IRENA
International Renewable Energy Agency

BIOENERGY FROM FINNISH FORESTS

Sustainable, efficient, modern use of wood

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Cover photograph by Ville Heikkinen. Report layout by Nacho Sanz.

DISCLAIMER

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ABBREVIATIONS

BFB bubbling fluidised bed

Ca calcium

CFB circulating fluidised bed

CHP combined heat and power

DH district heating

FBC fluidised bed combustion

GWh gigawatt hours

K potassium

KOH potassium hydroxide

kW kilowatt

kWh kilowatt hour

Luke Natural Resources Institute Finland

m^2 square meter

m^3 cubic meter

Mg magnesium

Mha million hectares

MJ megajoule

Mm^3 million cubic metres solid

mm^3 cubic millimetres

Mt megatonne; million tonnes

$MtCO_2$-eq million tonnes carbon dioxide equivalent

MWh megawatt hour

MW_e megawatt of electricity

MW_{heat} megawatt equivalent for heat

MW_{fuel} megawatt equivalent for fuel

Na sodium

Na_2S sodium sulphide

NaOH sodium hydroxide

NO_x nitrogen oxide

PEFC Programme for Endorsement of Forest Certification

PJ petajoules

ppm part per million (100 milligrams per kilogram, 0.01%)

SO_2 sulfur dioxide

TAN total acid number

TWh terawatt hours

One euro (EUR) is equivalent to approximately 1.2 United States dollars (USD) at time of publication.

EXECUTIVE SUMMARY

Finland is a northern European country with vast forest resources and sustainable wood production that supports industrial output, energy supply, economic growth and social well-being. This report describes Finland's approach to sustainable solid biomass supply, the country's application of forest wood resources for production of heat and power, and three specific cases where Finnish forest resources have been used in an innovative fashion.

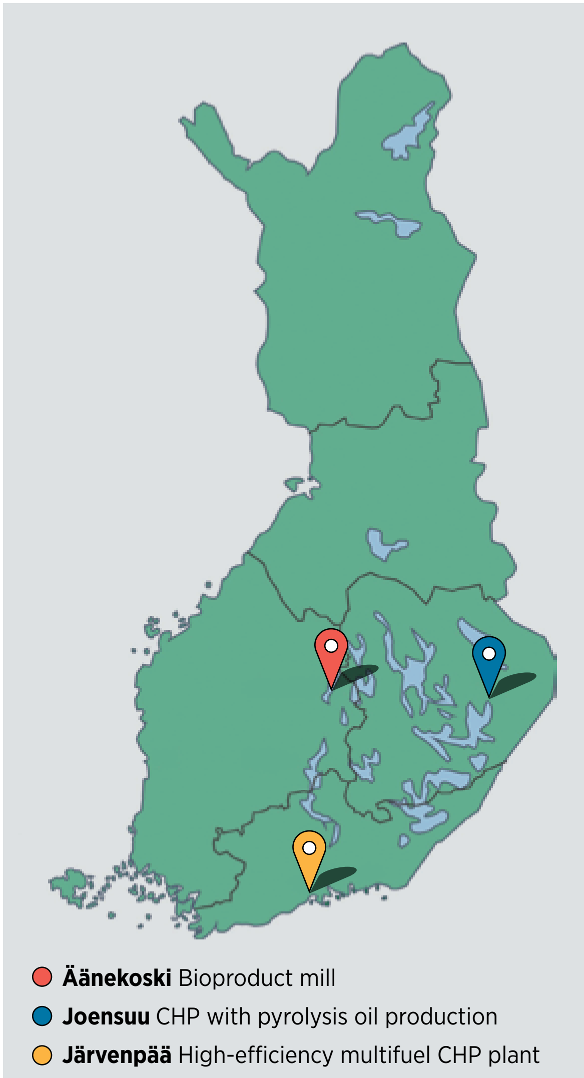
The study – prepared by the country's Technical Research Centre, VTT, in co-operation with the International Renewable Energy Agency (IRENA) – provides insights for other countries intent on developing forest bioenergy.

The annual growth of Finnish forests has nearly doubled since the 1950s, and so has the amount of wood that can be sustainably extracted from these forests. Less than half of all wood extracted is used for heat and power, while more than half is converted to products. Together, the unextracted forest growth and durable products, which continue to store carbon for years or decades, are equivalent to over half the roundwood harvest.

Typically, wood energy resources are used in highly efficient district heating (DH) systems and combined heat and power (CHP) plants. Most of these rely on direct combustion, but the most modern CHP plants use fluidised bed boiler or circulating fluidised bed technology to gasify a wider range of low-quality forest residues, reducing operating costs. Gasification also allows forest residues to displace coal in coal-fired CHP plants, which cannot use residues directly.

Three case studies, located as shown in Figure 1, provide useful insights for policy makers on the value of increased scale and flexibility in energy conversion when planning and implementing bioenergy strategies. One case, in southern Finland, illustrates biomass use in a municipality to which biomass is transported from forests. Cases in central and eastern Finland illustrate the integration of biomass supply with local forest industries. The advanced CHP plants highlighted here can use a wide range biomass from forests. This means greater flexibility in timing and sourcing feedstock collection, and hence lower costs.

Figure 1 Case studies in southern, central and eastern Finland



Source: VTT

CHP = combined heat and power

The boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

The first case study examines Metsä Fibre's new bioproduct mill in Äänekoski in central Finland. This mill, fuelled by various wood residues, is much more energy efficient than typical pulp mills fuelled by fuel oil. The bioproduct mill uses 100% renewable energy sources. It is optimised to produce electricity for the bioproduct mill, the Nordic power market and district heat for the neighbouring town and industries.

On top of standard products such as pulp, tall oil, bark, turpentine, electricity and process steam, the mill can make high-value-added bioproducts such as textile fibres, biocomposites, fertilisers, biofuels and lignin upgrades in collaboration with local partners. Such an integrated production strategy provides new avenues for renewable energy uptake.

The second case study describes a high-efficiency multifuel CHP plant at Järvenpää, in southern Finland, owned by the electric utility Fortum. In 2014, the plant operated with 99.5% biomass fuels at 96.5% efficiency. Such extremely high efficiency is made possible by a flue gas condenser, which enables the plant to capture energy from moist fuel that would otherwise be wasted through evaporating the inherent water content of such fuel. The plant can also use residues, such as farmyard manure, for up to 30% of its fuel. Despite its extraordinary efficiency and fuel flexibility, the plant is still in the lower half of the cost range for a typical biomass-fuelled boiler in a CHP plant utilising bubbling fluidised bed (BFB) technology.

The third case looks at a pyrolysis oil plant connected to a CHP plant at Joensuu in eastern Finland, also owned by Fortum. Pyrolised fuel is produced at high efficiency from forest residues and sawdust, which are by-products of the local forest industry. A fluidised bed boiler acts as a heat source for pyrolysis, and the coke and uncondensed gases from pyrolysis are used to generate additional heat and electricity. The case thus demonstrates how fuel production can be made more cost-effective by integrating it with heat and power production.

Taken together, the three case studies point to the advantages of fuel flexibility. A key challenge for bioenergy production from forest biomass is sourcing feedstock consistently, in sufficient quantity, in one place, to allow efficient conversion to heat and electricity at an industrial scale. Agricultural residues, which in many countries provide an alternative to or supplement for scarce woody biomass, are produced seasonally and not always in sufficient quantities. Re-tuning traditional CHP technology to allow a wide range of feedstock is a big part of the solution.

Additional flexibility is provided by options to convert biomass to gas or pyrolysis oil. The gas or liquid oil is often less costly to transport than raw biomass, and it can be stored. Thus it can be saved for use as needed to balance supply and demand for heat on a district heat grid or electricity on a power grid. In addition, if available biomass exceeds local requirements for heat and power, the gaseous and liquid fuels produced can be exported for heat and power production or transport use elsewhere.

Sustainable and efficient use of bioenergy plays an integral role in most low-carbon scenarios. Bioproducts can be used to mitigate greenhouse gas emissions in many sectors that have few alternative options. Combining different technologies as shown in the Finnish case studies can boost energy and economic efficiency by enhancing fuel flexibility and the range of products offered, enabling customised strategies to match local resource supply and product needs.

1 SUSTAINABLE SOURCING AND HARVESTING OF FINNISH FOREST WOOD

Forest covers a greater share of land in Finland than in any other European country. More than three-fourths of the land, some 26.2 million hectares (Mha), is forested. Of this, 4.5 Mha (17%) is in nature reserves off-limits to production, while another 3 Mha (13%) is protected. The remaining 18.7 Mha (70%) is actively managed to increase both forest cover and wood output.

Finnish managed forestry has maintained a consistently growing biomass stock in the forests over the last 50 years. Forests have thus been a notable carbon sink while also supporting the economic activities of landowners, forest industries and the energy sector. The net carbon sink of Finnish forests in 2006-15 averaged 38.2 million tonnes (Mt) carbon dioxide equivalent ($MtCO_2eq$) per annum, storing 382 $MtCO_2eq$ in the course of the decade, despite growing use of wood for energy and industry. Over the same period, the carbon sink of harvested wood products averaged 2.1 $Mt.CO_2$-eq per year and totalled 21 $MtCO_2eq$ in all.

The net annual increment (net growth) of Finnish forests has almost doubled since the 1970s. Two-thirds of the increase in net growth is due to active forest management, use of improved plant materials and drainage of peatlands. One-third has resulted from higher ambient temperatures and rising CO_2 levels associated with climate change. Overall, the net annual increment of 110 million cubic metres solid (Mm^3), or 4.5% of total forest growing stock (2 357 Mm^3) in 2016, is projected to increase by about 1 Mm^3 (nearly 1%) per year.

Figure 2 Roundwood at the roadside

Source: Natural Resources Institute Finland (Luke)

Sustainable forest management in Finland has roots in the 17th century and was first codified in the Forest Act of 1886, which declared that "You shall not devastate the forest." The principles of ecological, social and economic sustainability are laid out in the Forest Act of 1996. The Act on Financing of Sustainable Forestry sets loan conditions to encourage sustainable timber production and maintain forests' biological diversity. It also provides grants for afforestation, tending of young stands, harvesting of energy wood, and forest recovery and fertilisation. More than 90% of commercial Finnish forests have been certified by the PEFC (Programme for Endorsement of Forest Certification) but only 4% have been certified by the Forest Stewardship Council (Alakangas, 2016; Singh *et al.*, 2016; PEFC Finland, 2014).

Biodiversity in the forest environment was more strongly incorporated in forest management practices from the 1990s. The Forest Biodiversity Programme METSO was started in 2008. The programme aims to halt the decline of forest habitats and species as well as establish favourable trends in the forest ecosystems of southern Finland by 2025. The programme enlarges Finland´s network of protected areas, increases the connectivity of protected forests and develops nature management methods used in commercially managed forests. Protection is always based on voluntary initiatives of forest owners. Forest areas can also be bought for conservation by the state. About one-quarter of Finland's forest species, numbering between 4 000 to 5 000, depend on decaying wood to survive. Some of these can survive on standing dead trees, but the majority require sturdy, downfallen dead trees.

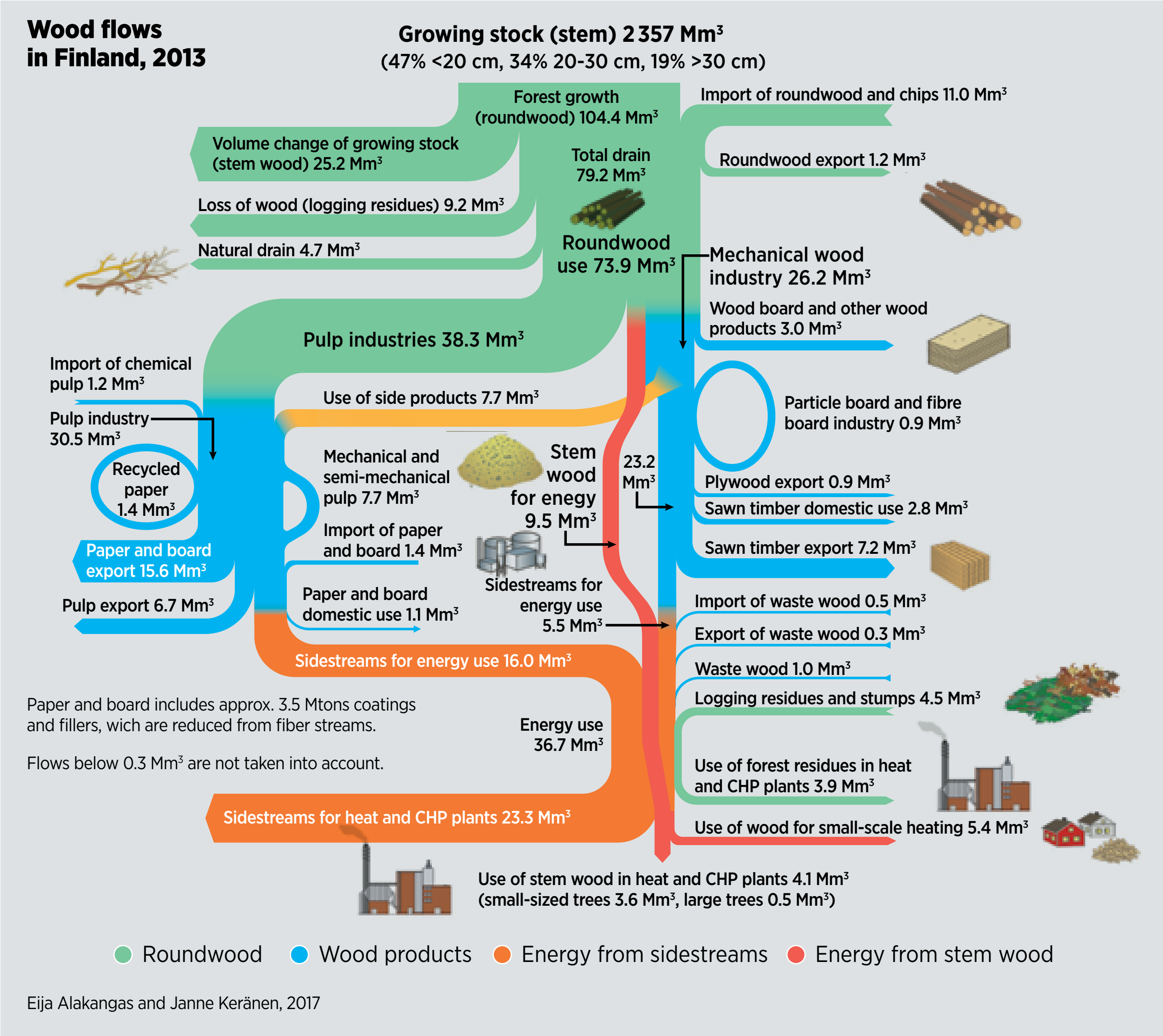
Valuable habitats in commercial forests have been mapped, and these sites are as a rule left outside the scope of commercial treatment. Furthermore, features typical of natural forests are conserved and enhanced by leaving retention trees and deciduous trees in felling areas and by carrying out controlled burning. Retention trees left alive in felling areas eventually turn into deadwood. Nature management monitoring results compiled by the Forestry Development Centre Tapio show that the volume of large decaying trees in commercial forests has started to increase as a result of the new methods. The volume of wood in retention trees left in regeneration felling sites totals almost 1 million cubic metres per annum. According to Natural Resources Institute Finland (Luke), the amount of dead wood in Finnish forests has increased over the last 20 years (Luke, 2017).

1.1 Wood flows in Finland: Half for products, half for energy

Allowable wood cuts each year are established by the Natural Resources Institute based on a planning tool, MELA, which calculates the maximum amount that may be sustainably removed.[1] Maximum sustainable cutting of stem wood in 2011-20 is estimated at 85 Mm^3 per year (Luke, 2017). In 2013, for example, as shown in Figure 3, there was 79.2 Mm^3 of "total drain" (including stems, wood, stumps, logging residues and natural drain). Forest mass grew by 104.4 Mm^3, of which nearly one-quarter (25.2 Mm^3) was left in growing trees, adding to forest wood stocks. Of the 79.2 Mm^3 total drain, 9.2 Mm^3 were lost as uncollected logging residues (which were not considered of sufficient economic value for the forest industry), and 4.7 Mm^3 were a "natural drain" (mainly leaves and very small branches left to enrich the forest soil), leaving 65.3 Mm^3 for use in the economy. This was supplemented by 9.8 Mm^3 of net wood imports from other countries, so a total of 75.1 Mm^3 of wood was used, primarily 73.9 Mm^3 of roundwood (Koponen *et al.*, 2015; Alakangas *et al.*, 2016a).

1. The maximum sustainable allowable cut is calculated by Luke using a large-scale forest planning tool called MELA, with integrated stand level simulation and forest level optimisation. Simulation generates many feasible management actions within Finnish forest management guidelines. A linear optimisation package, JLP, is used to select an optimal combination of management alternatives. The maximum sustainable removal is defined by maximising the net present value with a 4% discount rate subject to non-declining periodic total roundwood and energy wood removals, saw log removals, and net income. There are no sustainability constraints imposed concerning tree species, cutting methods, age classes or the growth/drain ratio, in order to efficiently utilise the dynamics of forest structure.

Figure 3 Wood flows in Finland 2013



Note: Red and orange show energy use. Yellow shows sawmill residues used as raw material.
Blue shows different wood-based products. Green shows roundwood (not processed wood).
Source: VTT

Of this total roundwood use, 38.3 Mm^3, or more than half (52%), was used by the pulp and paper industry. Meanwhile, 26.2 Mm^3 (35%) of total roundwood use was by the mechanical wood industry, and 9.5 Mm^3 (13%) was stemwood used for energy (5.4 Mm^3 in small-scale uses in the form of firewood, wood pellets and wood chips, and 4.1 Mm^3 in heat or CHP [combined heat and power] plants).

Of the roundwood used in the pulp and paper industry (38.3 Mm^3), 41% went to paper and board exports and 17% to pulp export. Therefore, nearly three-fifths (58%) was converted to pulp or paper.

The remaining 42% constituted sidestreams for energy use, primarily in CHP plants providing energy for pulp and paper production by industry, but also in municipal CHP plants.

Of the roundwood used in the mechanical wood industry (26.2 Mm^3), 38% went to sawn timber and 18% to other wood products (like wood board, particle board and plywood). Such wood, which accounted for well over half the wood industry output, resides for many years in buildings or furniture and continues to store carbon there. Some 16% of the wood industry roundwood went to large-scale heat and electricity generation, and 7% went to a mixture of smaller flows.

Overall, some 36.7 Mm^3 of the wood output from Finnish forests was used for energy in some way, of which 23.3 Mm^3 was used in large-scale heat and CHP plants. Thus, just less than half of the 73.9 Mm^3 of roundwood harvested in Finland was used for energy, while just more than half of wood went into various products such as timber, plywood, pulp or paper.

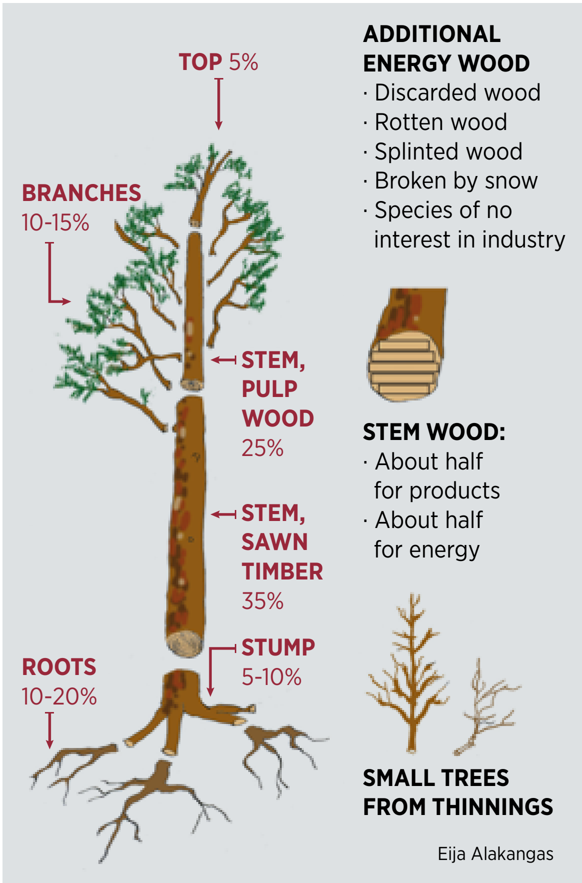
Considering the 14.7 Mm^3 of durable wood products (lumber, board and plywood) that were added to the built environment, along with the 25.2 Mm^3 of volume that was added to the growing forest, a combined total of at least 39.9 Mm^3 of the year's forest growth continued to store carbon in subsequent years. This was equivalent to three-eighths (38%) of the 104.4 Mm^3 in forest growth or more than half (54%) of the 73.9 Mm^3 in roundwood harvest.

1.2 Harvesting of industrial roundwood and energy wood

Efficient and cost-effective supply chains are essential to meeting wood needs for industry, energy and other uses. The split between energy and non-energy uses corresponds, in large part, to the different portions of forest trees, as shown in Figure 4. About 60% of a typical mature tree is "stemwood" from the tree's trunk, with 35% from the thicker lower trunk mainly suited to lumber production and 25% from the thinner lower trunk mainly suited to pulp production. Additional energy wood (discarded, rotten, splintered, broken) is not readily usable in durable products.


Photograph: Tage Fredriksson

Figure 4 Different parts of wood from final felling



Source: VTT

2 COMBINED HEAT AND POWER PRODUCTION FROM WOOD IN FINLAND

Combined heat and power (CHP) production has a long tradition in Finland, where industrial or urban heat demand is large enough to support district heating (DH) systems. Many large CHP plants in the country are fuelled by coal or peat, but a growing number are fuelled by wood. Finland had 136 CHP systems operating in 2016, with a combined generating capacity of 7 000 megawatts (MW) for electricity (MW_e) and 8 000 megawatts for heat (MW_{heat}). CHP plants produced 26% of the country's electricity and 42% of its heat that year. Biomass supplies nearly half (45%) of the country's renewable electricity, mostly in CHP plants, as well as more than two-fifths (42%) of its heat, from a mix of CHP plants, DH systems and home furnaces. About three-quarters of the biomass (74%) is used for DH and process steam, with the rest used for heating households and office and service buildings. The National Energy and Climate Strategy, published in 2016, aims to increase the use of renewable energy in general and boost the use of biomass in CHP and DH plants in particular to sharply reduce their use of petroleum fuel and completely phase out their use of coal by 2030 (Alakangas, 2016; Finnish Ministry of Economic Affairs and Employment, 2017).

2.1 Fluidised Bed Combustion Technology for Biomass Fuels

A very efficient way to fire demanding fuels, such as those with high ash or moisture content, is fluidised bed combustion (FBC). Fluidised bed boilers have been manufactured in Finland since the 1970s. While other countries have mainly used them for efficient coal combustion, the Finnish interest was in enabling efficient combustion of many kinds of biomass in the pulp and paper industry and energy utilities. Such boilers are more efficient than conventional ones in using solid fuels with low calorific value (such as bark and wood residues) because they are able to burn such fuels more thoroughly (Kokko, 2016).

An important medium-term application of FBC is the gasification of woody biomass for use in existing fossil-fueled-power plants, making part of their fuel use renewable. Gasification of biomass enables its use in high-efficiency pulverised coal-fired power boilers, which do not tolerate direct biomass feed on a large scale. The generated product gas also supports boiler operations at low heat and power load levels by enabling more efficient and flexible control (Tiilikka *et al.*, 2014).

Several hundred boilers using FBC have been delivered globally. They use either bubbling fluidised bed (BFB) or circulating fluidised bed (CFB) technology. Both technologies offer considerable fuel flexibility, making it possible to use different kinds of fuel in the same boiler. CFB offers particular flexibility in terms of accepting fuels with high caloric value, high ash and high moisture content. CFB is also cost-competitive for a wide range of system sizes, with a thermal capacity of up to 1 000 megawatts for fuel (MW_{fuel}) and electric capacity of 20-800 MW_e. BFB offers especially high combustion efficiency and low excess air demand (see Järvenpää case).

In the CFB process, heat required for gasification reactions is produced through the partial combustion of the fuel, while the rest of the fuel is converted into product gas. Carbon conversion for reactive fuels in CFB gasification is very thorough: typically, 95-98% efficient. A large amount of inert bed material involved in the process makes it possible to have a lot of variation in fuel properties or to change fuels during operations without much disturbance. Circulating solids improve heat transfer and make it possible to burn high calorific value fuels while maintaining combustion temperature steady at 850-900°C. A low combustion temperature minimises fouling and slagging of heat surfaces because ash melting and softening points are much higher than combustion temperature. A low temperature level and suspension phase in the furnace also make emission control quite easy. Solids circulation in CFB boilers provides a long residence time for fuel and limestone particles, meaning high combustion efficiency and low sorbent consumption for in-furnace sulfur dioxide (SO_2) reduction. CFB can bind nitrogen oxide (NO_x) and remove it from flue gases in particles so that relatively low NO_x levels are reached by simply adding calcium to the combustion chamber without any specific NO_x removal technology (Kokko, 2016).

2.2 Large wood-fuelled CHP plants

Figure 5 shows a typical large-scale CHP plant applying CFB technology. The power plant's main fuels are peat, forest residues, and by-products and residues from the wood processing industry. Use of woody biomass is 50%. CFB-boiler capacity is 495 MW_{fuel}, with maximum electric power of 215 MW_e. In cogeneration, the maximum heating capacity is 260 MW_{heat}, with electric output of 163 MW_e.

The world's largest biomass gasification plant is located in Vaasa (Figure 6). With 140 MW_{fuel} capacity, it is integrated with an existing coal-fired power plant that produces 230 MW_e of electricity and 170 MW_{heat} of district heat. By co-firing product gas from the gasifier in the power plant boiler, 25-40% of the power plant's coal use can be replaced with renewable energy.

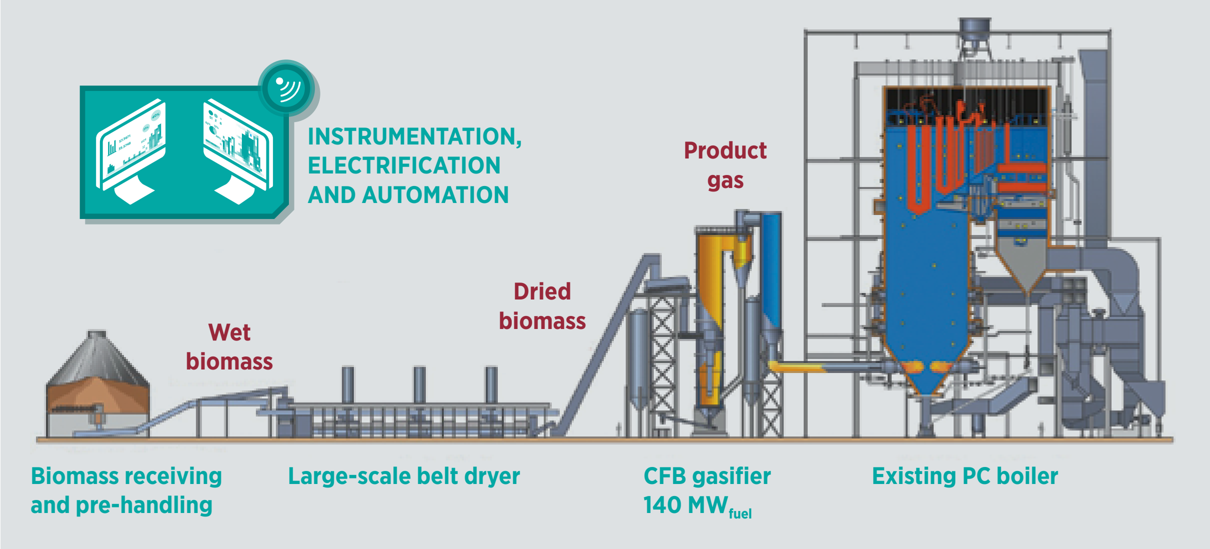
2.3 Wood-fuelled heating plants

Large CHP plants cover the base heating load of Finland's cities and towns, but small plants provide additional heat at times of peak load. While peak heating plants have traditionally been fueled by oil or gas, they can also be fueled by biomass. Modern peaking plants fueled by wood pellets, combining pulverised combustion technology with traditional water boilers, are fully automated, with flexible load control to integrate with CHP plants seamlessly. Several dozen such plants have been built at a scale of up to 10 MW_{fuel}, but they can also be larger.

Figure 5 Keljonlahti CHP Plant in Jyväskylä

Source: Sumitomo SHI FW Energia Oy

Figure 6 Vaskiluodon Voima Oy biomass gasification plant in Vaasa



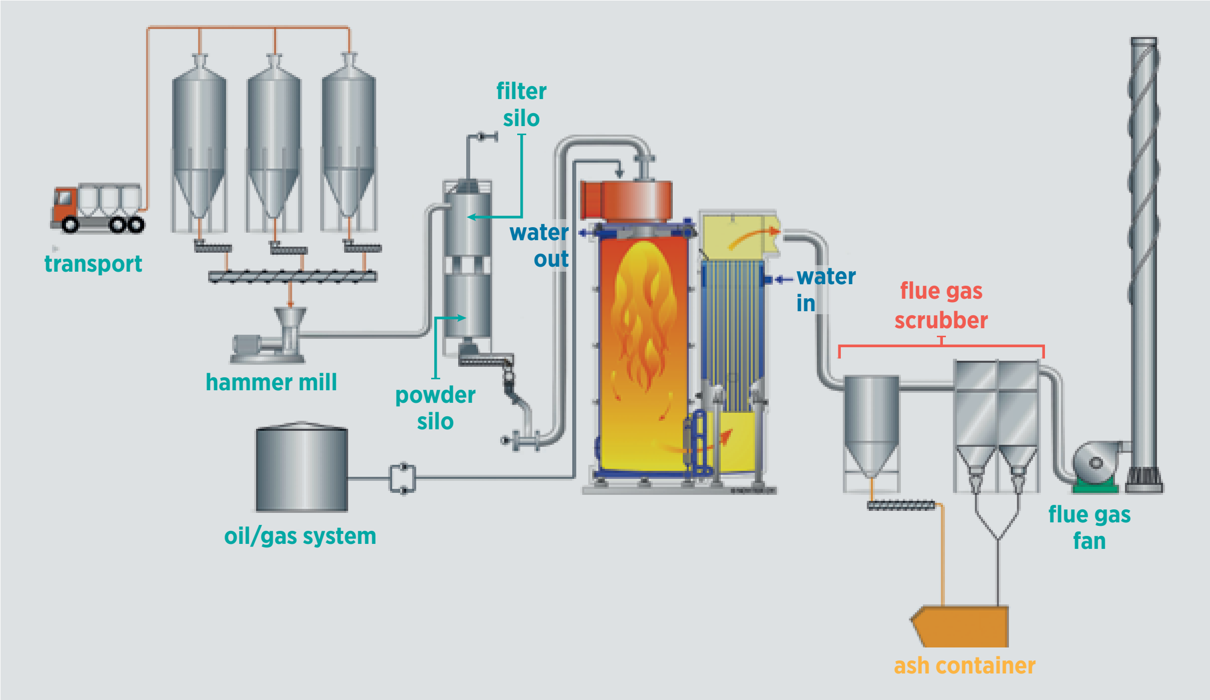
Source: Valmet

In late 2012, the energy authority in Tampere, one of Finland's larger towns, started up a new 33 MW_{fuel} pellet-fired heating plant for peak load and backup. A flow chart for the plant is shown in Figure 7. The start-up and load control of the combustion process is extremely high, and the pulverised fuel allows for clean, energy-efficient and flexible heat generation. The wood powder burner is a multi-fuel burner that can be fired with gas or oil in addition to wood powder, if necessary. The unmanned plant is controlled via a remote broadband connection from the company's main control room at the main power plant, about ten kilometres away.

HELEN, the energy utility in Finland's capital of Helsinki, has built a 100 MW_{fuel} pellet plant for DH production with a capital investment of some EUR 20 million (about USD 25 million). This is the largest pellet-fired plant in Finland. The plant uses 40 000 tons of wood pellets annually, processed by pulverised combustion. It is a base-load plant producing district heat for Helsinki city.

Chipping of logging residues *(LHM Hakkurit Oy)*

Figure 7 Peak load heating plant in Tampere with pulverised combustion of wood pellets



Source: Valmet

High-quality wood chips from delimbed birch trees *(Natural Resources Institute Finland — Luke)*

3 CASE STUDY: METSÄ FIBRE BIOPRODUCT MILL AT ÄÄNEKOSKI

Metsä Fibre bioproduct mill is of interest for several reasons (Kemppainen, 2017):

- It operates at a completely new level of energy efficiency compared to typical pulp mills. The mill is optimised to produce electricity for the Nordic power market and district heat to the neighbouring town and industries situated in the same area.
- Unlike other mills, it does not use any fossil fuels but applies gasification technology in a lime kiln, which normally depends on fuel oil.
- While the core products of the mill are standard pulp mill products, such as pulp, tall oil, bark, turpentine, electricity and process steam, this mill has been designed to enable its by-products to be developed into new, high-added-value bioproducts such as textile fibres, biocomposites, fertilisers and earth work materials, new biofuels, and lignin upgrades.
- The business concept for the bioproducts will be built in collaboration with a partner network formed around the mill.

Bioeconomy, including wood supply, is one of the key development sectors in Central Finland. It currently employs 15 000 people and expects to employ 19 000 by 2040. It encompasses 1 100 companies and expects to include 1 800 by 2040. Renewable energy makes up 42% of Central Finland's energy supply and should provide 90% of the region's energy by 2040. Metsä Fibre bioproduct mill can also support the achievement of national and Central Finland's bioeconomy and renewable energy targets. Metsä Fibre's advanced cellulose and wood fibre ecosystem is located in Äänekoski, a forest industry location in Central Finland (Alakangas *et al.*, 2012; Regional Council of Central Finland, 2014).

In Central Finland, three mills use almost all the pulpwood that is harvested in Central Finland. Two of them, which are known today as UPM Jämsä River mills (UPM Jämsänkoski and UPM Kaipola), are located in Jämsä and produce mechanical pulp. The third one, Metsä Fibre mill, is located in Äänekoski.

In April 2015, Metsä Fibre announced the construction of world's first bioproduct mill at the site of the existing pulp mill in Äänekoski (Figure 8). With investment of EUR 1.2 billion (about USD 1.5 billion), the Äänekoski bioproduct mill currently represents the biggest investment in forest industry in the Nordic countries and possibly in the northern hemisphere (Alakangas *et al.*, 2016b).

3.1 Feedstock supply

The new bioproduct mill will use in total 6.5 Mm^3 soft wood and birch annually. The new factory will have 40 000 cubic metres (m^3) of solid roundwood storage and 4 x 90 000 m^3 of loose m^3 pulp chip storage. Biomass fractions that will not be used at the bioproduct mill such as logging residues, stumps, small-sized stem wood and bark will be burned in a local CHP plant.

About 2 500 jobs will be created as a result of the mill, mostly in wood supply chains. About 40 railway cars will transport pulp for export and for domestic markets on an average day. Finland's first hybrid locomotive will operate in Äänekoski, using a mix of electricity and diesel fuel. To enhance wood supply, 10 to 15 wood terminals, each occupying about 1 to 2 hectares of land, will be established at a radius of about 100-150 kilometres (km) from the mill. Every day, 240 trucks and 70 railway cars will be supplying wood for the mill. In Finland, about three-quarters (76%) of all roundwood transported from roadside storage terminals to plant are conducted by timber truck, with the rest moved by rail.

Figure 8 Äänekoski bioproduct mill shown behind the existing plant

Source: Metsä Fibre

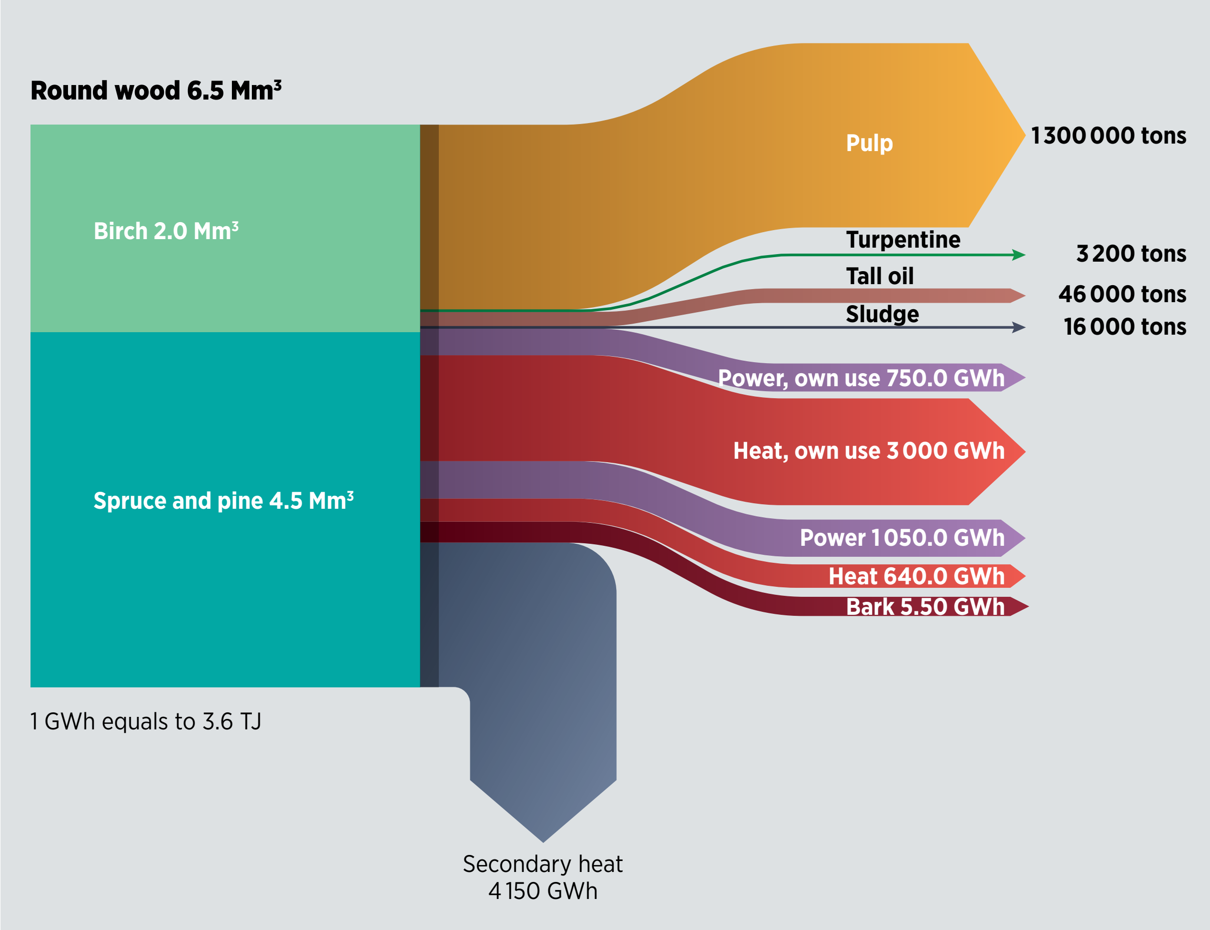
3.2 Bioproducts

Although the core products of the future bioproduct mill are typical pulp mill products (*e.g.*, pulp, tall oil, bark, turpentine, electricity and process steam), the bioproduct mill has the additional potential to utilise its by-products and to develop new, high-added-value bioproducts in collaboration with a partner network formed around the mill. Investment decisions for the production of sulphuric acid and product gas have already been made. Other possible future bioproducts include new textile fibres, fertilisers and earth work materials, new biofuels, and lignin upgrades. The mill began operations in August 2017 and delivered its first pulp to customers the next month, with full capacity operation planned by August 2018.

Energy and resource efficiency is a key design feature of the mill. The plant also supports a circular economy by the efficient use of sidestreams and by maximising biopower output. Some CO_2 emissions from the plant will be captured and used for pigment production.

The Äänekoski bioproduct mill will produce 1.3 Mt of pulp (0.8 Mt from softwood and 0.5 Mt from birch wood). Its main markets will be Europe and Asia. The estimated market value of produced pulp will be EUR 800 million (about USD 990 million) annually. Global markets for soft wood pulp reached 24 million metric tons in 2014 and should reach 26 Mt or EUR 15 billion (USD 18.5 billion) by 2025, with the bulk of expansion in China and elsewhere in Asia. About 800 000 tons of pulp from the Metsä Fibre pulp mill will be transported to Vuosaari harbour in Helsinki. Metsä Fibre has built storage with 30 000 m^2 of capacity of pulp. In addition, the Äänekoski mill will produce 46 000 tonnes of tall oil and 3 200 tonnes of turpentine. Different products are presented in Figure 9.

Figure 9 Sankey diagram of Äänekoski mill roundwood use and bioproducts



Source: VTT and Metsä Fibre

A unique ecosystem is under development at Äänekoski mill. Five companies (Metsä Board, CP Kelco, Specialty Minerals, Äänevoima Oy and Valio) are technically already integrated into Metsä Fibre's mill. Wood yard logistics are operated by the Mantsinen Group, and EcoEnergy SF has invested in and operates a biogas plant. Meanwhile, Ekokem and Kekkilä Oy will use sandy bark and similar sidestream products, and Äänekosken Energia is feeding waste water sludge to EcoEnergy SF's plant. New partners include M. Rauanheimo, AGA and VR Transport.

Aqvacomp will invest to produce new biocomposites, which compound wood pulp and fossil polymers by using novel proprietary technology licensed by SME Elastopoli. Aqvacomp is producing biocomposite for loudspeakers with good acoustic properties in Rauma Metsä Fibre mill. LG is using this biocomposite in their Soundbar SJ9 loudspeakers.

Sulphuric acid production from sulphur-rich waste gases is based on catalytic conversion. However, this is a first-of-its-kind concept in a globally integrated pulp mill. In the first stage, 35 t of acid per day will be produced daily. This is about half of the bioproduct mill's demand.

The new textile fibres are targeted to meet the cellulose gap of the future. The market for cellulose-based textile fibres today is about 5 Mt, with growth of about 5% per annum. There is an opportunity to supplement cotton-based fibres, for which the market size today is about 30 Mt. The textile fibre technology based on ionic liquids is still in the laboratory stage. Metsä Fibre is testing the quality of fibre products with Itochu.

Finland's Ministry of Economic Affairs and Employment has granted EUR 32.1 million (about USD 40 million) in investment aid for the demonstration of innovative technologies with high efficiency and the production of renewable energy.

Technological innovations in the Äänekoski mill include the recovery boiler's higher steam parameters (110 bar and 515°C) compared to the typical values in older mills (80 to 90 bar and 480 to 490°C). This enables more electricity production and higher plant efficiency. The other new feature at the mill is its fossil-free operation, *i.e.*, the lime kiln in the mill process will use biomass-based product gas instead of the usual heavy fuel oil or natural gas. Table 1 explains the mill's high efficiency compared to a typical modern pulp mill.

The Äänekoski mill's new equipment and increased use of renewables will also improve the air quality in the region. When the mill is in full operation, CO_2 emissions will be decreased by 518 000 tonnes annually. Valmet plc and Andritz Oy are the main technology suppliers for the mill equipment.

The global impact of retrofitting typical modern pulp mills to the level of the Metsä Fibre bioproduct mill would be significant as the amount of sold electricity should increase over 30% per tonne of pulp. According to global scenarios assessed by VTT Technical Research Centre of Finland Ltd., the amount of electricity produced by the pulp industry could reach up to 120 terawatt-hours (TWh) by 2020. The scenarios are based on TIMES-VTT energy system modelling (see *e.g.*, Koljonen and Lehtilä, 2012), and the forest-based scenarios are described in Kallio *et al.*, 2015. Depending on assumptions of development, with estimated electricity production (+10% per tonne of pulp) and the share of sold electricity (+10 percentage points) from Table 1, the amount of sold electricity could increase up to 10 TWh. This has the potential to be a substantial income source and a contribution to global climate change mitigation.

3.3 Mill process

The bioproduct mill process is based on traditional Kraft pulping technology (Figure 10). This is the dominant pulping process in the pulp and paper industry. The mill is non-integrated, so the pulp is transported to another location or exported for further utilisation for paper or cardboard production. Pulp is also used in nearby MetsäBoard and CP Kelco.

Pulpwood (both hardwood and softwood) is debarked and chipped, and the wood chips with suitable particle sizes are fed into the continuous digester with the cooking chemicals sodium hydroxide (NaOH) and sodium sulphide (Na_2S) dissolved in water. In the digester, about half of the wood is dissolved (the lignin and part of the hemicelluloses) at an elevated temperature

Table 1 Comparison of typical modern pulp mill and Metsä Fibre bioproduct mill

Production	Unit	Typical modern pulp mill	Metsä Fibre bioproduct mill
Electricity production	kWh/tonne pulp	1170	>1300
Own electricity use	kWh/tonne pulp	660	>600
Electricity for sale	kWh/tonne pulp	510	>700
Average energy production with 1.3 Mt pulp production	GWh per annum	663	>900
Average sold electricity output	MW_e	78	>105

Source: Sweco (Saarelainen, 2014)
GWh = gigawatt-hours; KWh = kilowatt-hours

of approximately 150-170°C. After the digester process is finished, the weak black liquor is separated from the pulp. Brown pulp is bleached using oxygen and washed to remove lignin from the pulp. White pulp is also bleached with chlorine dioxide and hydrogen peroxide.

The weak black liquor is evaporated from about 15-17% dissolved solids concentration (by weight) to about 83%. During the evaporation, impure methanol, turpentine and soap (salts of fatty acids) are separated. The soap is acidified to obtain crude tall oil, which is a by-product suitable for the production of renewable chemicals or jet fuel.

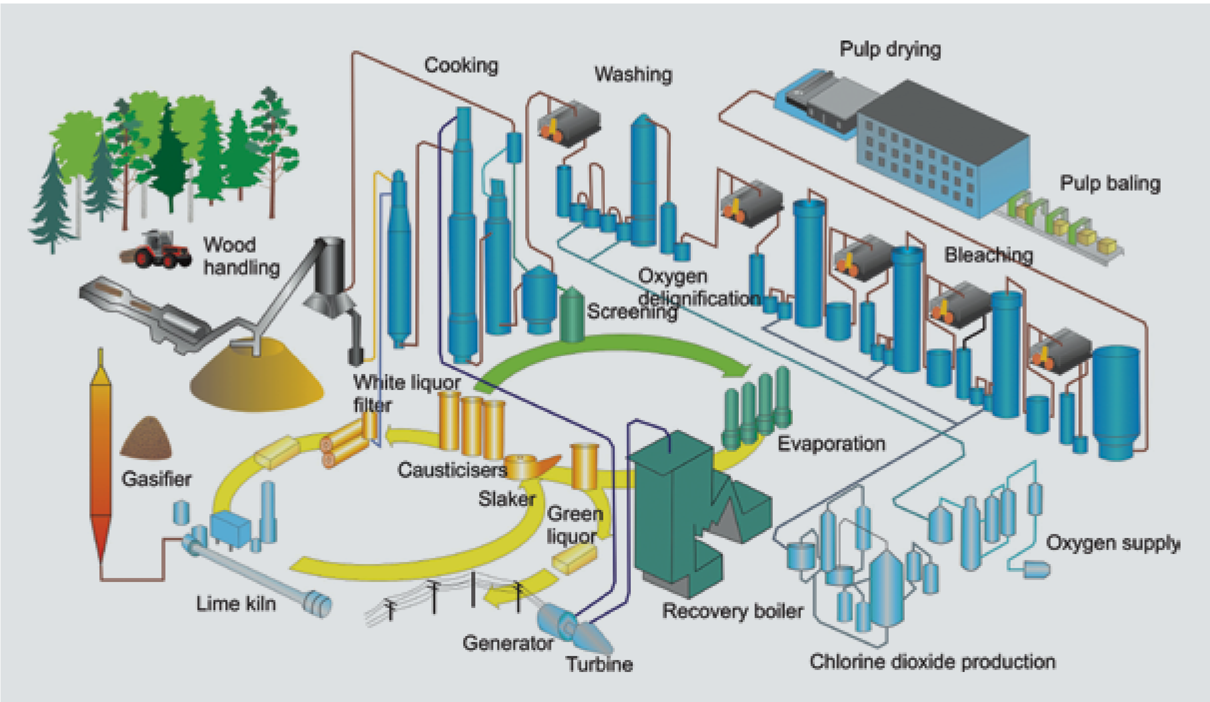
The strong black liquor is combusted in the recovery boiler to reduce the sulphate in the black liquor back to sulphide, which is the form needed in the digester, and to produce energy. The molten ash is separated from the bottom of the recovery boiler and dissolved in water to separate green liquor dregs, which contain unwanted elements present in the raw material, such as calcium and other metals. The dissolved part green liquor is reacted with calcium hydroxide to convert sodium carbonate into sodium hydroxide. The solid calcium carbonate can be separated and regenerated in the lime kiln to convert it to calcium oxide, which is reacted with water into calcium hydroxide.

The waste waters from the pulp mills are fed into a waste treatment plant where sludge containing organic and inorganic solids is separated from the waste water. The sulphur dioxide from the combustion of sulphur-containing gases is captured and converted into sulphuric acid, which is utilised as a chemical at the mill, for example, in tall oil separation.

3.4 Biogas and CHP production

Biogas production from pulp mill sludge at the Äänekoski mill will be brought about through investment in a biogas plant by EcoEnergy SF. Tekes has supported the research and development and piloting phase of the technology. In the first stage, 20 gigawatt-hours (GWh) of biogas will be produced annually. In 2018-19, third-party waste from Central Finland will be used and will produce 50 GWh of additional biogas. Post-2020, bio-synthetic natural gas (bio-SNG) production

Figure 10 Bioproduct mill schematic drawing



Source: VTT and Valmet

The mill uses 100% renewable energy

(100 GWh to 600 GWh per annum) is planned. Increased capacity would enable conversion to liquefied biogas.

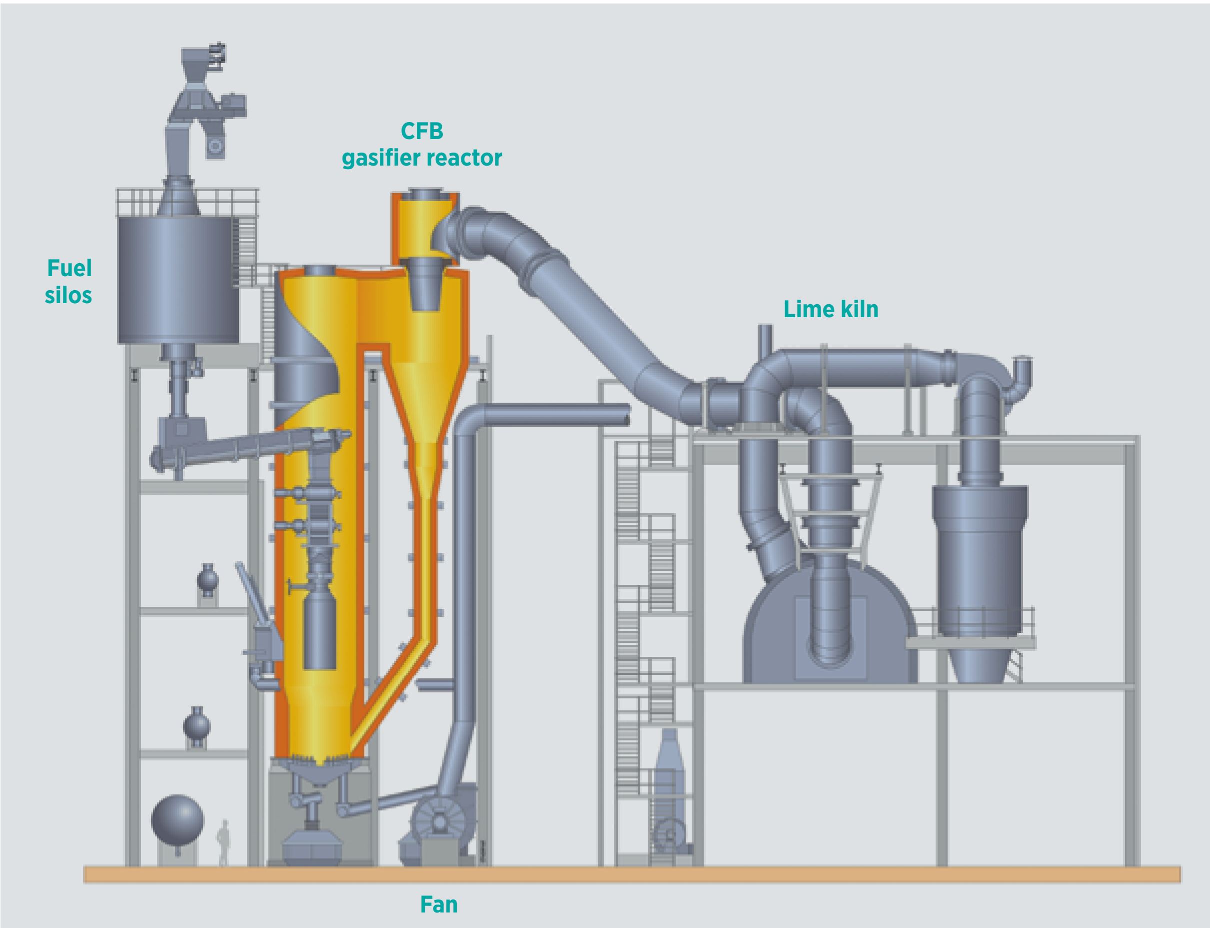
Three 3 000 m^3 reactors are under construction. The technology for the reactors is based on Envor Protech Oy's EPAD-process, which is further developed to be able to use sludges from pulp mills. The biogas plant can handle 60 dry tons per day. Biogas is cleaned to obtain methane for transportation fuel. The use of collected CO_2 from biogas cleaning is under survey in the pulp mill.

The solid product after digestion includes a large amount of lignin, which after being dried and pelletised can be used as a high-calorific fuel. This solid product can also be used as a fertiliser. Waste water, which includes nitrogen, will be recycled in a cleaning plant to reduce the need to purchase nitrogen.

The fuel for the lime kiln is the product gas produced by the bark gasifier (Figure 11). Product gas by bark gasification makes the bioproduct mill fully free of fossil energy. Its capacity is 90 MW of product gas.

The recovery boiler produces steam having high parameters (a temperature of 515°C and pressure of 115 bar) and further fed to a back pressure steam turbine to produce the needed middle and low pressure steam for the process as well as electricity.

Figure 11 Bark gasifier schematic drawing



Source: Valmet

The pulp mill is self-sufficient in heat, requiring no fossil fuel to operate. In addition, a condensing part in the steam turbine allows steam not needed in the pulp mill process to be led through a condensing part of the turbine to generate additional electricity.

About 1 800 GWh of bioelectricity will be generated; 750 GWh is used in the mill each year (implying a self-sufficiency ratio of supply to demand of 240%). DH for Äänekoski city and process heat for mills in the bioecosociety is 7 000 GWh. This plant will supply about 2.5% of Finland's renewable energy. Use of renewable energy in Finland was 455 petajoules (PJ) in 2015, which was 39.3% of the country's final energy consumption. Electricity production by renewable energy was 29.7 TWh that year, which was 44.9% of Finland's total electricity generation.

Future by-products such as biofuels and chemicals can be produced from wood residues or from bark that is not needed in the bark gasifier. Lignin is one of the main components of wood along with cellulose and hemicellulose. Lignin precipitated from black liquor, for example, can use the LignoBoost™. There are two commercial-scale LignoBoost™ plants in the world. By treating the black liquor with carbon dioxide and a strong acid, the lignin is precipitated, which is then washed and dried. Lignin is an organic polymer and has a net calorific value similar to coal. The extracted lignin can be used to replace fossil fuel, or as a raw material in the chemical industry.

Typical Multifuel CHP Plant in Finland *(Sumitomo SHI FW Energia Oy)*

4 CASE STUDY: HIGH-EFFICIENCY MULTIFUEL COMBINED HEAT AND POWER PLANT AT JÄRVENPÄÄ

Fortum Power and Heat built a high-efficiency multifuel CHP plant at Järvenpää in southern Finland in 2013 (Figure 12). The plant has a flue gas condenser that enables it to convert a wide range of moist biomass fuels into heat and power with high efficiency. It has three major advantages over regular biomass CHP plants using BFB technology:

- It is more efficient than typical power plants.
- It can use 100% of biomass and up to 30% of recycled energy wastes.[2]
- Despite the extra costs of these features, Fortum's plant is in the lower half of the cost range for a typical biomass BFB CHP boiler.

The plant is able to achieve very high efficiency, as demonstrated in 2014 when it operated for the entire year with 99.5% of its fuels sourced from forests at an average efficiency of 97%. Some key features of the plant are highlighted in Table 2.

4.1 Standardised innovation

Fortum Power and Heat aims to increase the plant's efficiency and decrease its costs by using similar designs in different sites. The practicalities differ based on local legislation, available fuels, heat demand, and the price of electricity and heat, but Fortum has built two similar plants in Estonia and one in Latvia. Latvia's plant is almost identical to the one in Järvenpää.

Figure 12 Aerial view of Järvenpää multifuel CHP plant

Source: Valmet

2. Including paper, cardboard, waste wood, recycled wood, horse farmyard manure and fly ash from other power plants if unburned material remains.

Fortum installed a large battery storage system at the Järvenpää power plant site in March 2017 to study new solutions to combine the benefits of CHP, variable renewables such as solar, demand-side response and virtual power plants. The system, called Batcave (for battery cave, or a container equipped with the latest technology to test new ideas) is the Nordic countries' largest lithium-ion battery storage facility, with a nominal output of 2 MW and energy storage capacity of 1 megawatt hour (MWh) (Fortum Mediaroom, 2017). It consists of some 6 600 lithium-ion cells offering quick, second- and minute-level grid flexibility for frequency regulation, supplied by French manufacturer SAFT. Fortum will receive a 30% subsidy from the Finnish Ministry of Economic Affairs to assist with the EUR 1.6 million (USD 2 million) investment.

4.2 High efficiency proven in annual operation

The main components of the new CHP plant are its fuel terminal and storages, BFB boiler, turbine, generator, heat exchanger and flue gas condensing unit, as illustrated in Figure 13. The turbine and generator supply electricity to the national grid. The heat exchanger increases the temperature of the local district heat network's water with excess heat from the turbine and recovered heat from the fuel gas condenser.

The BFB boiler was manufactured by Metso Power (currently Valmet). It can co-fire various fuels with different heat contents and physical properties. The BFB boiler can operate with a biomass share from 0-100%, peat share from 0-100% and recycled energy waste[3] share from 0-30%. The estimated annual shares from 2017 onward will be 80% of biomass and 20% of recycled energy wastes. The boiler requires natural gas or oil for start-up; natural gas is also a backup fuel.

The boiler's thermal power is 76 MW_{fuel}, the turbine can produce 23.3 MW_e of electricity, the steam cycle produces 45 MW_{heat} of district heat, and the flue gas condenser's excess heat provides 15 MW_{heat} extra DH (AVI, 2012). The plant has an installed power and heat efficiency of 110% when calculated from the previous numbers, using net calorific value for wood fuels (energy input). This is possible due to the standard procedure used to calculate power plant efficiency according to European practices. The thermal output is calculated from the net calorific value (lower calorific value), which does not include the heat of vaporisation of the water; the water in the flue gases remains as a vapour. The flue gas condenser cools the water vapour in flue gases below 100°C and collects the heat of vaporisation. Biomass has a relatively high moisture content, reducing the net calorific

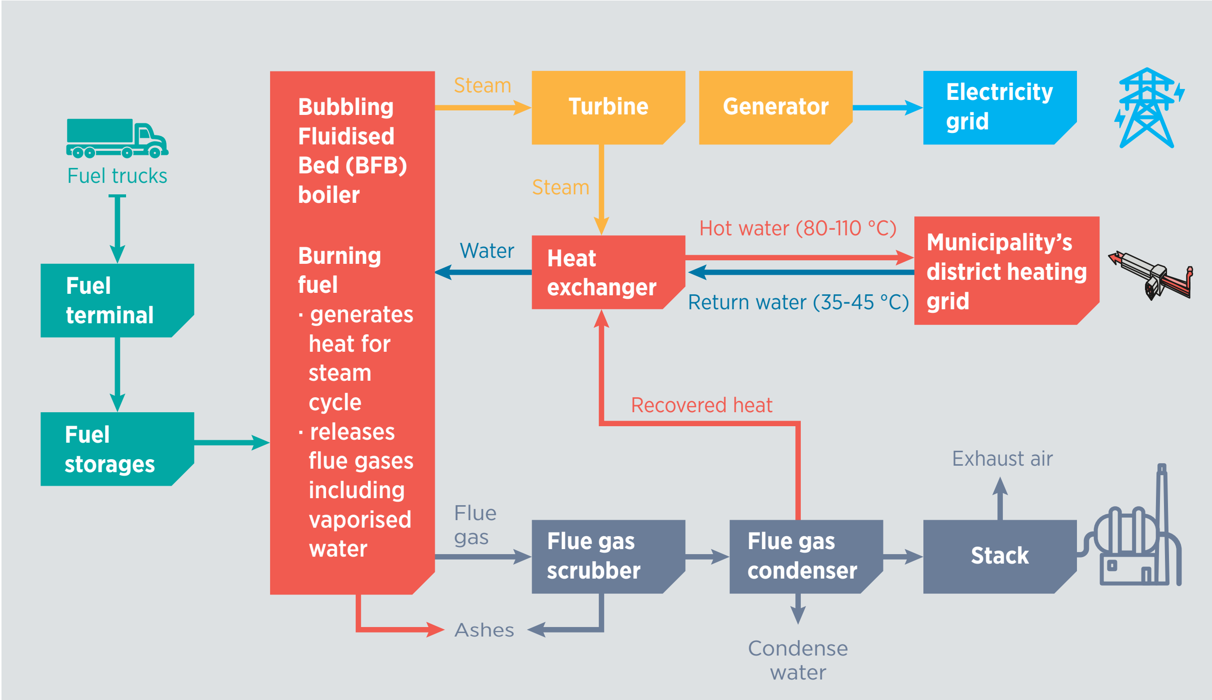
Table 2 Overview of the Järvenpää multifuel CHP project

Owner	Forum Power and Heat Ltd
Construction time	20 months (October 2011 through June 2013)
Total cost	EUR 81 million (about USD 100 million)
Boiler and flue gas condenser	Metso Power (currently Valmet), Finland
Turbine	MAN Diesel & Turbo, Germany
Fuel supply system	BMH Technology, Finland
Project consultant	Pöyry Finland

Source: Peltoranta, 2013; Lassila, 2012

3. Paper, cardboard, waste wood, recycled wood, horse farmyard manure and fly ash.

Figure 13 Schematic flow chart of the Järvenpää multifuel CHP plant



Source: VTT

heat value and the nominal thermal power, but the installed flue gas condenser recovers the lost heat and increase the total heat output (Table 3). In a coal-only plant, this effect would be smaller because the fuel has less moisture content, but the effect would still exist because the burning of fuel creates water vapour.

The flue gas condenser is always in use when the plant operates with full power. The flue gas condenser can be bypassed or used when the plant is operating at partial load. The plant provides base load power and heat for up to 7 800 hours per year (a capacity factor of up to 90%). The plant can adjust the heat and electricity ratio more than a typical back-pressure CHP plant because it can bypass the flue gas condenser.

The plant's measured annual efficiency was 97% in 2014. This is lower than the maximum efficiency of 110% because the plant was operated for part of the year on a partial load basis. This reduces efficiency slightly, but it remains very high (Table 4).

From April to September, a typical Finnish DH network's load is only 20% of the winter average or 10% of the winter peak, but the operation load of an individual plant depends on the scales of the network and the characteristics of a plant. Fortum's plant operated 7 335 hours in 2014, while the calculational full load hours were 5 485 hours.

The plant also has three older boilers (16 MW_{fuel} each) built in 1985. They are currently reserves that produce only during peak loads in the winter season. These three older boilers run approximately 1 100 hours per year and use natural gas. The new and old boilers are able to operate separately or simultaneously.

Table 3 Technical characteristics of the Järvenpää multifuel CHP project

Boiler technology	Bubbling Fluidised Bed (BFB)
Fuels	Biomass/wood, peat, waste
Investment cost	EUR 81 million (c. USD 100m), 2013
Construction time	19 months
Thermal capacity	76 MW_{fuel}
Electricity capacity	23 MW_{e}
District heat capacity+ extra DH by flue gas condenser	45 + 15 MW_{heat}
Efficiency	110%
Heat rejection	Possible
Estimated start-up and shut-down time	4 hours
Estimated start-up cost	EUR 2 500 (about USD 3 000)
Estimated minimum Load	40%
Estimated minimum economic operation time per start-up	1 week
Estimated variable operation and maintenance	EUR 4/MWh (under USD 5/MWh)
Estimated maintenance break	July

Source: Fortum Heat and Power, 2017; Hast et al., 2016

Table 4 Operational data for the Järvenpää multifuel CHP plant

	2014
Operation hours	7 335
Full load hours	5 485
Fuel, biomass/wood (GWh/PJ)	417/1 501
Fuel, natural gas (GWh/PJ)	2/5
Fuel, total (GWh/PJ)	419/1 508
Annual biomass share of fuels	99.5%
Produced electricity (GWh/PJ)	85/306
Produced district heat (GWh/PJ)	320/1 150
Annual average efficiency	(85 GWh + 320 GWh)/419 GWh = 97%*

**Maximum efficiency goes up to 110%; see Table 3.*
Source: AVI, 2016

4.3 Versatile fuel feedstock

The range of possible fuels includes forest chips; other woody biomass; peat; and recycled energy wastes including paper, cardboard, waste wood, recycled wood, horse farmyard manure and fly ash from other power plants if unburned material remains. Fortum has a small supply of fly ash from pellet power plants from which small amounts of biomass remain unburned, and this ash is fed into the BFB boiler to finalise combustion. In addition, natural gas is used only for start-ups and as a reserve. Oil is a secondary fuel for start-ups. All these fuels have varying heat content, moisture and other properties, but nevertheless the fluidised bed is able to burn these solid fuels efficiently.

Fortum provides the net calorific value on a dry basis and the moisture content of different fuels at the receiving station (Table 5). The average net calorific value of forest residues increases from 9.1 megajoules (MJ)/kg to 10.5 MJ/kg by seasoning on site.[4]

The forest chips are produced from stems, small-sized trees and logging residues. Bark, sawmill residues, sawdust and other wood chips are also used (Koskitukki, 2017). These are not limited to any specific wood type. The biomass is produced within 100 km and is delivered to Järvenpää by truck. According to Fortum, 35 truckloads of forest chips are transported to the site on an average weekday. This increases traffic near the site, but it is built in the outskirts of the city and next to a large highway to address both noise and traffic issues. The fuel production chain employs about 80 people (Fortum Heat and Power, 2017).

Fortum received a permit to co-fire recycled fuels/energy waste starting in June 2016 (AVI, 2016). Actual operations with these fuels started in early 2017. The plant's BFB boiler is designed to heat flue gas to at least 850ºC for a minimum of 2 seconds to reduce harmful substances when burning waste fuels. The BFB boiler's flue gas emissions go through a scrubber and a condenser, which further

4. According to Fortum, the new BFB boiler used 142 000 tonnes of forest residues at 2014 equaling 417 GWh measured by net calorific value, dry basis.

Table 5 Fuel data for the Järvenpää multifuel CHP plant[5]

	Net calorific value, as received (MJ/kg dry basis)	Moisture as received (percentage of mass)	Ash content (percent, dry basis)	Sulphur content (percent, dry basis)	Chlorine content (percent, dry basis)	Fluorine content (percent, dry basis)
Forest chips	9.1 (6.8-11)	50 (40-60)	2.0 (0.5-6)	0.02 (0.01-0.2)	0.01 (0.01-0.1)	0.002 (0.0-0.1)
Peat	10.1 (8-13)	50 (38-55)	6 (4-8)	0.27 (0.1-0.3)	0.02 (0.02-0.1)	0.002
Recycled energy waste*	17.7 (13-18)	20 (13-30)	8 (5.5-15)	0.2 (0.1-0.4)	0.35 (0.1-0.4)	0.005
Waste wood	11-17	15-35	1-4	0	0.1 (0.02-0.12)	0.05
Farmyard manure	6.5 (5-8)	60 (50-60)	8 (7-15)	0.2 (0.1-0.3)	0.05 (0.04-0.1)	0.002

**Including paper, cardboard, waste wood, recycled wood, horse farmyard manure and fly ash.*
Source: AVI, 2016

reduces the amount of air pollution generated by the process. Fortum is also preparing to reduce air emissions with activated carbon to absorb mercury and other heavy compounds when using waste fuels. Odour from fuel is prevented by covering the trucks transporting the fuel to the plant, using a fuel terminal (silos at right in Figure 12) and using transportation belts within the plant.

Recycled energy waste has a lower moisture content than biomass. Increasing the share of recycled waste fuels will lower the share of biomass and likely decrease the efficiency of the heat condenser because the moisture content of the fuel will decrease. The efficiency of the condenser is dependent on a specific moisture content of the fuel. This is higher with moist fuel because more energy can be condensed from it. On the other hand, a higher share of waste fuels gives Fortum more flexibility to burn moister biomass and save biomass seasoning time. Fortum estimates that with a 20% share of recycled wastes, the heat recovery from the condenser would decrease from 45 GWh/year to 2 GWh/year, but actual operation figures are not yet available.

4.4 Efficient and versatile compared to a typical biomass CHP plant

Fortum's plant has three major advantages compared to default biomass BFB CHP power plants, as presented in Table 6.

- It is more efficient than typical power plants.
- It can use 100% of biomass and up to 30% of recycled energy wastes.[6]
- Despite the extra costs of these features, Fortum's plant is in the lower half of the cost range for a typical biomass BFB CHP boiler.

In addition, Fortum's plant was built much faster than a typical plant. Fortum's plant is designed for a slightly smaller electricity share than a typical back-pressure plant, because the electricity market price is quite low in the Nordic market. Net efficiency and heat share are higher than in typical power plants. Other compared characteristics are within a typical range for that technology.

The technology presented here is much more efficient than a typical waste incinerator, when there is a suitable feedstock of recycled energy

5. Typical ranges of values are in brackets.
6. Including paper, cardboard, waste wood, recycled wood, horse farmyard manure and fly ash.

A flue gas condenser enables efficient use of different moist fuels

wastes. Otherwise, the comparison to a typical waste incinerator is not straightforward because the Järvenpää CHP plant cannot incinerate common municipal and industrial wastes. Adding these capabilities would add costs and decrease the plant's efficiency. Nevertheless, the plant can use recycled energy waste up to 30% of its fuel input, providing a very economical option to utilise certain types of wastes.

Photograph: Biowatti Oy

Table 6 Comparison of Fortum's new BFB boiler with typical boilers and incinerators

	Järvenpää CHP	Typical BFB, CHP, Biomass	Typical waste incineration, CHP
Technology	**BFB**	**BFB/CFB**	**Not specified**
Fuels	**Biomass, peat, energy wastes**	**Biomass, coal***	**Waste**
Investment cost, EUR/kW$_{fuel}$	1 070	1 030-1 160[a, b]	1 650-2 400[a, b]
Investment cost, EUR/kW$_e$**	3 500	2 950-4 000[a, b]	6 000-10 000[a, b]
Construction time, years	1.5	4.5[a]	3[a]
Maximum biomass share	100%	30-100%*	?*
Efficiency, electricity + heat	110%	105%[a]	86-93%[a, c]
Efficiency, electricity**	31%	29a-35%[b]	24[a]-27%[b]
Efficiency, heat	79%	70-76%[a, b]	70-73%[a, b]
Minimum load	40%	40%[a]	75%[a]
Electricity capacity, MW$_e$ net	23	10-50[a, b]	50[b]

** Biomass share is not explicitly reported. The issue is discussed and studies indicate that higher shares of biomass are possible, but with increased costs.*

*** Fortum's plant is designed for a slightly smaller electricity share because the electricity market price is quite low in the Nordic market. Net efficiency and heat share are larger than in default power plants*

Note: One euro (EUR 1) = approximately USD 1.2 at time of publication.

Sources: a) DEA, 2016; b) Joint Research Centre, 2014; c) Klinghoffer and Castaldi, 2013

5 CASE STUDY: BIO-OIL PRODUCTION INTEGRATED INTO COMBINED HEAT AND POWER PLANT AT JOENSUU

Located at Joensuu in eastern Finland, Joensuu CHP produces heat for the inhabitants of Joensuu and electricity for the national grid. The main fuels in the Joensuu CHP plant are wood and peat. The addition of pyrolysis bio-oil production to the plant at Joensuu will make it the world´s first integrated CHP and bio-oil production facility. In the integrated plant, heat for pyrolysis will be transferred from hot sand of a fluidised boiler. By-products from pyrolysis, char and off-gases are used as fuel in the boiler. Using the pyrolysis by-product as fuel to replace boiler fuel improves energy efficiency, because the by-products are used in the production of power and heat (Lehto, 2010; Solantausta *et al.*, 2012; Meier *et al.*, 2013).

Pyrolysis integration is a good solution for three reasons:

1. It allows for better use of lower-quality biomass fuel (residues and sawdust) that would otherwise be used at lower efficiency in conventional CHP.
2. It allows for production of bio-oil, which has higher aggregated value and can be used to displace carbon-intensive liquid fossil fuels.
3. It allows for greater use of available biomass in a situation where demands for heat and power are limited.

Currently the production covers roughly 95% of district heat needed in Joensuu. The rest of the district heat is produced in heating stations located in different places on the heating grid. Current production capacity for electricity is 50 MW_e; for DH, 110 MW_{heat}; and approximately 220 MW_{heat} from the heating stations. Fortum is also responsible for maintaining the DH network of 200 km in Joensuu.

5.1 Bio-oil production from biomass

Biomass can be converted to more valuable energy forms via a number of processes including thermal, biological, and mechanical or physical processes. Pyrolysis has been applied for thousands of years for charcoal production, but fast pyrolysis at moderate temperatures of around 500°C and at very short reaction times of up to 2 seconds has only emerged in the last 30 years and has become of considerable interest.

Finnish companies have a long and successful history of developing FBC technology. Finnish fluidised bed boiler manufacturers have delivered hundreds of boilers for the commercial production of electricity and heat for pulp and paper industry and power generating companies worldwide. As environmentally friendly energy technologies become more popular, the focus for technology development has shifted towards energy efficiency, replacing fossil fuels and increasing the value gained from biomass. A pyrolysis bio-oil plant can be integrated into a CHP plant, where heat for the pyrolysis process is transferred from the hot sand of a fluidised boiler.

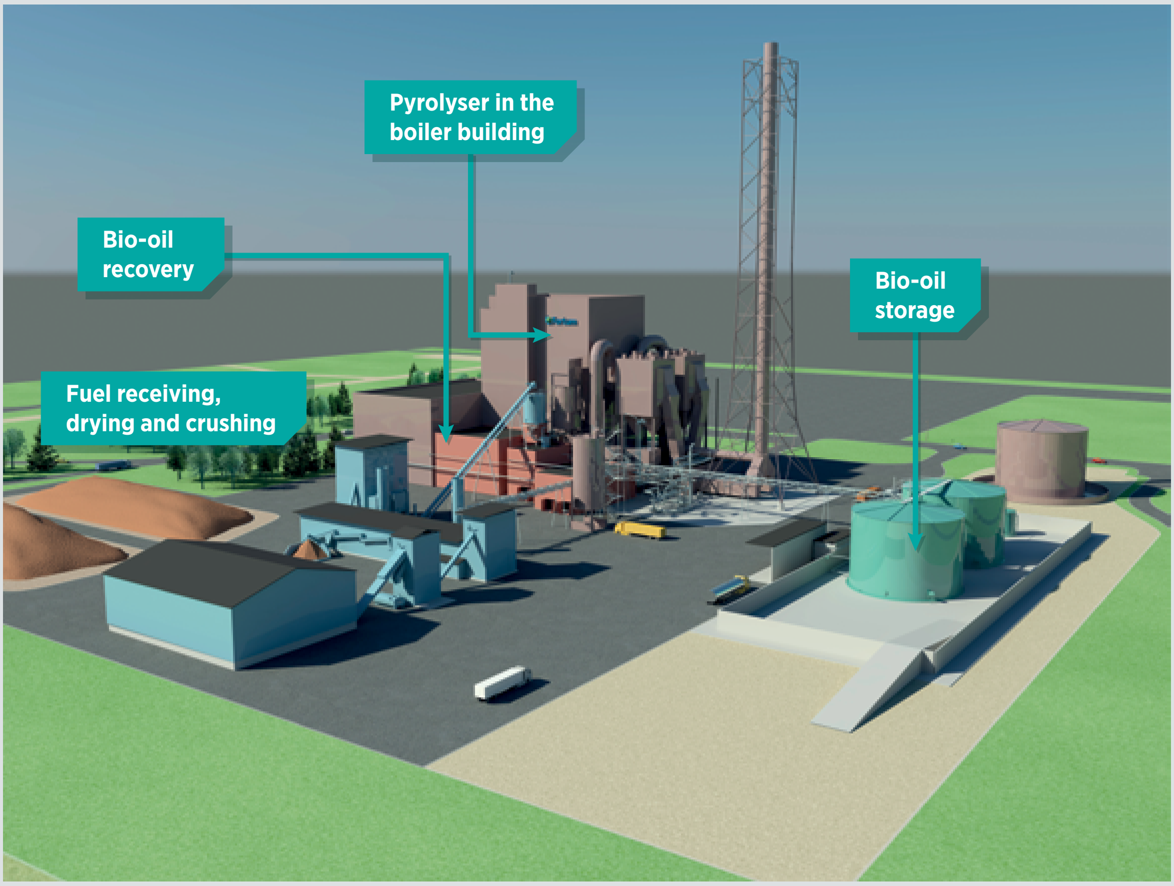
Fortum has invested about EUR 30 million (USD 37 million) in its bio-oil plant and in modification work (*e.g.*, pyrolyser, fuel gas condenser) to its heat plants, and the project has also received about EUR 8 million (nearly USD 10 million) in government investment subsidies for new technology demonstration. Development and conceptualisation of the new technology has been done collaboratively between Fortum, Valmet, UPM and VTT Technical Research Centre of Finland Ltd. The research has been part of Tekes Biorefine programme.

Fortum signed its first agreement to supply bio-oil produced in Joensuu to Savon Voima, which will use the bio-oil to replace the use of heavy and light fuel oil in its district heat production in Iisalmi. Additionally, Fortum will use bio-oil in its own heat plants in Joensuu and in Vermo, Espoo. If a heavy-fuel oil plant is switched to pyrolysis oil, fuel storage, pumps, valves and burners have to adapt to material that can resist low pH (see Table 7).

The hot sand of a fluidised bed boiler offers considerable potential for the integration in that system of the pyrolysis and combustion processes. In Joensuu, the existing fluidised bed boiler was used. A fluidised bed boiler acts as a heat source for pyrolysis, in addition to which it can easily combust the coke and uncondensed gases produced during the pyrolysis process to produce electricity and heat. In this way, high efficiency can be achieved for the pyrolysed fuel production process. In addition, when integrated with a fluidised bed boiler, pyrolysis is a cost-efficient way of producing bio-oil, which can be used to replace fossil oils. Considerable savings can be achieved in operating costs and the price of the investment in both new boiler projects and retrofit solutions. The integrated concept is easy and smooth to operate and has good control characteristics. Proof-of-concept has been carried out. Fortum has produced bio-oil from sawdust and forest residues since 2015. Development of the concept has been supported by experimental work of fast pyrolysis at VTT.

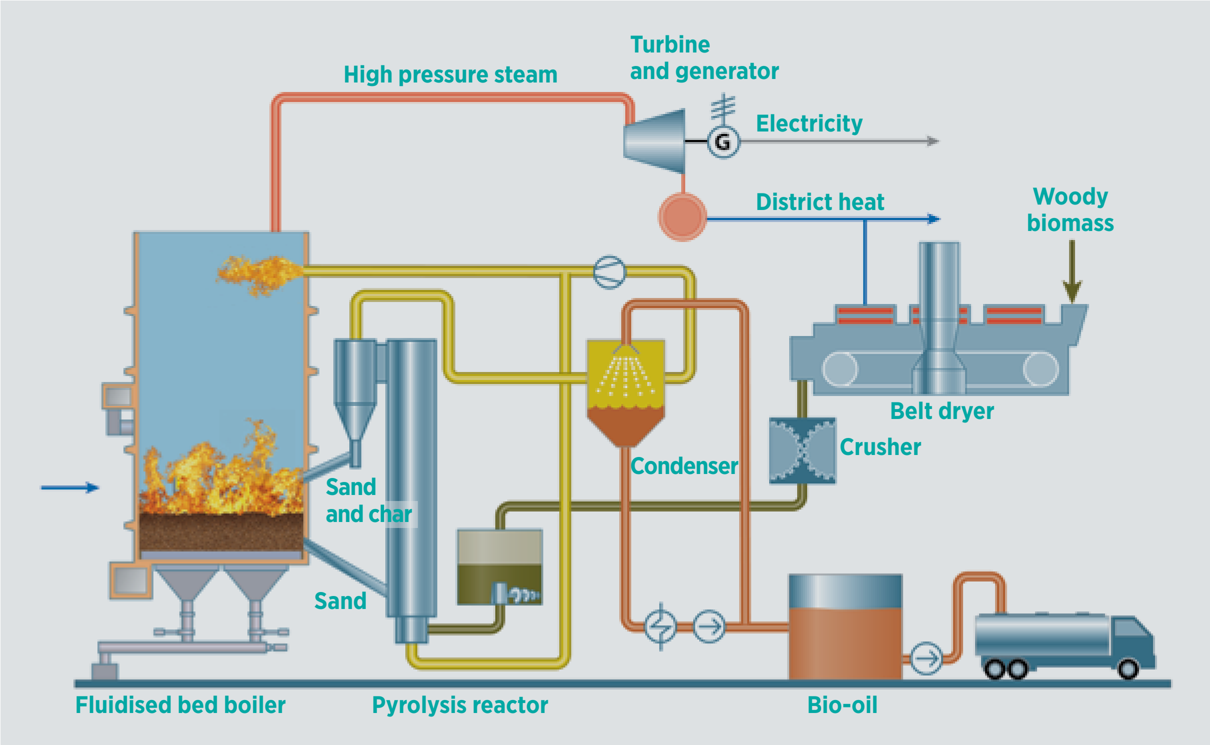
The integrated CHP plant in Joensuu is producing heat, electricity and 50 000 tonnes of bio-oil as a maximum planned capacity per year. The plant began full operation in 2015 (Figures 14 and 15).

Figure 14 Model of industrial-scale integrated bio-oil plant in Joensuu



Source: Valmet

Figure 15 Process diagram of integrated bio-oil plant in Joensuu



Source: Valmet

5.2 Feedstocks

Feedstocks for bio-oil are forest residues and sawdust, the by-products from local forest industry companies. While the moisture content of these feedstocks is typically high, fast pyrolysis oil requires dry feed. Feedstock moisture content is usually less than 10% by weight and particle sizes are less than 5 mm. Feedstock moisture is the main parameter, which is followed constantly during processing. The main parameters to be monitored with respect to liquid quality are water and solid content. Any increase in water content may indicate a change of feedstock moisture or processing conditions, or the presence of catalytic reactions. At the mill site, excess available waste heat can be used to dry the pyrolysis feed. The production of bio-oil will double Fortum's wood energy use in energy production in Joensuu from 300 000 to 600 000 solid cubic metres per year.

5.3 Fast pyrolysis

In fast pyrolysis, biomass decomposes very quickly (1-2 seconds) in the absence of oxygen to generate mostly vapours and aerosols and some charcoal and gas. After cooling and condensation, a dark brown homogenous mobile liquid is formed that has a heating value about half that of conventional fuel oil. A high yield of liquid is obtained with most biomass feeds low in ash. The main product, bio-oil, is obtained in yields of up to 75% of weight on a dry-feed basis, together with by-product char and gas, which can be used within the process to provide the process heat requirements so there are no waste streams other than flue gas and ash. Liquid yield depends on biomass type, temperature, hot vapour residence time, char separation and biomass ash content, the last two having a catalytic effect on vapour cracking. A fast pyrolysis process includes drying the feed to typically less than 10%

moisture content in order to minimise the water in the product liquid oil, grinding the feed to give sufficiently small particles to ensure rapid reaction, fast pyrolysis, rapid and efficient separation of solids (char), and rapid quenching and collecting of the liquid product (bio-oil). Crude pyrolysis liquid or bio-oil is dark brown and approximates to biomass in elemental composition. It is composed of a very complex mixture of oxygenated hydrocarbons with an appreciable proportion of water from both the original moisture and reaction product. Solid char may also be present. The typical properties of bio-oil are presented in Table 7.

Fortum bio-oil can be used at heat plants or in industrial steam production as a replacement for heavy and light fuel oil. In the future, bio-oil can be used as a raw material for various biochemicals or traffic fuels. VTT's analysis of the bio-oil production potential in the European pulp and paper industry indicates that up to 50 pyrolysers integrated in fluidised bed boilers can be built.

The sustainability system Fortum uses is approved by Finland's Energy Authority and indicates that Fortum bio-oil is produced from environmentally sustainable wood-based raw materials. Every quarter, customers who purchase the bio-oil receive a sustainability declaration with key information about the sustainability of the amount purchased.

Table 7 Typical characteristics of fast pyrolysis bio-oils

Property	Typical range	Unit
Gross calorific value, wet basis	14-19	MJ/kg
Net calorific value, wet basis as received (ar)	13-18	MJ/kg
Water content, wet basis	20-30	% *(m/m)*
pH	2-3	-
Total acid number (TAN)	70-100	mg KOH/g
Kinematic viscosity at 40°C	15-40	mm^2/s
Density at 15°C	1.11-1.30	kg/dm^3
Pour point	-9-36	°C
Carbon, dry basis	50-60	% *(m/m)*
Total hydrogen, dry basis	7-8	% *(m/m)*
Nitrogen, dry basis	<0.5	% *(m/m)*
Sulfur, dry basis	<0.05	% *(m/m)*
Oxygen, dry basis	35-40	% *(m/m)*
Solids, wet basis	<1	% *(m/m)*
Carbon residue, wet basis	17-23	% *(m/m)*
Ash, wet basis	<0.3	% *(m/m)*
Flash point	40-110	°C
Sustain combustibility	does not sustain combustion	-
Sodium (Na), Potassium (K), Calcium (Ca), and Magnesium (Mg) dry basis	0.05-0.2	% *(m/m)*
Chlorine (Cl)		ppm

Source: Oasmaa and Peacocke, 2010

KOH = potassium hydroxide; mg KOH/g = miligrams of potassium hydroxide per gram; mm2/s = square millimetres per second (viscosity); kg/dm3 = kilograms per cubic decimetre; ppm = parts per million

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