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Carl Wilén | Kai Sipilä | Sanna Tuomi | Ilkka Hiltunen | Christian Lindfors | Esa Sipilä | Terttu-Leea Saarenpää | Markku Raiko

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Puun torrefiointi – markkinanäkymät ja integrointi puujalostus- ja energiateollisuuteen.
Carl Wilén, Kai Sipilä, Sanna Tuomi, Ilkka Hiltunen, Christian Lindfors, Esa Sipilä, Terttu-Leea Saarenpää & Markku Raiko. Espoo 2014. VTT Technology 163. 55 p.

Abstract

The research project “Biocoal – a new energy carrier for saw mills, CHP plants and wood industry integrates” was carried out within the Groove programme of Tekes during the years 2010–2013. The main objective of the project was to enhance the commercialization of integrated wood torrefaction technology into current forest industry operations. Several integration concepts were elaborated together with the participating companies with a focus on sawmills and municipal and industrial CHP plants.

The European forest industry constitutes a potential platform for the production of torrefied wood pellets and other bioenergy carriers. VTT, in collaboration with industrial partners, has developed new bioenergy carrier solutions integrated into forest industry operations in sawmills. A new torrefaction process was developed and market analysis was performed, including a road map for demonstrations and market introduction. Some preliminary test work was also carried out in order to assess the possible advantages of the use of torrefied biomass in fixed-bed and fluidised bed gasification applications, bio-oil production and as a potential raw material for new advanced wood products.

The primary prerequisite for the torrefied pellet market is the energy plants’ need for and interest in using them as fuel. The main users are assumed to be found in the power production sector. Substituting coal by co-firing biomass in large pulverised coal-fired power plants needs significant green electricity incentives, however, or a considerably higher CO_2 price in order to be feasible.

From the raw-material point of view, the benefits from integrated torrefied pellet production are related to by-product utilization at sawmills or plywood mills, but also to general wood procurement logistics at forest industry plants. In the case where processing residues can be utilized at site, cost savings can be achieved if the alternative option is to transport residues to an external facility. A market analysis of integrated bioenergy carrier production was undertaken at sawmills in Finland. It was concluded, that the market conditions for torrefied pellets, and for solid biomass fuels in general, is challenging due to the unexpected low prices for CO_2 (about €5/t CO_2) certificates and for coal (about €8/MWh). The results indicated that there needs to be a feed-in tariff or similar support mechanism for torrefied pellets to guarantee a paying capability for coal fired power plants above €35/MWh so as to make the investments viable.

Keywords torrefaction, pellets, biomass, co-firing, forest industry, integration

Puun torrefiointi – markkinanäkymät ja integrointi puujalostus- ja energiateollisuuteen

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Tiivistelmä

Tutkimusprojekti ”Biohiili – uusi bioenergiakantaja sahojen, CHP-voimaloiden ja metsäintegraattien yhteyteen” toteutettiin Tekesin Groove-ohjelmassa VTT:ssä vuosina 2010–2013. Projektin tavoitteena oli edesauttaa biohiilen valmistustekniikan (puun torrefioinnin) kaupallistamista osana metsäteollisuuden toimintoja. Tutkimukseen osallistuvien yritysten kanssa tarkasteltiin useita integrointimahdollisuuksia, erityisesti sahoihin ja yhdyskunnan ja teollisuuden CHP-laitoksiin.

Euroopan metsäteollisuus muodostaa potentiaalisen alustan torrefioitujen puupellettien ja muiden bioenergiakantajien tuotannolle. VTT on yhdessä teollisuusosapuolten kanssa kehittänyt uusia ratkaisuja bioenergiakantajien valmistuksen yhdistämiseksi sahateollisuuden toimintoihin. Tutkimuksessa suunniteltiin uusi torrefiointiprosessi ja laadittiin tiekartta pilotoinnin ja demonstroinnin toteuttamiseksi. Torrefioidulla puulla tehtiin myös alustavia kaasutus- ja pyrolyysikokeita pienessä kokoluokassa mahdollisten etujen selvittämiseksi verrattuna perinteisten puuraaka-aineiden käyttöön. Koetoiminta käsitti myös torrefioidun puun käytön uusien puutuotteiden valmistuksessa.

Torrefioitujen puupellettien laajamittainen käyttö toteutunee ensisijaisesti kivihiilivoimaloiden oheispolttoaineena. Jotta hiilen korvaaminen suurilla pölypolttolaitoksilla oheispolttamalla torrefioituja puupellettejä olisi kannattavaa, vaaditaan kuitenkin merkittäviä vihreän sähkön kannustimia tai huomattavasti korkeampaa CO_2-päästöjen hintatasoa.

Integroimalla torrefioitujen pellettien tuotto metsäteollisuuteen saavutetaan synergiaetuja sahojen ja puutuotetehtaiden sivuvirtojen hyödyntämisessä ja yleisemmin raaka-aineiden hankinnassa ja logistiikassa. Kun sivuvirrat voidaan hyödyntää paikan päällä, saavutetaan selviä säästöjä verrattuna niiden toimittamiseen ja käyttöön ulkopuolisella laitoksella.

Tutkimuksessa tarkasteltiin bioenergiakantajien (torrefioitu puupelletti, bioöljy) valmistusmahdollisuuksia ja -kustannuksia suomalaisilla sahoilla. Torrefioitujen puupellettien ja yleensä kiinteiden biopolttoaineiden markkinatilanne on haastava alhaisen CO_2-päästöhinnan (noin 5 €/tCO_2) ja hiilen hinnan (noin 8 €/MWh) takia. Torrefioitujen pellettien rajahinnaksi laitoksella tulee noin 35 €/MWh, ja on ilmeistä, että torrefioitujen puupellettien käytön tueksi tarvitaan sähkön syöttötariffia tai vastaavanlaista tukimekanismia varmistamaan voimalaitoksen maksukyky.

Avainsanat torrefaction, pellets, biomass, co-firing, forest industry, integration

Preface

The research project “Biocoal – a new energy carrier for saw mills, CHP plants and wood industry integrates” was carried out within the Groove programme of Tekes – the Finnish Funding Agency for Technology and Innovation during the years 2010–2013. The Groove – Growth from Renewables programme enhances the business capabilities of Finnish small and medium-sized enterprises working with renewable energy by improving their international competitiveness and developing networks with the financier network. The project was coordinated by VTT.

This publication summarises the results and findings of this project. The main objective of the project was to enhance the commercialization of integrated wood torrefaction technology into current forest industry operations. Several integration concepts were elaborated together with the participating companies with a focus on sawmills and municipal and industrial CHP plants. A technology road map was drawn up, and economic assessments were carried out so as to accelerate market introduction integrated torrefaction solutions. The study was extended to include non-energy use of the torrefied products in the mechanical wood industry.

The steering group comprised representatives of the organisations and companies funding the research project: Marjatta Aarniala/Tekes, Jukka Heiskanen/Fortum Power and Heat Oy, Markku Karlsson and Heikki Ilvespää/UPM-Kymmene Oy, Jaakko Soikkeli/Vapo Oy, Juhani Kyytsönen/Ostem Oy, Marko Kylä-Sipilä and Jarkko Tenhunen/Renewa Oy, Vesa Rommi/Realite Technologies Oy, and Kai Sipilä and Carl Wilén/VTT. Subcontractors were Esa Sipilä/Pöyry Management Consulting Ltd and Markku Raiko/ÅF-Consult Oy.

The authors would like to acknowledge all those who have participated and contributed to the project, as well as the steering group for active and fruitful participation.

Espoo, March 2014

Authors

Contents

1. Introduction

Ambitious goals have been set in the European energy and climate policy for the year 2020 regarding the promotion of renewable energy sources and the reduction of CO_2 emissions. Large growth scenarios for the use of biomass in second generation transportation fuels as well as production of green electricity have been presented. Torrefied biomass pellets are an interesting option for replacing fossil fuel in existing pulverised coal-fired boilers and fuelling entrained flow gasification plants. Replacing 10% of the coal in the present European coal power plants gives a rough estimate of 60–70 Mt/a of torrefied pellets potential and the need for 600-700 new torrefied pellet or traditional wood pellet production plants with the capacity of 100 000 t/a each. An investment of 30–40 M€ per plant gives a theoretical investment potential of €18–28 000 million. The volume of the wood pellet market was 10.8 Mt in 2010 and a market outlook of 40–50 Mt in 2020 has been anticipated.

Torrefaction technology has developed towards demonstration and commercial market introduction. Several different concepts have been developed by technology suppliers in Europe and North America. However, full commercial-scale operations have been hampered by technical and economic challenges. The torrefaction sector faces a chicken-and-egg problem. The coal-fired power plants would prefer to contract huge quantities, millions of tons of torrefied pellets so as to co-fire reasonable amounts of renewables, but the supplier side mainly consist of small and medium scale production companies. Consequently, there is an imbalance between production and potential use. In the past, the wood pellet industry survived “the valley of death” due to the fact that wood pellets attracted residential users and smaller district heating companies, and later large combined heating and power plants. The production could develop in phase with utilisation. Today, the largest plants produce 500 000–1 000 000 t/a of wood pellets.

VTT, in collaboration with industrial partners, has developed new bioenergy carrier solutions integrated with forest industry operations in sawmills. Sawmills offer attractive business solutions for solid white or brown pellet production, as well as bioliquids produced by fast pyrolysis technology from sawdust and forest residues. There are significant synergies for bioenergy carrier integration due to favourable procurement and logistics, energy and labour benefits. A new torrefaction process was developed and market analysis was performed, including a road map for demonstrations and market introduction in Northern Europe. Some preliminary test work was also carried out so as to assess the possible advantages of the use of torrefied biomass in fixed-bed fluidised bed gasification applications and as a potential raw material for new advanced wood products.

The European forest industry constitutes a potential platform for the production of torrefied wood pellets and other bioenergy carriers. The main users are assumed to be found in the power production sector. Substituting coal by co-firing biomass in large pulverised coal fired power plants needs significant green electricity incentives, however, or a considerably higher CO_2 price in order to be feasible. These questions are also elaborated in the chapters that follow.

2. European forest industry structure

The fundaments of torrefied pellet market dynamics both from the raw-material and end-use point of view are discussed below. The analysis focuses on raw material integration opportunities at European forest industry sites as well as end-use options in energy plants in Europe.

2.1 Wood raw material flows in Europe

The basis of the European forest industry consists of the sawmill industry, pulp industry and wood panel industry. These sectors are primary processors of wood raw materials producing intermediary products such as sawn wood, pulp, a variety of reconstituted wood panels made of small pieces of wood and other panels such as plywood. In addition, there are various other processing industries such as paper, paperboard and the carpentry industry that produce forest industry products but do not use round wood as a raw material.

The round wood use in the European forest industry in 2012 was about 340 Mm^3 (680 TWh). In the same year the European coal use in power and CHP production was above 700 Mt (nearly 3 000 TWh). If theoretically all current round wood was used in co-firing, up to 20–25% of coal could be replaced by wood. The challenge is to what extent coal can be replaced with wood fuels and which key incentives at the EU or national level are required. The wood flows in EU in 2012 are shown in Figure 1.

The sawmill industry typically uses large diameter logs in the production of sawn wood, creating considerable amounts of processing residues. For every 1 m^3 of sawn wood produced, roughly 0.6 m^3 of slabs/chips, 0.2 m^3 of sawdust and 0.3 of m^3 bark is generated. A proportion of the bark and sawdust is typically used on site in kiln-drying of sawn wood, and the rest is sold for other uses e.g. particle board, or the pellet or energy industry. Chips are typically sold to the pulp or re-constituted panel industry. In general, the sawmilling industry plays a significant role as a raw-material supplier for other forest industry sectors.

The pulp industry mainly uses small-diameter logs and slabs/chips as raw material, but in some cases sawdust is also used. Small-diameter logs are debarked at site, generating fuel that is typically used in the production of process steam.

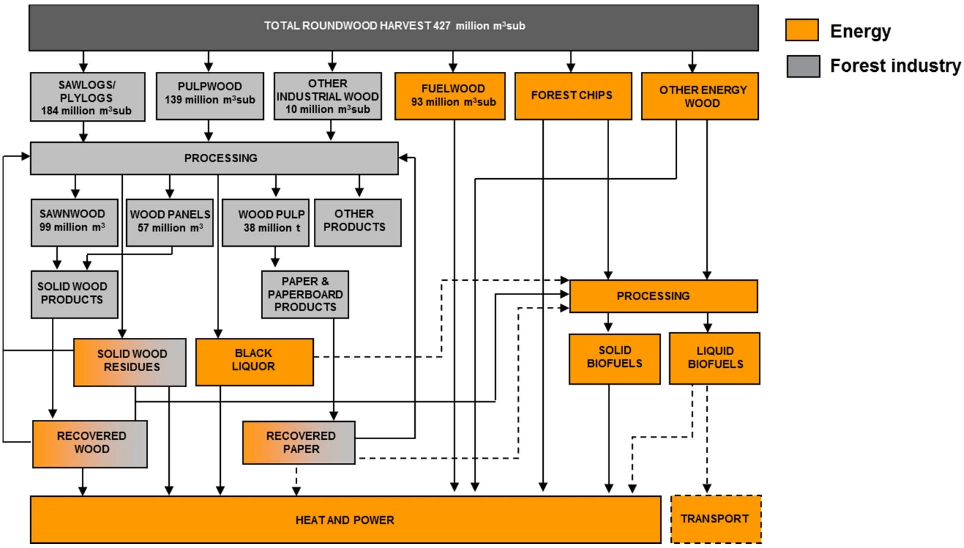

Figure 1. Wood harvest and utilisation flows in EU 2012 (Pöyry).

Apart from the forest industry, the energy industry is a major wood consuming sector in Europe. Industrial boilers to produce process energy for forest industry are typical users of process residues such as bark. These boilers typically produce either heat or steam only or heat/steam and electricity in combined heat and power (CHP) plants. Biomass-based heat or CHP production by energy utilities is common especially in Scandinavia, but increasingly also in other parts of Europe.

Condensing power plants that produce only electricity are typically owned and operated by energy utilities. The tradition of using biomass in these plants is relatively short. Contrary to heat and CHP plants, these plants in Central and Southern Europe are typically based on pulverized combustion technology restricting the use of unprocessed or heterogeneous biomass as fuel. At the moment, there are selected condensing power plants in Europe using wood pellets as a partial replacement for coal.

2.2 European forest industry by countries

The sawn wood, pulp and panel industries are roughly equal in size in terms of production value in the EU. In terms of wood processing, the sawmilling industry is the largest sector with a 40% share of the EU total. The pulp industry accounts for some 35% and panel industry some 20% of total industrial wood processing in Europe. These shares refer to primary wood processing, and include double counting of residues originating from sawmills and plywood mills which are used in the pulp and reconstituted panel industry. European round wood consumption in 2011 is presented in Figure 2.

Sweden, Germany and Finland are clearly the largest forest industry countries in Europe. The estimated value of primary wood processing in these countries amounts to close to €10 000 million each. Finland and Sweden have a similar forest industry structure. In these countries, the pulp industry dominates the industry structure followed by the sawmilling industry. In Finland, there is also panel production, mainly plywood, but in Sweden the role of the panel industry is insignificant. In Germany, the forest industry structure differs from that in Sweden and Finland. Sawn wood and panel industry are the largest industry sectors in Germany, and wood pulp industry plays a relatively small role.

The next largest forest industry countries in Europe are France, Austria and Poland. The estimated value of primary wood processing in these countries amounts to some €4 000 million each. In Poland, the panel industry, mainly particle board and medium density fibreboard (MDF), dominates the industry structure. In Austria and France, the industry structure is distributed more evenly sawmilling industry being the largest sector. The panel industry is larger in France and wood pulp industry in Austria.

Other significant forest industry countries include Spain, Portugal, Italy, Romania, Czech Republic, Slovakia, Latvia, UK and Belgium. The estimated value of primary wood processing in these countries is some €1–2 000 million each. In Portugal and Spain, pulp industry is the largest sector, whereas in Eastern European countries sawn wood processing typically dominates the forest industry structure. Panel industry plays an important role in UK, Belgium and Italy, with some 50–70% share of the estimated value of primary wood processing in these countries.

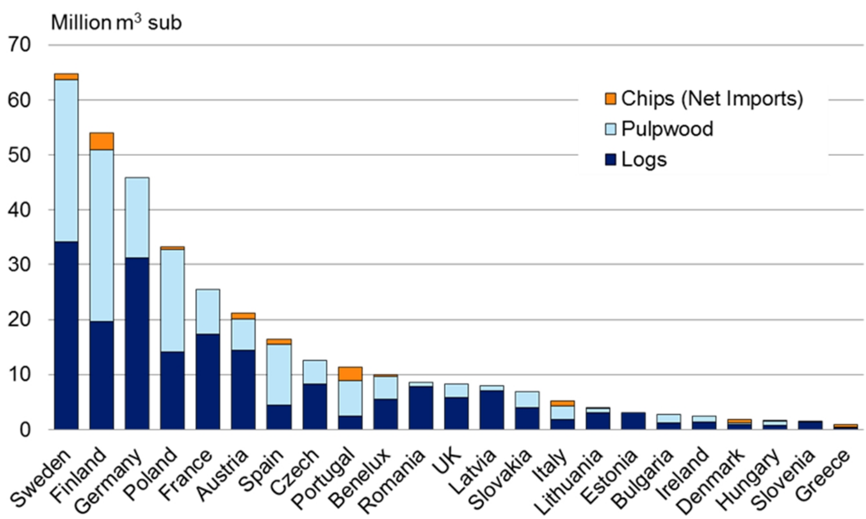

Figure 2. Industrial round wood consumption in EU countries in 2011 (Pöyry).

2.3 European forest industry structure by sectors

The size of forest industry plants varies greatly, especially in the sawmilling industry. Germany has the largest sawmills in Europe, with two sawmills having an annual production capacity of over 1 million m^3 of sawn wood, Table 1. In addition, there are some 10 sawmills in Germany with a production capacity of between 500–1 000 000 m^3/a and 15–20 sawmills with a capacity between 200–500 000 m^3/a, the rest consisting of a number of smaller sawmills.

Table 1. Number of sawmills by capacity range.

Capacity range	50-200 000 m^3	200-500 000 m^3	>500 000 m^3
Germany	42	15	12
Sweden	67	25	4
Finland	32	19	2

In Sweden and Finland, there are no sawmills with an annual production capacity of over 1 million m^3. In Sweden, there are a few sawmills with a capacity of between 500–1000 000 m^3 and some 25–30 sawmills with a size of 200–500 000 m^3/a. Finnish sawmills are smaller than those in Sweden, the largest having a capacity of 500 000 m^3. In addition, there are some 20–25 sawmills in Finland with a capacity of 200–500 000 m^3. In both countries, there are also a large number of small sawmills. In general, sawmill structure in Europe is very scattered, as the number of sawmills is large and their production capacities may range from some hundreds to a million m^3/a. A sawmill with an annual production of 500 000 m^3 generates some 430 000 m^3 of chips and sawdust, which is equivalent to a raw material requirement of a torrefied pellet plant with an annual output of some 120 000 t. Forest residues available from the fellings are a significant additional feedstock source.

There are more than 150 plywood mills in the EU with an annual production of around 3–4 million m^3 of plywood. The majority of them are small mills with an annual production capacity below 50 000 m^3. The largest mills are in Finland, with capacities of nearly 500 000 m^3 and 300 000 m^3. The next largest mills are smaller, with a capacity of some 100–200 000 m^3. In addition to Finland, mills of this size are found, for example, in the Baltic States. A plywood mill with a capacity of 100 000 m^3 produces some 110 000 m^3 of production residues annually, covering the raw material need of a torrefied pellet plant with annual output of 30 000 tons.

There are large particle board mills located in Eastern Europe, mainly in the Czech Republic, Romania and Poland, but also in Western European countries such as Belgium, Germany, France, the United Kingdom, Austria and Italy. The largest mills have an annual production capacity of 600–1000 000 m^3, and they uses some 800–1 400 000 m^3 of wood per mill, mainly round pulpwood, chips, sawdust and/or recycled wood. There are roughly 100 particle board mills in the EU, producing around 30 million m^3 of particle board annually. Some 30 of the mills have a production capacity of above 500 000 m^3/a. In addition to mills producing only particle board, there are mills that produce several panel types such as particle board and MDF.

In the EU, there are nearly 50 MDF mills producing some 10 million m^3 of MDF annually. The largest mills have an annual production capacity of 600–1 000 000 m^3, and they are located in Poland, Germany and Italy. Figure 3 depicts the major mills in Europe.

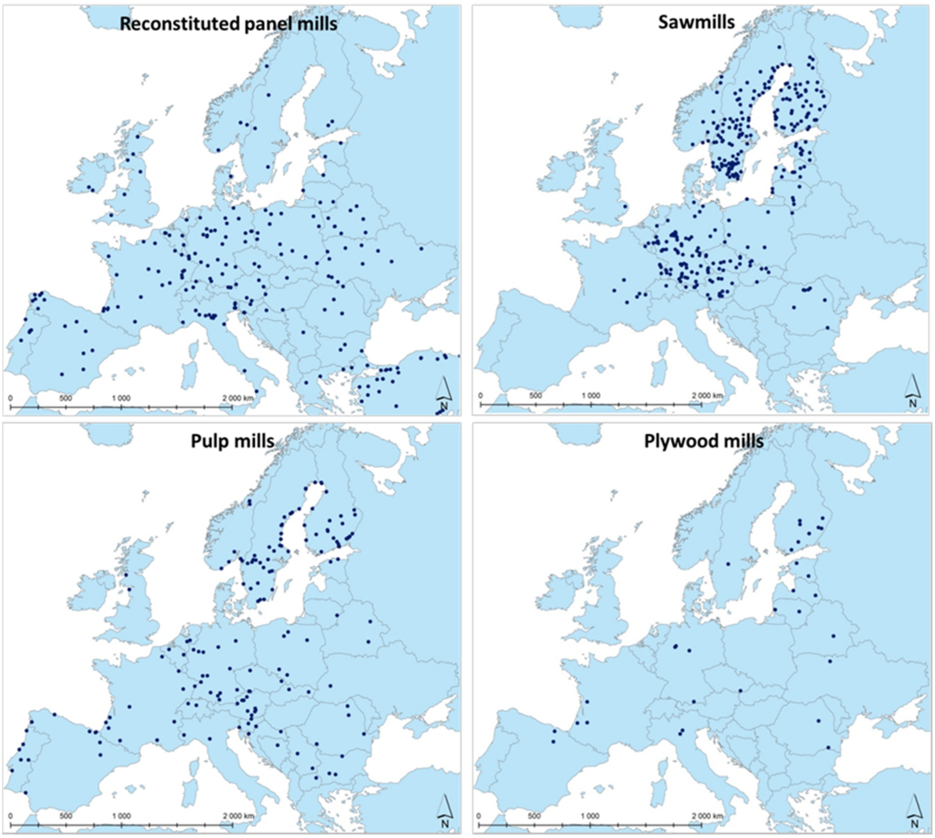

Figure 3. European forest industry map. Selected major mills with an annual capacity of >50 000 m^3 or t (Pöyry).

3. Market prospects of torrefied pellets

3.1 Potential end-uses of torrefied pellets in Europe

Torrefied pellets can be used in virtually any kind of existing energy plant using solid fuels to any extent. In biomass energy plants they can be used to improve the fuel mix, but also in coal plants to increase the share of energy produced with renewable energy sources. In this case, the maximum share of torrefied pellets in the fuel mix is limited by the technical aspects of the energy plant. It is, however, possible to design new energy plants or modify existing solid fuel boilers to use only torrefied pellets. Despite the variety of alternative end-use options, the maximum benefit of the characteristics of torrefied pellets is achieved especially in pulverized coal-fired power plants.

Pulverized coal-fired power plants are found in nearly all European countries with a total capacity of around 200 GWe. The great majority of these plants are, however, located in Germany, the UK and Poland, Table 2.

Table 2. Pulverised coal-fired power plants in Europe.

	Total capacity GWe	Number of boilers #	Average capacity MWe
Germany	50	240	210
Poland	30	330	90
United Kingdom	20	60	380
Total Europe	**190**	**1170**	**160**

These three countries represent more than 50% of the total electricity capacity based on pulverized coal combustion technology. In Poland and Germany, there are some 200–300 boilers the average size of which is in Germany slightly above 200 MWe and in Poland somewhat below 100 MWe. In the UK, the number of pulverized coal boilers is smaller, around 50, but the average size of the boilers is considerably higher, above 350 MWe. A plant of this size uses around 6 TWh of fuel annually when operating full-time at 40% efficiency. This equals with roughly 1 million tons of torrefied pellets. In other words, a hypothetical mill producing 100 000 tons of torrefied pellets per year can cover 10% of the annual fuel input of an average-sized pulverized coal-fired power plant in the UK.

Pulverized coal-fired power plants typically produce only electricity. Therefore, the attractiveness of co-firing torrefied pellets with coal is heavily dependent on national support schemes for renewable electricity generation. There are great variations in the type, amount and coverage of the green electricity support mechanisms between European countries. In some countries there may be a reduced or zero subsidy for biomass co-firing with coal, whereas others may promote co-firing through subsidies.

Another factor that may affect the torrefied pellet or biomass market in general is the generating efficiency potentially, in some cases, favouring biomass use in cogeneration plants. In this case, the taxation of fossil fuels also plays a significant role when evaluating the attractiveness of torrefied pellets, as fuels used for heat production are generally subject to energy taxes.

3.2 Torrefied pellet price formation

The price paid for torrefied pellets is the key to the economic functioning of the whole pellet supply chain. The price needs to be high enough to cover all the costs of production and delivery, but at the same time, low enough to be an attractive option for an energy plant. In addition, price stability and predictability is important in order to mitigate risks related to investments that are required for torrefied pellet production.

At the moment, there is as yet practically no existing market for torrefied pellets and therefore, no information is available on market prices. It is, however, possible to estimate the price through the expected value of torrefied pellets. One option is to define the value through the opportunity cost of using an alternative fuel, e.g. coal, for an energy plant. The opportunity cost describes the theoretical maximum value that a power plant can pay for biomass. In addition, the value of competing biomass, such as standard pellets, affects the value of torrefied pellets.

The main components affecting the opportunity cost of using coal are 1) the market price for coal, 2) the energy taxes on coal, 3) the value of CO_2-emissions, 4) other benefits from using renewable fuels instead of fossil fuels, e.g. feed-in tariffs, and 5) the investments required to use torrefied pellets.

The market price for coal has been relatively volatile in the past. In 2008, the prices peaked strongly in Europe, but have stabilized since then. Over the past couple of years, the price of coal has moved downwards, partly driven by the growing use of gas in the USA and thus, surplus volumes of coal exported from the USA to Europe.

Taxation of coal varies between the European countries. The directive on energy taxation on energy products sets a minimum tax rate for coal used for heating. Some countries apply considerably higher taxes, whereas others have tax rates close to minimum. Fuels used for electricity generation may be exempted from energy taxes, but some countries apply taxes on them as well. Also, fuels used in cogeneration may be treated differently in terms of taxation. In recent years, many countries have revised their taxation rates regularly.

The value of CO_2-emissions has also been very volatile since the beginning of the European emission trading system. Recently, the price for CO_2 has been very low, reducing the pressure to implement measures to cut GHG-emissions. In the long term, it is possible that the price for CO_2 will be higher than today, boosting measures to cut GHG emissions, mainly investments in alternative energy sources.

The benefit of using renewable fuels instead of fossil fuels is generated through various green energy support mechanisms. Typically, these mechanisms apply to electricity production either in the form of feed-in tariffs/premiums or green electricity certificates. These support mechanisms vary greatly between the EU member states. In addition to the type of support mechanism, there are variations in the amount of support and also in its applicability i.e. the eligibility of alternative combustion technologies for support schemes. In many countries the green electricity support systems have been revised recently or are currently being revised either by reducing the level of support or by restricting the applicability of certain combustion technologies for the schemes.

The investment required by an energy plant to use torrefied pellets also affects the economic attractiveness of using them. In general, the total investment requirement depends largely on the power plant in question and on the technological solutions applied for the combustion of torrefied pellets. Also, an investment requirement for using alternative biomass, such as standard pellets, affects the attractiveness of torrefied pellets as fuel.

Green electricity support mechanisms typically play a decisive role in terms of the attractiveness of torrefied pellets for coal fired electric power plants. This is because recent prices for coal and CO_2 emission alone have not been high enough to cover the production and supply costs of torrefied pellets. This results in strong regional and country-specific variations in torrefied pellet market potential, as the differences in ex-tax prices for coal between countries are generally small; the price for CO_2 is the same everywhere in the EU, but the value of green electricity subsidy varies greatly between the countries.

Global CO_2 tax and emission trading mechanisms are presently being debated. European climate and energy targets call for a 20% reduction in greenhouse gas (GHG) emissions by 2020, and at the beginning of 2014 the EC proposed a 40% reduction by 2030. The ambitious targets of considerable GHG reduction would increase the emission allowance price in Europe. Some estimates indicate that a price even up to €50/tCO_2 might be expected. Figure 4 shows how the price of CO_2 would influence the price of fossil fuel. A typical PC-boiler in condensed mode power generation with 40 % efficiency could theoretically pay €27/MWh at plant for biomass with a quality that assures equal performance data.

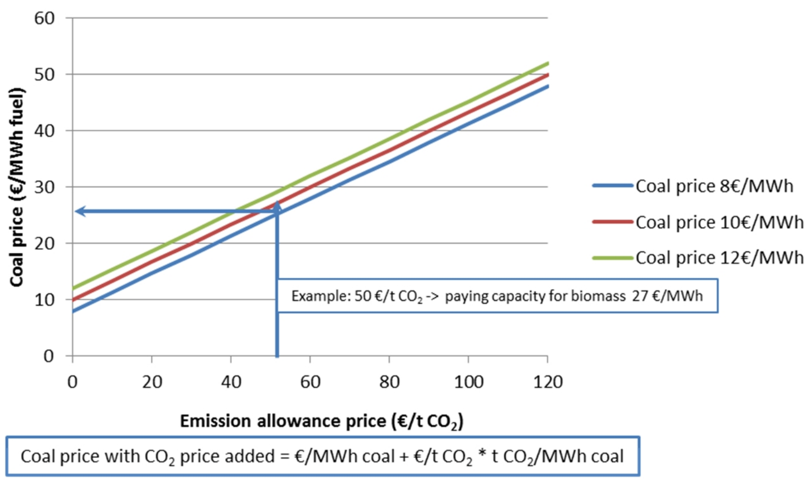

Figure 4. The influence of the emission allowance price on the coal price in PC-boilers.

Several authorities and agencies have introduced new guidelines for the reduction of GHG emissions in power generation. In 2013 the European Investment Bank (EIB) launched a new Emissions Performance Standard (EPS). New fossil-fuelled power plants would be able to emit 550 gCO_2/kWh. The European Commission has recommended a level of 450 gCO_2/kWh. Conventional coal combustion plants have typical emissions of 1 000 gCO_2/KWh. Several plants could continue to burn coal if they mixed it with biomass in large proportions. Torrefied wood pellets offer a good option for meeting this requirement. A share of 40–50% (by energy) of torrefied wood mixed with coal should not pose any problems from the combustion point of view in PC-boilers [1]. Figure 5 shows the new regulation and standard proposals [2]. Canada has introduced an EPS level of 420 gCO_2/kWh, which is a clearly a stronger driver than the European EIB standard proposal. In the US, the Environmental Protection Agency (EPA) is set to introduce a performance standard of 440 CO_2/kWh, at the same level as standards in place in the UK. As of 2016, the Industrial Emissions Directive (IED) will introduce tougher pollution limits on large combustion plants for sulphur dioxide, nitrogen oxides and dust, but not for carbon dioxide.

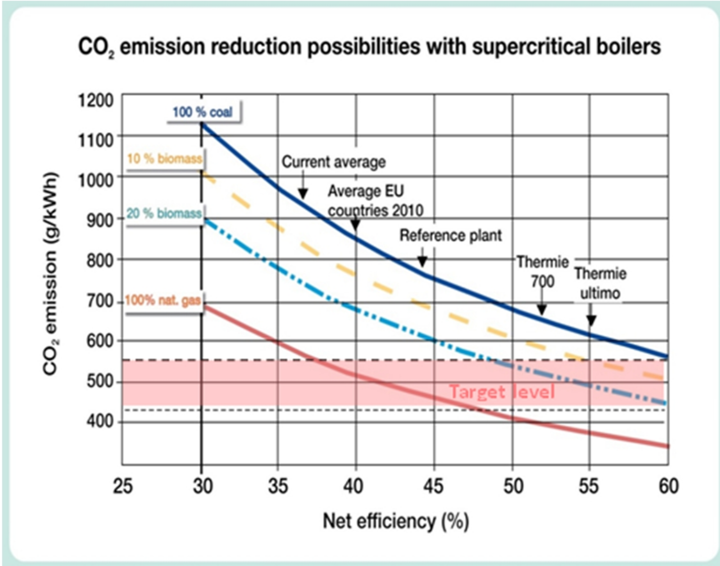

Figure 5. CO_2 reduction possibilities [2].

3.3 Market conclusions

The primary prerequisite for the torrefied pellet market is the energy plants' need for and interest in using them as fuel. At the moment, the need is created through country-specific renewable energy targets and related subsidy mechanisms to increase the interest in renewable energy among energy companies. Energy plants have a certain upper limit for the value of renewable fuels that they are capable of paying, based on the opportunity cost of using an alternative fuel such as coal. In order to create a market for a new biomass product, such as torrefied pellets, the production costs need to be below this value in order to establish production plants with economic viability. How much lower the costs need to be depends on investment return expectations, but also on the value of competing biomass sources such as traditional pellets.

Another factor that is needed to boost the investments in torrefied pellet production is a general confidence that the market remains predictable. Changes in the policy environment have, perhaps, been the underlying factor hampering recent development in new biofuel technologies in Europe, creating market uncertainty among investors. There are, however, considerable differences between European countries as regards renewable energy subsidies, and it is possible that the torrefied pellet market is created driven by subsidy mechanisms in certain countries. Assuming that the market can be created, there is good reason to believe that the future trade flows of torrefied pellets will follow the same routes as the current wood pellet trade, Figure 6.

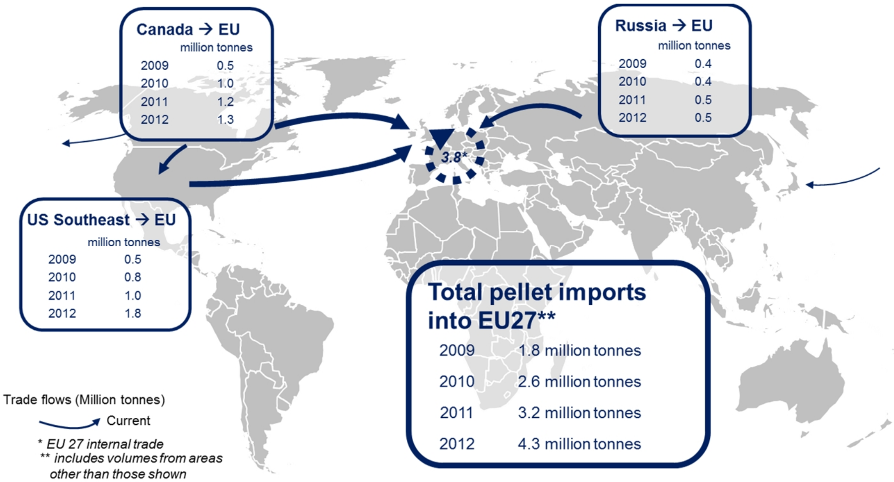

Figure 6. Global wood pellets trade flows (Pöyry).

In case the market for torrefied pellets is created, cost competitiveness is expected to play a crucial role in locating potential torrefied pellet production facilities. The cost competitiveness is affected by several factors such as raw-material prices, and other production costs, as well as the cost of delivery to the energy plant. Thus, the business opportunities for integrated torrefied pellet production at European forest industry sites depend largely on the prevailing market situation and competitive positioning of non-European producers.

Assuming that torrefied pellet production is a viable option also in Europe, the sector competes for raw material with other wood-using industries. Even though there is hardly any surplus volume of industrial residues available in Europe, it is possible to establish a torrefied pellet production plant integrated with, for instance, a sawmill. This requires that the torrefied pellet producer is capable of paying the same or a higher price for the residues than the current buyer, and that the current buyer can use alternative sources, for instance forest biomass, without any additional cost effects, otherwise there is a risk that competition for raw-material will push wood prices upwards with adverse effects on the profitability of wood-using industries.

From the raw-material point of view, the benefits from integrated torrefied pellet production are related to by-product utilization at sawmills or plywood mills, but also to general wood procurement logistics at panel mills or pulp mills. In the case where processing residues can be utilized at site, cost savings can be achieved if the alternative option is to transport residues to an external facility. In panel or pulp mills, where the processing residues are not generated (except bark), the existing wood procurement infrastructure and logistics can be utilized to procure additional raw material volumes for a potential torrefied pellet plant.

4. Torrefaction technology development

4.1 Introduction

Commercial development of torrefaction is in its early phase. Several technology companies and their industrial partners are moving towards commercial market introduction. The general view is that most of the demonstration plants have technical problems that have delayed their commercial operation. Several thousand tonnes of torrefied pellets have, however, been produced by European and US companies, mainly for large scale co-firing tests at coal power plants.

A number of smaller pilot installations covering a wide range of different technologies are available at research institutes and universities. Several different technologies have been suggested and tried out for torrefaction operation, in many cases technologies usually applied for drying different raw materials, Figure 7 [3]. A more detailed description of torrefaction processes is available in [1] and [4]. National and international research and development work has been intensified over the last few years, the SECTOR project being one of the essential European research and demonstration projects [5, 16].

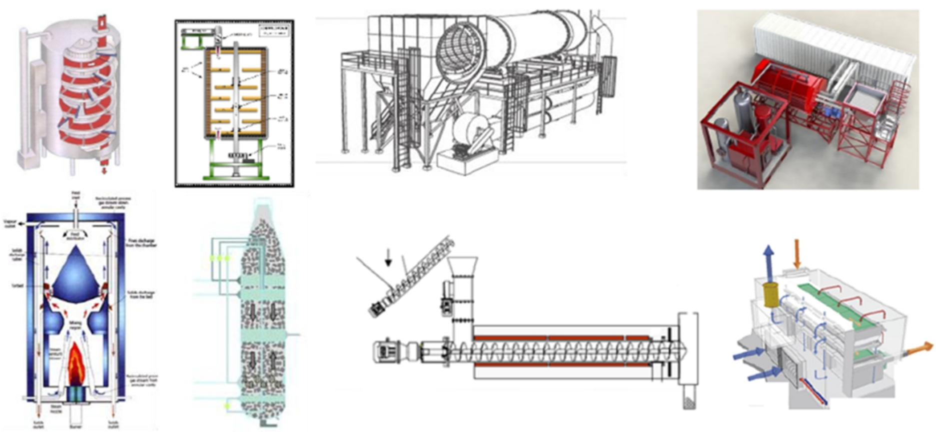

Figure 7. A selection of torrefaction technologies.

4.2 A new fluidised bed technology

In the course of this project, a task force lead by VTT and ÅF-Consult Oy elaborated on several possible fluidised bed (FB) technologies to be utilised in a conceptual torrefaction process. The ultimate objective was to create an Integrated Thermal Processing (ITP) solution for integrating the torrefaction of biomass to FB boilers. This concept has earlier been developed at VTT concerning the production of bio oils by fast pyrolysis. The first demonstration plant is currently being commissioned at the Joensuu power plant [6].

A spouted-bed torrefaction reactor was considered in more detail. The aim was to obtain an even and easily controllable temperature in the reactor and a good heat transfer to ensure a torrefied product of uniform quality. Initially a reactor solution including a sand bed to enhance the heat transfer was developed. This solution resembled the ITP pyrolysis concept integrated into a fluidised boiler, circulating part of the sand of the boiler as the heat source for the fast pyrolysis process. This solution was later rejected due to the foreseen difficulties in separating the torrefied biomass from sand.

A preliminary design of pilot scale torrefaction equipment was undertaken. The design phase also included the creation of a low cost silo dryer for the biomass chips. The scale of the equipment was chosen to be large enough, about 1 ton per hour of torrefied chips, to facilitate a reasonable fluidisation of commercial wood chips and ensure up-scaling to a demonstration scale plant, Figures 8 and 9.

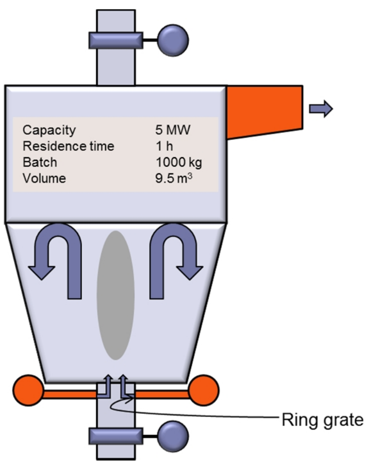

Figure 8. Spouted-bed pilot scale torrefaction reactor.

The silo dryer is designed to use low temperature air at approx. 50°C. The air can be heated by waste heat streams at heating plants or saw mills. Drying of the chips is slow, and about 10-hour drying times are expected. The inlet moisture content of the wood chips is 50%, and the chips are dried to below 20% humidity.

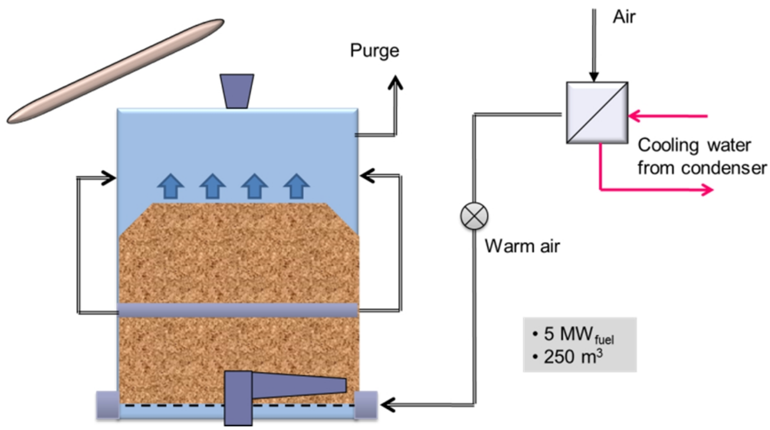

Figure 9. Pilot scale silo dryer.

Plans for setting up a torrefaction pilot plant in connection to a boiler plant were drawn up together with the boiler manufacturer Renewa Oy. A batch reactor, described above, was integrated with a 10 MW bubbling fluidised bed heating plant, Figure 10. The boiler plant would provide both low temperature flue gases for drying and flue gases of about 300°C for the torrefaction. The cooling was also to take place in the same reactor. Piping and valves were sized and the instrumentation outlined. The pilot plant was designed only for two years experimental work and was therefore a low cost solution. The investment was estimated at about €1–2 million.

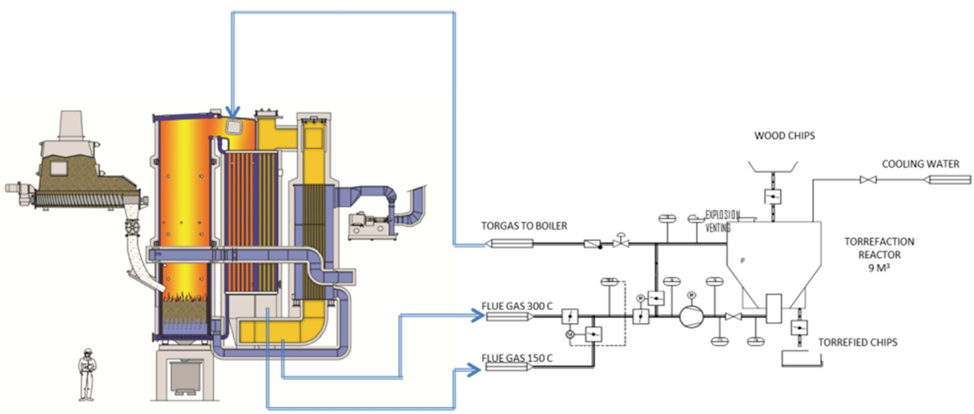

Figure 10. The torrefaction pilot plant connected to an FB boiler at a district heating plant.

A road map was drafted and scheduled for demonstrating the new torrefaction technology in about two years' time. Piloting the process according to the principle described earlier would last about two years, including setting up the equipment performing extensive testing. A sufficient amount of torrefied wood products would be produced for storage and combustion tests. The next step demonstration plant could be built in connection with an existing saw mill to provide for a suitable infrastructure. A plant size of 30 000 t/a would be feasible, presuming that the product can be sold to a potential user. Costs of the first pilot phase were estimated at €2–3 million and the demo phase at €8–10 million. The investment of a commercial torrefaction plant of the capacity of 100 000 t/a was also estimated.

5. Torrefaction integration options

Integration of the torrefaction process with existing biomass-fired boiler plants, such as district heating plants, utility boilers or wood industry boilers, offers a possibility to benefit from energy streams and feedstock handling available at the host plant. There are several options to realize the integration, and some options are elaborated in what follows.

5.1 Connected to large power plant boilers

One possible integration option for biomass torrefaction is based on the ITP-process concept. In this example a spouted-bed torrefaction unit is connected to a large municipal or industrial bubbling or circulating fluidised bed biomass boiler (BFB and CFB boiler).

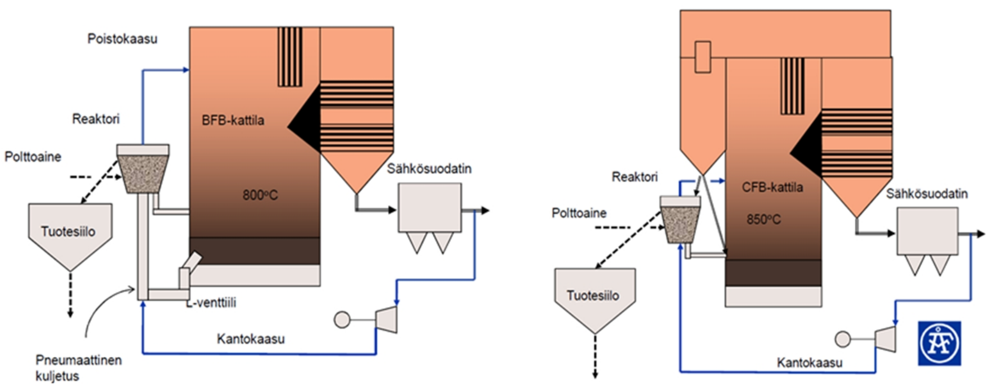

Figure 11. Torrefaction integrated to a BFB and CFB boiler.

A spouted-bed torrefaction process using the bed material of the FB boiler as heating media is depicted in Figure 11. To circulate the bed material in the BFB option requires pneumatic conveying of the bed material by flue gases to the torrefaction reactor. In the case of the CFB boiler the bed material is taken from the dust circulation after the cyclone. The bed material and all volatiles are fed back to the boiler.

A preliminary dimensioning and an indicative cost assessment were carried out by ÅF-Consult Oy, based on their in-house data from similar studies. A 300 MW torrefaction unit was connected to a large boiler. The feedstock, wood chips is dried in a separate silo dryer from the average inlet moisture content of 45% to below 10%, using pre-heated air generated by waste heat streams from the boiler. About 350 000 t/a of torrefied wood chips is produced. Assuming a production time of 8 000 hours, an investment of the order of €12 million and a feedstock price of €18/MWh results in a production costs estimate of €23/MWh. Even if this cost estimate (which does not include pelleting) is in line with the production costs of torrefied wood pellets usually reported in other feasibility studies, the preliminary nature of this case study has to be emphasised. The technology described has not been demonstrated, nor have such large integration solutions been considered earlier.

5.2 Sawmill integration

A sawmill is an attractive host for future biocarrier production plants due to the good availability of chips and sawdust, Figure 12. Integrated sawmill torrefaction and pyrolysis liquid concepts aim at creating added value from sawmill side streams and at enhancing sawmills' competitive position through increased profitability. Bark can be used to produce required drying energy for both processes. Pulpwood from final felling can also be used for biocarrier production depending on market conditions.

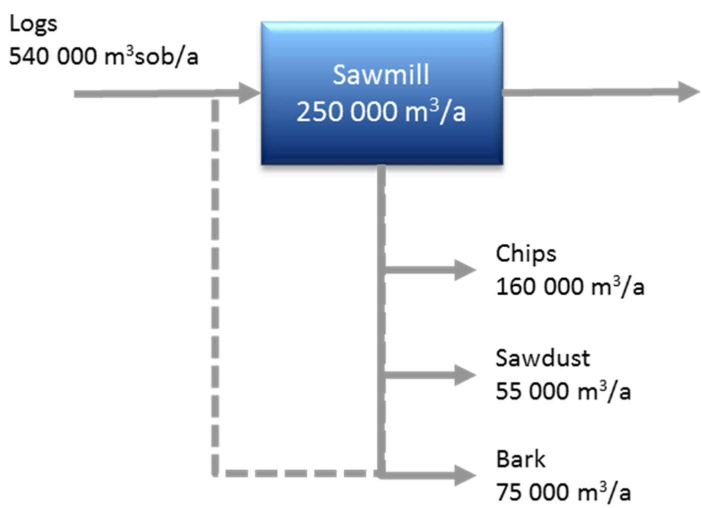

Figure 12. Wood flows around a sawmill. Chips saw dust and bark volumes expressed in solid wood equivalent.

A sawmill integration scheme based on the silo drying and spouted-bed torrefaction concepts described above was developed together with Pöyry Oy, Figure 13. Wood chips from the sawmill are used to produce torrefied pellets or, optionally, wood for engineered products like particle board or composites. The boiler and the lumber dryer are connected to the torrefaction and drying stages. The heat requirement of the torrefaction process is designed to be taken from hot flue gases of the biomass boiler in different temperature points achieve good control of the torrefaction process.

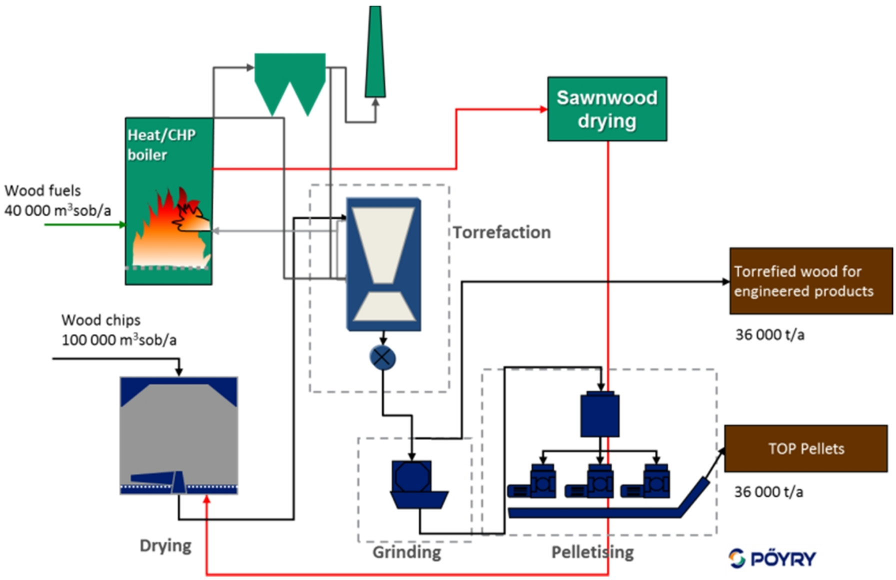

Figure 13. Wood torrefaction integrated to a sawmill (Pöyry).

5.3 Integration with utility boiler

The torrefaction integration may also be realised using a combined heat and power (CHP) plant as the host plant. A corresponding scheme to the sawmill integration was designed for a medium-scale biomass-fired CHP plant, Figure 14. In this case the drying energy is extracted from the district heating net.

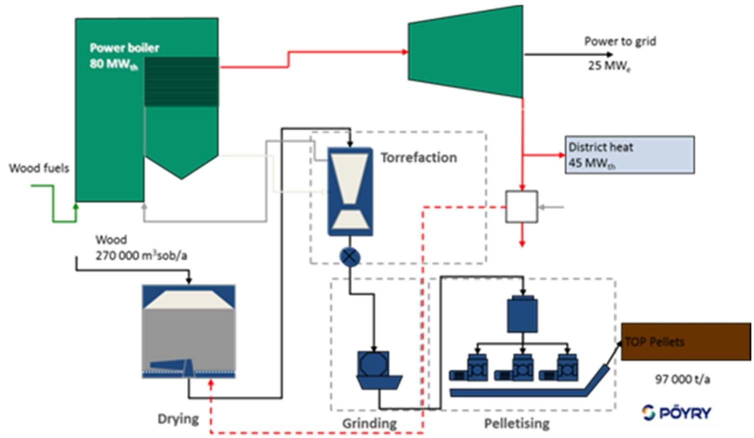

Figure 14. Wood torrefaction integrated to a CHP plant (Pöyry).

A case study was carried out with Fortum, ÅF, Pöyry and VTT on integrating a wood torrefaction production plant with an existing municipal CHP plant in Estonia operated by Fortum. The fuel effect of the fluid bed boiler was 80 MW, power production capacity 25 MW and district heat 45 MW. The torrefaction plant, designed for 97 000 t/a torrefied pellets production, needs an additional wood fuel feed of 270 000 m^3sob/a. The background of the case study was that Estonia has been an industrial wood net exporting country. Pulp wood export to Nordic countries has dominated, and annual fuel wood export has averaged in 2005–2010 some 45 000 t/a. Estonia has unexploited forest resources, and cutting volumes can be increased to some extent as well as the collection of forest residues.

In the study two questions were of interest; first, are there economic benefits to operating the bioenergy carrier unit integrated with the CHP plant and utilizing the part load operation possibilities given by the annual heat load curve? The second question is related to the whole value chain from the forest procurement site and CHP plant to the marine and truck transport delivery to an existing coal fired power plant. What is the total delivery cost and what is the breakdown of the costs?

In Figure 15 the total delivery cost is given at an existing costal coal-fired power plant in Southern Finland. The calculation is based on the following criteria; the price of heat to the dryer is assumed to be zero due to the utilization of secondary heat and flue gases from the boiler. The price of wood is assumed to be €32 /m^3sob corresponding to €16/MWh, which is about the price the sawmill gets from selling the surplus chips. Delivery costs of pellets to the coal fired power plants are assumed to be €20/t, equal to a transport distance of around 300 kilometres. The delivery price of torrefied pellets was estimated to about €32/MWh. This clearly indicates that the local biomass price should be low in order to create a profit for large-scale operations and benefit for the operators in the value chains. Regional low-value wood residues or global saw mill residues may generate opportunities for bioenergy carriers production and use.

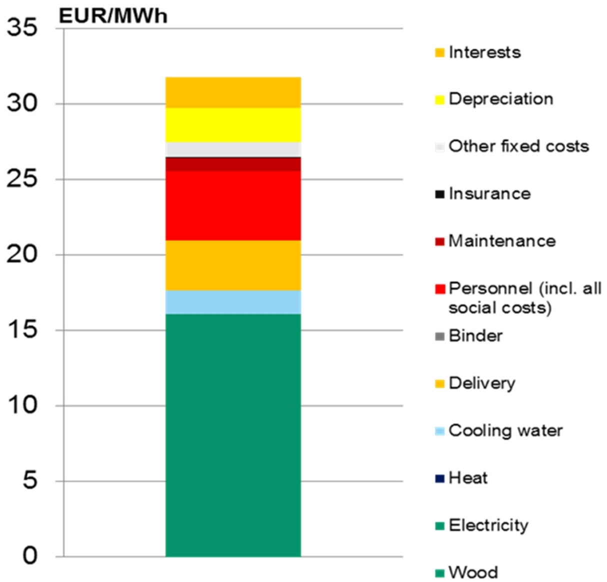

Figure 15. Production costs of torrefied wood pellets integrated to a CHP plant in the Baltic area.

5.4 Integrated bio-oil production

An industrial consortium together with VTT has developed the world's first integrated bio-oil production concept to provide an alternative energy carrier to fossil fuels [6]. The integration of a fluidised-bed boiler and fast pyrolysis is currently being demonstrated, see Figure 16. A 50 000 t/a bio-oil production plant is in the commission phase at the Fortum Oy biomass-fired CHP plant in Joensuu, Eastern Finland. The technology is provided by Valmet Oy, Finland. The main integration benefits of this concept are the ability use the fluidized bed boiler also as a "recovery or reheat boiler" for the pyrolysis, enabling high overall efficiency and increased usage of the boiler plant by additional heat load for the pyrolysis oil process fuel drying. The bio-oil will be used for the production of heat for both industry and communities. Like the torrefaction process, this fast pyrolysis process can be integrated with both saw mills and power plants. Accordingly, there are two options to produce renewable energy carriers to substitute fossil fuels.

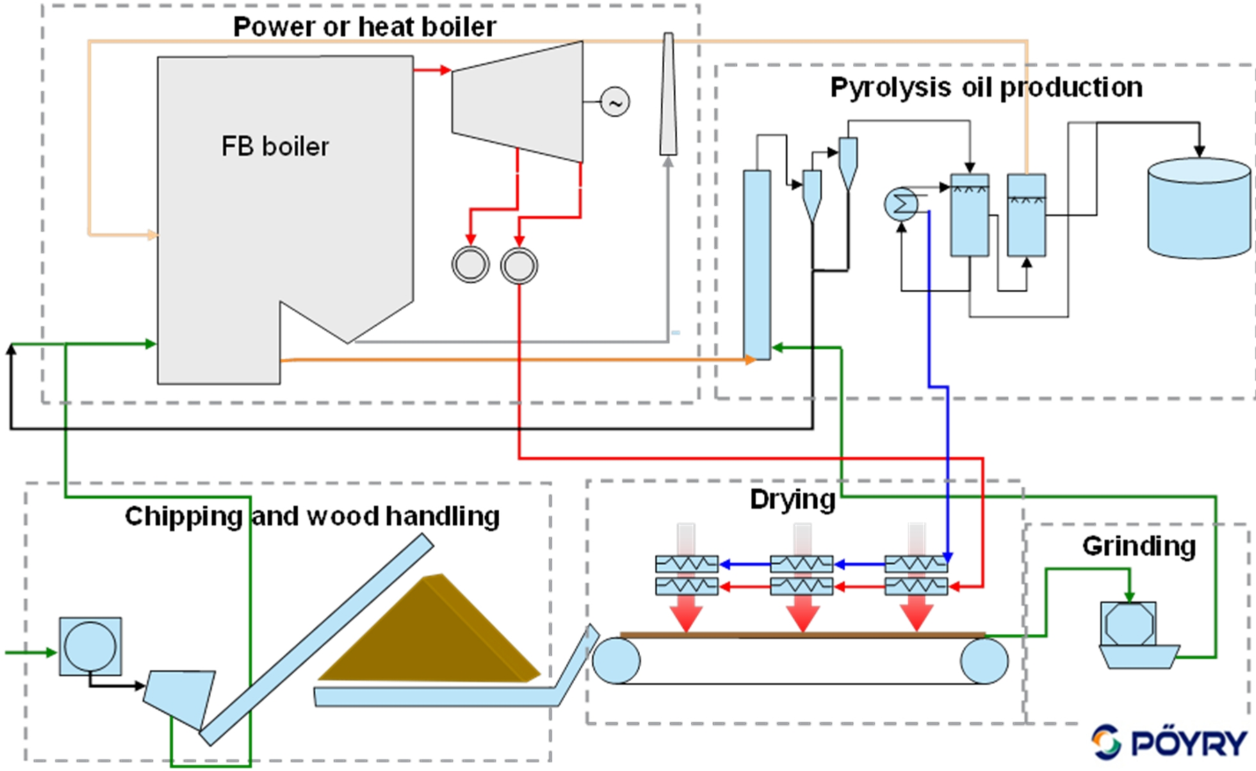

Figure 16. Process scheme of integrated pyrolysis oil production concept (Pöyry).

6. Bioenergy carrier production options in Finland

6.1 Production costs analysis

The two integrated concepts described above were analysed against known stand-alone concepts to determine the cost levels of bioenergy carrier production in Finland with the current price levels and asset base in order to meet the national renewables targets by 2020 and replace up to 7 TWh of coal.

The objective was to evaluate the production or supply cost of bioenergy carriers in different forms to existing coal and peat fired power plants. In the analysis, a typical unit size and cost structure was calculated based on the publicly available information and Pöyry-VTT knowledge on these processes. Bioenergy carrier process options were also selected in such a way that they represent the current market situation in terms of raw material price and availability. For example, pellets production was assumed to be based on pulpwood due to the limited availability of sawdust and shavings in Finland for a large scale production. The main assumptions of the selected torrefaction concepts are shown in Table 3.

The investment costs of the selected production units are based on publicly available investment costs or costs modelled by Pöyry and VTT. The torrefaction and pyrolysis units are yet to be commercially proven so there is a large uncertainty in the actual achievable investment cost for the commercial units. In this analysis, the investment costs are not the most critical component though, because the main goal is to compare the production cost levels and cost breakdown to discover the main uncertainties and their role in future business decisions.

Table 3. Basic information regarding the torrefaction cost analysis.

Concept	Capacity	Based on	Investment estimate	Raw material and cost
Stand-alone wood pellet	250 000 t/a	Pöyry model	35 M€	Pulpwood 44 €/m^{3}sob
Stand-alone torrefaction	200 000 t/a	Pöyry model	50 M€	Pulpwood 44 €/m^{3}sob
ITP-torrefaction CHP	100 000 t/a	VTT concept	24 M€	Forest residues 36 €/m^{3}sob
Sawmill torrefaction	36 000 t/a	VTT concept	10 M€	Sawmill chips 43 €/m^{3}sob

The production costs of the analysed bioenergy carrier concepts were based on the current price levels in Finland. To compare product costs against anticipated market price, a base case for the end product prices was added to the cost breakdown chart presented in Figure 17. For wood pellets the market price was assumed to be €30/MWh which represents the PIX index price of pellets in Baltic Sea region. For torrefied pellets, the price was assumed to be €35/MWh, which has been presented as a working figure for the coming feed in tariff discussions in Finland aiming at coal replacement in coastal CHP plants. The pyrolysis oil price was assumed to be based on heavy fuel oil replacement in the heating sector in Finland. The estimated price was €54/MWh, taking into account the taxation and a discount to make the fuel switch attractive also for the end-user.

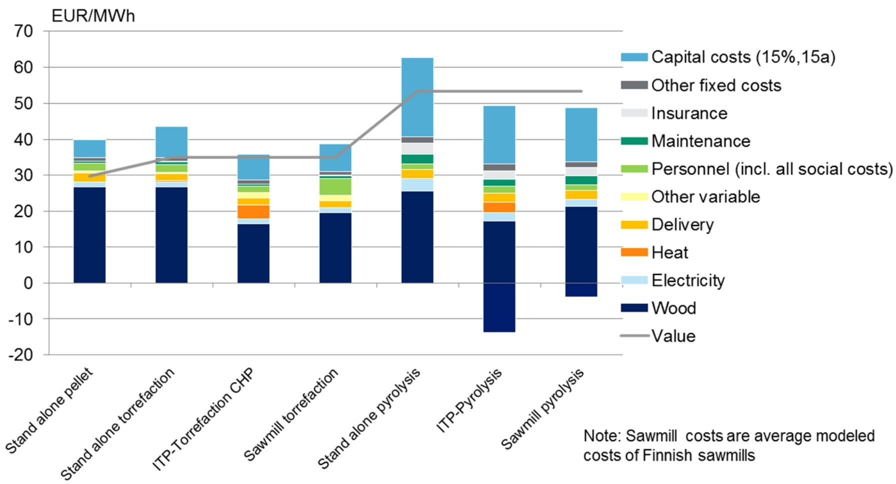

Figure 17. Estimated cost breakdown of bioenergy carriers in Finland [7].

The cost comparison shows that it would not be feasible to produce large quantities of pellets or torrefied pellets from pulpwood in stand-alone units with the current price levels. There is, though, a large level of uncertainty in the cost structure of the torrefied pellet plant, but with the current price levels the results indicate that an integrated concept may offer potential benefits in order to meet the required cost level. Pyrolysis oil production requires some sort of integration, because it seems that the integration benefits are significant, and the stand-alone might be too expensive with current price levels. The pyrolysis oil integration requires significant integration benefits from, for example, wood sourcing, energy and operations. All in all, the cost breakdown analysis indicates that the required price for torrefied pellets is around €35–40/MWh and for pyrolysis oil €50–60/MWh to make the bioenergy carrier business in Finland feasible. In the coal replacement market, the direct replacement value of bioenergy carriers is the price of coal with taxes and CO_2 cost, but with the current and forecasted medium term low CO_2 prices there needs to be a direct feed-in tariff for the bioenergy carriers to make the replacement economically viable.

The price of feedstock is the most significant variable influencing the production costs of bioenergy carriers. Figure 18 presents the current pulpwood prices delivered at plant in a global perspective. The price of forest and sawmill residues may vary significantly depending of local market conditions, and may be attractive for regional energy use.

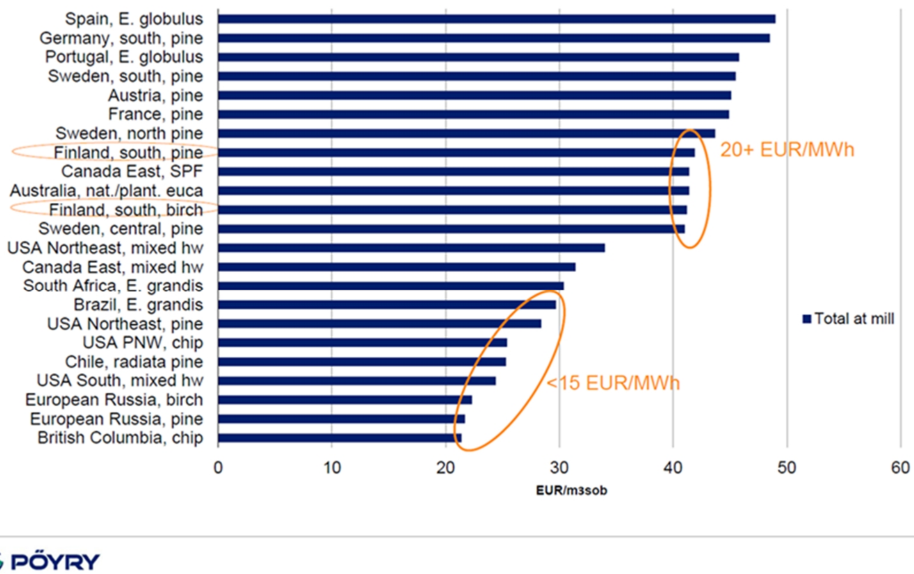

Figure 18. Pulpwood costs, delivered at plant, in selected regions 2013, in m^3 sob (solid over bark) [8] (Pöyry).

6.2 Sawmill integration case study

As the cost breakdown analysis of integrated bioenergy carriers indicates, the integrated concepts provide a clear cost benefit compared to stand-alone plants and sawmills, as a special integration host shows great potential. On top of the direct cost benefits, sawmill integration can have even more benefits and synergies. Sawmills, and especially privately owned sawmills, have been traditionally in a worse position than large forest industry groups in the wood and side product market. Surplus pulpwood, sawmill chips and some small proportion of sawdust have been sold to pulp mills. Due to the fairly high cost of transporting the chips and sawdust, the price of these by-products has been dominated by the nearest chemical pulp mills based on the availability and cost of pulpwood in its sourcing area. Sawmill has had the opportunity to sell the chips to another pulp mill as shown in the map below, Figure 19, the transport cost of chips to the second closest pulp mill has already significant additional costs. A model of Finnish sawmills and pulp mills was developed so as to determine the distance from each sawmill to the nearest chemical pulp mills. By modelling the distance, the price difference of sawmill chips at different sawmills was calculated, based on the same delivered price but varying transport cost. The analysis of the sawmill chips price at the sawmill shows the most potential sawmills for bioenergy carriers production from the raw material cost and availability point of view [7]. As the previous analysis highlighted, the raw material cost is the single most important cost factor in the bioenergy carrier production.

The same mapping tools can be used to analyse the end product delivery cost from the sawmill to the potential end-users. The location based model gives potential supply cost curves to selected end-user CHP plants and power plants. Including saw mills in Finland with capacity above 85 000 m^3/a the supply cost of sawmill based torrefied pellets and pyrolysis oil to the nearest potential end-user was calculated. The results indicated that there needs to be a feed-in tariff or similar support mechanism for torrefied pellets to guarantee a paying capability for coal fired power plants above €35/MWh to make the investments viable. The same applies to the pyrolysis oil in the case of coal replacement, but the existing legislation and tax exemptions for pyrolysis oil make the heavy fuel oil replacement in heat production viable even with the current price levels.

In order to point out the most promising sawmills for bioenergy carrier production, separate supply cost curves were calculated for Helsinki. The reasoning for this was to show the applicability of this method to single plant supply cost evaluation as well as to analyse the key factors that determine the supply cost of bioenergy carriers. The supply cost curves for Helsinki are shown in Figures 20 and 21.

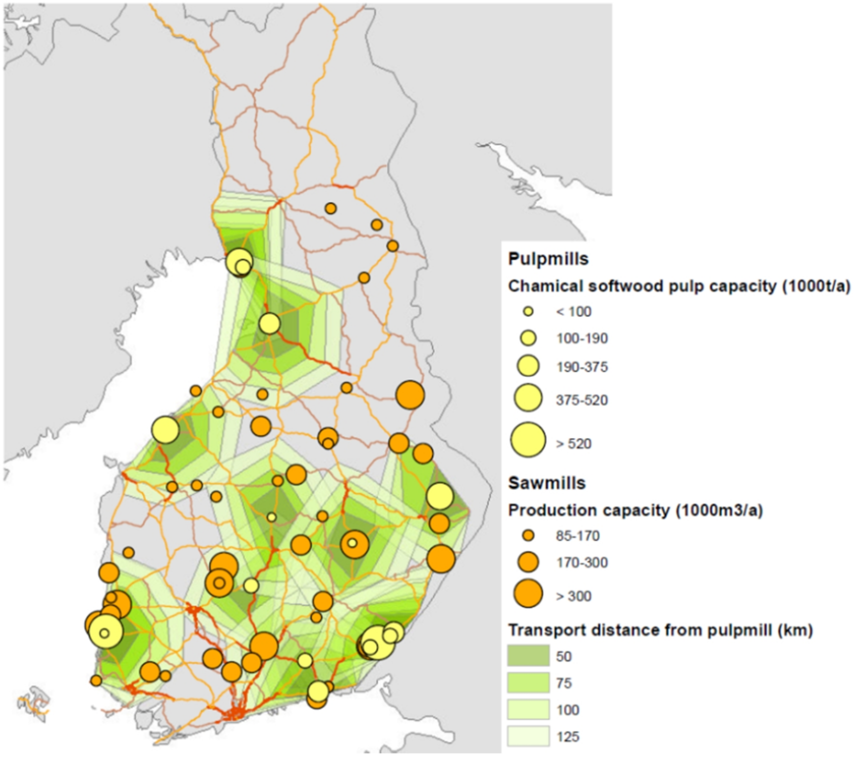

Figure 19. Map of sawmills and chemical pulp mills in Finland with sourcing radius [7].

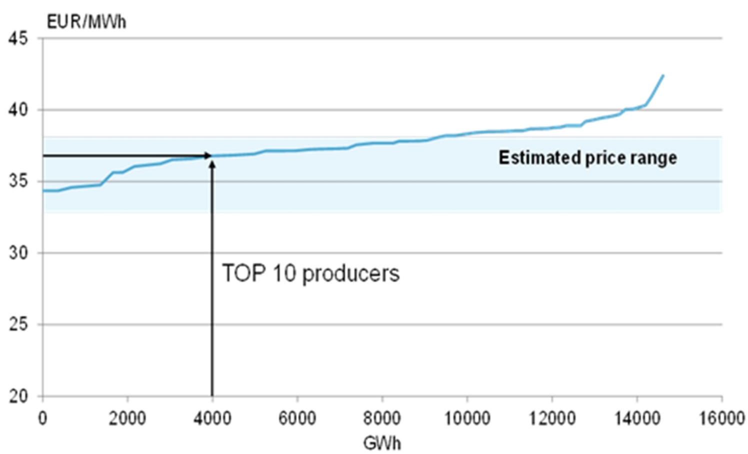

Figure 20. Supply cost curves of sawmill torrefaction for Helsinki [7].

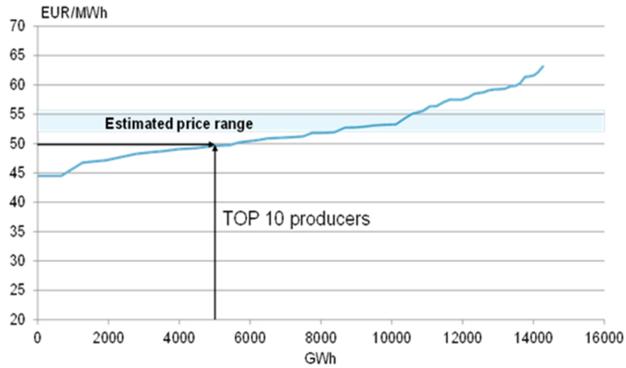

Figure 21. Supply cost curves of sawmill pyrolysis for Helsinki [7].

From the Helsinki supply cost curves the top 10 sawmills were highlighted to discover the number of sawmills required to produce a significant number of carriers and to find their location. The top 10 sawmills could produce 4 TWh of torrefied pellets or 5 TWh of pyrolysis oil to Helsinki with modelled costs of €37 and €50/MWh. The majority of these top 10 sawmills are located fairly close to Helsinki in Southern Finland, but in the case of pyrolysis oil there are also a few sawmills in Eastern Finland. The maps in Figure 22 also indicate the different cost structure of torrefaction and pyrolysis processes. The pyrolysis is more sensitive to wood price in the same way that torrefaction is sensitive to end product transport distance. This is understandable due to the higher value of pyrolysis oil than torrefied pellets, which allows longer transport distances per tonne of product.

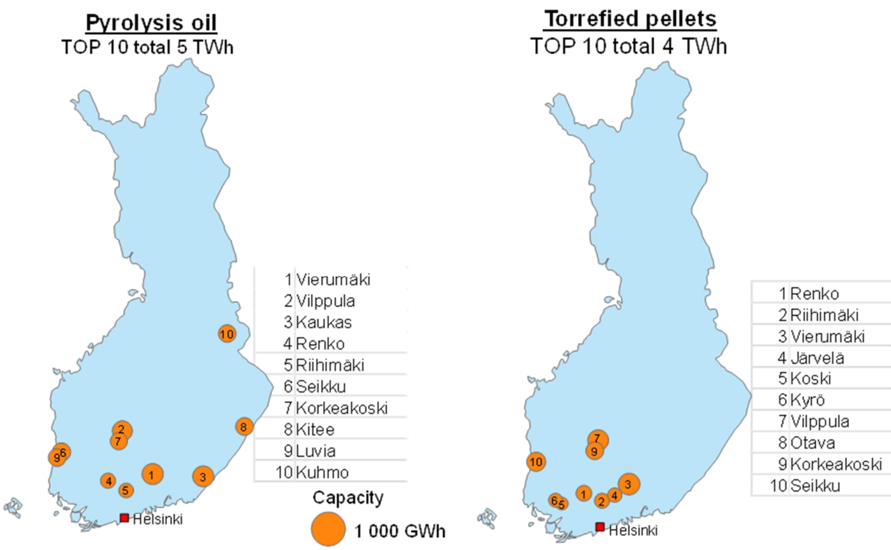

Figure 22. TOP 10 producers of bioenergy carriers to Helsinki [7].

The sawmill industry is known to be subject to cyclic economic fluctuations which may from time to time affect the profitability of the core business. Complementing the product portfolio with torrefied biomass pellets or bio-oil could help the sawmill to overcome periods of weak demand within the timber trade. The torrefied pellet or bio-oil production capacity can be kept constant on a high level also during low timber production by supplementing the wood chips generated at the saw mill with surplus feedstock from energy thinnings and forest residues. The net operation profit of the saw mill could thus be kept on a positive level, Figure 23.

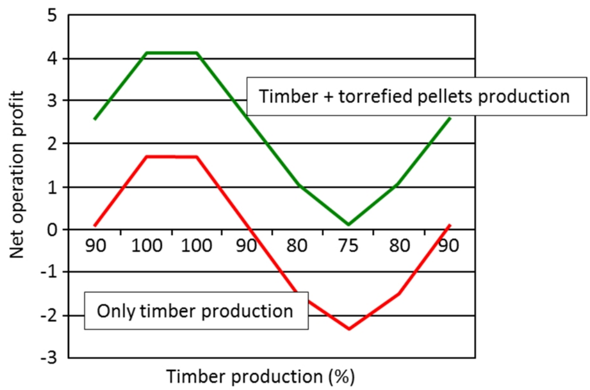

Figure 23. A schematic presentation of reducing the influence of economic fluctuation on profitability by integrating torrefied pellets product with a sawmill.

7. Gasification and pyrolysis tests with torrefied wood

To elaborate on the possible advantages of using torrefied wood instead of conventional wood fuels in the production of gaseous and liquid energy carriers, a set of preliminary fluidized-bed gasification and pyrolysis test was carried out at VTT. Additionally, fixed-bed gasification tests were conducted at two district heating plants.

The objective of the gasification and pyrolysis tests was to investigate the performance of torrefied tree wood compared to that of untreated wood. The focus was on gas and bio-oil quality (gas composition, tar concentration, chemical composition). The assumption was that the chemical composition (less volatiles, higher carbon content) would bring some benefits to the gas and bio-oil produced with regard to, for instance, less tars and better bio-oil properties.

Entrained flow gasification (EFG) is widely used for the production of synthesis gas from coal, often refined to liquid fuels. Utilising solid biomass in this process concept has been challenging, mainly due to the extensive pretreatment required to be able to feed the biomass into the (pressurised) gasifier. The main technical challenge is the pretreatment and feeding of the biomass. Torrefied biomass has many coal-like properties and is considerably more brittle than conventional biomass feedstocks. The natural fibrous nature of the torrefied biomass is broken down in the milling phase, and a finer biomass powder is obtained, making feeding into the gasifier easier. It is also foreseen that the hydrophobicity of the torrefied biomass would make slurry preparation with a high enough solid contents possible. Biomass torrefaction is, therefore, seen as a promising preatretment step for producing transportation biofuels via EFG.

EFG tests with torrefied biomass will be further developed in an ongoing (2012–2015) EU project entitled Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction “SECTOR” [5].

7.1 Fixed-bed gasification tests with torrefied wood

Gasification experiments were carried out in two small scale fixed bed gasification combined heat and power (CHP) plants (plant A and plant B) [9]. Whole tree wood chips (WC 255C) torrefied at 255°C and untreated wood chips were used as feedstock. Both CHP plants consist of a fuel feeding system, downdraft gasifier, gas filtration, gas cooling, gas engine and generator. Tests were carried out at a power level of 15 kWe at plant A and at 25 kWe at plant B. Air was used as the gasification medium. Figure 24 shows the principle of small-scale gasification CHP and Figure 25 depicts the feedstock used.

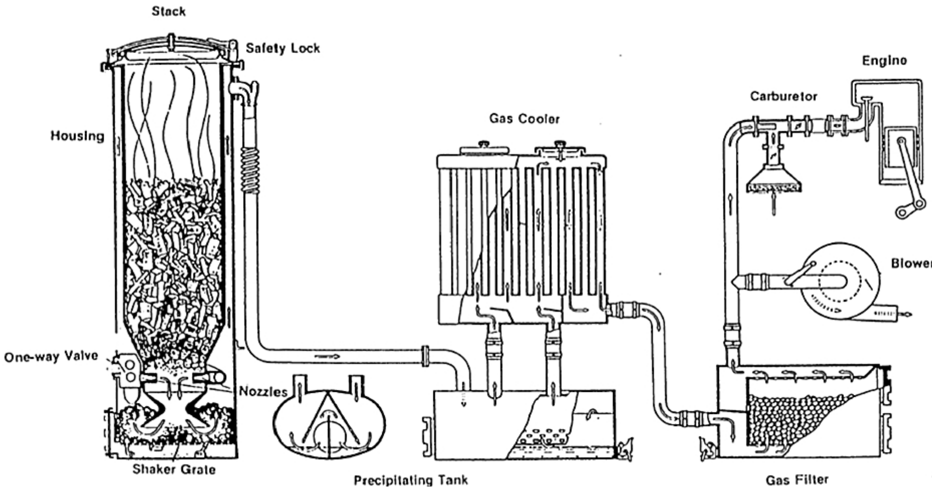

Figure 24. A small-scale downdraft gasification CHP plant.

Figure 25. Wood chips and torrefied wood chips used in the fixed-bed gasification tests.

Product gas composition was continuously measured after the gasifier. Tar samples were taken after the gasifier according to the standard method described in Tar Protocol CEN/TS 15439:2006. Whole tree wood chips torrefied at 255°C were prepared at ECN [1]. The moisture content of the torrefied wood chips was about 3% compared to that of the original wood chips of 14–16%.

Dry product gas composition is quite similar, with torrefied wood compared to untreated wood. However, a lower CO_2 content and higher CO content was obtained in gasification experiment with torrefied wood compared to untreated wood. Tar and benzene concentration in gasification experiments at plant B is shown in Figure 26. At plant B concentrations of tars were clearly lower with torrefied wood chips than with conventional wood chips. The reason for the lower tar concentrations may be a higher gasification temperature because of lower moisture content of torrefied wood or lower amount of volatiles in torrefied wood.

At both plants, torrefied wood chips caused the same problem. Torrefied wood chips are brittle and break up easily into small pieces and dust that are problematic for downdraft gasifiers. Small particles and dust block the bed in the downdraft gasifier, preventing free flowing of the bed, and produce a greater pressure drop. Small particles and dust must be removed by sieving from the torrefied wood chips.

Based on the results, torrefaction pre-treatment had only a minor effect on product gas composition, tar yield or carbon conversion in downdraft fixed-bed gasification. Therefore, torrefaction was found to offer no clear benefits in downdraft gasifiers. Nor does it seem feasible to use more expensive torrefied wood chips at a small scale gasification plant if conventional dried wood chips are available.

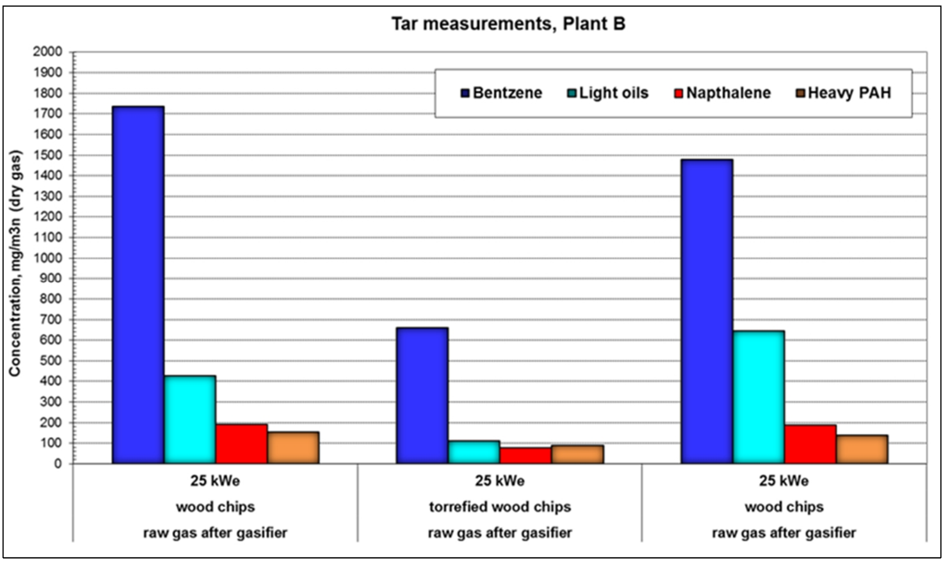

Figure 26. Tar and benzene concentration in product gas at plant B. Two set points with wood chips and one with torrefied wood chips.

7.2 Fluidized-bed gasification of torrefied wood

Air/steam and steam gasification experiments were carried out with a bench-scale atmospheric bubbling fluidized-bed gasifier [10]. Pellets produced from torrefied wood chips at two different temperatures, 235 and 255°C (WC 235C and WC 255C) and conventional wood pellets were used in the gasification experiments. The torrefied wood pellet samples were prepared at ECN [1]. At VTT the pellets were further crushed and sieved to a particle size of about 0.5–1.0 mm. Product gas composition was continuously measured after the gasifier. Tar samples were taken after the gasifier according to the standard method described in Tar Protocol CEN/TS 15439:2006.

Tar and benzene yield in gasification experiments is shown in Figure 27. Higher torrefaction temperature (255°C) slightly reduced tar yield in air/steam gasification conditions, while tar yields obtained with untreated wood and wood torrefied at 235°C were in the same range. In steam gasification experiments, tar yield was clearly higher with torrefied wood compared to untreated wood. This difference might be partly explained by the smaller particle size of torrefied wood (0.5–1.0 mm) compared to that of untreated wood (0.5–3.15 mm) used in the tests. In a bubbling fluidized-bed reactor the finer fuel particles are more easily carried out of the gasifier without having enough time to react and therefore possibly also yielding more tars.

In air/steam gasification experiments carbon conversion was lower with wood torrefied at 255°C (95%) whereas similar carbon conversions of around 99 % were obtained with untreated wood and wood torrefied at 235°C. In steam gasification conditions, the difference between carbon conversions obtained with torrefied wood (91%) and untreated wood (84%) was more significant. These results are in agreement with those presented in a recent study [11] where torrefaction pre-treatment was found to reduce char oxidation and gasification reactivity. Moreover, lower carbon conversion with torrefied wood in the steam gasification experiment can partly be explained by the smaller particle size.

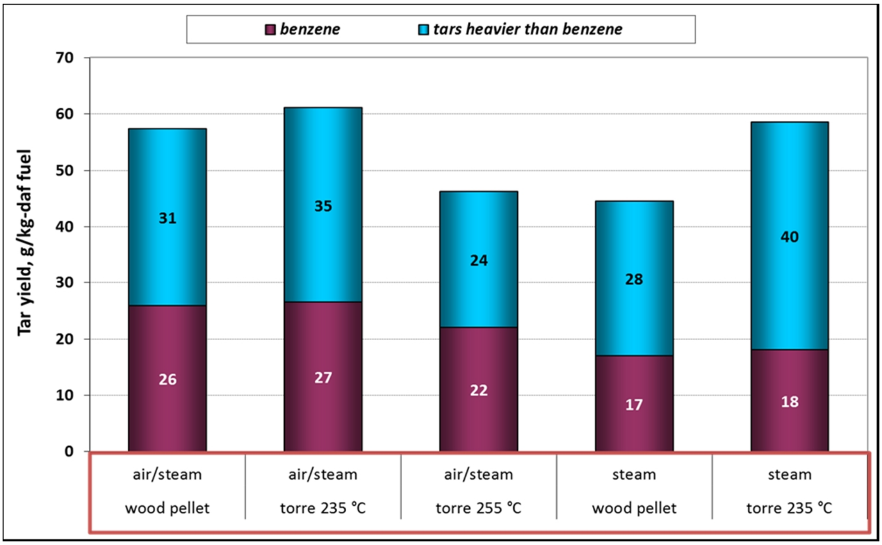

Figure 27. Tar and benzene yield (g/kg daf fuel) in air/steam and steam gasification tests with torrefied wood and untreated wood.

These preliminary gasification tests indicated that the torrefaction pretreatment had no significant effect on product gas composition, tar yield or carbon conversion in air/steam gasification conditions. Higher torrefaction temperature (255°C) showed a minor reduction in tar yield but also a lower carbon conversion. Therefore, torrefaction was found to offer no clear benefits in air/steam gasification conditions. In steam gasification conditions, higher tar yield and lower carbon conversion was obtained with torrefied wood compared to untreated wood. The results might be affected by the different particle size of untreated wood and torrefied wood used in the tests as was already pointed out.

7.3 Fast pyrolysis of torrefied wood

Fast pyrolysis is a promising process for producing liquid fuels from solid biomass. The chemical composition of bio-oil is mainly dependent on the biomass, but also on the process conditions (temperature, residence time, heating rate) used. The major compound groups identified in bio-oil are water, aldehydes, ketones, carboxylic acids, furans, carbohydrates, and lignin fragments. During fast pyrolysis, the biomass components (hemicellulose, cellulose and lignin) are broken down into smaller components.

Pyrolysis liquid is not suitable as a feedstock for traffic fuel production without upgrading, because of its relatively low energy content, high water content (20–30 wt-%), acidity and poor storage stability. The high oxygen content in bio-oil, usually 45–50 wt-%, is the primary reason for the differences in the properties and behaviour between hydrocarbon fuels and biomass pyrolysis oil. The high water content has a negative impact on the heating value, but on the other hand it improves the bio-oil flow characteristics, such as viscosity. Because of the low pH, bio-oil is corrosive in some common construction materials such as carbon steel and aluminium. The quality of bio-oil can be improved in many different ways, such as chemical pre-treatment of the biomass and catalytic upgrading of the bio-oil. In addition to these routes, torrefaction could also be used as a candidate for improving bio-oil quality [12]. Recent research results [14] indicate that these problems can, at least partially, be addressed through the use of torrefaction as a pretreatment method. During torrefaction, mainly the hemicelluloses fraction of biomass degrades, resulting in a more uniform and desirable feedstock for pyrolysis. Torrefaction and the subsequent fast pyrolysis step of aspen improved storage stability and energy content.

Two fast pyrolysis experiments were carried out with raw material torrefied at two different temperatures and pelletized by ECN [1]. At VTT the torrefied wood pellets were grinded in a cutting mill with a bottom sieve of 2 mm. After grinding, the raw material was sieved to a particle size of 0.55–0.92 mm. After pyrolysis, the chemical composition of the bio-oil was analysed and the results were compared with typical values for bio-oil produced from pine sawdust. A schematic flow diagram of the bench scale fast pyrolysis unit (feed 1 kg/h) used in the experiments is shown in Figure 28 [13].

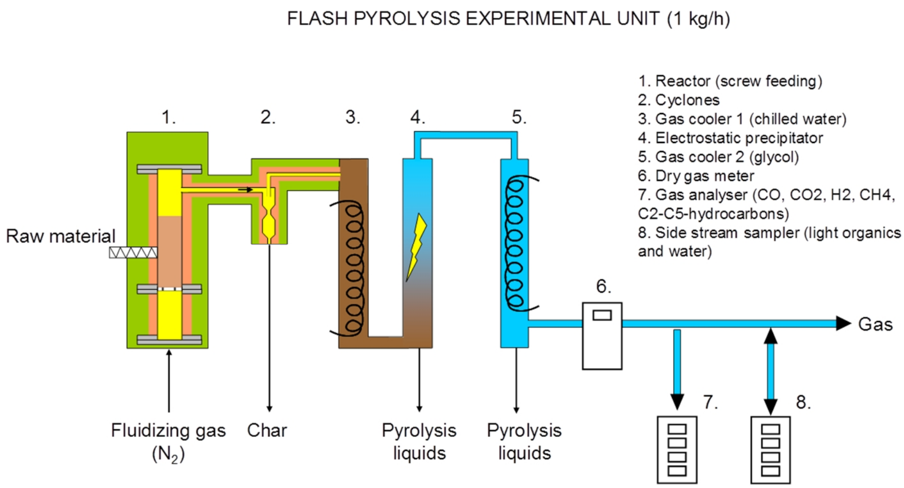

Figure 28. Schematic flow diagram of the bench scale fast pyrolysis unit at VTT.

The torrefaction conditions and mass yields are shown in Table 4. The mass loss of 23% in torrefaction at 255°C is most probably due to decomposition of hemicelluloses. In fast pyrolysis, carboxylic acids and a proportion of the carbonyl compounds are formed from hemicelluloses. Decomposition of hemicelluloses could theoretically lead to bio-oil with a lower amount of acids and of improved stability due to a lower amount of carbonyl compounds. Analyses of the feedstocks used and the bio-oil products are summarised in Table 5.

Table 4. Torrefaction conditions and mass yields.

Torrefaction temperature °C	Dry biomass in kg	Product quantity out kg	Mass yield %
235	613	559	91
255	1222	941	77

Table 5. Elemental composition of bio-oil obtained from torrefied wood and pine sawdust. Carbonyl content of pine pyrolysis oil was not analysed, but a typical value for it is included in the table.

Raw material	Torrefied whole tree 235 °C	Torrefied whole tree 255 °C	Pine sawdust
Water KF*, wt- %	23,9	16,0	15,5
Solids, wt- %	0,10	0,13	0,08
Ash, wt- %	0,09	0,04	n/a
Elemental composition of dry oil			
C, wt- %	54,9	55,8	54,8
H, wt- %	6,1	6,3	5,8
N, wt- %	0,3	0,2	0,0
O (by difference), wt- %	39	38	39
MCR (Micro carbon residue)	19,2	22,4	
pH	2,24	2,28	2,43
Carbonyls, mmol/g	4,6	4,7	abt. 3,5

*Karl-Fisher titration

Fast pyrolysis experiments with torrefied wood resulted in a lower organic liquid yield and a higher char and gas yield. The torrefaction pre-treatment had however no effect on the elemental and chemical composition of bio-oil. The carbonyl content of all bio-oils was practically the same, which indicates that the stability of the bio-oil from torrefied wood had not improved. Also, the pH of the bio-oils was similar. The small changes in the bio-oil quality from torrefied wood may depend on too low a torrefaction temperature. Some decomposition of hemicelluloses has taken place, because the mass loss in torrefaction at 255°C was 23%.

7.4 Conclusions

The preliminary small-scale gasification and pyrolysis tests indicated that no or only minor advantages can be obtained by pretreatment of the woody biomass in a torrefaction process. The brittle physical nature of the torrefied wood chips makes this product unsuitable for fixed bed gasification. No significant effect on product gas composition, tar yield or carbon conversion was obtained in fluidized-bed gasification conditions. Nor did the torrefaction treatment improve the quality of bio-oil produced by fast pyrolysis. Further tests should, however, be carried out to fully verify the effect of torrefaction.

8. Torrefied wood in the production of engineered products

Torrefied wood has unique properties also as a raw material for wood-based products. Torrefied wood chips have a lower density than original wood chips and a significantly improved hydrophobic nature. These are features that can be utilised in wood-based engineered materials production of, for instance, moisture resistant particle boards (PB) and torrefied wood composites. An indicative elaboration of the fundamentals and possibilities of these new products was undertaken within this study together with Pöyry and Ekolite Technologies.

8.1 Particle board

A short test programme on producing particle board from torrefied wood chips was carried out at the KYAMK University of Applied Sciences [15]. Rectangular particle board samples of 500 mm x 500 mm, 13 mm thick were produced from three different torrefied wood chips grades. A normal urea formaldehyde type of resin was used, and 12% was added to the chips in all tests but one, in which the addition was increased to 15%. The torrefied wood chips were produced from Finnish wood chips and crushed forest residue chips by Energy research Centre of the Netherlands (ECN) within a previous research project described in VTT Technology 122 [1]. Normal spruce chips were used as a reference. Torrefied materials tested were:

- FR 250C (forest residue chips, torrefaction temperature 250^{o}C)
- WC 245C (whole tree wood hips, torrefaction temperature 245^{o}C)
- WC 235C (whole tree wood hips, torrefaction temperature 235^{o}C)
- WC 235C, PL 15% (same as previous, 15% resin)
- Spruce ref (reference material, wood chips produced from spruce).

The preparation of the board samples went smoothly; the only manufacturing process-related problem occurred in flaking the torrefied chips. The ratio between core (coarser fraction) and surface (finer fraction) chips was not ideal, and a large amount of dust produced. This relates to the brittle nature of the torrefied wood chips compared to virgin wood chips. The board samples are shown in Figure 29.

Figure 29. Samples of particle boards produced from spruce chips and torrefied wood chips.

The torrefied particle board samples were produced with different pressures at 180°C, resulting in boards with densities between 475 and 725 kg/m^3. A number of physical characteristics were measured so as to compare the torrefied particle board samples to the reference board. The measurements included strength measurements, swelling and water absorption. The results of the bending strength and swelling measurements are given in Figures 30 and 31.

The preliminary tests show that light and moisture resistant boards can be produced from torrefied wood chips. The strength properties are somewhat weaker than for normal particle boards, but the hydrophobic character of the torrefied wood gives the torrefied particle board very good swelling properties. Raising the torrefaction temperature seems to enhance water resistance and swelling properties. The tests were carried out with a common urea-based resin. The bond does not seem unsatisfactory, and further testing and research for a more suitable resin is needed.

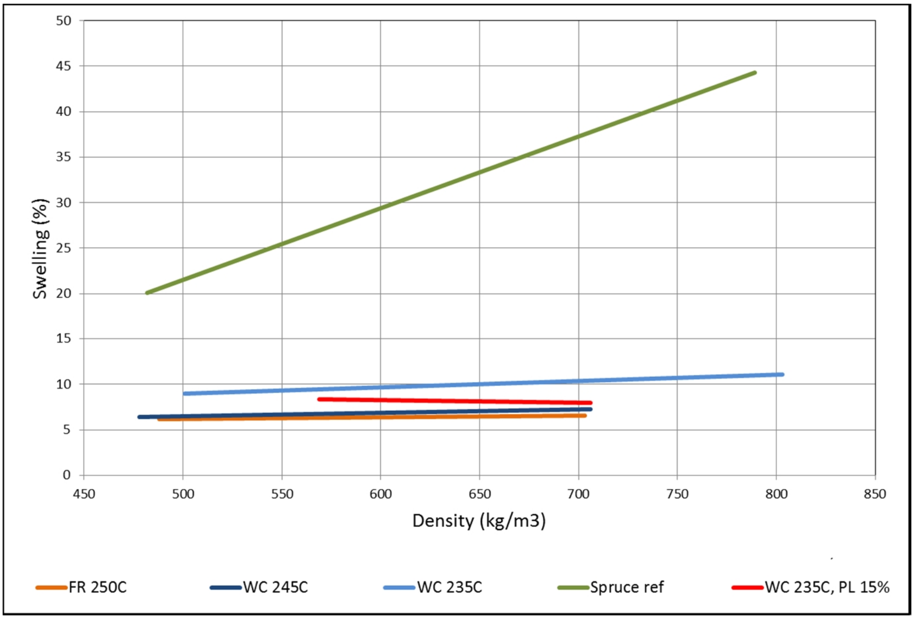

Figure 30. Thickness swelling of the particle board samples during a 24-hour water immersion.

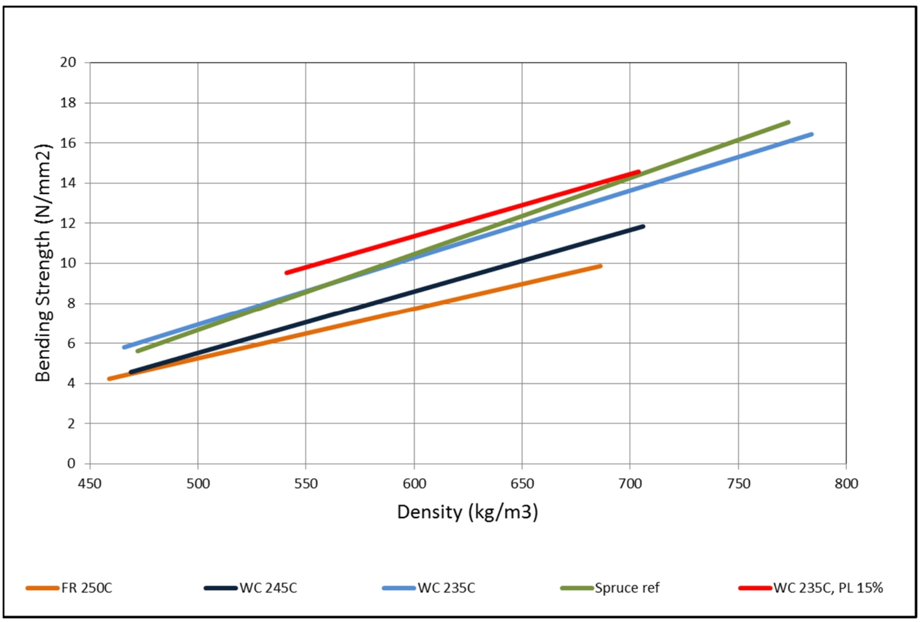

Figure 31. Bending strength of the particle board samples.

The moisture-resistant particle board could have significant quality benefits compared to traditional products due to its better moisture resistant properties in areas where a traditional product loses its form and strength. Another trend is lightweight boards with density of around 500 kg/m^3 for the furniture industry. Using torrefied wood chips could bring significant added value to these product applications.

A preliminary elaboration on particle board manufacturing costs is given in Figure 32. The low density of the torrefied wood chips means more wood consumption and a lighter board (approx. 500 kg/m^3). The cost of the wood is the main cost component in particle board and high wood consumption leads to higher manufacturing costs.

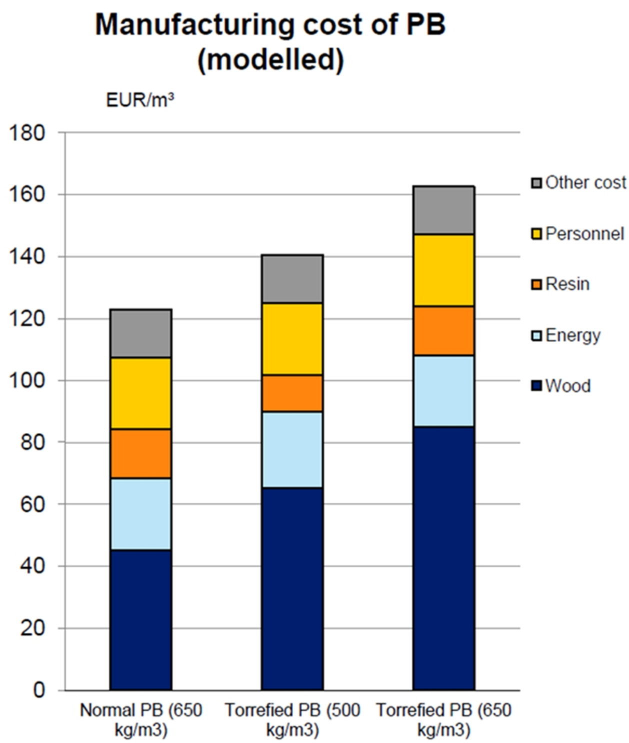

Figure 32. Indicative manufacturing costs of particle board from torrefied wood chips.

The use of melamine urea formaldehyde (MUF) resin would result in a weather-resistant particle board which could be used in outdoor applications and countries with very humid climates. Using torrefied wood chips results in higher manufacturing costs, but the sales price could be significantly higher with a lightweight weather-resistant particle board**.** VTT has protected the innovation as a utility model.

8.2 Wood plastic composites

Wood plastic composites (WPC) combine natural fibres (e.g. wood) and thermoplastics (e.g. polypropylene, PP) with different additives. These additives include coupling agents, colour pigments, UV-agents, lubricants, etc.

The end-product defines the production method. The most common methods are extrusion and injection moulding. The biggest end-uses are decking and automotive parts. Automotive parts are usually manufactured from bast fibres (flax, hemp etc.) with injection moulding. Decking and other profiles are made with extrusion, and wood fibres are commonly used. Complex dimensions are possible especially with injection moulding.

A preliminary test on producing wood plastic composite from torrefied wood was carried out by Realite Technologies Oy. The tests showed that the share of virgin plastics (polyethylene, polylactide) can be less than 30% instead of the normal 50–70% addition. The benefit of a smaller proportion of plastics is the cost difference between wood and plastics, so a smaller proportion of plastics means lower raw material costs for the end product, Figure 33. An additional option is also to use recycled plastics instead of virgin plastics that can further reduce the production costs of the composite.

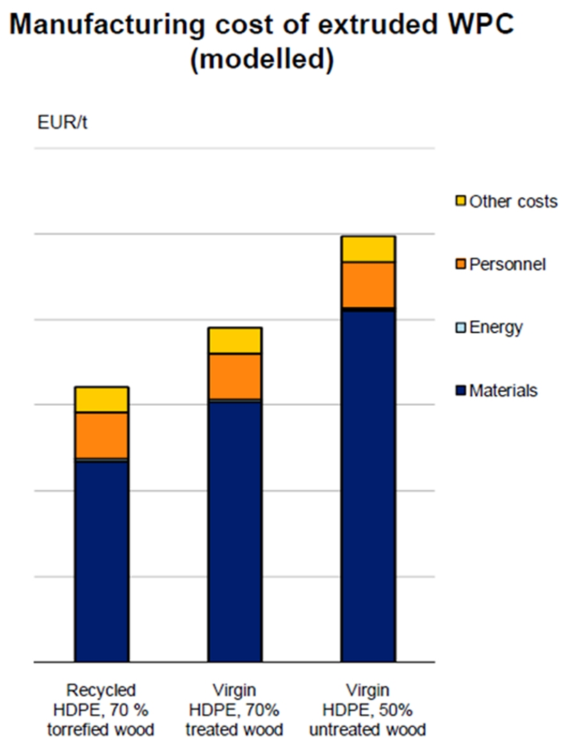

Figure 33. Manufacturing costs of wood plastic composites.

Torrefied wood-based composites have better properties in terms of how much plastics are required to make the profile moisture- and weather-resistant. The benefit of torrefied wood-based wood-plastic composite is the reduced production costs as a higher proportion of wood can be used compared to current products due to better moisture- and weather-resistance.

Based on this preliminary evaluation, the torrefied wood is a potential raw material for new advanced wood products that are not just substitutes current products but create new business in new end-uses.

9. Summary and conclusions

VTT, in collaboration with industrial partners, has developed new bioenergy carrier solutions integrated with forest industry operations. The basis of the European forest industry consists of a sawmill industry, pulp industry and wood panel industry. Sawn wood, pulp and panel industries are roughly equal in size in terms of production value in the EU. Sweden, Germany and Finland are clearly the largest forest industry countries in Europe. The total value of primary wood processing in these countries amounts close to €10 000 million each.

The size of forest industry plants varies greatly, especially in the sawmilling industry. Germany has the largest sawmills in Europe, with two sawmills having an annual production capacity of over 1 million m^3 of sawn wood. In general, the sawmill structure in Europe is very scattered, as the number of sawmills is large and the production capacities may range from some hundreds to million m^3/a. A sawmill with annual production of 500 000 m^3 generates some 430 000 m^3 of chips and sawdust, which is equivalent to the raw material requirement of a torrefied pellet plant with annual output of some 120 000 t.

In addition to the forest industry, the energy industry is a major wood consuming sector in Europe. Biomass-based heat or CHP production by energy utilities is common especially in Scandinavia, but increasingly also in other parts of Europe.

Assuming that torrefied pellet production is a viable option also in Europe, the sector competes for raw material with other wood-using industries. Even though there is hardly any surplus volume of industrial mill residues available in Europe, it is possible to establish a torrefied pellet production plant integrated with, for instance, a sawmill. This requires that the torrefied pellet producer is capable of paying the same or a higher price for the forest or mill residues than the current buyer, and that the current buyer can use alternative sources, e.g. forest biomass, without any additional cost effects.

Torrefied biomass pellets are an interesting option for replacing fossil fuel in existing pulverised coal fired boilers and fuelling entrained flow gasification plants. Pulverized coal-fired power plants are found with a total capacity of around 200 GWein nearly all European countries. The great majority of these plants are, however, located in Germany, the UK and Poland. These three countries represent more than 50% of the total electric capacity based on pulverized coal combustion technology. A hypothetical plant producing 100 000 t of torrefied pellets per year can cover 10% of the annual fuel input of an average sized pulverized coal-fired power plant in UK.

Sawmills offer attractive business solutions for solid white or brown pellet production, as well as bio-liquids produced by fast pyrolysis technology from sawdust and forest residues. There are significant synergies for bioenergy carrier integration due to favourable procurement and logistics, energy and labour benefits. A new torrefaction process was developed, and the ultimate objective was to create an Integrated Thermal Processing (ITP) solution for integrating the torrefaction of biomass to FB boilers at saw mills and CHP plants. A preliminary design of pilot-scale torrefaction equipment was undertaken and a road map for demonstrations was elaborated. A market analysis of integrated bioenergy carrier production at saw mills in Finland was undertaken. It was concluded, that the market conditions for torrefied pellets, and for solid biomass fuels in general, is challenging due to the unexpected low prices for CO_2 (about €5/t CO_2) certificates and for coal (about €8/MWh). The results indicated that there needs to be a feed-in tariff or similar support mechanism for torrefied pellets so as to guarantee a paying capability for coal fired power plants above €35/MWh in order to make the investments viable.

To elaborate on the possible advantages of using torrefied wood instead of conventional wood fuels in production of gaseous and liquid energy carriers, a set of preliminary fluidized-bed gasification and pyrolysis tests was carried out at VTT. Additionally, fixed-bed gasification tests were conducted at two district heating plants. The preliminary small scale gasification and pyrolysis tests indicated that no or only minor advantages can be obtained by pretreatment of the woody biomass in a torrefaction process.

Torrefied wood has unique properties also as a raw material for wood-based products. A short test programme on producing particle board from torrefied wood chips was carried out, and particle board was produced from three different torrefied wood chips grades. The preliminary tests showed that light and moisture-resistant boards can be produced from torrefied wood chips. The strength properties are somewhat weaker than for normal particle boards, but the hydrophobic character of the torrefied wood gives the torrefied particle board very good swelling properties. Based on this preliminary evaluation, torrefied wood is a potential raw material for new advanced wood products that are not just substitutes for current products but create new business in new end-uses.

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Title	**Wood torrefaction – market prospects and integration with the forest and energy industry**
Author(s)	Carl Wilén, Kai Sipilä, Sanna Tuomi, Ilkka Hiltunen, Christian Lindfors, Esa Sipilä, Terttu-Leea Saarenpää & Markku Raiko
Abstract	The research project "Biocoal – a new energy carrier for saw mills, CHP plants and wood industry integrates" was carried out within the Groove programme of Tekes during the years 2010–2013. The main objective of the project was to enhance the commercialization of integrated wood torrefaction technology into current forest industry operations. Several integration concepts were elaborated together with the participating companies with a focus on sawmills and municipal and industrial CHP plants. The European forest industry constitutes a potential platform for the production of torrefied wood pellets and other bioenergy carriers. VTT, in collaboration with industrial partners, has developed new bioenergy carrier solutions integrated into forest industry operations in sawmills. A new torrefaction process was developed and market analysis was performed, including a road map for demonstrations and market introduction. Some preliminary test work was also carried out in order to assess the possible advantages of the use of torrefied biomass in fixed-bed and fluidised bed gasification applications, bio-oil production and as a potential raw material for new advanced wood products. The primary prerequisite for the torrefied pellet market is the energy plants' need for and interest in using them as fuel. The main users are assumed to be found in the power production sector. Substituting coal by co-firing biomass in large pulverised coal-fired power plants needs significant green electricity incentives, however, or a considerably higher CO_2 price in order to be feasible. From the raw-material point of view, the benefits from integrated torrefied pellet production are related to by-product utilization at sawmills or plywood mills, but also to general wood procurement logistics at forest industry plants. In the case where processing residues can be utilized at site, cost savings can be achieved if the alternative option is to transport residues to an external facility. A market analysis of integrated bioenergy carrier production was undertaken at sawmills in Finland. It was concluded, that the market conditions for torrefied pellets, and for solid biomass fuels in general, is challenging due to the unexpected low prices for CO_2 (about €5/t CO_2) certificates and for coal (about €8/MWh). The results indicated that there needs to be a feed-in tariff or similar support mechanism for torrefied pellets to guarantee a paying capability for coal fired power plants above €35/MWh so as to make the investments viable.
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Nimeke	**Puun torrefiointi – markkinanäkymät ja integrointi puujalostus- ja energiateollisuuteen**
Tekijä(t)	Carl Wilén, Kai Sipilä, Sanna Tuomi, Ilkka Hiltunen, Christian Lindfors, Esa Sipilä, Terttu-Leea Saarenpää & Markku Raiko
Tiivistelmä	Tutkimusprojekti ”Biohiili – uusi bioenergiakantaja sahojen, CHP-voimaloiden ja metsäintegraattien yhteyteen” toteutettiin Tekesin Groove-ohjelmassa VTT:ssä vuosina 2010–2013. Projektin tavoitteena oli edesauttaa biohiilen valmistustekniikan (puun torrefioinnin) kaupallistamista osana metsäteollisuuden toimintoja. Tutkimukseen osallistuvien yritysten kanssa tarkasteltiin useita integrointimahdollisuuksia, erityisesti sahoihin ja yhdyskunnan ja teollisuuden CHP-laitoksiin. Euroopan metsäteollisuus muodostaa potentiaalisen alustan torrefioitujen puupellettien ja muiden bioenergiakantajien tuotannolle. VTT on yhdessä teollisuusosapuolten kanssa kehittänyt uusia ratkaisuja bioenergiakantajien valmistuksen yhdistämiseksi sahateollisuuden toimintoihin. Tutkimuksessa suunniteltiin uusi torrefiointiprosessi ja laadittiin tiekartta pilotoinnin ja demonstroinnin toteuttamiseksi. Torrefioidulla puulla tehtiin myös alustavia kaasutus- ja pyrolyysikokeita pienessä kokoluokassa mahdollisten etujen selvittämiseksi verrattuna perinteisten puuraaka-aineiden käyttöön. Koetoiminta käsitti myös torrefioidun puun käytön uusien puutuotteiden valmistuksessa. Torrefioitujen puupellettien laajamittainen käyttö toteutunee ensisijaisesti kivihiilivoimaloiden oheispolttoaineena. Jotta hiilen korvaaminen suurilla pölypolttolaitoksilla oheispolttamalla torrefioituja puupellettejä olisi kannattavaa, vaaditaan kuitenkin merkittäviä vihreän sähkön kannustimia tai huomattavasti korkeampaa CO_2-päästöjen hintatasoa. Integroimalla torrefioitujen pellettien tuotto metsäteollisuuteen saavutetaan synergiaetuja sahojen ja puutuotetehtaiden sivuvirtojen hyödyntämisessä ja yleisemmin raaka-aineiden hankinnassa ja logistiikassa. Kun sivuvirrat voidaan hyödyntää paikan päällä, saavutetaan selviä säästöjä verrattuna niiden toimittamiseen ja käyttöön ulkopuolisella laitoksella. Tutkimuksessa tarkasteltiin bioenergiakantajien (torrefioitu puupelletti, bioöljy) valmistusmahdollisuuksia ja -kustannuksia suomalaisilla sahoilla. Torrefioitujen puupellettien ja yleensä kiinteiden biopolttoaineiden markkinatilanne on haastava alhaisen CO_2-päästöhinnan (noin 5 €/tCO_2) ja hiilen hinnan (noin 8 €/MWh) takia. Torrefioitujen pellettien rajahinnaksi laitoksella tulee noin 35 €/MWh, ja on ilmeistä, että torrefioitujen puupellettien käytön tueksi tarvitaan sähkön syöttötariffia tai vastaavanlaista tukimekanismia varmistamaan voimalaitoksen maksukyky.
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Wood torrefaction – market prospects and integration with the forest and energy industry

The European forest industry constitutes a potential platform for the production of torrefied wood pellets and other bioenergy carriers. VTT, in collaboration with industrial partners, has developed new bioenergy carrier solutions integrated into forest and energy industry operations.

Torrefied biomass pellets are an interesting option for replacing fossil fuel in existing pulverised coal fired boilers and fuelling entrained flow gasification plants. Substituting coal by co-firing biomass in large pulverised coal-fired power plants needs significant green electricity incentives or a considerably higher CO_2 price in order to be feasible.

The European forest industry constitutes a potential platform for the production of torrefied wood pellets and other bioenergy carriers. From the raw-material point of view, the benefits from integrated torrefied pellet production are related to by-product utilization at sawmills or plywood mills, but also to general wood procurement logistics at forest industry plants. In the case where processing residues can be utilized at site, cost savings can be achieved if the alternative option is to transport residues to an external facility. A market analysis of integrated bioenergy carrier production was undertaken at sawmills in Finland. It was concluded, that the market conditions for torrefied pellets, and for solid biomass fuels in general, is challenging due to the unexpected low prices for CO_2 (about €5/t CO_2) certificates and for coal (about €8/MWh). The results indicated that there needs to be a feed-in tariff or similar support mechanism for torrefied pellets to guarantee a paying capability for coal fired power plants above €35/MWh so as to make the investments viable.

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