	0,6	700	-	-0,02	0,6
Torrefaction plant	19,1	14,0	5,1	15100	-	-0,33	4,7
Chip producer	11,9	9,8	2,0	7944	-	-0,17	1,9
Total	132,2	81,1	51,1	23744	234754	4,64	55,7

** Amount of GHG emissions from coal production and combustion that torrefied pellet use offsets.*

It would be interesting to see how net social benefits change if the quantity of torrefied pellets produced and used increases or decreases. When performing sensitivity analysis, I will also test the effect of a 50 % increase and decrease in torrefied pellet volumes.

Current policy case

Comparing the energy producer’s profits in different cases is of special interest to me. So far I have calculated the energy producer’s profits using a profit function that excludes the effect of climate policy instruments. For comparison, I recalculate the energy producer’s profits in the cofiring case by using a modified profit function that takes current Finnish climate policy (i.e. emissions trading and the tax on heat produced from coal, referred to here as the coal tax) into account. I also calculate the energy producer’s profits under current policy in a case where the only fuel is coal, which represents the current situation at the Salmisaari power plant. In this case torrefied pellet use is zero ($t = 0$) and coal use is 600 000 MWh higher than in the cofiring case, in order to generate the same output. Results for both current policy cases are presented in table 7.2.

By comparing the the energy producer’s profits in tables 7.1 and 7.2, we can see the effect of current climate policy on the profits of the energy producer. In the case of co-firing coal and torrefied pellets, profits are 13,4 million euros lower under current policy than in the theoretical case in which the effect of climate policy instruments is not included. Taking coal taxes into account in the profit function increases the energy producer’s costs by nearly 17 million euros, but the additional revenue (or decrease in costs) from taking part in emissions trading is only 3,4 million, which explains the rather big difference in co-firing profits between the theoretical and current policy cases.

Table 7.2. Energy producer’s revenue, costs and profits under current climate policy both when using coal as the only fuel and when co-firing.

	Revenue (M€)	Costs (M€)	Private profits (M€)	Total emissions * (t CO2)
Current situation; t = 0				
Energy producer	99,3	64,8	34,6	850118
Cofiring; t = 100 000 tonnes				
Energy producer	99,3	69,3	30,0	648285
** Energy producer's actual emissions under current policy.*				

In the current situation where only coal is used, the energy producer burns more coal than in the co-firing case and thus pays more coal taxes. Neither does it benefit from a reduced need for emission allowances that the use of torrefied pellets would bring about. Despite these facts, private profits in the current situation where no torrefied pellets are used (34,6 M€) are higher than in the co-firing case (30,0 M€), when current policy is taken into account. The reason behind this is the difference in coal and torrefied pellet prices, the latter being a lot higher. This means that it would not be privately optimal for the power plant to co-fire 100 000 tonnes of torrefied pellets a year at current prices and costs. In order for the energy producer’s profits under current policy to be equal in the coal-only and cofiring cases, the emission allowance price would need to be significantly higher, if the coal tax level and coal and torrefied pellet prices were to remain unchanged.

It is worth to note, that the private profit figures in table 7.2. correspond to a situation where the energy producer gets all the emissions allowances it needs for free. If the energy producer initially gets less allowances than it needs, it must buy the remainder from the market – profits in both cases would thus be lower. The difference between profits, however, remains the same. So, whether or not the energy producer initially buys some of the allowances it needs from the market, profits in the coal-only case are 4,6 million euros higher than when cofiring.

Changes in forest soil carbon stocks

Taking the decrease in forest soil carbon stocks into account increases the GHG emissions of the torrefied pellet production chain. Table 7.3 shows how this affects net climate benefits and social welfare. As the calculatory carbon dioxide emissions from changes in forest soil carbon stocks decrease over time, I have studied the effects of two different time horizons, 20 years and 100 years. I can then compare the results for these cases with the theoretical case that ignored changes in forest soil carbon stocks.

Table 7.3. The effect of a decrease in forest soil carbon stocks on net climate benefits and social welfare when the time horizon for assessing climate effects is 20 and 100 years.

	Emissions - offsets (t CO2-eq)	Private profits (M€)	Net climate benefit (M€)	Social welfare (M€)
Decrease in forest soil carbon stocks accounted for; 20-year time horizon				
Total	-89183	51,1	1,96	53,1
Decrease in forest soil carbon stocks accounted for; 100-year time horizon				
Total	-162422	51,1	3,57	54,7

By comparing the results in table 7.3 and table 7.1, we can see that the net climate benefits that torrefied pellet production and use generates are smaller when the indirect CO2 emissions caused by a decrease in forest soil carbon stocks are taken into consideration. As private profits remain unchanged, net social benefits fall by the same amount as net climate benefits. The shorter is the time horizon for assessing the climate impact of forest-based torrefied pellets, the less society benefits from their use. However, even when the time horizon is as short as 20 years, the offset benefits from replacing coal exceed the emissions of the torrefied pellet chain, meaning that net climate benefits remain positive. This implies that cofiring torrefied pellets with coal in combined heat and power production leads to a reduction in GHG emissions and creates climate benefits to society, even if indirect CO2 emissions from a decrease in forest soil carbon stocks are taken into account.

We can see from table 7.3 that a decrease in net climate benefits reduces the net social benefits of the whole chain by only few millions of euros. This implies that social welfare mostly depends on net private profits of the companies involved in the chain. The total value of net climate benefits is, however, very dependent on the monetary value assigned to marginal climate damage and climate benefit. The sensitivity of results to changes in this value will be tested in chapter 7.2.

7.2 Sensitivity analysis

The results presented in chapter 7.1 are only valid for the applied set of parameter values. In this chapter, I perform a sensitivity analysis in order to find out how changes in key parameters affect the results. For example, how does a change in the volume of torrefied pellet production and use affect private profits, net climate benefits and social welfare?

I have chosen to test the sensitivity of results to the following parameters: price of electricity (both the weighted and non-weighted average market price, p_e and w_e), price of district heat (p_d), unit gate price of coal (w_k), unit gate price of torrefied pellets (w_t), energy producer’s other operational costs (∅), EUA price (p_c), unit price of forest chips (w_h), value of marginal climate benefits and climate damage (q) and, finally, the quantity of torrefied pellets produced and used (t). Many of the chosen parameters are related to the energy producer’s profit function, because the energy producer’s profits make up a lion’s share of the total social welfare generated in the chain and SW is thus likely to be highly dependent on changes in these profits.

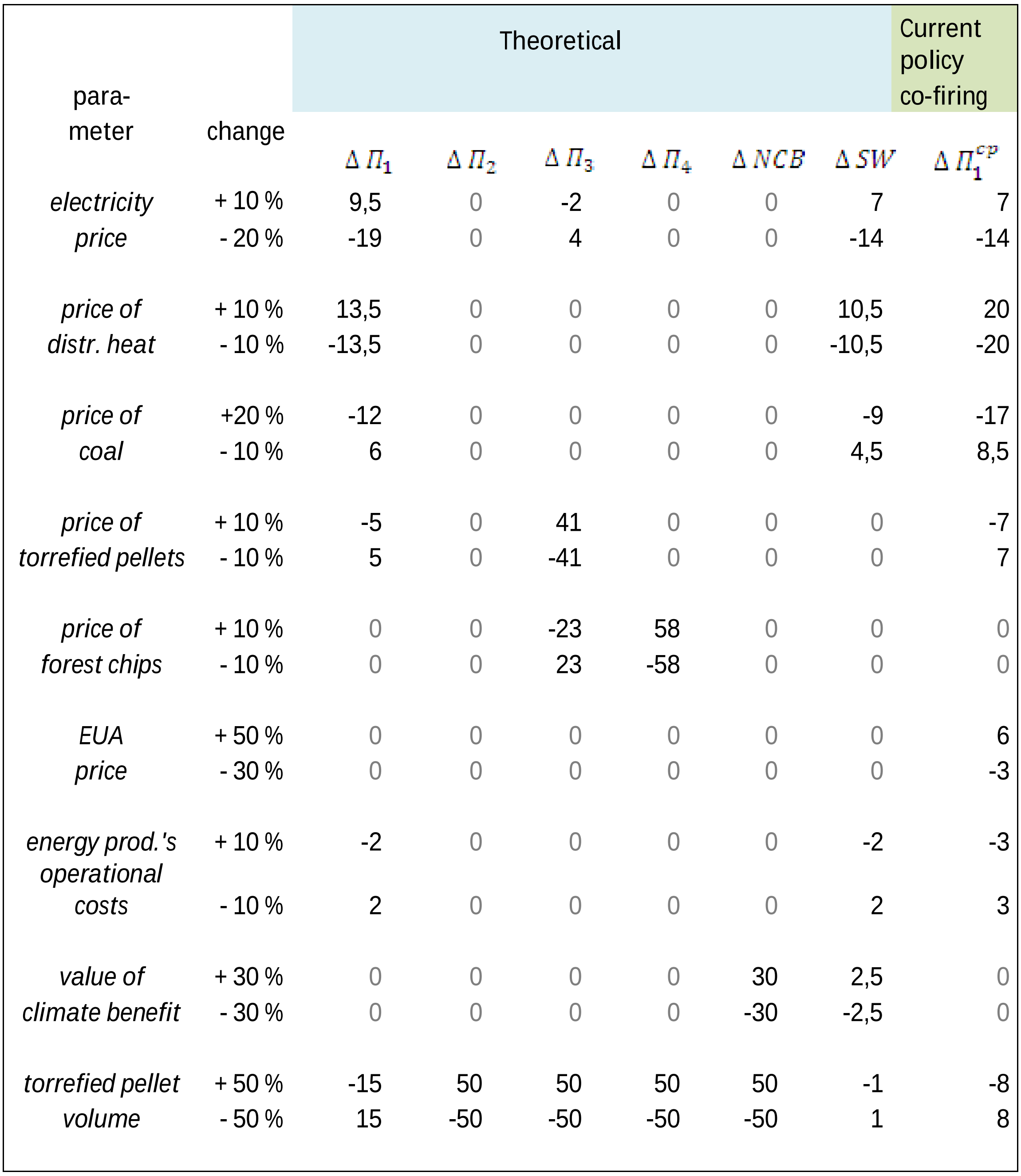
Increases and decreases in parameter values reflect ranges within which the values might vary. For example, the average Finnish electricity price in year 2011 has been somewhat high compared to the last few years, so I chose to investigate the effect of a 10 % increase and 20 % decrease in the price. Respectively, there was a significant drop in EUA prices in mid-2011, but some expect the price to rise sharply in the course of the third emissions trading period, so the chosen range is - 30 % and + 50 %. I have also chosen a rather wide range for the value of marginal climate benefits and climate damage, since there is a lot of variation in the estimates presented in literature.

Results of the sensitivity analysis are presented in table 7.4. Figures represent percentual changes in results when the value of a certain parameter is increased or decreased. We can see that the energy producer's profits are very sensitive to changes in electricity and district heat prices.

A change in electricity price affects both the energy producer and the torrefaction plant that needs electricity in the torrefied pellet production process. The energy producer's profits are more sensitive to changes in the price – when p_e increases by 10 %, the producer's theoretical profits increase by 9,5 %. The respective change in social welfare is 7 %. District heat is the energy producer's main product, so changes in the heat price affect its profits even more: a 10 % increase in the price of heat leads to a 13,5 % increase in theoretical profits. As a result, social welfare increases by 10,5 % – this is yet another sign of the major impact the energy producer's profits have on net social benefits in the case studied.

Changes in fuel prices also have a significant effect on the energy producer's profits, although this effect is not as substantial as the effect of changes in output prices. If the coal price decreases 10 %, the energy producer's theoretical profits rise by 6 %, and if torrefied pellets become 10 % cheaper, the increase in profits is nearly 5 % as well. The same 10 % decrease in the torrefied pellet price would lead to a whopping 41 % decrease in the torrefaction plant's profits. However, due to the structure of the model, changes in the energy producer's and torrefaction plant's profits cancel out, and SW remains unsensitive to changes in w_t. The same happens when the price of forest chips is changed: a 10 % increase in the price of chips raises the chip producer's profits by 58 % but decreases the torrefactions plant's profits by 23 %. These changes in profits again cancel out, and net social benefits are left unchanged.

Table 7.4. Percentual changes in the energy producer’s, shipping company’s, torrefaction plant’s and chipping company’s theoretical private profits, net climate benefits, ex-post social welfare and the energy producer’s co-firing profits under current policy when a parameter is changed (%).



para-meter	change	Theoretical						Current policy co-firing
		$\Delta \Pi_1$	$\Delta \Pi_2$	$\Delta \Pi_3$	$\Delta \Pi_4$	ΔNCB	ΔSW	$\Delta \Pi_1^{cp}$
electricity price	+ 10 %	9,5	0	-2	0	0	7	7
	- 20 %	-19	0	4	0	0	-14	-14
price of distr. heat	+ 10 %	13,5	0	0	0	0	10,5	20
	- 10 %	-13,5	0	0	0	0	-10,5	-20
price of coal	+20 %	-12	0	0	0	0	-9	-17
	- 10 %	6	0	0	0	0	4,5	8,5
price of torrefied pellets	+ 10 %	-5	0	41	0	0	0	-7
	- 10 %	5	0	-41	0	0	0	7
price of forest chips	+ 10 %	0	0	-23	58	0	0	0
	- 10 %	0	0	23	-58	0	0	0
EUA price	+ 50 %	0	0	0	0	0	0	6
	- 30 %	0	0	0	0	0	0	-3
energy prod.'s operational costs	+ 10 %	-2	0	0	0	0	-2	-3
	- 10 %	2	0	0	0	0	2	3
value of climate benefit	+ 30 %	0	0	0	0	30	2,5	0
	- 30 %	0	0	0	0	-30	-2,5	0
torrefied pellet volume	+ 50 %	-15	50	50	50	50	-1	-8
	- 50 %	15	-50	-50	-50	-50	1	8

A change in the EUA price only affects the energy producer’s profits when current policy is taken into account. When the energy producer co-fires coal and torrefied pellets, an increase in the EUA price leads to higher profits in this model, because the allowances that the energy producer does not need and can sell on the market thanks to using a biomass fuel are now more valuable. For example, if emission allowance prices increase by 50 %, the energy producer’s profits rise by 6 %, because it either benefits from selling dispensable allowances at a higher price or saves even more in costs compared to a coal-only situation where it would need more allowances than when co-firing.

Net climate benefits are defined as the difference between offsets and GHG emissions, multiplied by the monetary value of marginal climate benefits and climate damage. If this value increases 30 %, net climate benefits also increase by 30 %. This in turn increases net social benefits by 2,5 % (or decreases them by 2,5 %, had the value of climate benefit instead been 30 % lower). As noted before, the energy producer's profits have a much larger impact on social welfare than anything else, so even a rather large increase or decrease in the value of marginal climate benefits affects social welfare only slightly.

In my case study, the volume of torrefied pellet production and use was fixed at 100 000 tonnes per year. In the case at hand, would it be optimal to produce and use less or more torrefied pellets? I tested this by scaling the volume of torrefied pellets in the chain up and down by 50 %. In order to do this, I scaled up or down all parameter values that are dependent on the volume of torrefied pellets, such as the energy producer's coal use (k), total torrefied pellet transportation costs ($c(t)$), the torrefaction plant's input use (h, e_e, e_d) and the forest chip production volume (h). As a result, total GHG emissions and offsets changed as well. Two assumptions have been made. Firstly, I assume that unit prices and unit costs are independent of torrefied pellet and forest chip production volumes. Secondly, I assume that the power plant's other production related costs do not change when the quantity of torrefied pellets used is scaled up or down. It is hard to say how realistic this assumption is: a larger torrefied pellet share in co-firing reduces, for example, sulphur removal costs because wood contains less sulphur than coal, but might lead to higher storage costs and repair and maintenance costs.

We can see that increasing torrefied pellet use to 150 000 tonnes per year decreases the energy producer's theoretical profits by 15 %. When coal taxes and emissions trading are taken into account, the decrease in profits is more modest, but still 8 %. This means that it is not optimal for the energy producer to increase torrefied pellet use by 50 % at current prices, even though increasing the bio share in co-firing results in paying less coal taxes and benefiting more from emissions trading. Increasing torrefied pellet use by 50 % at the expense of coal leads to 50 % higher climate benefits to society. Despite this and the increase in profits of the other companies that the increase in torrefied pellet volumes would bring about, theoretical net social benefits are 1 % lower than in the base case where torrefied pellet use is 100 000 tonnes. A higher level of torrefied pellet production and use in this chain would thus not benefit society. However, this conclusion is very dependent on current prices and the chosen value for climate benefits. If climate benefits were valued higher or if the price difference between coal and torrefied pellets was smaller, the result would be opposite.

The model used in this study is a linear model, so a 50 % decrease in torrefied pellet production and use volumes has the same effect on results as a 50 % increase, but in the opposite direction. When torrefied pellet use is 50 kilotonnes instead of 100 kilotonnes, the energy producer's theoretical profits increase by 15 % and profits under current policy by 8 %. The large difference in coal and torrefied pellet prices is the main reason behind this result. Coal is a cheaper fuel, so using more coal and less torrefied pellets is beneficial for the energy producer. Smaller torrefied pellet production volumes reduce the profits of the other three companies in the chain as well as net climate benefits, but despite this, net social benefits are 1 % higher than in the base case.

To sum up, changes in the energy producer's profits have the greatest impact on social welfare in this model. Changes in climate related parameters such as the EUA price and the value of marginal climate benefit have a smaller effect on results than changes in, for example, electricity and district heat prices. Analyzing the effects of a 50 % increase and 50 % decrease in torrefied pellet use and production volumes showed that it would be profitable for the energy producer to co-fire less than 100 kilotonnes of torrefied pellets, even when the effect of climate policy instruments is taken into account. This result is, however, very dependent on current fuel prices as well as current EUA prices and tax levels. Increasing torrefied pellet production and use by 50 % would lead to higher climate benefits to society and higher profits for e.g. the torrefaction plant and the chip producer, but the energy producer's profits would decrease both in the theoretical scenario and under current policy. As a result of the substantial changes in the energy producer's theoretical profits, net social benefits would be 1 % lower and 1 % higher when the volume of torrefied pellets is 50 % smaller and 50 % larger, respectively. However, if the price of torrefied pellets turns out to be lower than expected, if coal prices increase or if society places a higher value on GHG emission reductions, this result would soon be reversed. After all, a +/- 1 % change in social welfare is a rather small change.

8 Conclusions and discussion

In this thesis, I examined the climate impacts and social returns of torrefied pellet production and use as an alternative fuel to coal in Finland. I first defined the production chain or, in other words, the life cycle of torrefied pellets in a case where the raw material of pellets is forest chips. I assessed the environmental impacts arising at different stages of the chain, focusing on climate impacts. Based on literature, I estimated a greenhouse gas balance for torrefied pellets and compared it to the GHG emissions from coal production and combustion. I then developed a model for analyzing how desirable torrefied pellet production and use would be from society’s viewpoint, when both private profits and climate benefits are taken into account. The model was applied to a hypothetical case in which torrefied pellets are produced in Northern Finland and transported to Helsingin Energia’s cogeneration plant in Southern Finland to be co-fired with coal at a fixed ratio. As a result, I was able to calculate the private profits, net climate benefits and social welfare i.e. net social benefits that torrefied pellet production and use would generate in this case. A sensitivity analysis was performed on results.

In the model and in the case study, the torrefied pellet chain was thought to consist of four profit-maximizing companies: the chip producer, torrefaction plant, shipping company and energy producer. Focus was on the operational side of the chain, so fixed costs and possible investment costs were not included in profit functions. The volume of torrefied pellet production and use in the chain was defined by the energy producer’s coal-to-torrefied pellet blending ratio, which was fixed at 100 000 tonnes per year. My results show that in this case, the profits of all four companies are positive. The energy producer’s profits are by far the largest of the four.

I also calculated the energy producer’s profits under current Finnish climate policy by taking emissions trading and the excise tax on coal-based district heat production into account. I compared profits in two cases, co-firing (the base case in this study) and coal-only (represents current real life situation). Results show, that under current climate policy and at current prices and costs, co-firing torrefied pellets with coal would not be profitable for the energy producer compared to a situation where the only fuel is coal, although profits in both cases are positive. The big difference in the prices of coal (12,9 €/MWh) and torrefied pellets (35 €/MWh) explains this result. Of course no proper market for torrefied pellets yet exists, and it is difficult to say what prices would be when the market is up and running, but the price estimate is assumed to be in the right range. The emission allowance price would need to significantly higher in order for the profits in the co-firing and coal only cases to be equal, if fuel prices and the coal tax were to remain at the same level.

Both my case study and the more general GHG balance analysis in chapter 4.3 show that torrefied pellet production and use in place of coal in energy production has the potential to reduce GHG emissions, when emissions over both the coal life cycle and the torrefied pellet life cycle are taken into account. In the studied case, net climate benefits, that are defined as the difference between CO2-eq. offsets and emissions and assigned a monetary value, are thus positive. When indirect CO2 emissions caused by a decrease in the forest soil carbon stock are taken into account, net climate benefits decrease but remain positive. The total reduction in GHG emissions when replacing coal with 100 000 tonnes of torrefied pellets is approximately 160 000 t CO2-eq. when the time horizon is 100 years and 89 000 t CO2-eq. when the time horizon is 20 years. Thus, torrefied pellet production and use in the place of coal in combined heat and power production reduces GHG emissions and creates climate benefits to society, even if changes in forest soil carbon stocks are taken into account.

Social welfare, or the net social benefits of torrefied pellet production and use are a sum of producers' and consumers' surplus. In this case, social welfare was calculated by adding up private profits (producers' surplus) and net climate benefits (consumers' surplus). Results indicate that the net social benefits of torrefied pellet production and use are positive – at least when investment costs and fixed costs are not taken into account. The energy producer's profits make up a lion's share of total social benefits.

The sensitivity analysis performed on results was perhaps the most interesting part of the socio-economic analysis. A change in electricity and heat prices or fuel prices has a significant impact on both the energy producer's theoretical profits and social welfare. When current policy is taken into account, the effects of changes in these factors (except in the price of electricity) on the energy producer's profits are even larger. A significant rise or decrease in the emissions allowance price, on the other hand, would have a much more modest effect.

Compared to private profits, net climate benefits play a minor role in total social welfare. Thus, social welfare would increase or decrease only slightly, if the value assigned to net climate benefits is changed.

Increasing the share of torrefied pellets in the fuel mix by 50 % would lead to a 15 % drop in the energy producer's theoretical profits. Equivalently, a 50 % decrease in torrefied pellet usage would increase profits by 15 %. Taking current policy into account smoothes out the changes in profits, but does not change the direction of effects. Due to the composition of the model, a 50 % increase (decrease) in the volume of torrefied pellet production and use would increase (decrease) profits of the other three companies and net climate benefits by 50 %. Despite this, when torrefied pellet production and use increases or decreases by 50 %, net social benefits are 1 % lower and 1 % higher respectively.

To sum up, the production and use of torrefied pellets as an alternative fuel to coal in combined heat and power production leads to GHG emission reductions and generates positive private profits in the short run (when fixed costs and investment costs are not taken into account), which means that net social benefits are positive. Increasing torrefied pellet production and use from the base case level would lead to further GHG emission reductions and higher profits for the torrefaction plant and chip producer, but due to a significant price difference in torrefied pellet and coal prices, it would not be profitable for the energy producer. Since net social benefits are highly dependent on the energy producer's profits in this model, increasing torrefied pellet production and use from the base case level would not be beneficial to society, although net social benefits would still remain positive. However, the differences in social benefits at different volumes of torrefied pellet use are very small, so a slightly higher coal price or a higher value placed on climate benefits could turn the situation around.

Both the literature review and my case study revealed, that the indirect CO2 emissions caused by a decrease in forest soil carbon stocks can have a significant impact on the net climate effect of the production and use of fuels made from forest residue. The shorter the time horizon within which the climate impact of forest fuels is assessed, the larger are the indirect emissions and the smaller the GHG reductions and climate benefits that can be achieved through replacing fossil fuels (see e.g. Liski et al. 2011, Repo et al. 2010, Wihersaari 2005a). In Finland, there has been a lot of discussion about the climate friendliness of forest fuels. Some say it is crucial to slow down global warming in the next few decades, which means we should favour other renewable energy options (solar, wind) or those parts of biomass that would undergo rapid natural decomposition even if not used in energy production. Others say that instead of focusing on short time horizons and arguing whether or not burning stumps for energy generates more GHG emissions than using fossil fuels, we should look at the bigger picture: The carbon stored in forest residues is released into the atmosphere over the course of 50-150 years even if residue is not used and is left on the harvesting site, but the carbon stored in fossil fuels would be permanently stored away, if the fuels were not burned. One might also ask, that if forestry practices continue to create residues, isn’t it wiser to take advantage of the energy content of residues instead of leaving them at the site, since the carbon stored in residues would sooner or later be released into the atmosphere anyway.

The model developed in this study could be further extended so that instead of being restricted to climate externalities, it would also take into account other externalities such as non-GHG emissions from combustion, reduced fossil fuel dependency or the effects of forest residue removal on forest biodiversity. The different external effects of torrefied pellet production and use could be compared and incorporated into social welfare analysis by assigning them monetary values. Some externalities, like biodiversity effects, are more difficult to measure and value than others. This sometimes leads to these externalities being left out of assessments and analyses. Now that the demand for biomass fuels is increasing and their sustainability has been subject to a lot of debate, a comprehensive numerical analysis in the area would be welcome.

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Appendix 1. Glossary

Key terminology translated from English into Finnish.

English	**Finnish**
Biofuel	Biopolttoaine
Biomass fuel	Kiinteä biopolttoaine
Calorific value	Lämpöarvo
Carbon dioxide equivalent	Hiilidioksidiekvivalentti
Chipping	Haketus
Chips	Hake
Clear cutting	Avohakkuu
Cogeneration	Yhteistuotanto
Cogeneration plant	Yhteistuotantolaitos
Condensing power	Lauhdevoima
Crushing	Murskaus
Decaying wood	Lahopuu
District heating	Kaukolämpö
Early thinning	Ensiharvennus
Emission allowance	Päästöoikeus
Energy wood	Energiapuu
EU Emissions Trading Scheme	EU:n päästökauppa
Felling	Hakkuu
Fine particulate matter	Pienhiukkaset
Forest chips	Metsähake
Forest soil carbon stock	Metsämaan hiilivarasto
Forest residue	Metsätähde
Fuel chain	Polttoaineketju
Industrial wood	Ainespuu
Log	Tukkipuu
Logging	Hakkuu
Logging residue	Hakkuutähde
Lower heating value	Tehollinen lämpöarvo
Nutrient leaching	Ravinteiden huuhtoutuminen
Pelletisation, pelletising	Pelletöinti
Power plant	Voimalaitos

English	**Finnish**
Pulpwood	Kuitupuu
Renewable energy source	Uusiutuva energianlähde
Security of supply	Huoltovarmuus
Small-diameter wood	Pienpuu
Small-sized trees	Pienpuu
Soil carbon balance	Maaperän hiilitase
Solid fuel	Kiinteä polttoaine
Stem wood	Runkopuu
Stump	Kanto
Stumpage price	Kantohinta
Thinning	Harvennus
Timber	Puu, puutavara
Torrefied biomass	Torrefioitu eli paahdettu biomassa
Torrefaction gas	Paahtokaasu
Torrefied pellet	Paahtopelletti, biohiili
Useful energy	Hyötyenergia
Wood chips	Hake
Wood pellet	Puupelletti

Appendix 2. Summary table of parameter definitions

Parameter	Description
p_e	Price of electricity
α	Electricity share in CHP production
$Q(k,t)$	CHP production function; electricity and heat ouput
p_d	Price of district heat
$1-\alpha$	Heat share in CHP production
w_k	Unit gate price of coal
w_t	Unit gate price of torrefied pellets
k	Energy producer's coal use per year
t	Energy producer's torrefied pellet use per year
$\emptyset$	Energy producer's other variable costs
b	Coal tax
p_c	"Non-distorted" EUA price
ε_c	Amount of CO2 from coal combustion that one unit of torrefied pellets offsets
δ	Unit price of torrefied pellet shipping and storage
$c(t)$	Total torrefied pellet transport costs
$\hat{w}_t$	Net unit price of torrefied pellets
$f(h, e_e, e_d)$	Torrefied pellet production function; output per year
w_e	Price of electricity input
e_e	Electricity input
w_d	Price of additional heat input
e_d	Additional heat input
w_h	Unit price of forest chips
h	Forest chip input per year
λ	Torrefaction plant's other operational costs
$\beta(h)$	Forest chip production costs
q	Value of marginal climate damage and climate benefit
ε	Amount of GHG emissions from coal that one unit of torrefied pellets offsets; defined over coal life cycle
z_1	Total CO2 emissions of torrefied pellet transportation
z_2	Total CO2 emissions of auxiliary energy production
z_3	Total GHG emissions of forest chip production
γ	Decrease in forest soil carbon (carbon leakage) per unit of torrefied pellets
$\hat{\varepsilon}$	$(\varepsilon - \gamma)$

Appendix 3. Technical details of hypothetical peat and wood fuelled cogeneration plant

Production capacity	88	MW
Electricity	26	MW
Heat	62	MW
Fuel capacity	100	MW
Peat	60	MW
Wood	40	MW
Yearly operating hours	6000	h
Power plant efficiency	88	%