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Health Issues in Bioenergy Production and Use

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Health Issues in Bioenergy Production and Use

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Sustainable Bioenergy
Solutions for Tomorrow

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Name of report: Health Issues in Bioenergy Production and Use

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Summary

The use of bioenergy in Finland has increased during the last decade. In 2012, the total use of forest chips in heat and power plants was about 15 TWh, which, according to the 2020 target, should be increased to 25 TWh. The number of employees working with bioenergy is therefore expected to grow, making it increasingly important to learn about the bioenergy production processes and the health and safety issues involved in the biomass supply chain. Inhabitants may also be exposed to more bioenergy use as it grows.

The aim of this literature review was to compile key data on the health issues related to bioenergy production and use. The report includes a short overview of the use of bioenergy in Finland, the health and safety factors involved in the bioenergy sector and the health effects of biomass combustion aerosols. The report also includes examples from earlier research. For instance, self-heating and dust explosions of biomass, and fire risks and off-gassing in pellet production and storage have separate chapters in the report. In addition, earlier studies carried out by VTT during 2005-2008 on occupational health hazards of new biofuels are included as a separate chapter.

Based on the literature review, it was found that the occupational hazards of modern energy production that utilises renewable biomass have not been well studied. More surveys and measurements need to be carried out to assess the health and safety hazards.

Workers in the bioenergy supply chain and biomass-burning power plants can be exposed to many chemical compounds and biological agents at the same time. Multiple exposure is dependent on many things, such as work tasks, length of the work day, use of protective clothing and respirators, the fuels used and the weather. Wood dust, inorganic dust, diesel exhausts and gases from the degradation process appear to be the most harmful chemical agents in the bioenergy supply chain and biomass-burning power plants. Similar biological agents are bacteria, fungi and zoonotic pathogens, which can easily spread to the air during heavy biomass processes. There is little data on the dose-response relationship between humans and micro-organisms. The main physical factors involved in biomass work tasks are noise and vibration exposure, which arise in, for example, chipping and crushing. More knowledge is needed about off-road machine operators' exposure to impulse vibration and cumulative long-term exposure to noise and vibration.

Self-heating and dust explosions are real risks of handling renewable fuels. Self-heating and spontaneous ignition can occur in the storage and transport of wood pellets, and off-gassing can pose a safety and health threat to workers.

In the future, it will be especially important to study biological exposure at biomass power plants as well as the health effects of combustion ashes. With increased biomass use and combustion, it will be important to assess the public health effects and give recommendations for future scenarios.

Helsinki, April 2014

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1 Introduction

Leena Fagernäs (VTT) and Leena Korpinen (TTY)

Bioenergy plays an important role in Finnish energy production. According to advance information on energy statistics, the proportion of wood-based fuels of the total energy consumption in 2012 was 23%. The total use of wood-based fuels amounted to 89 TWh, of which the proportion of forest industry waste liquors was 38 TWh. The amount of solid wood fuels used at heat and power plants was 34 TWh, whereas small-scale residential wood combustion amounted to 17 TWh. According to the 2012 statistics, the forest industry's waste liquors and solid wood fuels accounted for 14% of the energy sources in electricity generation.

The background report for the National Energy and Climate Strategy by the Finnish Ministry of Employment and the Economy notes that Finland's use of forest chips has increased eight-fold during the 2000s. The proportion of renewable energy in the final energy consumption for Finland should be 38% by 2020. The Ministry of Employment and the Economy has set a target of 25 TWh for the use of forest chips by 2020. Against this background, future bioenergy solutions are a key area for research in Finland.

In 2013, CLEEN Ltd and FIBIC Ltd, both part of the Strategic Centres for Science, Technology and Innovation's (SHOK) network, launched a research programme called Sustainable Bioenergy Solutions for Tomorrow (BEST). BEST is the first joint research programme between the two SHOK companies – CLEEN and FIBIC – and it is also cross-sectoral. The duration of the programme is four years, but so far the funding granted by the Finnish Funding Agency for Technology and Innovation only covers the first two years.

One of the BEST programme's research groups is the Health, Safety and Environment (HSE) group, which focuses on studying health and safety issues in the bioenergy supply chain. The group's primary aim is to study the biological exposures encountered at power plant sites and the health issues related to ash. Businesses are clearly paying more attention to health, safety and environment issues, and the group aims to meet these needs and provide new perspectives for the bioenergy sector.

The HSE research group is led by Tampere University of Technology's Department of Electronics and Communications Engineering (Environmental Health Group), and its members include VTT Technical Research Centre of Finland (VTT), the Finnish Institute of Occupational Health (FIOH) and the Eastern University of Finland (UEF), as well as companies such as Metso Power, UPM, ANDRITZ and Fortum.

The first task of the HSE group was to produce a literature review that gathered key data on health issues related to bioenergy production. The report includes a short overview of the use of bioenergy in Finland, the health and safety issues related to the bioenergy sector and the health effects of biomass combustion aerosols.

The report also includes examples from earlier research, including topics such as self-heating and dust explosions, and fire risks and off-gassing in pellet production and storage, with separate chapters devoted to each topic. VTT conducted research on the occupational health hazards of new biofuels in 2005-2008; the results of these studies are discussed in their own chapter.

The report is mainly written from the perspective of Finnish operators and bioenergy users. Bioenergy is used across Europe and the world in different ways, so it was important to define our scope while compiling the report. Peat resources and utilisation are also covered briefly in the report. Peat is a slowly renewable biomass resource for which there are many uses, particularly in energy and horticulture (ENVIR 009[1]). Peat producers have committed to following the principles of wise use of peatlands. As an energy source, peat closely resembles wood, and the two are often used together in co-fired applications.

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[1] Quality guidelines for fuel peat, Fuel classification and quality assurance, sampling and analysis of properties, NT method, ENVIR 009. 2005, 24 p.

2 Bioenergy in Finland

Martti Flyktman and Kirsi Korpijärvi (VTT)

2.1 Resources

Based on the 11th National Forest Inventory (2009-2011), growing stock volumes on forest land and poorly productive forest land totalled about 2300 million m^3 in Finland. The total forestry area is approximately 26 172 000 ha, which is about 77% of the land area (METLA 2012). The annual increment of growing stock on forest land and poorly productive forest land is 104 million m^3.

The theoretical biomass potential of Finnish forests has been estimated at about 105 TWh (Kärhä et al. 2010). The techno-economical potential has been estimated at 27 TWh and the techno-ecological potential at 43 TWh in the base case. In the report from the Finnish Forest Institute (Anttila 2013), the techno-economical potential is estimated at 14-16 million m^3 depending on the production method. In 2011, wood consumption in Finland was about 70.6 million m^3. Of this, 61.6 million m^3 was used in the forest industry and the rest in energy production.

METLA has estimated that, in Finland, the total mire area is about 8.9 million ha, with 5.1 million ha covered by geological mires with a peat layer deeper than 30 cm. The total Finnish national peat reserves account for 69.3 billion m^3 in situ, which corresponds to 6.3 billion dry solid tons. The carbon storage of Finnish mires has been assessed at 3.2 billion tonnes. Mires, which are technically suitable for the peat industry, cover a total area of 1.2 million ha and contain 29.6 billion m^3 of peat in situ. Slightly humidified peat suitable for horticultural and environmental use totals 5.9 billion m^3 in situ, and energy peat totals 23.7 billion m^3 in situ with an energy content of 12 800 TWh. The effective energy density of the areas suitable for energy production is 0.54 MWh/m^3 in situ. All mires in Finland include peat reserves that are technically suitable for industry. Calculations of economic and environmental facts that limit the use of mires have not been taken into account (Virtanen et al. 2003).

In Finland, the peat production area is approximately 60 000 ha, which is about 0.7% of the total peatland area (Flyktman 2012). Table 2.1 shows peat use in the last three years.

Table 2.1. Peat use in energy production in Finland (Suomen virallinen tilasto, Energiatilasto 2013)

	TJ	TWh
2010	94545	26.3
2011	84938	23.6
2012*	66030	18.3

*) 2012 estimated value

Peat use has decreased significantly. The main reason for this is that peat production has not been very successful because of the very bad weather conditions during the last two summers. Peat is mainly replaced by coal and forest chips in energy production. Changes in peat production and use in Finland during the last decades are illustrated in Figure 2.1.

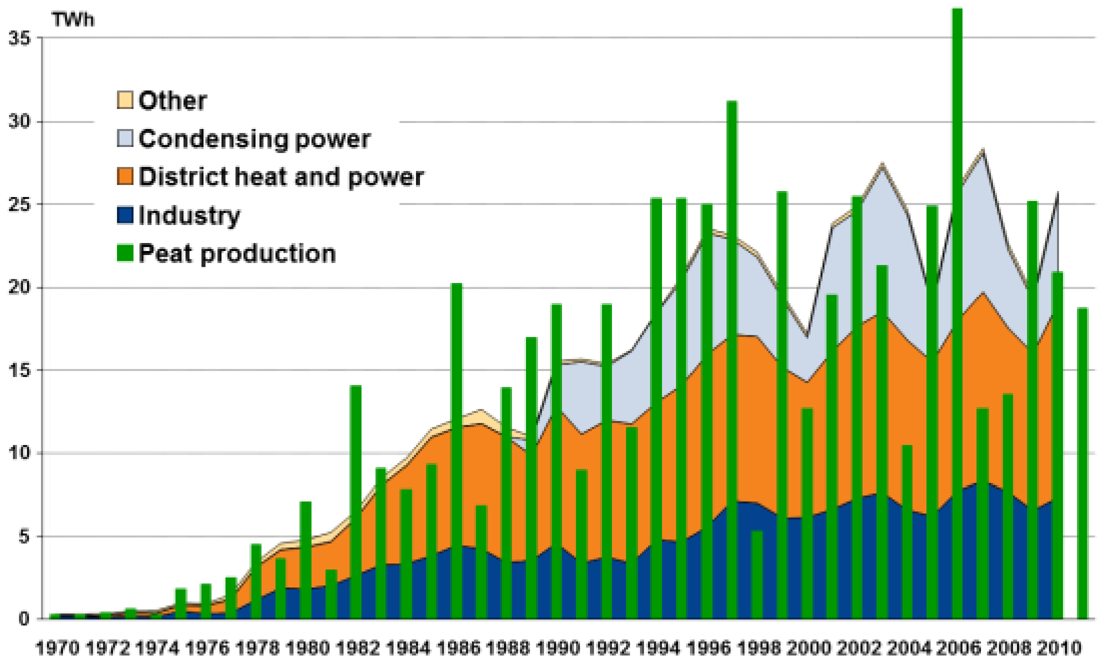


Figure 2.1. Peat production and use in 1970-2011 (Flyktman 2012)

2.2 Bioenergy utilisation

The conventional method in bioenergy production is to use fuel wood in small units. By-products from the forest industry have also always been used in energy production in Finland. During the last two decades, the consumption of forest chips has increased significantly.

Figure 2.2 shows the total wood fuel consumption in Finland in 2012 (Ylitalo 2013), and Figure 2.3 shows the solid wood fuel consumption in heat and power plants in 2012.

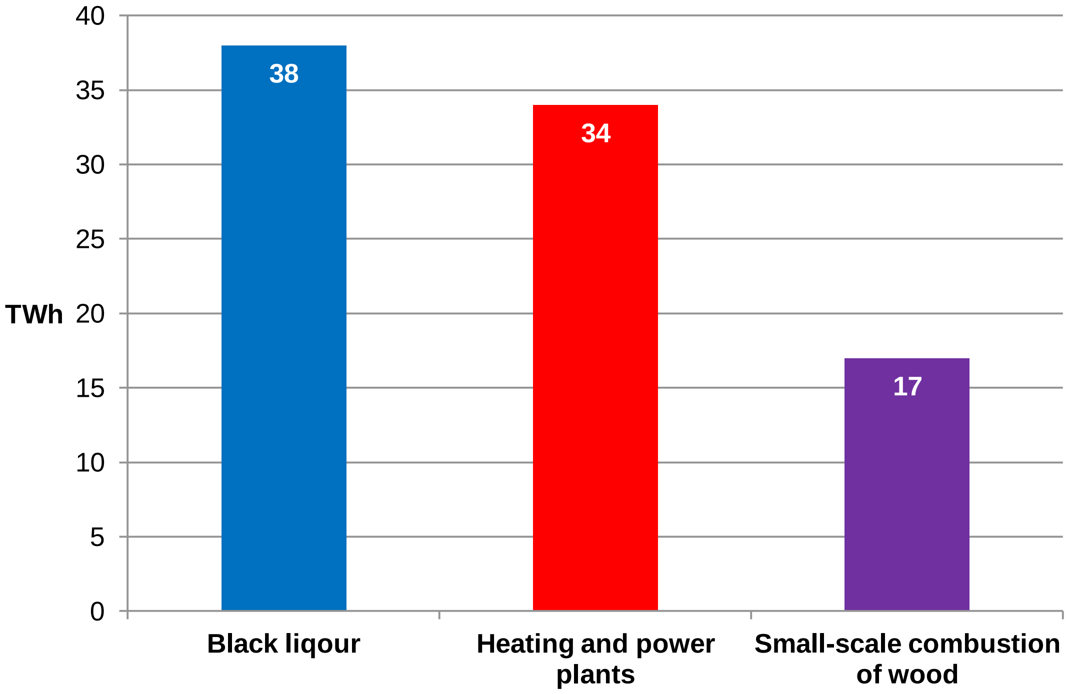


Figure 2.2. Wood fuel consumption in Finland in 2012 (Ylitalo 2013)

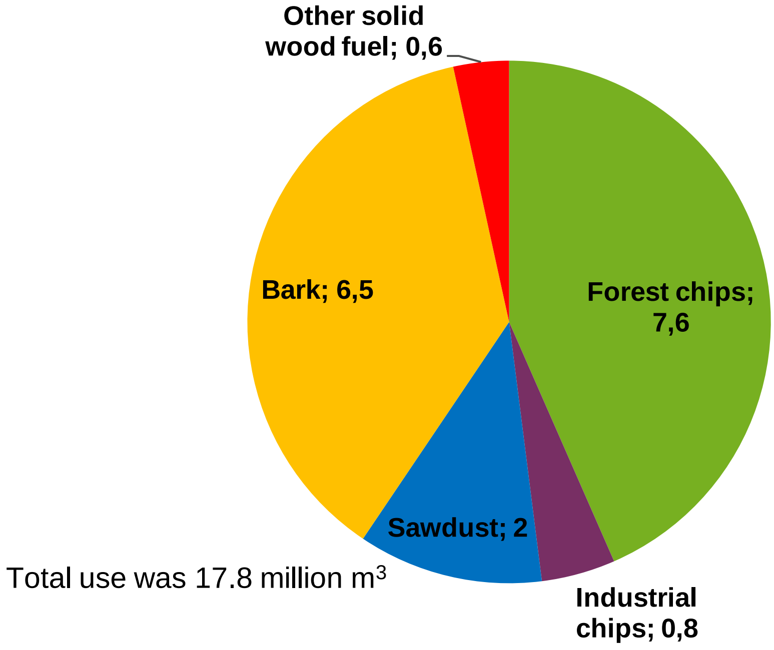


Figure 2.3. Solid wood fuel consumption in heat and power plants in 2012 (Ylitalo 2013)

Figure 2.4 shows the total consumption of forest chips between the years 2000 and 2012 in energy production plants (Ylitalo 2013), and Figure 2.5 compares the use of forest chips in heat and power plants in 1999 and 2011.

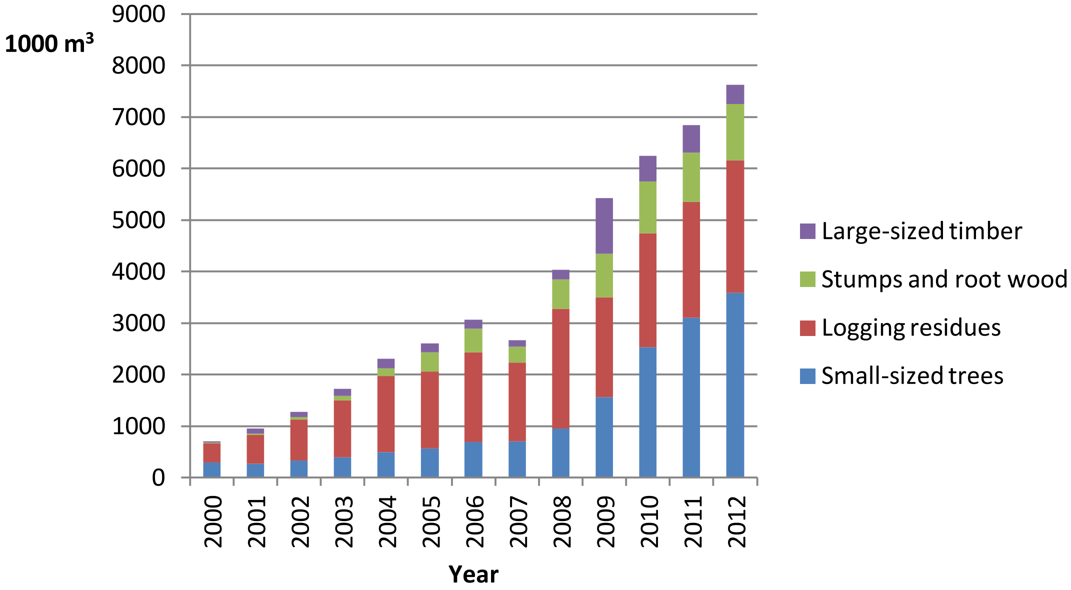


Figure 2.4. Consumption of forest chips in energy production plants in Finland (Ylitalo 2013)

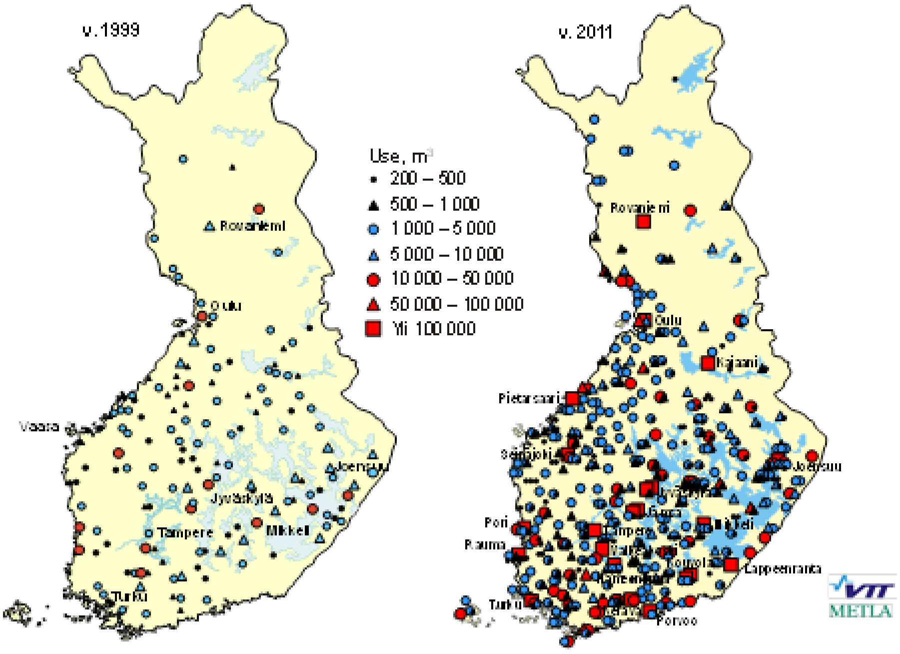


Figure 2.5. Use of forest chips in heat and power plants in 1999 and 2011 (Alakangas 2013)

In 2012, about 860 heat and power plants used forest chips in Finland (Ylitalo 2013). There are also about 100 plants using by-products and residues from the wood processing industry. In total, almost a thousand heat and power plants use wood-based biomass in Finland. The main combustion methods are grate combustion in small heating plants and fluidised bed combustion in bigger plants (thermal output greater than 5 MWth). Finland has about 80 combined heat and power plants (CHP) producing heat for the district heat network, or process steam and electricity.

In 2012, the total consumption of forest chips in heat and power plants was 15.2 TWh. About 80% of the forest chips were used in CHPs and the remaining 20% in heating plants. Big CHP plants that use forest chips normally also use other fuels, such as peat, coal and by-products from the forest industry. Typically, only small heating plants (heat output less than 2 MW) use one fuel, such as forest chips.

Finland has set the target for consumption of forest chips at 25 TWh in heating plants and CHPs by 2020. Forest chip consumption therefore has to grow by about 10 TWh (67%) compared with that in 2012.

2.3 Bioenergy production

2.3.1 Forest energy

The main raw materials for wood chips are logging residues from final fellings and small trees from thinning of young stands. Forest chips can be divided into four sectors based on the wood raw material:

- logging residues from final cuttings
- stumps and root wood from final cuttings
- small wood from early thinnings
- large-sized timber

Figure 2.6 shows changes raw material of forest ships between the years 2000 and 2012. Although the share of logging residues such as forest chips as raw material has essentially decreased in recent years, from 60% to 35%, the absolute volume has increased. Small-sized trees represent almost 50% and stumps about 15% of the raw material.

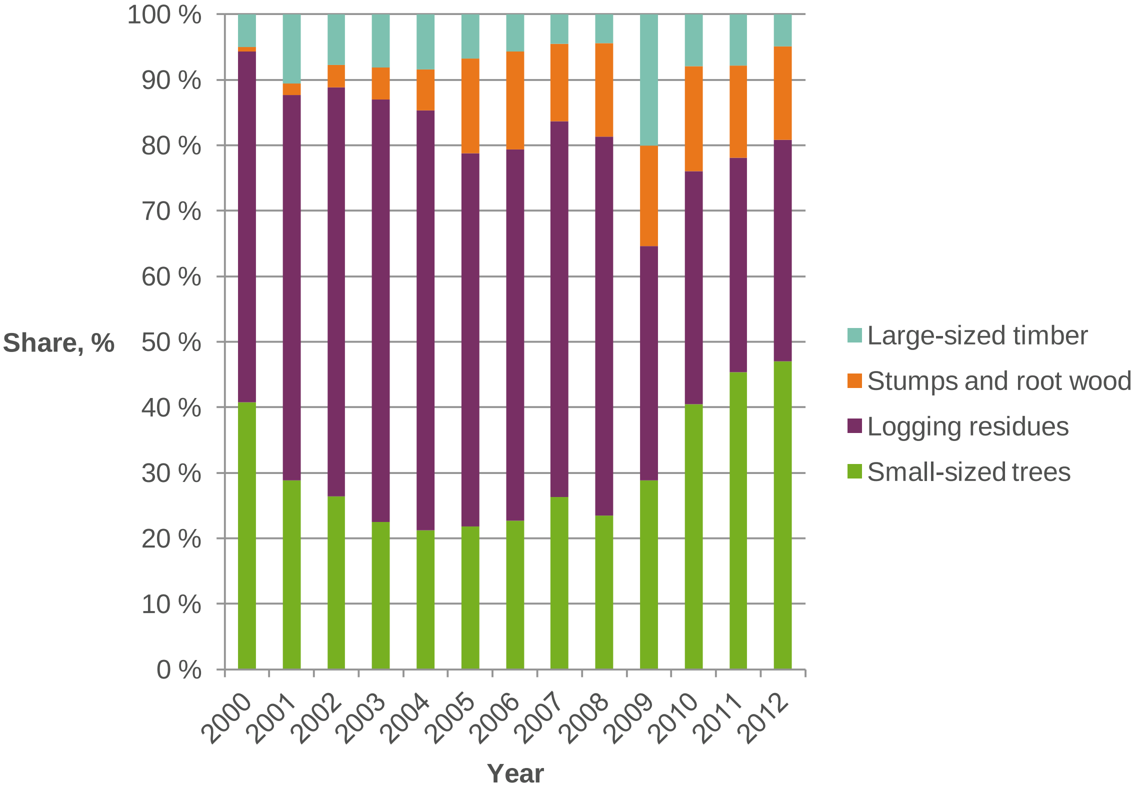


Figure 2.6. Raw materials for forest chips (METLA 2012)

2.3.2 By-products and residues from the wood processing industry

The forest industry (sawmills, plywood mills, pulp and paper mills) also produces a large amount of by-products and residues, such as bark, sawdust and wood chips. The most important solid by-product is bark. The total use of by-products and residues from the wood processing industry in energy production was about 17 TWh in 2012.

In 2012, about 38 TWh of black liquor and other concentrated liquors were used in recovery boilers of pulp mills.

2.3.3 Upgraded wood products

In 2011, the total wood pellet production was 308 000 tons, of which 136 000 tons were exported. In 2011, domestic consumption was 178 000 tons. The pellet consumption in heat and power plants was 61% of the total, and the remaining 39% was used by households and farms (METLA 2012). In 2012, about 510 GWh of wood pellets were used in heating plants and CHPs (Suomen virallinen tilasto, Energiatilasto 2012). The principles of the wood pellet production process are shown in Figure 2.7 and the locations of pellet production plants in Figure 2.8.

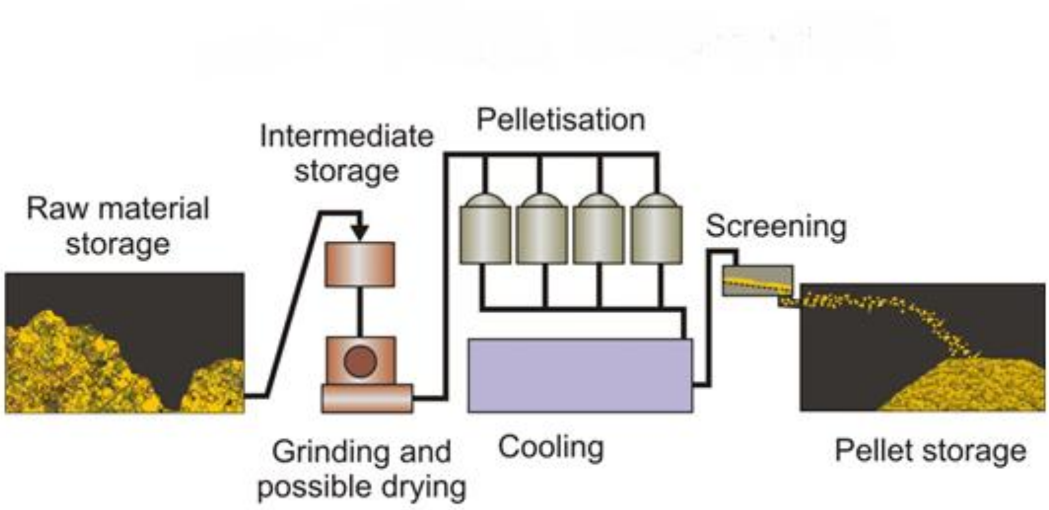
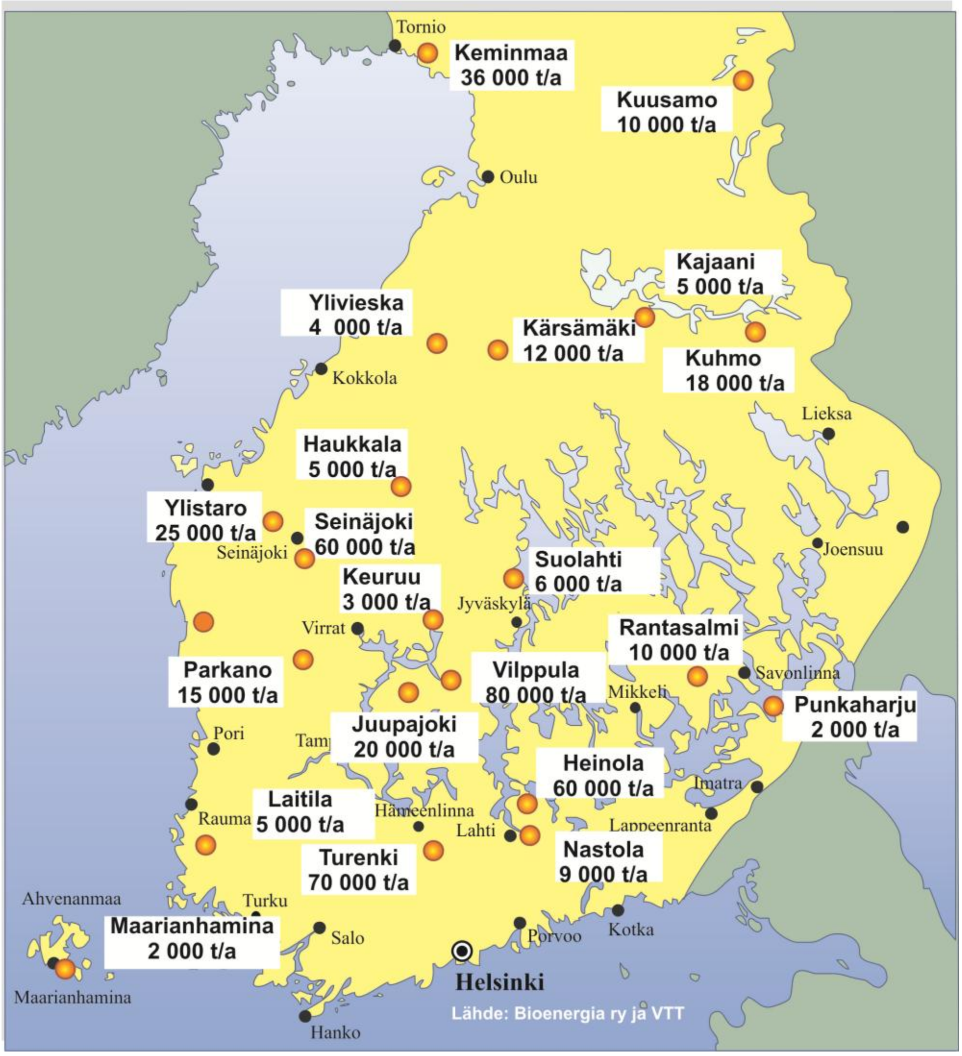


Figure 2.7. Production process of wood pellets (Alakangas and Paju 2002)



Lähde: Bioenergia ry ja VTT

Figure 2.8. Locations and capacities of pellet plants in Finland (Alakangas 2013)

2.3.4 Waste treatment and solid recovered fuel production

Energy recovery from waste has increased in Finland in the past few years. Source-separated municipal solid waste is typically used in incineration plants, and higher quality industrial wastes or solid recovered fuels (SRF) are co-fired in biomass boilers. Energy recovery was the biggest waste treatment method in Finland in 2012 (Table 2.2).

Table 2.2. Municipal waste in 2012 in tonnes (Suomen virallinen tilasto 2013)

	Amount	Treatment		
		Recycling	Energy recovery	Landfilled
Mixed waste	1 394 746	6 171	519 761	868 814
Separately collected waste, of which	1 203 148	894 014	297 473	11 661
Paper and board waste	364 902	327 904	36 986	12
Organic waste	363 259	328 445	31 270	3 544
Glass waste	30 476	29 947		529
Metal waste	123 915	123 913	1	1
Wood waste	78 563	3 793	74 769	1
Plastic waste	36 127	4 451	31 676	0
Electrical and electronic scrap	67 871	67 829	42	
Other	140 201	12 411	107 591	20 199
Total	2 738 095	912 596	924 825	900 674

Figure 2.9 shows the principle of the urban waste management scheme including SRF production, and Figure 2.10 shows the main processes when solid recovered fuel (SRF) is produced from waste.

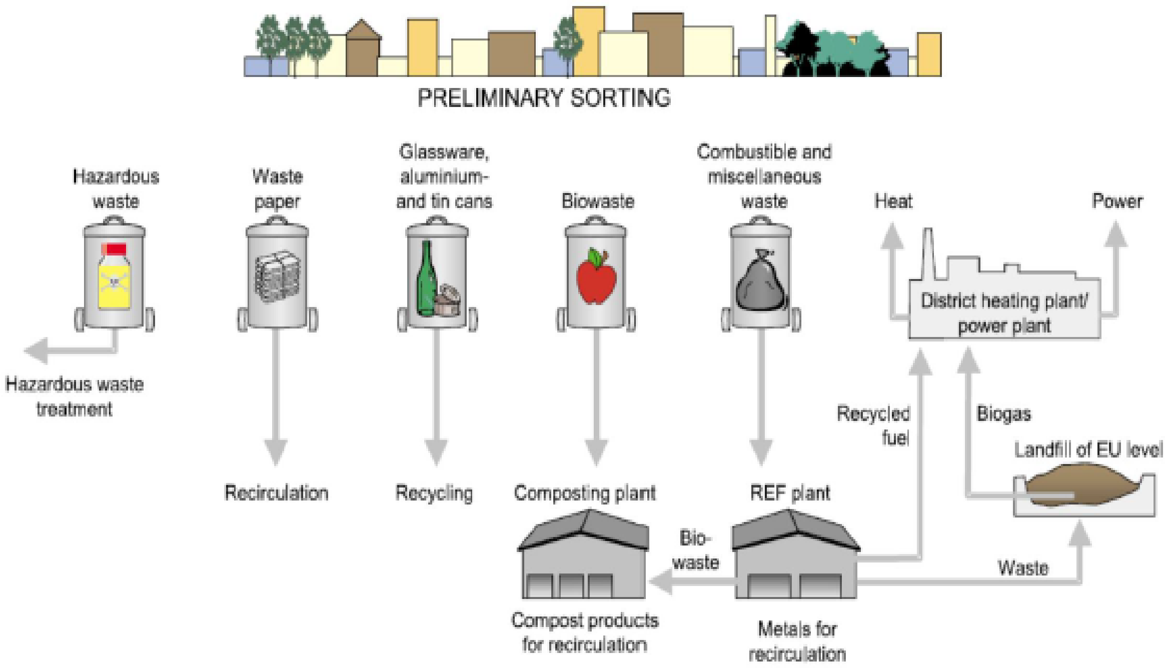


Figure 2.9. Waste treatment system – the Finnish approach (Wilen et al. 2004)

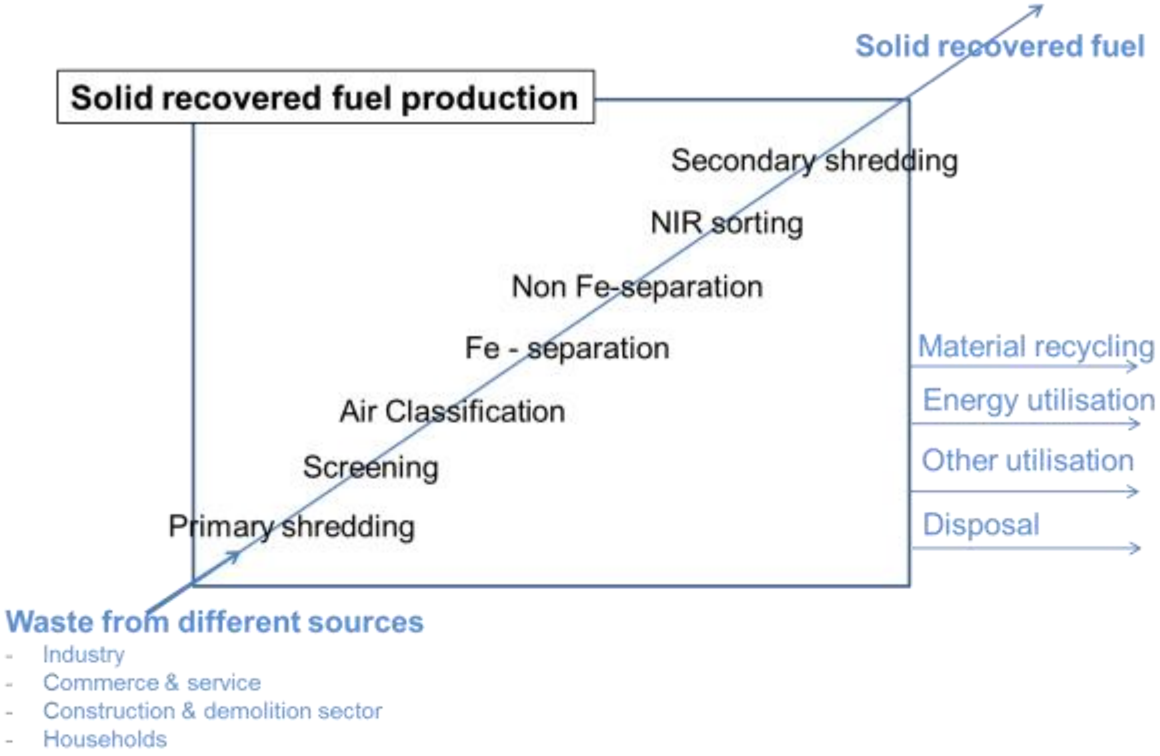


Figure 2.10. Solid recovered fuel production (Hannula 2013)

Finland has about ten power plants that co-fire recovered fuels and fuels produced from municipal waste sorted at the point of origin or comparable fuels produced from waste from retail shops and industry (SRF). The share of SRF is usually about 5-15%, but there are some plants at which SRF represents almost half of the fuel energy. SRF is typically mixed with other fuels like forest chips, bark, peat, etc. As well as co-firing, municipal solid waste is incinerated at seven plants.

2.4 Energy wood harvesting and handling

Several different methods are in use to harvest energy wood, depending on the harvesting stands, properties of the harvested energy wood and the users. The woody biomasses to be harvested are delimbed and whole trees, logging residues and tree stumps.

Harvesting delimbed energy stems is often similar to thinning pulpwood stands, in which a harvester both fells and delimbs the trees and a forwarder takes the stems to the roadside. The typical length of the stems is 2.7-5.0 m and the top diameter is 4-5.5 cm. This working method is well suited to thinning stands in which the average tree size is big enough (e.g. 60 dm^3). The advantages of delimbed stems are good storability and transport efficiency for long-distance transport. Chips made from delimbed stems are suitable for different users, from small buildings to large power plants. The yield from delimbed stems is about 20-30% lower than for undelimbed stems. Harvesting often requires clearing in advance.

Harvesting of whole trees is often done by a harvester or feller-buncher with a special energy wood grab. Harvesting can also be carried out with a normal harvester equipped with a multi-stem handling grab. This method is best suited to young forests in which the seedling stand management has been neglected. The typical length of harvested stems is 6-7 m. Whole trees are transported with a forwarder to roadside storage, where they are usually seasoned and chipped prior to long-distance transport. In whole tree harvesting, integrated harvesting machines can also be used with which trees can both be felled and transported to the roadside.

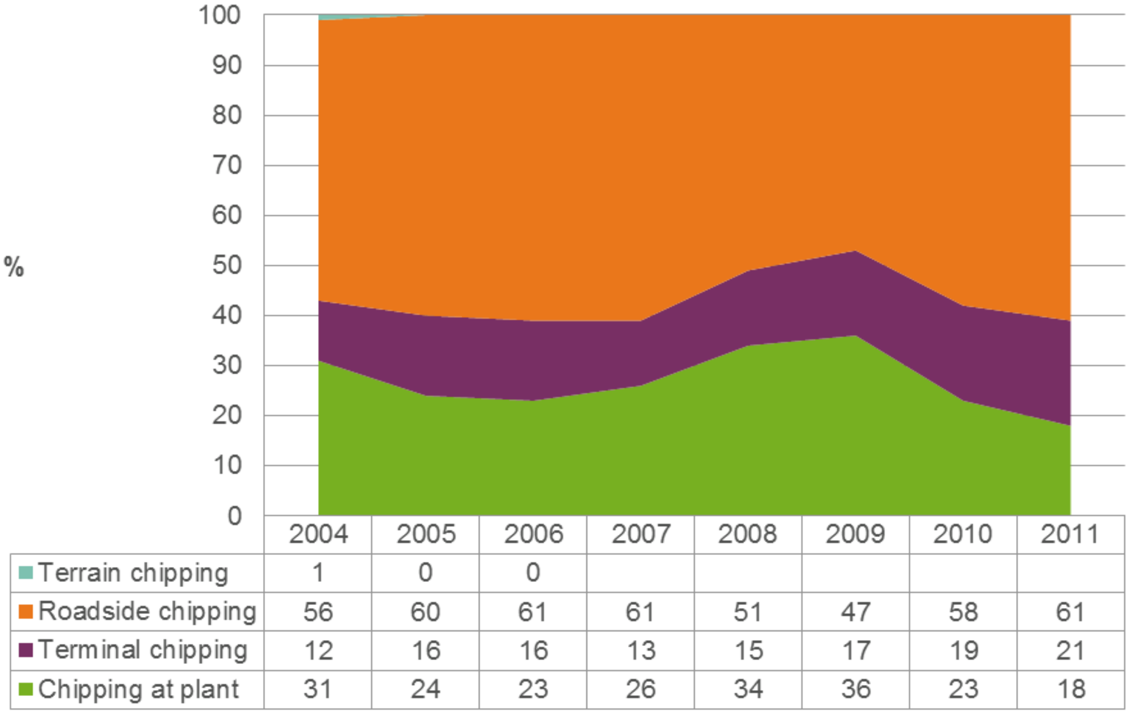
Energy wood bundling is a new method in energy wood harvesting. In this method, the felling machine is equipped with a bundler that packs harvested wood directly into bundles. Forest transport takes place with a normal forwarder that collects the bundles and transports them to the roadside storage. This method enables efficient forest and long-distance transport. The bundler can also bundle pulpwood.

Logging residues are typically collected from spruce-dominated final felling stands. The harvester delimbs branches and cuts tops in a pile. The forwarder collects residues and transports them to roadside storage. To improve transport efficiency, logging residue or slash is often chipped at the roadside storage prior to long-distance transport.

Tree stumps can also be collected from final felling stands. Stumps are usually harvested from spruce-dominated stands with rich soil. The most common is to remove them from the ground with an excavator equipped with a simple lifting harrow. The excavator lifts and splits stumps, and the forwarder takes them to the roadside storage. At the roadside storage, tree stumps can be dried and chopped prior to long-distance transport, reducing the amount of soil on the stumps. The tree stumps are usually transported by truck directly to the user site where they are crushed. In Finland, the stumps are used as fuel in big CHP plants. These plants often have a stationary crusher suitable for crushing stumps (Alakangas et al. 2012).

2.5 Energy wood chipping and logistics – supply chains

Energy wood is supplied to CHPs using different supply chains. The harvesting, handling and logistics methods for energy wood differ depending on the wood biomass used as energy wood (small trees, logging residues and tree stumps). The most commonly used methods are roadside chipping, terminal chipping and chipping at the plant. Figure 2.11 shows chipping methods of forest chips in 2004-2011.



	2004	2005	2006	2007	2008	2009	2010	2011
🟦 Terrain chipping	1	0	0					
🟧 Roadside chipping	56	60	61	61	51	47	58	61
🟪 Terminal chipping	12	16	16	13	15	17	19	21
🟩 Chipping at plant	31	24	23	26	34	36	23	18

Figure 2.11. Chipping methods for forest chips in 2004-2011 (METLA 2012)

2.5.1 Roadside chipping

In roadside chipping, the harvested energy wood is first forwarded to roadside storage where a mobile chipper chips energy wood directly into trucks that transport the chips to the plant (Figures 2.12 and 2.13). Roadside chipping is the most commonly used production chain for energy wood chipping in Finland. This supply chain is used, in particular, for small tree and logging residue supply (Alakangas et al. 2012). In Finland, 72% of harvested small-sized trees and 74% of logging residues were produced by roadside chipping. About 21% of logging residues are chipped at terminals. Stumps are mainly crushed at the end-user facility (45%) or a terminal (44%) (METLA 2012).

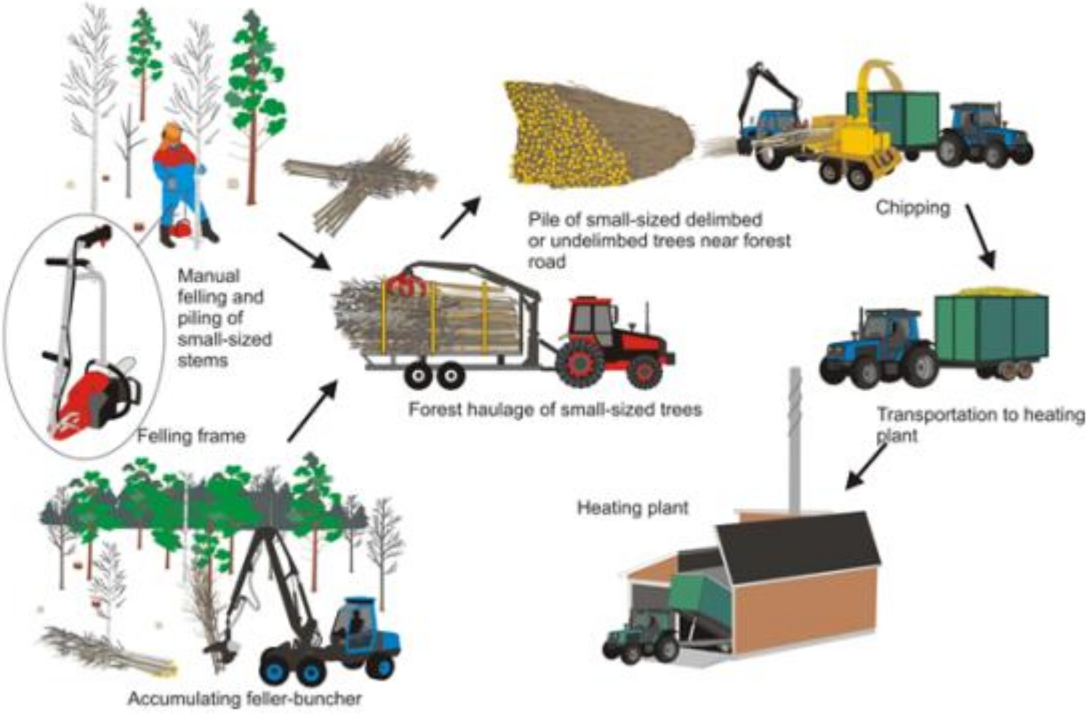


Figure 2.12. Options for harvesting small-sized trees (Drawing: Eija Alakangas, VTT)

Figure 2.13. Harvesting logging residues using the road-side method (Drawing: Eija Alakangas, VTT)

2.5.2 Terminal chipping

With terminal chipping, energy wood is transported to fuel terminals where the wood is chipped or crushed. The wood fuel is transported from the terminal to an energy plant on trucks or trains (Figure 2.14). The share of terminal chipping is expected to increase in the future.

Terminals have been built in the last decades for several reasons. Forest chip storage is not in a hot chain that helps secure chip deliveries, especially in seasons with bad weather and when the roads in the forests cannot all be used. The terminal can be used for good quality management of chips. The same terminal can also be used to deliver forest chips to several small plants. Many small heating plants do not have the possibilities to store forest chips. The terminal can also be utilised when the harvesting sites are small. Comminution is effective at the terminal.

The terminal system has some drawbacks, including:

- establishment expenses of the new terminal
- identification of appropriate terminal areas
- extra handling time
- extra handling costs of raw materials and/or wood chips such as unloading and loading

Figure 2.14. Terminal chipping (Vapo 2006)

2.5.3 Chipping at the plant

Electricity can be used for chipping if forest chips are manufactured at an energy production plant. This method is suitable for large-scale production of chips and for a cost-effective total supply chain with relatively short transportation distances.

The system also has some drawbacks, including:

- low-energy content of loose material loads
- long transportation distances
- long-distance transportation costs
- large roadside storage space and large storage fields at the plants are required
- untidy roadside storage areas after harvesting operations

Chipping at the plant is used, in particular, for root and stump wood because stump chipping needs very effective crushers. Figure 2.15 shows the principle of comminution at the plant.

Figure 2.15. Comminution at the plant (Drawing: Eija Alakangas, VTT)

2.6 Biomass operations at heat and power plants

The biomass operations at heat and power plants are illustrated in Figure 2.16 and overviewed in the following paragraphs.

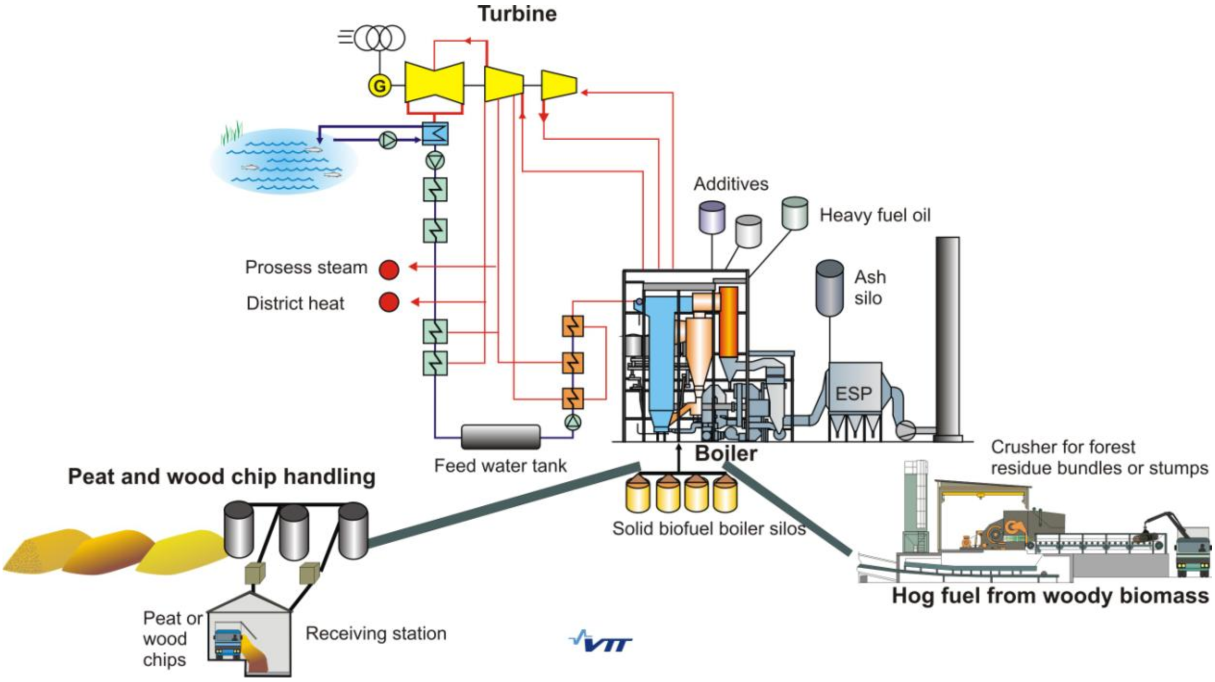


Figure 2.16. Operations related to biomass use at heat and power plants (Drawing: Eija Alakangas, VTT)

2.6.1 Fuel handling systems

In small heating plants, the fuel handling system is very simple. Fuel is transported to the plant by a truck or tractor. The forest chips are unloaded to the fuel store and transferred to the boiler by conveyers. Fuel storage is normally dimensioned so that there is enough fuel for weekend consumption (68 hours at full load). At sawmills, bark is normally stored at the field.

The fuel handling system is more complex at large municipal CHPs. The fuel handling system normally includes the fuel-receiving system in which trucks are unloaded. The fuel is then transferred by conveyors to big fuel stores. From there, the fuel is conveyed to boiler silos through fuel screening and an oversized crushing system. From boiler silos, fuel is fed to the boiler. An example of the fuel handling system is shown in Figure 2.17.

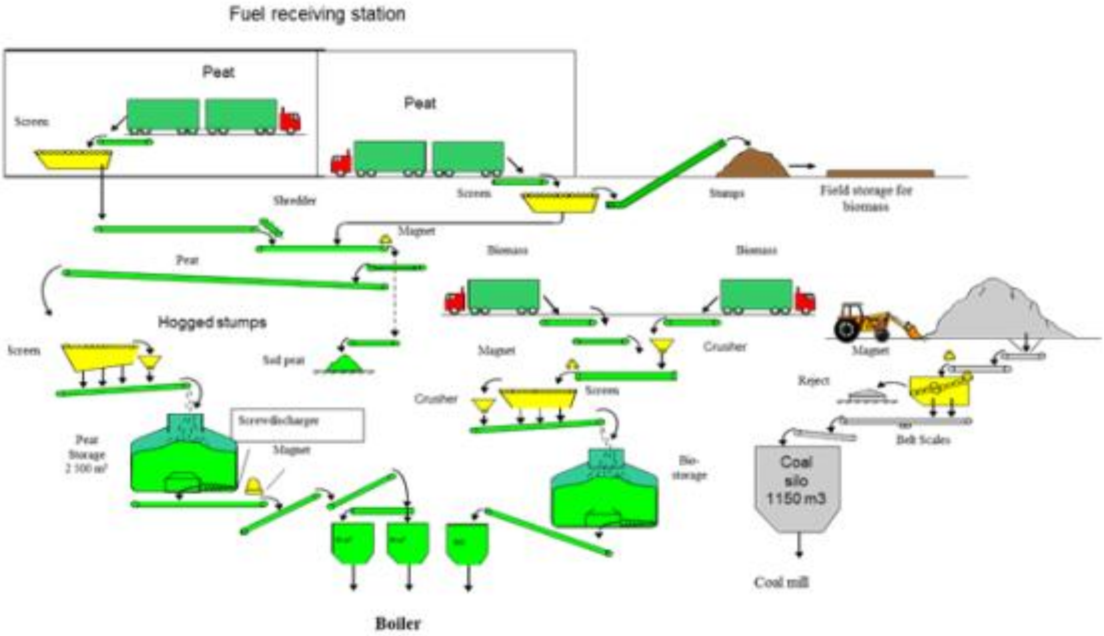


Figure 2.17. Fuel handling system in a CHP plant using different kinds of fuels like forest chips, stumps, peat and coal (Impola 2013)

At power plants situated next to forest industry, the by-products from the processes are normally stored in the field area, from where the fuels are transferred to the power plant's fuel handling system. Figure 2.18 shows a modern fuel handling system in which the fuel mixture is formed on a boiler house conveyor.

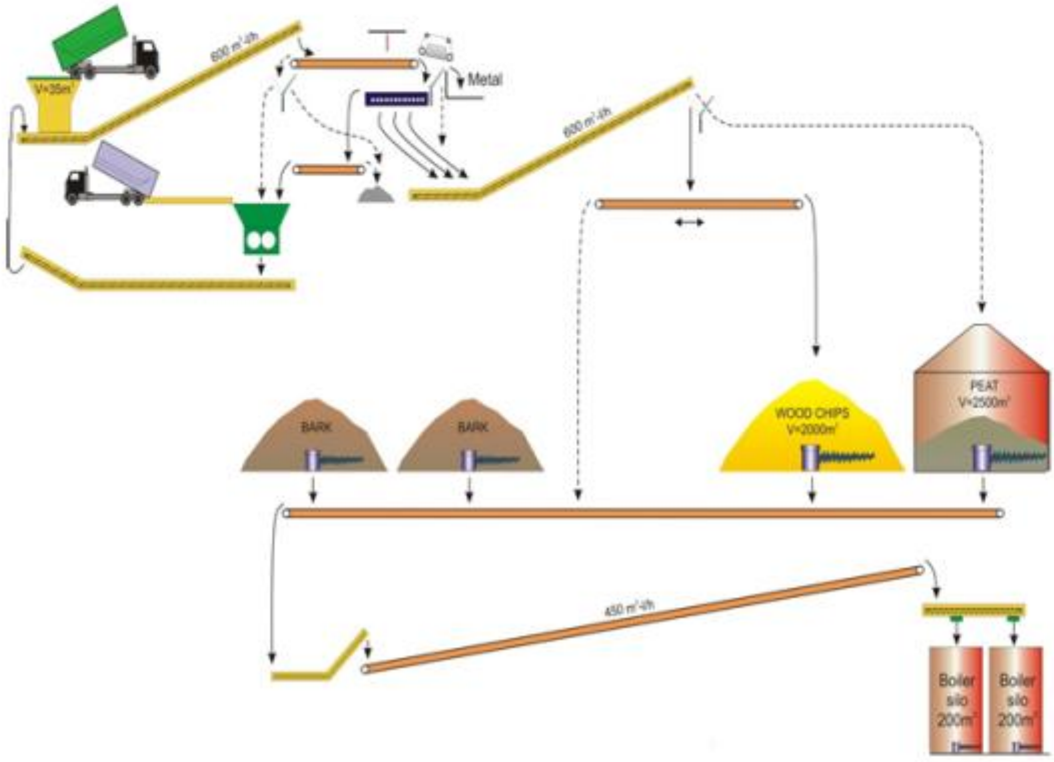


Figure 2.18. Modern fuel handling system (Impola 2013)

2.6.2 Combustion technologies

The Finnish solid fuel-fired boiler plants consist of 700 grate boilers, approximately 120 fluidised bed boilers and about 25 pulverised fuel boilers. Most of the biomass fuels and peat are combusted in fluidised bed boilers. Grate boilers are small and often used for heating purposes. Pulverised fuel boilers mainly combust coal.

Grate firing is the oldest firing principle used in boilers and the best known on a small scale (under 5 MW). Fuels are fed to the grate, where they are first dried then pyrolysed and finally the char is burnt. Static or mechanically activated sloped grates are typically used for biofuels. Controlling the combustion process and emission is more difficult in grate firing than in, e.g., fluidised bed (FB) combustion (Finnish Environment Institute 2001).

FB combustion is especially suitable for inhomogeneous biofuels. There is no need to pulverise or dry the fuel; mechanical crushing is enough to facilitate its feeding to a boiler. Other advantages of FB combustion are flexibility for different fuels, cheap sulphur capture, low NO_x emissions and low content of unburnt carbon (Hyppänen and Raiko 1995). Combustion is performed in a bubbling fluidised bed (BFB) or a circulating fluidised bed (CFB). A typical BFB boiler is presented in Figure 2.19 and an illustration of its function is shown in Figure 2.20. Biofuels are dried and pyrolysed instantly in contact with the hot bed. The bed material is usually sand with a certain particle size. In CFB combustion, part of the bed material is carried out from the bed, separated from the flue gas by a cyclone and returned back to the boiler. This circulation smoothens the temperature profile in the boiler (Finnish Environment Institute 2001).

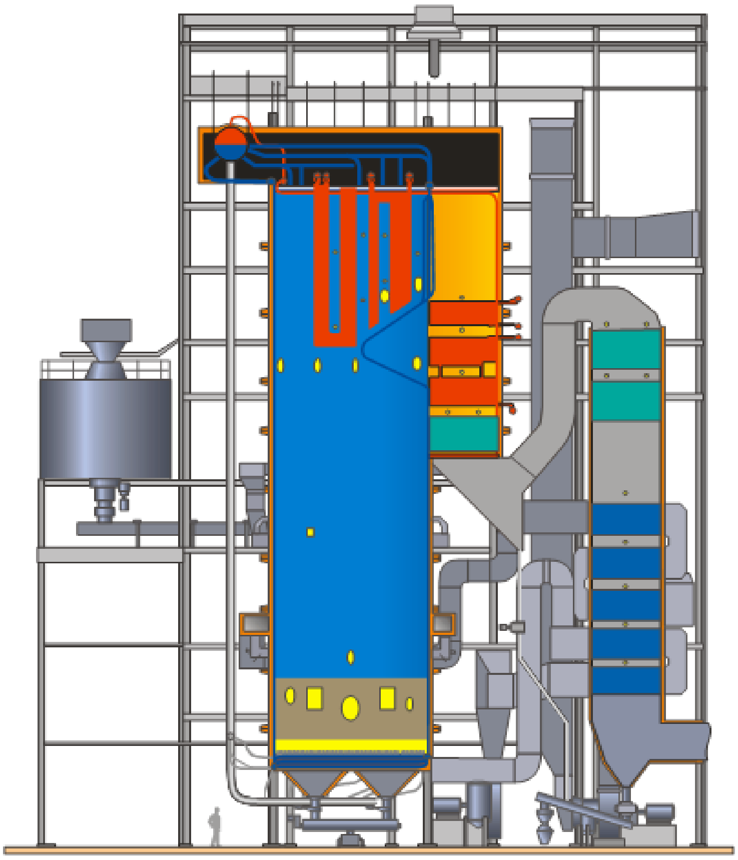


Figure 2.19. Typical bubbling fluidised bed boiler (BFB) (Courtesy of Valmet)

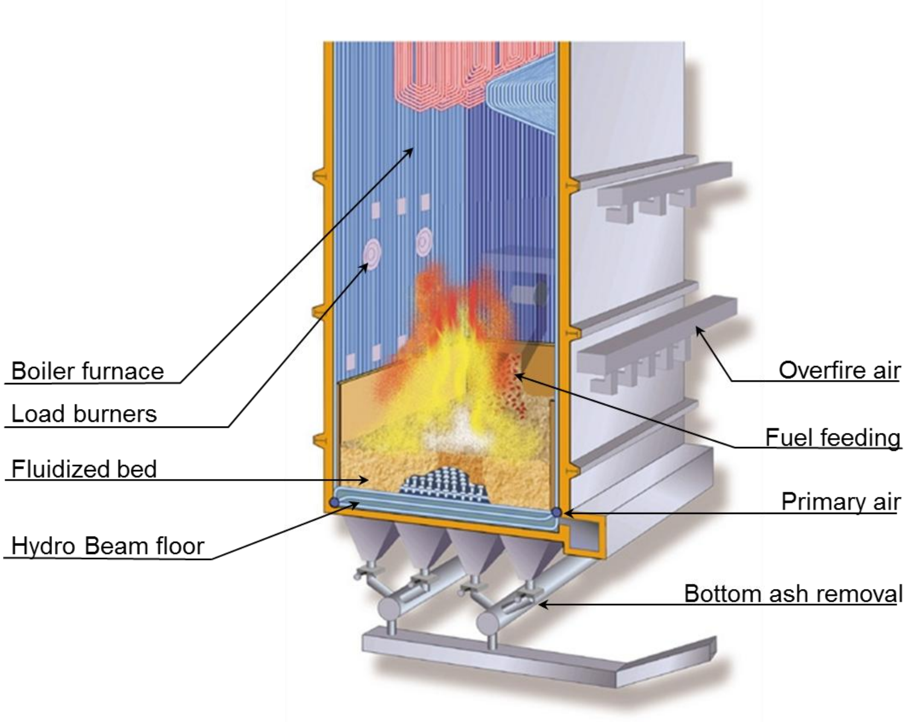


Figure 2.20. Illustration of the bubbling fluidised bed function (Courtesy of Valmet)

Two different ash fractions are usually collected in a combustion plant. The bottom ash fraction is collected from the bottom of a combustion chamber and fly ash is separated from the flue gases by electrostatic precipitators or fabric filters. Coarse fly ash (boiler fly ash, cyclone fly ash) may also be collected in a power plant. In grate boilers, the bottom ash usually accounts for 60 to 90% of the total ash generated. In fluidised bed boilers, the fly ash fraction is the largest, usually 80-90% of the total ash generated.

2.6.3 Biomass ashes

In general, the combustion technology and flue gas cleaning system determine the basic characteristics of the ashes and form the basis of ash management, i.e. they define the ash types, amounts, etc. The properties and therefore behaviours of ashes are also always highly dependent on the fuels used and the prevailing combustion conditions.

Ashes are regarded as waste, and their utilisation is regulated by many European and national laws and degrees. Environmental permission is needed if wastes are utilised, with certain exceptions, such as, the utilisation of peat and biomass ashes in Finland as fertilisers according to the fertiliser product legislation and the utilisation of coal, peat and biomass ashes in certain earth construction applications, according to the decree on the recovery of certain wastes in earth construction (notification procedure). In addition to environmental suitability (e.g. total content and leaching of harmful substances), the ashes need to have a minimum technical applicability for the intended applications.

Current utilisation practices for biomass ashes in Europe include (van Eijk 2012):

- forest fertiliser
- fertiliser or liming agent in agriculture
- additive to compost production
- earth construction material
- construction or covering material at landfills
- concrete filler
- asphalt filler
- soil stabilisation
- grouting mines

A large amount of the ashes is still landfilled because options for recycling have not been found.

Approximately 500 000 tons of peat and biomass ashes are produced annually in Finland as by-product of energy production. The total annual ash production in Finland is about 1 200 000 tons, about half of which is produced in coal combustion. There is some variation between years depending on the amount of coal used in energy production and the availability of other fuels (e.g. peat). No official statistical data are available on the utilisation degree of ashes in Finland. A few years ago, the utilisation degree was about 50%. Since then, there have been significant changes in legislation. The most influential change may have been the classification of fly ashes as taxable wastes. The rise of landfill costs has forced power plant owners to look for new ways to utilise ashes.

2.7 Highlights

- Bioenergy production in Finland in 2012

    - The total use of forest chips was about 15 TWh at almost 900 heat and power plants
    - The use of by-products and residues from the wood processing industry was about 17 TWh
    - Most biomass fuels are used in the pulp and paper industry – 38 TWh of energy was produced by combustion of black liquor in recovery boilers
    - A total of 89 TWh of wood-based fuels was used including recycled wood and wood used on a small scale
- In most of the cases, forest energy procurement is combined with commercial roundwood harvesting. The most common chipping methods are roadside chipping, terminal chipping and chipping at the plant. The role of fuel terminals will grow in the future. Fuel quality will also play a bigger role in the future.
- The Finnish national renewable energy action plant sets the 2020 target for the use of forest chips in the generation of heat and power at 25 TWh. Increasing the use of forest chips in multi-fuel boilers is the most central and cost-effective way to increase the use of renewable energy in the generation of power and heat. If forest chips are used to replace coal in energy production in coastal areas, the logistics of fuel supply will be important. In Finland, there are many plans to utilise forest biomass in the production of different upgraded fuels, e.g. bio-oil, biodiesel and bio-coal. Transport distances will grow because the biggest unutilised biomass potential and potential biomass fuel users are situated in different areas.

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3 Health and safety factors of bioenergy production

3.1 Physical factors

Esko Rytkönen (FIOH)

Exposure to loud noise, particularly over long periods of time, can cause noise-induced hearing loss. Noise does not need to be excessively loud to cause problems in the workplace. Noise can interact with other workplace hazards to increase the risks to workers by, for example, increasing the risk of accidents by masking warning signals and interacting with exposure to certain chemicals to further raise the risk of hearing loss (EASHW 2013).

In the noise directive 2003/10/EC (EC 2003), the physical parameters used as risk predictors are defined as follows: daily noise exposure level (LEX, 8h): time-weighted average of the noise exposure levels for a nominal eight-hour working day; peak sound pressure level (Lp, peak): maximum value of the ‘C’-frequency weighted instantaneous noise pressure level. These occupational noise exposure values can be applied to bioenergy supply chain workers. The fixed noise values are presented in Table 3.1.

Table 3.1. The exposure limit values and exposure action values with respect to daily noise exposure levels and peak sound pressure are fixed

	$L_{EX,8h}$	$L_{p,peak}$
exposure limit values	87 dB(A)	140 dB(C)
upper exposure action values	85 dB(A)	137 dB(C)
lower exposure action values	80 dB(A)	135 dB(C)

Noise emission directive 2000/14/EC (EC 2000) applies to certain equipment for use outdoors, e.g. loaders, dumpers, grass trimmers, hedge trimmers and shredders/chippers. These emission values can be used to help evaluate environmental and occupational noise exposure.

Work-related vibration exposure can be split into two forms: whole-body vibration (WBV), which is transmitted by mobile or fixed machines when the operator is standing or seated, and hand-arm vibration (HAV), which is transmitted by hand-held or guided tools. Directive 2002/44/EC (EC 2002) lays down minimum requirements for the protection of workers from risks to their health and safety arising, or likely to arise, from exposure to mechanical vibration during their work. The values are shown in Table 3.2.

Table 3.2. Daily exposure limit and action values standardised for an eight-hour reference period

	daily exposure limit value	daily exposure action value
whole-body vibration	1.15 m/s^2	0.5 m/s^2
hand-arm vibration	5 m/s^2	2.5 m/s^2

Exposure to hand-arm vibration may cause vibration-induced ‘white finger syndrome’. Whole-body vibration is uncomfortable and tiring and can cause serious harm over time. The combined exposure by workers to vibration and muscular work and to awkward postures is a matter of concern. Common noise and vibration sources in the forestry industry include vehicles, stump grinders, wood chippers, chainsaws and peeling machines Risks increase when proper damping techniques are not applied, machines are not maintained, tools are not alternated and workers use a vibrating tool or vehicle for long periods without a break (EU-OSHA 2008).

Forty-two accounts of noise exposure and 164 accounts of whole-body and hand-arm vibration exposure were collected from 43 forestry workers. The data were collected on 10 days over 8 weeks during various felling, logging and log handling operations. Substantial overexposure to noise and vibration was seen (Neitzel and Yost 2002).

The exposure by forest machine drivers to whole-body vibration and noise was studied in harvesting, tilling of soil and drainage/road building. Twenty-two forest machines of different ages and manufacturers were chosen as the objects of the study. The RMS acceleration of vibration measured in the driver's seat exceeded the action value 0.5 m/s^2 in 21 forest machines. The limit value 1.15 m/s^2 was exceeded in 11 forest machines and in all the tilling machines. The noise exposure for the drivers was below 85 dB(A) (Sorainen et al. 2005).

The exposure by 16 timber truck drivers to whole-body vibration and noise was measured. The seat vibration in the trucks exceeded the daily exposure action value of 0.5 m/s^2 in 63% of the cases. In the seats of the timber cranes, the vibration exceeded the daily exposure limit value of 1.15 m/s^2 in some cases. The noise exposure for the drivers was below 80 dB(A) (Sorainen et al. 2007).

Lowering the tyre pressure using a CTI system (Central Tyre Inflation) is one means to reduce vibration in the seat of the truck. Vibration measurements were taken from the tyre axle, the body of the timber truck, the floor of the truck cabin and the driver’s seat. The measurements were taken when driving on the same road using normal tyre pressure and using lowered tyre pressure with a loaded and an unloaded truck. Different road types were examined. The lowered tyre pressure reduced vibration most at the tyre axle with a smaller reduction at the measurement points nearer the driver’s seat. The vibration reduction with no load was greater than with a load (Oksanen et al. 2009).

In the working conditions for forest energy production, there are several health risks, e.g. accidents, whole-body vibration and noise (Hedlund et al. 2010). The operator noise exposure for seven mobile chippers was measured using noise dose meters on one working day. The noise levels were 73-90 dB(A) (Hedlund and Andersson 2013).

The Health and Safety Laboratory performed measurements of the noise emission and operator noise exposure of a range of mobile, hand-fed, wood chippers under simulated standard and real world operating conditions. Of the eleven selected, ten were disc type and one was a drum action chipper. The noise levels for the operator of the chipper varied between 96 and 106 dB(A) (Bruek 2008).

Many power plant workers are exposed to a high level of noise. A noise survey in an electric power plant indicated that the maintenance operator was exposed to noise at 85 dB(A) and the control room operator at 79 dB(A) (Junsupasen and Yodpiijit 2012).

The noise exposure levels for power plant operators varied between 70 and 93 dB(A), and, consequently, the exposure for service personnel between 69 and 100 dB(A). The noise levels of power plant noise sources are shown in Table 3.3 (FIOH, unpublished data).

Table 3.3. Examples of different industrial noise sources

coal grinder	88-100 dB(A)
pumps	86-96 dB(A)
turbines	85-93 dB(A)
generators	84-93 dB(A)
fans	87-98 dB(A)
compressors	89-102 dB(A)
diesel engine (reserve power)	100-108 dB(A)

In the conductor rails of power plants, there are big electric currents that cause magnetic fields. Examples of electric and magnetic fields are shown in Table 3.4 (Hietanen et al. 2005).

Table 3.4. Examples of different industrial electric and magnetic sources

	Electric field kV/m	Magnetic flux density µT
control room	1.5	75
power plant	6	150
current supply station	24	400

The electromagnetic fields directive 2013/35/EU is intended to address all known direct biophysical effects and indirect effects caused by electromagnetic fields. In this directive, the work-related exposure limit values and action levels are given for electric fields and magnetic fields (EC 2013).

3.2 Biological agents

Sirpa Laitinen and Marjaleena Aatamila (FIOH)

3.2.1 Introduction

Handling, storing and processing biomass produces organic dust, which is defined as dust containing particles of plant or animal origin. Another, often synonymously used, term for organic dust is bioaerosol, which can be defined as aerosol or particulate matter of microbial, plant or animal origin (Douwes 2003). Bioaerosols are generated by physical disturbance of organic material and can occur as liquid droplets or dry materials that are suspended in the air individually, as clusters or carried on other organic material. Heavy processes such as chipping and crushing wood may be significant sources of airborne bioaerosols. According to Finnish legislation (Ammattitautiasetus 1347/1988), organic dusts such as from plants (e.g. wood) and animals are classified as chemical agents (Section 3.3). Micro-organisms such as bacteria, viruses, fungi and parasites are biological agents.

In addition to the origin of the organic dust, health risks are posed by the size effect of the particle coming from biomass. Typically, bioaerosols have a particle size of 0.02-100 µm (Hinds 1999). Depending on the size, aerosol particles easily deposit in various parts of our airways. The smaller the particles, the further they can travel into the lung and thus pose a greater hazard. The most serious damage is done by respirable particles that are able to enter our bloodstream through the alveoli where the oxygen uptake takes place in our lungs.

In reality, particle size and shape can be complex and are difficult to measure. The size can be indicated as an aerodynamic diameter, which is the diameter of a unit-density (1 g cm^{-3}) sphere of the same gravitational settling velocity as the particle being measured (Willeke and Baron 1993).

The classification by aerodynamic diameter is as follows:

- Respirable dust (PM2.5): particles of less than 2.5 µm that will penetrate into the gas exchange region of the lungs
- Thoracic dust (PM10): particles of 10 µm diameter or less that will pass through the nose and throat and reach the lungs
- Inhalable dust (PM100): airborne particles of 100 µm diameter or less that can enter the nose and mouth during normal breathing

3.2.2 Occurrence of biological hazards and their health effects

Biological agents can consist of pathogenic or saprophytic, live and dead micro-organisms and their fragments. These can include, e.g., microbial cells, spores and toxins. Woody and other biomass provide favourable substrates for micro-organisms due to their nutrients and moisture. The most common micro-organisms in biomass are saprophytic micro-organisms whose mission is to decompose biomass back into nature. Only a few of these have been recognised as pathogenic to healthy humans. Wild animals can also carry pathogens and contaminate biomass by, e.g., faeces, which poses a health risk to workers when handling the biomass.

The most common routes of entry by biological agents are inhalation of airborne micro-organisms and their fragments and direct contact with organic material. Direct contact includes absorption through mucous membranes (eyes, nose and mouth) and chapped, sheared or any other broken skin. Ingestion during eating and smoking is also possible from contaminated hands.

There is little data on the dose-response relationship between humans and micro-organisms. The response to a micro-organism depends on its virulence, infectivity, and the resistance of the body. Thus, there is great difficulty determining limit values to which health effects can be ascribed. The general consensus is that exposure to high concentrations of micro-organisms should be avoided. Prolonged exposure to elevated levels significantly increases the risk of diseases. However, the greatest hazard to workers is usually caused by irritation of the mucous membrane and toxic or allergenic effects following inhalation of a large number of micro-organisms and their fragments (Douwes 2003).

3.2.3 Infectious diseases

These microbiological health effects are derived from pathogenic, viable organisms (viruses, bacteria, fungi or parasites) entering the host, propagating within the body and resulting in disease. Pathogenic responses are a rare occurrence. Unfortunately, the outcomes of infections by pathogens can be serious and some deaths have even been linked to them. Immunocompromised individuals are at particular risk of becoming seriously ill.

Infectious diseases, such as mycosis, may arise from inhalation of fungal spores in the course of handling decaying matter. For example, the common fungus *Aspergillus fumigatus* in wood chip piles can cause this kind of infectious mycosis, aspergillosis.

Some infectious diseases of workers may be zoonoses (Karesh 2012). These are human diseases caused by pathogens shared with wild or domestic animals. Thus, there is interaction between at least three species: one pathogen and two hosts (human and another animal species). Zoonoses can be categorised according to their route of transmission: food-borne or vector-borne. Here, we have tabulated zoonotic diseases that are only vector-borne (Table 3.5).

Table 3.5. Vector-borne zoonoses (IFA-Report 2011, Haagsma et al. 2012, Makary et al. 2010)

Pathogen	Disease	Vector
Anaplasma phagocytophilum	Human granulocytic anaplasmosis	Tick
Borrelia burgdorferi	Borreliosis	Tick
Francisella tularensis	Tularaemia	Insect, infected animal (hare, vole)
Puumalavirus (Hantavirus)	Epidemic nephropathy	Infected bank vole
Lyssavirus (rabies virus)	Encephalitis	Infected animal (fox, bat, raccoon dog)
Sindbis virus	Pogosta disease	Insect
Flavivirus (TBE virus)	Tick-borne encephalitis	Tick

In Finland, the Puumala virus is the most prevalent serious febrile zoonotic infection, and the burden of the disease is growing. Its host reservoir is bank voles, and the route of infection is believed to be through aerolised excreta. In 1995-2008, almost all the reported occupational cases (590) were related to farming or forest work and the principal population at risk was males of working age. Although the mortality rate is low, more than half of all reported cases are hospitalised (Makary et al. 2010). Typical symptoms are fever, headache, nausea, abdominal and back pain, and occasionally renal symptoms (Vapalahti et al. 2003). The bank vole populations vary greatly by year (3-4-year cycles), season and region. The epidemic is usually between late summer and early winter, and the incidence rate is higher in the eastern parts of Finland than the southwestern regions (Makary et al. 2010).

Occupational zoonosis transmitted by ticks or insects is seldom identified in Finland. In 2011, there were three occupational cases of tularemia but no cases of, e.g., borreliosis (Oksa et al. 2013), which is quite common in the Finnish population (1587 cases in 2012) (Jaakola et al. 2013). The small number of cases of occupational zoonosis may be a result of underreporting, due to the difficulty of identifying a link between the disease and work-related exposure (Haagsma et al. 2012). Finland is a rabies-free country, except in bats, and the risk to humans is very low at this time. However, there is high infection pressure in wild carnivore species in Russia and that poses a continuous risk of reintroduction of the disease (EFSA 2011).

3.2.4 Allergic and non-allergic respiratory diseases

The response by the body and immune system is highly specific to the individual, making it difficult to develop guidelines. The nature of the response mechanism is related to the organism and its fragments, though there are generally two groups of conditions (Douwes 2003):

- Allergic: extrinsic allergic alveolitis (EAA, sometimes called hypersensitive pneumonitis HP), asthma and allergic rhinitis
- Non-allergic: organic dust toxic syndrome (ODTS), chronic bronchitis, chronic obstructive pulmonary disease (COPD)

The main distinction between allergic and non-allergic respiratory diseases is that allergic respiratory symptoms reflect an immune-specific inflammation in which various antibodies can play a major role. The allergic responses are chronic conditions that, once the individual is sensitised by repeated exposure at low (non-toxic) doses, cause a reaction. The non-allergic respiratory symptoms reflect a non-immune-specific airway inflammation caused by an exposure to a toxic level of the hazard. ODTS is an acute febrile non-allergic illness, and its symptoms resemble those of influenza without long-lasting effects. The symptoms of EAA are very similar to ODTS but more serious and may lead to permanent lung damage and work disability.

Fungi such as moulds and yeasts may be the causative agents of these respiratory diseases together with bacteria. In bioenergy production, the amounts of handled and stored biomass are large, which enables elevated levels of airborne fungi and bacteria (Table 3.6). Mesophilic and thermophilic actinobacteria and *A. fumigatus* fungi have been found to be abundant at wood chip plants (Madsen 2006). This may be due to self-heating of wood chips causing growth of thermophilic and thermotolerant microorganisms. Prolonged exposure to bioaerosols is likely to give rise to increased risks of sensitisation to fungi. Workers who have previously been sensitised to moulds may experience an exacerbation of symptoms at very low exposure levels. Fungi and gram-positive bacteria such as Actinobacteria, *Bacillus* and *Clostridium* genera, may produce spores that will be resistant to heat, cold, desiccation and sunlight. Hence, these may also survive in bioaerosols.

Actinobacteria and fungi, in particular, have been described as promoting the development of EAA (Yocum et al. 1976, Halpin et al. 1994).

In the wood-processing industry, dose-response relationships have been found between personal exposure to fungi and bacterial endotoxin, and work-related symptoms (Alwis et al. 1999). All gram-negative bacteria in the organic material include endotoxin, which is a fragment of their cell walls. Endotoxins are pulmonary immunotoxicants. They can cause acute systemic and respiratory symptoms (dry cough, shortness of breath, fever, shivering and joint pain) and acute changes in lung function. The chronic effect of endotoxin can be an accelerated decline in lung function and increased bronchial reactivity, which can lead to COPD. The Nordic and Dutch Expert Group (2011) has concluded that adverse health effects are expected after chronic occupational exposure at approximately 90 EU/m^3 (EU = endotoxin unit). In addition, endotoxin may have adjuvant effects on reactions to allergens. It may synergistically enhance the release of allergic mediators and increase the production of antibodies.

Mycotoxins, metabolites of fungi, are potent carcinogens and teratogens (Fung and Clark 2004). However, very little is known about occupational airborne exposure to mycotoxins and the respiratory health effects.

Table 3.6. Levels of airborne microbes in processing biomass (cfu = colony forming unit, viable micro-organisms, total = dead and viable micro-organisms).

Bacteria	Endotoxin EU/m^3	Fungi (moulds)	Sampling place or situation/material
$6.6*10^{3}$-$9.4*10^{4}$ bacteria/m^3 (total)		$9.7*10^{3}$-$6.2*10^{4}$ fungi/m^3 (total)	Power plants using wood pellets[1]
$7.0*10^{5}$-$1.2*10^{6}$ bacteria/m^3 (total) $2.6*10^{4}$-$5.7*10^{4}$ cfu/m^3		$7.9*10^{5}$-$1.2*10^{6}$ fungi/m^3 (total) $2.0*10^{5}$-$5.4*10^{5}$ cfu/m^3	Handling/chipping of logging residue logs[2]
$0.5*10^{6}$ cfu/m^3 (max)	1300 (max)	$8.6*10^{6}$ cfu/m^3 (max)	Handling/crushing of stumps, logging residue logs and reed canary grass[3]
Actinobacteria $8*10^{4}$ cfu/m^3 (max)	<0.3-440	$1.7*10^{5}$ cfu/m^3 (max)	Crushing stumps, logging residue logs and reed canary grass[4]
$6.3*10^{6}$ bacteria/m^3 (total, max) $1.3*10^{6}$ cfu/m^3 (max)	1300 (max)	$7.1*10^{6}$ spores/m^3 (total, max) $2.1*10^{6}$ cfu/m^3 (max)	Biofuel plants using wood chips [5]
		$1*10^{7}$ cfu/m^3 (max)	Handling of wood chips[6]
$5.1*10^{2}$-$2.0*10^{4}$ cfu/m^3		$2.2*10^{2}$-$2.3*10^{4}$ cfu/m^3	Handling of wood chips and sunflower seed peel pellets[7]

[1] Alvarez de Davila et al. 1999 [2]Jirjis and Norden 2005 [3]Ajanko and Fagernäs 2006 [4]Ajanko 2009 [5]Madsen 2006 [6] Surakka et al. 2004 [7]Ławniczek-Wałczyk et al. 2012

3.2.5 Responses to allergens

The organic nature of biomass may result in impacts through allergenic routes. Allergic type I responses are generated by immunological sensitisation to a specific allergen and cause the production of a specific immunoglobin E response. These IgE-mediated allergies are asthma, allergic rhinitis and, on skin contact, dermatitis. The majority of the allergic responses will be minor and short lived, and the falling incidence of response is linked to increasing severity. Some fungal species such as *Alternaria* and *Cladosporium* have been described as producers of type I allergens. Other examples are pollens, seeds of reed canary grass and insects, which may include allergens.

Stinging and biting insects are a risk to outdoor workers. These insects include bees, wasps and hornets. If a worker is allergic to an insect's venom, more serious effects occur (NIOSH). The deer ked (*Lipoptena cervi*) is a blood-sucking ectoparasite of cervids that has been resident in Finland for about 50 years (Välimäki 2010). Though its predominant host species is the moose, they often attack and bite other animals, including humans. The bite is barely noticeable, but within three days the site develops into a hard, reddened welt. In deer ked dermatitis lesions, the itch is intense and long lasting (Dehio et al. 2004). Deer ked may act as a vector for zoonotic diseases. A study in Norway suggested that deer keds may be potential vectors for the transmission of *Bartonella* spp (Duodu et al. 2013).

3.3 Chemical agents

Mika Jumpponen and Juha Laitinen (FIOH)

3.3.1 Wood dust

Pure wood compositions vary considerably according to the species of the tree. Wood dust is composed mainly of cellulose, polyoses, lignin and a large and variable number of substances of lower relative molecular mass that may significantly affect the properties of the wood. These include non-polar organic extractives (fatty acids, resin acids, waxes, alcohols, terpenes, sterols, steryl esters and glycerols), polar organic extractives (tannins, flavonoids, quinones and lignans) and water-soluble extractives (carbohydrates, alkaloids, proteins and inorganic material) (WHO 1995). In addition, pure wood dust may contain natural wood impurities like sand, and chemical impurities such as biocides, pesticides, insecticides and herbicides (Työhygienia 2008). In the case of recovered waste wood, the content of chemical impurities may be even higher and include glues, surface coatings, plastics and wood preservatives (Enestam 2011).

Wood dust is divided into hardwood and softwood dusts. Roughly two-thirds of the wood used commercially worldwide belongs to the group of softwoods (WHO 1995). Dust from softwood, like spruce and pine, and birch are commonly found in forestry, the woodworking industry, the paper and pulp industry, pellet production and power production (Directive 90/394/EEC, Vna 716/2000, Kemikaalit ja työ 2005, Ahonen and Liukkonen 2007, HTP-arvot 2012). Workers in the biofuel supply chain can be exposed to softwood dust at the beginning of the supply chain during the chipping of wood, in the middle during transportation of biofuel to the power plant and, especially, at the end when the biofuel is received into the bio power plants.

Hardwoods tend to be denser and have a higher content of polar extractives than softwoods (WHO 1995). Hardwood dusts such as from oak and beech are classified as carcinogenic to humans by the EU (Directive 90/394/EEC). Most of the wood dust found in work environments has a mean aerodynamic diameter of more than 5 µm. Some investigators have reported that hardwoods may result in a higher proportion of smaller particle sizes than softwood does, but the evidence is not consistent (WHO 1995).

General knowledge of particle size indicates that wood dust can be deposited in human upper and lower airways, the deposition pattern depending partly on the particle size. Heavy exposure to wood dust may result in reduced mucociliary clearance and, sometimes, mucostasis. Exposure to wood dust may cause cellular changes in the nasal epithelium. Increased frequencies of cuboidal metaplasia and dysplasia were found in some studies of workers exposed to dust from both hardwood and softwood. These changes can potentially progress to nasal carcinoma. Impaired respiratory function and increased prevalence of pulmonary symptoms and asthma have also been found in workers exposed to wood dust (WHO 1995).

3.3.2 Inorganic dusts

The impurities in pure wood are mainly responsible for inorganic emissions during the chipping of wood in the beginning of the biofuel supply chain. These impurity emissions normally correlate to the soil composition of the forest where the woods are collected. In the peat collection fields, the mineral composition of the bogs also plays an important role, for example, the emissions of crystalline silica. During transportation and reception of biofuels in the bio power plants, these above-mentioned factors also affect workers' exposure to inorganic dusts. In the case of recovered waste wood, the most important factors for the levels of inorganic dust emissions are the degree of crushing and the quality of the materials.

The third important work phase at the end of the bioenergy supply chain is maintenance at the bio power plant, including ash removal and different maintenance work tasks inside the boilers. In these work tasks, the biofuels, ash removal techniques, processed materials and tooling techniques greatly affect the workers' exposure levels and quality of inorganic dusts (WHO 1999, Schenker 2000).

The concentrations of inhalable inorganic dusts during the crushing of stumps have been reported to vary from below 0.5 to 7.3 mg/m^3 at the beginning of the bioenergy supply chain (Ajanko-Laurikko 2009). The average inhalable inorganic dust concentration at the end of the bioenergy supply chain has been reported to be 39 mg/m^3 and 157 mg/m^3 during the ash removal tasks in small- and large-sized power plants inside the boilers, respectively. During the maintenance tasks, the same figure has been reported to be 71 mg/m^3 (Jumpponen et al. 2011).

At the beginning and middle of the bioenergy supply chain, one of the most important chemical agents in inorganic dust is crystalline silica, which the International Agency for Research on Cancer (IARC) has classified as carcinogenic to humans, which means it may cause lung carcinoma (WHO 1997). In the case of crystalline silica, the particle distribution of inorganic dust is the most important factor for health effects. Chronic silicosis is the disease most associated with long-term exposure to low-level respirable crystalline silica. Epidemiologic studies have found that chronic silicosis may develop or progress even after occupational exposure has ceased (Hessel et al. 1988, Hnizdo et al. 1993, Hnizdo and Murray 1998, Ng et al. 1987, Kreiss and Zhen 1996, Miller et al. 1998). Symptoms of acute silicosis may also develop shortly after exposure to high concentrations of respirable crystalline silica. Silicotics may also have higher risk of lung cancer than workers who do not have silicosis (NIOSH 2002). Furthermore, strong epidemiological evidence supports the association between long-term exposure to crystalline silica and severe health effects, e.g. chronic obstructive pulmonary diseases (COPD), cardiovascular disease and rheumatoid arthritis (Chen et al. 2012, Calvert et al. 2003, Preller et al. 2010, Sauni et al. 2012, Zhou et al. 2012, Hochgatterer et al. 2013).

The chemical impurities in inorganic dust have been found to be highest at the end of the bioenergy supply chain. In addition to crystalline silica, workers have been exposed to heavy metals and polycyclic aromatic hydrocarbons (Heating and Boiler Plant Equipment Mechanic, 5309, 1992, Jumpponen et al. 2011). In pellet, wood and recycled fuel-fired power plants, during ash removal or maintenance tasks, the average air concentrations of manganese have been found to be over the occupational limit values (OEL). In wood, peat and recycled fuel-fired power plants, the average air concentrations of aluminium have been found to be over the OEL. In addition to these, in peat-fired power plants or recycled fuel-fired power plants, the average air concentrations of arsenic and lead have been reported to be over or very near the OEL (Jumpponen et al. 2011). The exposure by workers to a single heavy metal may have various effects, but the effects of exposure to many metals simultaneously during ash removal and maintenance work tasks urgently needs to be assessed. The health effects of exposure to multiple metals have been evaluated by the Mixie program and can vary from irritation to the upper respiratory tracks through damage to the central nervous system and mutagenic effects (Shukla and Singhal 1984, Mani et al. 2007, Celic et al. 2007, Garcon et al. 2007, Halatek et al. 2009, Walton 2011).

3.3.3 Diesel exhausts

Workers can be exposed to gaseous and particular phases of diesel exhausts in different parts of the bioenergy supply chain. In the gaseous phase, diesel exhausts contain carbon monoxide (CO), hydrocarbons (HC) and, especially, nitric oxide, nitrogen dioxide and sulphur compounds (Zaebst 1991). In addition, diesel exhausts contain aldehydes such as formaldehyde and acetaldehyde, and aromatic compounds such as benzene, toluene and 1,3-butadiene, many of which are known or potential carcinogens. These gas phase compounds primarily originate from unburned fuel and lubricating oil, although some may be formed during the combustion process and by reacting with catalysts (Johnson et al. 1994).

The diesel particles consist of 80 to 90% organic and inorganic carbon (Lowenthal et al. 1994). The organic fraction of the diesel particle contains compounds such as aldehydes, alkanes and alkenes, aliphatic hydrocarbons, and PAHs and PAH derivatives (Zielinska 1990, Johnson et al. 1994, Kemikaalit ja työ 2005).

The most exposing work tasks are wood chipping, reception of biofuel, and working with trucks and wheel loaders in warehouses in power plants (Työhygienia 2008, Rytkönen et al. 2013). The inversion situation in winter is the most exposing weather situation for diesel exhausts. In this case, diesel exhausts may concentrate near vehicles, because the dilution effect due to the reverse temperature gradient is very low.

IARC (IARC 2012) has classified diesel engine exhausts as carcinogenic to humans (Group 1) based on sufficient evidence that exposure is associated with an increased risk of lung cancer.

Exposure to diesel exhausts can have immediate health effects such as irritating the eyes, nose, throat and lungs, and it can cause coughs, headaches, light-headedness and nausea. Exposure to diesel exhausts can also cause inflammation of the lungs, which may aggravate chronic respiratory symptoms and increase the frequency and intensity of asthma attacks. Diesel engines also produce fine particles, and people who already have emphysema, asthma, or chronic heart or lung disease are especially sensitive to them. Nitrogen oxides on the other hand can damage lung tissue, lower the body’s resistance to respiratory infection and worsen chronic lung diseases, such as asthma (Sydbom et al. 2001).

3.3.4 Other chemical agents

There are other chemical agents to which workers may be exposed in the bioenergy supply chain. Gases like ammonia, methane, carbon dioxide, carbon monoxide and reduced sulphur compounds can be present in closed biomass silos and warehouses, especially if the fuel has decomposed (Biojäte 2012, Kaleva 2013). Hazardous carbon monoxide concentrations have been reported, especially in warehouses of the silo type, when degradation of pellets has occurred. The highest carbon monoxide concentrations have been reported to be several magnitudes higher than the occupational exposure limit (Ahonen and Liukkonen 2007). In the even more hazardous case when the fuel transportation system from the silo to the boiler has not worked properly, gas concentrations have started to increase and ended up in fire or explosion accidents (Onnettomuustutkintaraportti 2004, Kaleva 2013).

Exposing gases can be categorised as irritating, asphyxiant or anaesthetic. A toxic effect of primary irritating gases is local inflammation in exposed cells. This normally takes place in the lungs, on the skin or eyes. The most water-soluble gases and vapours of the primary irritating chemicals interact with the upper part of the respiratory system such as the nose, pharynx and larynx. In this region, these chemicals may cause laryngitis and rhinitis. Examples of these are ammonia, sulphuric acid, formaldehyde and acetaldehyde. In addition, ammonia and air mixture can explode, and cause coughs, shortness of breath and sore throats when inhaled in high concentrations (ICSC:0414 2005). Median water-soluble gases and vapours of the primary irritating gases interact with the upper respiratory system, such as the region of the bronchial tubes. In this region, sulphuric dioxide, for example, may cause bronchitis or pneumonia. Low water-soluble, but very reactive, gases and vapours of the primary irritating gases include nitrogen oxides, which interact directly with the lower parts of the respiratory system such as the bronchial tubes and alveoli. In this region they may cause pulmonary oedema at high concentration levels (Lauwerys 1977).

The toxic effects of secondary irritating gases are local inflammation in exposed cells in the lower part of the respiratory system and systemic effects such as inhibition of the respiratory chain. Hydrogen sulphide is this kind of gas (Lauwerys 1977). Hydrogen sulphide is also an easily flammable gas and is classified as fatal if inhaled (Ova ohje 2013). Methyl mercaptan and air mixture can explode and cause coughs, headaches and suffocation in high concentrations (ICSC: 0299 2008).

The first category of asphyxiant gases only begins to be dangerous in very high concentrations when they start to replace oxygen and reduce the partial pressure of oxygen in inhaled air. These kinds of gases include methane and carbon dioxide. It is also important to remember that if the concentration of methane is high enough it can explode (ICSC: 0291 2005). Carbon dioxide can cause fatigue, headaches and suffocation in high concentrations (ICSC: 0021 2006).

The second category of asphyxiant gases is chemically suffocating gases. One such chemical is carbon monoxide (Lauwerys 1977). Carbon monoxide is also an easily flammable gas and can cause headaches and harm to the unborn child (OVA-ohje 2011).

The third group of gases is chemicals with the potential to cause neurological symptoms. These kinds of vapours are hydrocarbons (Lauwerys 1977).

At the end of the bioenergy supply chain, workers are exposed to gases and vapours originating from ashes and unburned fuel, especially in ash removal and maintenance work tasks. Fuel may still be burning, or burned ash may still be hot, during maintenance and ash removal work inside biomass-fired power plant boilers. When fuel is burning or smouldering inside the boilers, workers may be exposed to gases and volatile pollutants of hot ash. This ash may still be present when workers weld and grind materials inside the boilers, and its ingredients may evaporate or be released by the high temperatures of these maintenance tasks (Jumpponen et al. 2013).

During ash removal and maintenance tasks, the most commonly found gas in boiler air, boiler rooms and superheaters has been reported to be carbon monoxide, the average concentration of which was 0.5 ppm. The average air concentrations of carbon monoxide were 7-37% of the Finnish OEL of 30 ppm for ash removal tasks and 1-3% of the OEL for maintenance tasks. The maximum concentrations of carbon monoxide have been 7-61% of the Finnish STEL (short-term exposure limit) of 75 ppm for ash removal tasks, and 4-52% of the STEL for maintenance tasks. The second most commonly found gases have been reported to be nitric oxide, ammonia and sulphur dioxide. Nitric oxide and ammonia were found in the boiler air, the boiler rooms and the superheater air, but sulphur dioxide was only found in the superheater air. At these sampling points, the average concentrations of nitric oxide, ammonia and sulphur dioxide have been reported to be 0.06 ppm, 0.11 ppm and 0.42 ppm, respectively. The average air concentrations of nitric oxide have been below 0.4% of the Finnish OEL of 25 ppm for ash removal tasks, and 0.4% or below that for maintenance tasks. The third most commonly found gases have been reported to be nitrogen dioxide and hydrogen sulphide, which have been found in the boiler rooms and the superheater air. Nitrogen dioxide was also found in the boiler air. At these sampling points, the average concentrations of nitrogen dioxide and hydrogen sulphide were 0.05 ppm and below 0.01 ppm, respectively. The average air concentration of nitrogen dioxide was below 3.3% of the Finnish OEL of 3 ppm for ash removal tasks and maintenance tasks (Jumpponen et al. 2013).

A large number of mutagenic and carcinogenic polycyclic aromatic hydrocarbons (PAHs) have also been detected in fly ash particles (Dormans et al. 1999, Mani et al. 2007). The PAHs are carcinogenic to humans and suspected of damaging the mother and unborn child (FIOH 2010, 2013). During ash removal and maintenance tasks, 16 PAH compounds have been analysed in the air of biomass-fired power plant boilers. Phenanthrene and naphthalene have been the most commonly found PAHs in the air of boilers and superheaters. Their average concentrations have been 0.02 µg m^{-3} and 0.23 µg m^{-3}, respectively. The second most commonly found PAHs in boiler air and boiler rooms have been reported to be benzo[g,h,i]perylene, acenaphthene, fluoranthene and pyrene. The average concentrations of these compounds have been 0.08 µg/m^3, 0.01 µg/m^3, 0.002 µg/m^3 and 0.002 µg/m^3, respectively (Jumpponen et al. 2013).

Volatile organic compounds (VOCs) are those that are evaporated from the materials, i.e. wood. The VOCs of wood are alcohols, ketones, aldehydes, terpenes and organic acids. The evaporation rate of VOCs is dependent on e.g. the materials and environmental conditions (temperature, light, soil nutrients and humidity). About 40 000 different VOCs are emitted from the plants (Julkunen 2012, Hyvärinen 2001). VOCs can cause irritation to the eyes and respiratory system when inhaled and are flammable and harmful to humans in high concentrations (HTP-arvot 2012). There are many different materials that can evaporate VOCs into the air in power plants. Power plant fuels such as wood, pellets and peat can emit VOCs into the air. When fuel is burned, VOCs are also present in the flue gases of power plants. Petrol and diesel fuels, greases and chemicals used in power plants contain VOCs. The average concentration of total volatile organic compounds (TVOCs) has been reported to be 430 µg m^{-3} in the boiler air, boiler rooms and superheater air. The highest TVOC concentration has been 2900 µg m^{-3}, which had been measured during ash removal in the wood-fired power plants. All measured air concentrations (inside peat-fired, pellet-fired and wood-fired power plants) of TVOC have fulfilled the requirements of the Finnish normal industrial reference level 3000 µg m^{-3}. The spectrums of the VOCs have been reported to vary in the air of different parts of the power plant. The most commonly found VOCs were β-pinene, benzyl alcohol and tetradecane in the boiler air. In the case of superheater air, benzaldehyde, undecane and nonanal have been reported as most prominent (Jumpponen et al. 2013). High hexanal and aldehyde concentrations have been reported in warehouses of the silo type, where degradation of pellets has occurred. The concentrations of volatile compounds have been reported to be low when pellet degradation has not taken place (Ahonen and Liukkonen, 2007).

3.4 Heavy metal compounds in biomass combustion ashes

Hanna Koponen, Jarkko Tissari and Jorma Jokiniemi (UEF)

Heavy metals can be defined as individual metals and metal compounds that can affect human health (Martin et al. 2009). In biomass combustion, heavy metals exist in both the bottom and fly ash. Bottom ash is formed from low-volatile ash compounds whereas fly ash originates via the gas phase from easily volatile ash compounds. Humans can be exposed to metal-containing ashes by ingestion and inhalation. Exposure can happen via, e.g., maintenance work, ash removal work and end use (Jumpponen et al. 2011). The health effects of heavy metals vary. Exposure to chromium, for example, can cause e.g. breathing problems, skin ulcers and long-term exposure also damages to liver, kidney circulatory and nerve tissues. Cadmium and cadmium compounds are known as carcinogens and can cause e.g. stomach irritation. Long-term exposure can also lead to kidney diseases, lung damages and fragile bones (Martin et al. 2009).

The elemental composition of biomass combustion ashes is quite well known, but little information is available on the heavy metal compounds in the ashes and the health effects of those compounds. When evaluating the toxicity of metals, it is important to know in which oxidation number the metal exists, e.g. chromium (VI) compounds are toxins and known human carcinogens, whereas chromium (III) is an essential nutrient (Martin et al. 2009).

Some recent studies have investigated the properties of biomass ashes, including heavy metal compounds.

- Rajamma et al. (2009) investigated characterisations of biomass fly ashes from two power plants (a thermal power plant and a co-generation plant) using mainly forest (eucalyptus) wastes as fuels. The analysis was performed using X-ray diffraction (XRD), X-ray fluorescence spectroscopy (XRF), thermal gravimetric and differential thermal analysis (TG/DTA), X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM) and environmental scanning electron microscopy (ESEM). The samples were collected from electrostatic precipitators. The samples contained the following metal oxides: Fe_2O_3 (2.2-2.6 %), TiO_2 (0.3-0.4 %), MnO (0.3-0.7 %) and small amounts of Cd, Pb, Cu, Cr, Ni and Zn.
- Xiao et al. (2011) studied the physicochemical properties of different biomass ashes (rice straw, pine sawdust and the Chinese parasol tree leaf). The analyses were done using XRF, XRD and SEM. The found that the metal oxides were Fe_2O_3 (0.5-3.7 %) and TiO_2 (0.03-0.2 %).
- Kalembkiewicz et al. (2012) reviewed properties of ashes from co-combustion of coal and biomasses (different amounts of wood pellets, wood chips, straw, olive kernel, forest residue, shea meal, short rotation coppice, hazelnut shell and cotton residue). The ashes contained the following metal oxides: TiO_2, Fe_2O_3 and small amounts (0-1 %) of Mn_3O_4, Cr_2O_3, Zn, Cu, Co, Cd, Ni and V.
- Tortosa Masia et al. (2007) presented properties of different fuel ashes. The ashes contained the following metal oxides: Fe_2O_3, TiO_2, Mn_2O_4, BaO, Zn0 and V_2O_5.

3.5 Accidents

Kari Ojanen and Marjaleena Aatamila (FIOH)

Based on the literature review, it was found that the hazards of bioenergy production have not been well studied. The working methods and equipment are often similar to those used in traditional forestry and agricultural work, and the methods and/or equipment, for which the potential hazards are unknown or have not been studied, are also used.

This chapter focuses on the accident situation and potential hazards in the production chains of forestry and agricultural bioenergy. There is a lack of statistical data for these working tasks. The reason is that forestry and agricultural bioenergy work do not have their own Standard Industrial Classification (Statistics Finland 2008). The accidents linked to bioenergy at power plant sites cannot easily be found from the statistics. This may be the reason accidents in these occupations have not been studied much (Ruokolainen 2012).

The TOT Investigation (Finnish fatal accident investigation system) of bioenergy accidents, however, makes it relatively easy to find the few fatalities/year. Bioenergy transport accidents include traffic accidents, and storage and utilisation cases include power plant accidents. TOT cases from the 2000s have been examined in the ongoing accident research (FIOH 2012-2015). They are mainly related to the processing of wood chips (e.g. use of the loader in the storage area, unloading chips and other biomass hauls in the silos and, e.g., pellet storage gas accidents). The other cases identified to date are typically maintenance and repair work accidents at the power plant sites, the same type regardless of the fuel used (bio/no bio). The project will look at the development of the Finnish industry classification coding and, e.g., accident reporting keywords, so the identification of bioenergy-related accidents from the statistics is improved.

3.5.1 Laws and regulations

At EU level, Council Directive 89/391/EEC (Council Directive 1989) establishes the minimum occupational safety and health standards, such as methods to improve safety and health at workplaces, general duties of employers and workers, the hierarchy of control measures and requires risk assessments to be carried out. There are no specific EU laws or official regulations concerning forestry or agricultural bioenergy raw material production, although there are several directives providing guidance on risk assessment, personal protective equipment, safe use of work equipment, preventing exposure to chemical, biological and physical agents, etc. which all apply to forestry and agricultural work.

European occupational safety and health legislation has been transposed into national legislation in each member state, though, as mentioned previously, few countries have specific forestry work legislation. For example, the only legislation that touches on forestry bioenergy raw material production at national level in Finland is the state regulation concerning safety in wood harvesting work (Päätös puunkorjuun… 2001). This states that before starting wood harvesting processes, occupational risk factors connected with steep slopes, soft terrains, water crossings, power lines, passages and other risk factors must be considered. With regard to the logging site, there must be a preventive scheme and a map describing the work site, its borders, topography and possible hazardous places, as well as the main transport directions. This relates to general European legislation and standards defining the need for a completed risk assessment – planning and organising is the key to preventing accidents.

There are recommendations and instructions at national level, at least in Finland and Sweden, concerning, e.g., damage to trees left standing (e.g. the damage caused by the forwarder contacting the trees and damaging the bark) and the roots (e.g. damage done while driving over roots on or near the ground surface) of the trees.

The ILO has published an ILO code of practice (ILO 1998) ‘Safety and health in forestry work’. It deals in detail with the whole logging process and defines the general principles, legal framework and general duties concerning different actors such as civil authorities, employers, managers and supervisors, workers, and manufactures and suppliers of equipment and substances.

3.5.2 Safety and health in logging operations

An accident will occur as a consequence of an unforeseen and unwanted event of a random nature. Accidents in forestry work, as with any other work sector, may have various consequences ranging from fatalities to injury and lost working days or even minor events leading only to material loss and a brief interruption to the work. A special event related to accidents is the near-accident in which the situation might have led to an accident but luck or special alertness led to avoidance of the accident (Lewark 2005).

3.5.3 Modern mechanisation

When logging work was mechanised from the end of 1970s onwards, the risk levels decreased from being the most accident-prone occupation down to average risk levels (Finnish Occupational… 2011). Nowadays, in forestry and wood harvesting the accident rate in the northern countries is about the national average. In 2011, there were 11 accidents with more than three days of absence per million working hours, and the average value of all occupations was 13.2 accidents per million working hours (Federation of Accident 2011).

Forestry workers have 20-30 occupational accidents per 1,000 wage earners annually. Fatality rates in Sweden and Finland are on average 0.03 fatalities/10 million m^3 of harvested wood (professional forest workers, period 2000-2004). In Germany, the corresponding rates are 0.16, in Austria 0.83 and in Switzerland 1.00 (Klun 2007).

The majority of accidents occur while repairing and servicing forestry tractors at work sites. In the past decades, machinery has become more and more reliable, thus the need for repair and service work has decreased and so has the number of work accidents. The second potentially hazardous task is climbing into and getting out of the cabin of the forwarder or harvester. Too often, especially if the way in and out of the cabin is not usable (Figure 3.1), the operator jumps out of the cabin onto the rough terrain and/or slippery (e.g. snow, branch-strewn) ground.

Figure 3.1. If the way in and out of the cabin is not usable, the operator often jumps down when he comes out of the cabin. (Photo: Kari Ojanen, FIOH)

About 20 occupational diseases per 10,000 workers are notified annually in Sweden and Finland. The most common diseases are hearing loss, musculoskeletal diseases and skin diseases (due to hydraulic oils, fuel, etc.) (FIOH 2012).

Harvesting and handling methods for forestry and agricultural biomass production are similar to the production of roundwood, hay and feedstuff. The nature of the accidents is therefore likely to be similar in the two occupations. There is also machinery, stages and methods, such as lifting stumps, and chipping or crushing, that are specific to biomass production. Sufficient and appropriate orientation, working instructions and organising of work are needed to prevent increasing accident risks, especially when using new machinery or working methods. New equipment is continuously being developed and built, and sometimes ‘do it yourself’ developers do not take into account all the accident risks. It has to be noted that in bioenergy production, accident risks are not restricted to employees, e.g. transportation (road accidents) and storage (collapse or ignition of the piles) (Lepistö 2010).

3.5.4 Risks and accidents in forestry biomass production

In Finland, as well harvesting roundwood as energy wood, the State regulation concerning safety in wood harvesting work 749/2001 must be followed (Metsäteho 2002). During the production of forestry biomass, the workers are exposed to accidents in all phases of the production.

According to EU-OSHA, the main reasons for fatal accidents are falling trees (hung-up trees) as well as traffic and work machine and work device accidents (EU-OSHA

2008). Non-fatal accidents are most likely to be caused by falling trees and limbs, a fall or slip, or a work machine. The most common injuries are contusions and bruises, sprains and strains, wounds, fractures, and stings from mites and insects.

The accident rate in mechanical wood harvesting is relatively low. The majority of the accidents occur while repairing and servicing forestry tractors at work sites (Figure 3.2). Most of the injuries in these tasks are slight and concentrated to the hands and arms. Fires can also cause accidents in mechanical wood harvesting. The most usual reasons are leaking fuel systems, hydraulics or, e.g., overheated breaks. Working near electricity and phone lines also requires special care.

Figure 3.2. Maintenance of a chipper (here changing the blades of the cutting drum) is one of the riskiest tasks in terms of accidents. In many cases, the work is done above ground level, and sharp parts of the machine have to be handled. (Photo: Kari Ojanen, FIOH)

On the landings of energy wood biomass, e.g. logging residues and energy stumps of the trees, the material must be piled up so that it is not a hazard to workers or outsiders. The piles must be stable and not too high, to avoid them crashing down (Tapola 2000, Metsäteho 2002, Pesonen ym. 2005, Lepistö 2010).

The accident rate is higher when logging is done using a chain saw (motor-manual logging) than in mechanised logging (EU-OSHA 2008). To avoid accidents in motor-manual logging, the use of personal protectors is essential. The personal protectors for loggers are safety helmet, ear and eye protectors, safety trousers with protection against chain saw cuts, shirt in a safety colour and safety boots (Lepistö 2010). Nowadays, loggers commonly use all the personal protectors, and this has increased safety significantly (Perkiö-Mäkelä 2001).

Before utilising the forestry and agricultural bioenergy, the raw material must be chipped or crushed. There are no official reports on accidents from chipping and crushing. Nor is there is any research on the risks during this work. However, a block of the chipping machine, for example, can lead to hazardous situations. Chippers and crushers also need repair and maintenance, work that carries a risk of accident.

3.5.5 Risks and accidents in agricultural biomass production

Machines pose the greatest hazards in forestry and agricultural bioenergy production. In agriculture, the second most serious accidents are generally caused by machines. Most serious accidents are caused by the work environment (Sinisalo 2007). Machines are used in every phase of agricultural bioenergy production. Most of the machines are commonly used in traditional agricultural work. Some machines are also specially designed for bioenergy production. In the production of reed canary grass (Phalaris arundinacea), special crushers, which are not used in traditional corn and forage production, are used to split long reeds to make them suitable for burning (Karttunen 2006, Sinisalo 2007, FIOH 2011).

Accidents can also happen when handling bales of reed canary grass outside the storage areas or inside the warehouses. In both cases, the ground or floor must have sufficient carrying capacity for the piled bales to remain stable and not fall down (Lötjönen 2009). The use and storage of reed canary grass in biomass-burning power plants can pose the same kinds of safety risks as the use and storage of wood chips. As reed canary grass is used as a mixture fuel, in some conditions, it can cause assorting of the fuel mixture and that way increase the possibility of clogs or vault forming in conveyors (Paappanen 2008a and 2008b).

3.6 Highlights

Physical factors

- More knowledge/study is needed of
    - Off-road machine (harvesters, forwarders, chippers, crushers, stump excavators…) operators' exposure to impulse vibration
    - Long-term total exposure (noise and vibration) by chipper and crusher operators

Biological and chemical agents

- Based on the literature review, it was found that the occupational hazards of modern energy production that utilises renewable biomass have not been well studied. More surveys and measurements need to be carried out to assess the health and safety risks of the hazards.
- Wood dust, inorganic dust, diesel exhausts and gases from degradation processes seem to be the most harmful chemical agents in the bioenergy supply chain and also in biomass-burning power plants. In particular, the exposure to chemical agents in biomass-burning power plants can be very high when workers are working inside the boilers. Similar occupational health risks for workers may be bacteria, fungi and zoonotic pathogens, which can easily spread to the air during heavy biomass processes.
- Workers can be exposed to many chemical compounds and biological agents at the same time when they work in the bioenergy supply chain and also in biomass-burning power plants. Multiple exposure by workers is dependent on

many things, such as work tasks, length of the work day, use of protective clothing and respirators, the fuels and chemicals used and the weather.

- The work tasks for which the gas, dust and bioaerosol concentrations are highest should be identified in order to determine what technological measures and protective equipment are needed to reduce the health risks. Heavy processes, such as chipping and crushing wood, and unloading the biofuels may be the most significant sources of airborne bioaerosols.

Heavy metal compounds in biomass combustion ashes

- There are only a few studies on the exact chemical composition of biomass combustion ashes, particularly heavy metals and their health effects. More studies are needed to:
  - Find out in which form the heavy metals exist in ashes
  - Clarify the link between ash compositions and the toxicological responses they induce
  - Estimate the health effects caused by the heavy metals
  - Estimate the amount of exposure to heavy metals in end-use applications and duties where ashes are treated

Accidents

- There has been little accident and safety research focusing on forestry and agricultural bioenergy raw material (or refining the material). The occupations in the field of this area are also relatively young.
- Only the most serious occupational accidents (fatal) can be found from the statistics.
- More research is unquestionably needed, especially field research focusing on the special machinery used in this work (chippers, crushers…), working procedures and working conditions on landings at roadsides and power plants

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4 Health effects of biomass combustion aerosols

Hanna Koponen, Jarkko Tissari and Jorma Jokiniemi (UEF)

4.1 Background

Fine particles are the main pollutant globally in urban air. These particles originate from several different processes but, in particular, residential wood combustion, and coal and oil combustion. The traffic and metal industry are the main anthropogenic sources of the particles. In the official assessments, all the fine particles are considered to be equal, although there is a large variation in the chemical composition and physical properties of the particles. In Finland, particle concentrations in outdoor air are typically low and about half of the fine particles originate from long-range distances, mainly from Central Europe and Russia. During the winter and, especially in inversion weather conditions, fine particle concentrations can also increase to a high level in Finland.

Heating is one of the main sources of air pollution, including particulate matter (PM) pollution. Air pollution results in several hundreds of thousands of premature deaths in Europe each year, and the pollution from PM reduces life expectancy by on average almost nine months. The health costs to the European Union are also huge. There is no evidence of a safe level of exposure to PM below which no adverse health effects occur (EC 2003, WHO 2013). Exposure to ambient air pollution has been linked to a number of different health outcomes, e.g. modest transient changes in the respiratory tract, reduced performance, emergency room visits and mortality. PM pollution has been linked not only to respiratory diseases but also to cardiovascular effects, atherosclerosis, adverse birth outcomes, childhood respiratory disease, and possibly to neurodevelopment, cognitive function and other chronic disease conditions, such as diabetes. A number of groups are potentially more vulnerable to the effects of exposure to air pollutants, e.g. unborn and very young children, the elderly, those with cardiorespiratory disease, those who are exposed to other toxic materials that add to or interact with air pollutants, and the socioeconomically deprived (WHO 2004, WHO 2013).

4.2 Physical and chemical properties of combustion aerosols that affect the health effects from emissions

Gases and particles both have adverse health effects. Adverse health effects of particulate emissions can be linked to their chemical composition (metals, combustion-derived organic particles), physical properties (size, particle numbers and surface area) and sources of the particles (WHO 2013). The characteristics govern the deposition probability and deposition site of particles in lungs, on which the health effects of the particles are dependent (Bølling et al. 2009).

In complete combustion of hydrocarbons, only carbon dioxide (CO_2) and water (H_2O) are produced. However, unwanted combustion products are always produced: flue gas also contains, e.g., carbon monoxide (CO), hydrogen (H_2), partially combusted hydrocarbons (C_xH_y), sulphur dioxide (SO_2), nitrogen oxides (NO_x), hydrogen chloride (HCl) and different solid or liquid particles. The health effects associated with exposure to CO range from cardiovascular and neurobehavioral effects at low concentrations to unconsciousness and death after acute or chronic exposure to high concentrations (Raub et al. 2000). NO_x may cause health effects via the NO_2 itself and via its reaction products. NO_x are precursors for harmful secondary air pollutants, e.g. nitric acids, the nitrite part of secondary inorganic aerosols and photo oxidants (e.g. ozone). There is evidence that long-term exposure to NO_2 may decrease lung function and increase the risk of respiratory symptoms (WHO 2003). NO_x emissions increase ozone (O_3) concentrations. There is evidence of short-term effects of O_3 on mortality and respiratory morbidity and long-term effects of exposure on respiratory and cardiorespiratory mortality (WHO 2013).

There is strong evidence that PM from emissions affects mortality and morbidity, in both short- and long-term exposure (WHO 2013). PM tends to be divided into three principal groups based on size: coarse, fine and ultrafine particles. PM_{10} is used to describe particles with an aerodynamic diameter smaller than 10 µm. The division between coarse and fine particles usually lies between 1 µm (PM_1) and 2.5 µm ($PM_{2.5}$): the official division is 2.5 µm. The division between fine and ultrafine particles lies at about 0.1 µm (WHO 2004). In small-scale biomass combustion, at least, coarse particles have fewer health effects than fine particles, because they deposit in the upper respiratory tracks or not at all (Tissari et al. 2012). The differences can also be explained by differences in intake and biological mechanisms (WHO 2013). Small particles have been found to induce a more pronounced proinflammatory response than larger particles of the same material (Bølling et al. 2009). Exposure to ultrafine particles has been associated with cardiorespiratory health and the health of the nervous system. Short-term exposure to coarse particles has also been associated with adverse respiratory and cardiovascular effects, including premature mortality (WHO 2013). Aerosol particles from combustion processes usually contain two or more distinct particle size modes: coarse and fine. Particle mass size distributions of different fuels are compared in Figure 4.1. In this example, the geometrical mean diameters of particles from fuels varied between 60 and 150 nm (Sippula et al. 2010).

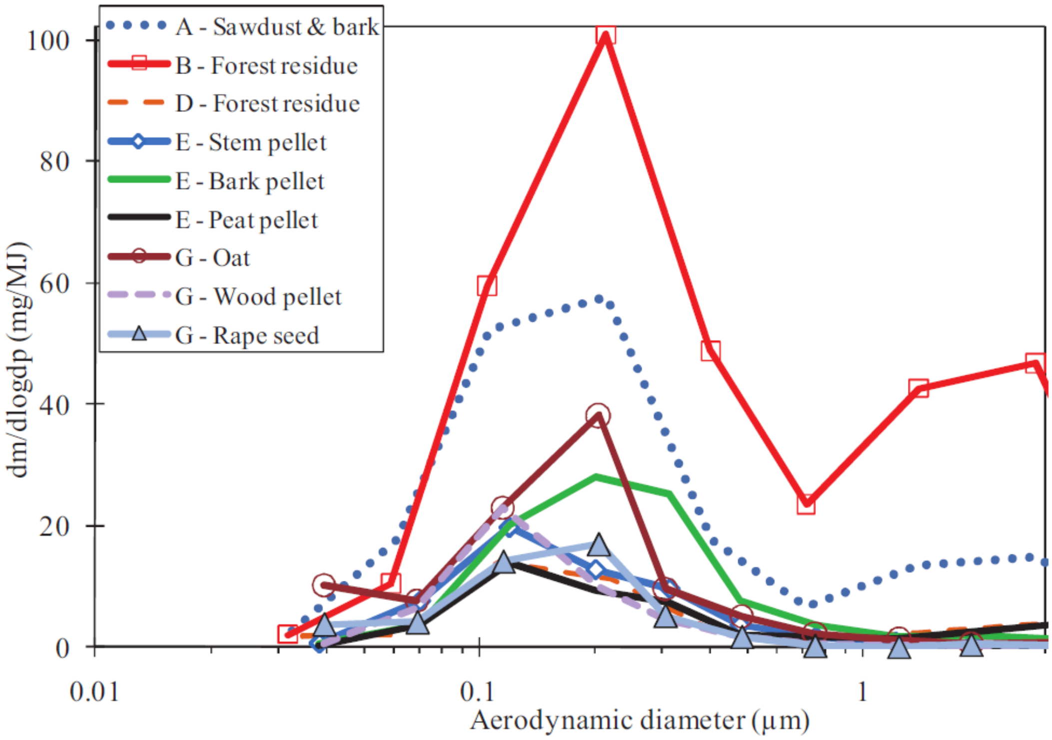

Figure 4.1. Particle mass distributions for different biomass fuels (Sippula et al. 2010)

Wood smoke particles can be divided into three classes based on their morphology and chemical composition: spherical organic carbon particles (from inefficient combustion), agglomerated soot particles and inorganic ash particles. However, in a real combustion situation, the particle classes co-exist and interact, and there are no two identical particles. In addition to the difference in chemistry, the particles vary with morphology (Figures 4.2 and 4.3). Morphology affects the deposition and retention of particles in the lungs and thereby the health effects caused by the particles (Bølling et al. 2009). In some cases, the particles can occur as fibre-like rods, which morphology has observed to be very harmful. For example, ZnO in biomass combustion can form rods if the Zn content in the fuel is high enough.

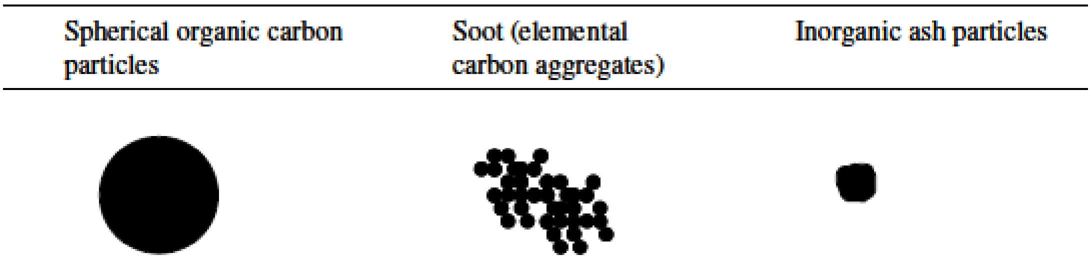

Figure 4.2. Morphology of different kinds of particles (Bølling et al. 2009)

In inefficient combustion, most of the formed particle mass consists of organic compounds. The organic fraction of particles from various sources also comprises, e.g., anhydrosugars, methoxyphenols, organic acids, aldehydes, ketones, PAHs (polycyclic aromatic hydrocarbons) and various chlorinated organics (Bølling et al. 2009). Many of these compounds are harmful, such as PAHs, dioxins and furanes. PAHs are formed in, e.g., small-scale combustion, and dioxins and furanes when burning fuels containing chlorine, especially in inefficient combustion (Tissari et al. 2012, Kaivosoja et al. 2013).

During incomplete combustion in air-starved conditions at high temperatures, PM emissions contain solid carbon aggregates called soot (black carbon). Soot consists of elemental carbon with variable amounts of organics condensed on the surface (Bølling et al. 2009). There is evidence that links soot particles to cardiovascular effects and premature mortality, for short-term and long-term exposures (WHO 2013).

In complete combustion conditions, the emissions are dominated by inorganic ash particles. The particles are mainly formed from alkali metal compounds, e.g. alkali salts of potassium, sodium sulphates, chlorides and carbonates. The emissions also contain small amount of trace elements, e.g. metals. The content of metals such as vanadium, zinc, iron, copper and nickel seems to influence the health effects of the particles (Bølling et al. 2009, Sippula et al. 2009). Epidemiological studies have also reported associations between sulphates or nitrates and human health. However, neither the role of cations (e.g. ammonium) nor of metals has been well documented (WHO 2013).

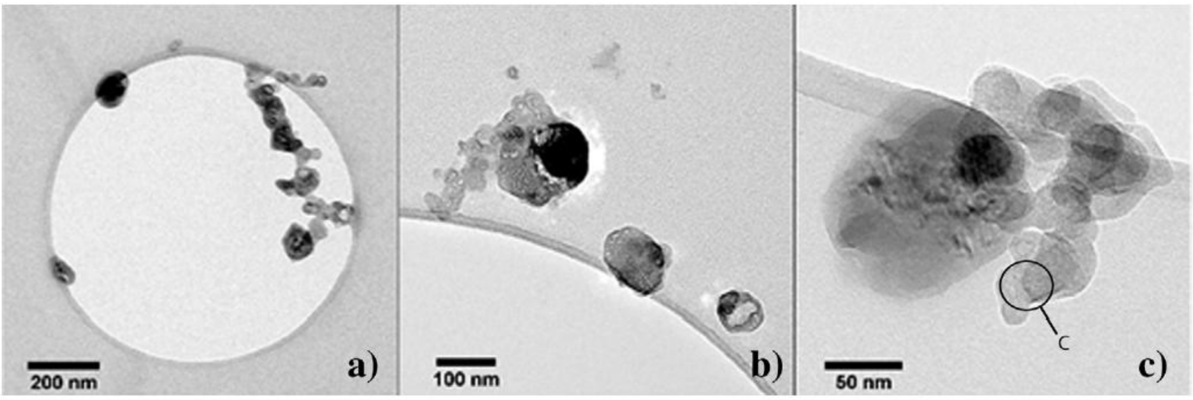

Figure 4.3. TEM (transmission electron microscope) micrographs of fine particles collected from pellet combustion. The particles vary in size and shape and consist mostly of K, S, Cl and Na. In Figure c, large amounts of carbon, marked with C, can be seen (Kaivosoja et al. 2013).

Other properties, e.g. solubility, may influence the toxicity of PM. The solubility may affect, e.g. inorganic particle deposition probability and the deposition site via hygroscopicity, the clearance rate from the lungs and biological effects at cellular level (Bølling et al. 2009).

4.3 Emission factors of different combustion appliances

Large- and medium-scale emission factors are usually low because of the automated and adjusted control of combustion and emission cleaning techniques. In small-scale appliances, emission factors are higher, especially in batch combustion. Conventional heaters produce higher emissions than, e.g., modern pellet boilers. The emission factors of different burners and fuels are presented in Table 4.1 (Tissari et al. 2012).

Table 4.1. Average emission factors (range in parenthesis) from the combustion of different fuels and during different combustion conditions. The results are collected mainly from UEF and VTT emission measurements (table published partly by Tissari et al. 2012).

	Size	CO (mg/MJ)	NO_x (mg/MJ)	SO_x (mg/MJ)	PM_1 (mg/MJ)
Conventional masonry heaters	<300 kW	2200 (700-13 000)	110	-	90 (30-300)
Modern masonry heaters	<300 kW	750 (300-2100)	80	-	55 (20-200)
Continuously heated sauna stoves	<300 kW	6500 (5500-7700)	-		160 (110-180)
Pellet/wood chips, partial load	<300 kW	160 (5-1300)	120	-	20 (5-50)
Pellet/wood chips, nominal output	<300 kW	270 (65-700)	110	-	30 (10-50)
Wood chips, bark, logging waste, sawdust	1-10 MW	30 (4-80)	100	25	15 (0.6-40)
Heavy fuel oil	1-10 MW	1.3 (0.1-2.5)	190	450	8 (4-16)
Peat, wood chips, logging waste, black liquor	>10 MW	20 (1-50)	90	20	0.9 (0.01-4.7)

4.4 Factors that affect the health effects from emissions after their release into the environment

After releasing emissions into the environment, they disperse into the atmosphere and go through transformations caused by aging. The health effects caused by emissions depend on, e.g., the level of exposure and biological effects in tissues (Figure 4.4).

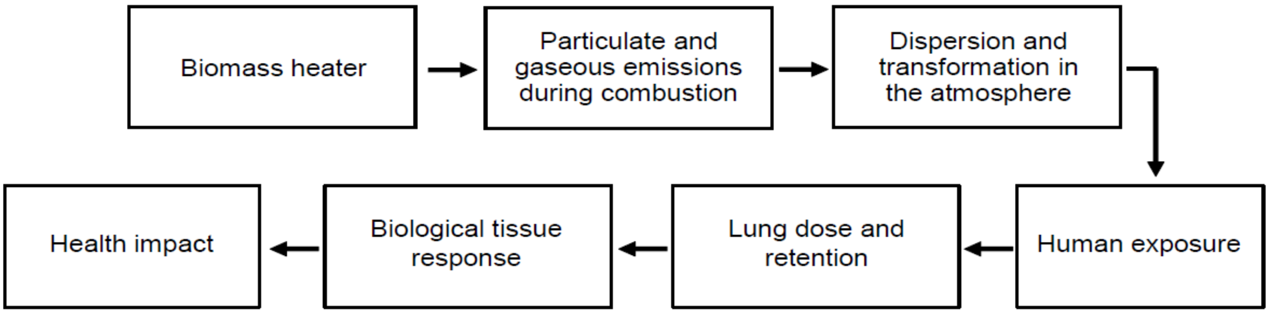

Figure 4.4. Chain of events from heater emissions and health impacts (Jokiniemi et al. 2012)

Aging in the atmosphere affects the particles' physical and chemical structure via reactions with, e.g., atmospheric photooxidants (OH, O_3, NO_3, NO_2, etc.), acids (HNO_3, H_2SO_4, etc.), water and UV radiation (Pöschl 2005). Leskinen et al. (2007) observed new particle formation and growth in environmental chamber experiments with wood chip combustion aerosols. They also found that during aging, volatile compounds may condense and heavier compound photodegrade into lighter ones in the particles (Figure 4.5).

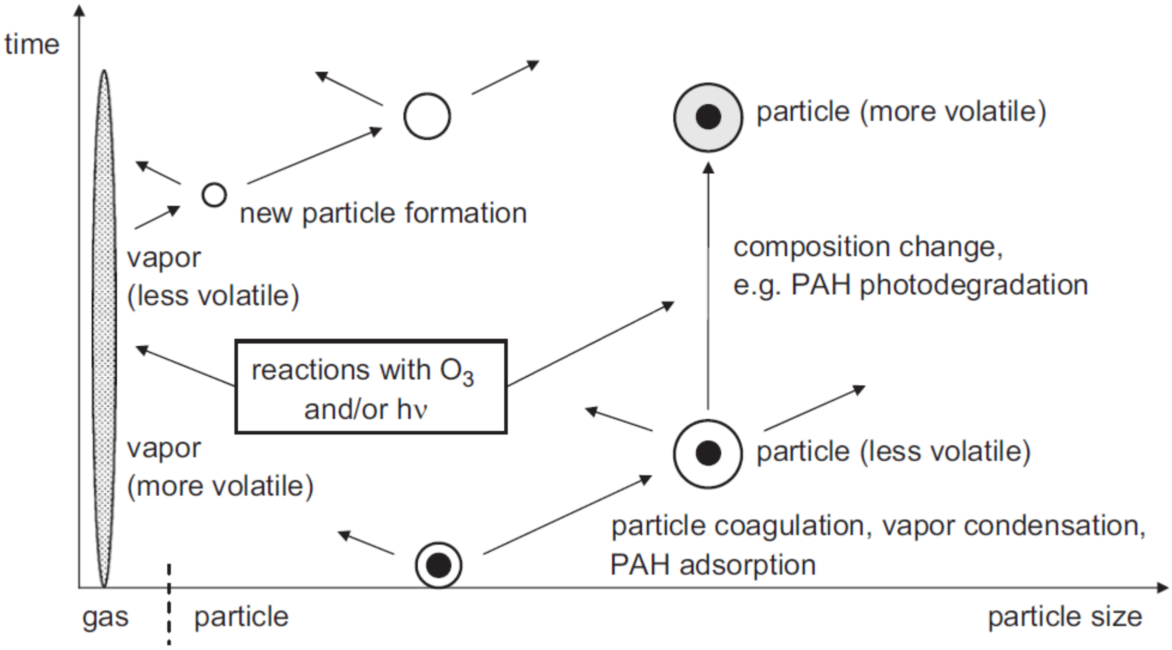

Figure 4.5. A schematic picture of possible pathways of aerosol transformation due to environmental aging (Leskinen et al. 2007)

Exposure to biomass combustion aerosols takes place both outdoors and indoors. It has been estimated that biomass combustion contributes 10-40% to the fine particle concentrations ($PM_{2.5}$) in large cities such as Seattle, Phoenix, Beijing, Prague and Helsinki. Residential wood combustion has also been reported to increase levels of air pollution locally. In general, people in developed countries spend the majority of their time indoors and thus the indoor particle levels have a large impact on human exposure (Bølling et al. 2009).

The exposure time affects the health effects of emissions. Long-term (years) exposure to $PM_{2.5}$ is associated with mortality and morbidity. There is weaker evidence for PM_{10}. Daily (24-hour average) exposure to PM has been linked to mortality and morbidity, immediately and on subsequent days. Peak exposures have been observed to lead to immediate physiological changes. It has also been found that the effects of long-term exposure are much greater than those observed for short-term exposure and that the effects of long-term exposure are not the sum of the short-term effects (WHO 2013).

When inhaled by humans, gases and particles are transported and probably deposited in the lungs. Particles in coarse aerosol mode are typically removed in the upper airways by inertial impaction, but fine and ultrafine particles are able to penetrate much further into the lung, eventually depositing in the alveoli (Figure 4.6 and Figure 4.7). The particles may be removed from the lungs or end up in the epithelial cells. Very small particles may enter the blood stream and from there they can lodge in other organs, e.g. the liver or heart (Kennedy 2007).

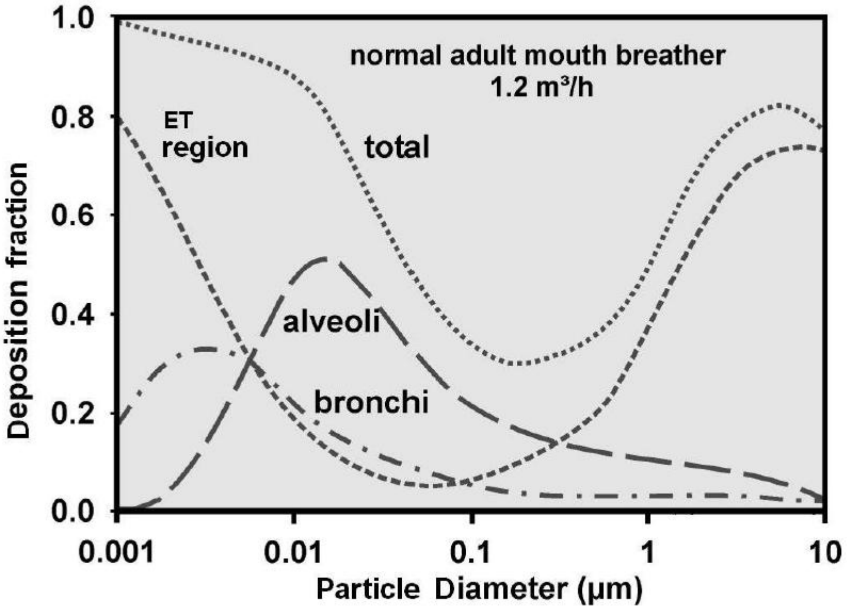

Figure 4.6. Particle deposition in the lungs: total deposition, deposition in the upper respiratory tracks (ET region), deposition in the alveoli and deposition in the bronchi (Hussain et al. 2011)

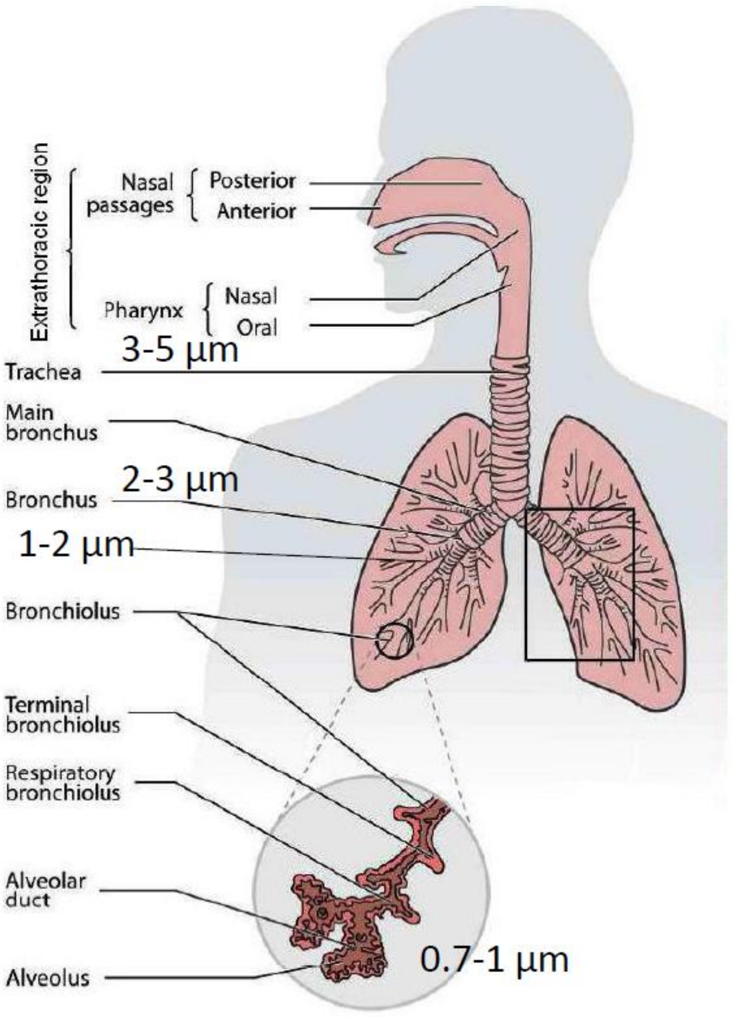

Figure 4.7. Particle sizes typically observed in the upper respiratory tracks (adapted from figure published by Hussein et al. 2011)

After the particles have been taken up by the cells, they can affect the biological function of the cells and organs. The impact on the cardiovascular system is complex and not very clear, whether it is related to composition, size, surface charge or other characteristics of the particles. It is also not clear if the effects are due to signalling from responses in the lung or if they arise from particles translocated to the cardiovascular system (Kennedy 2007). Oxidative stress, inflammation, cytotoxicity and genotoxicity are markers that have been proposed to explain the association between particle exposure and adverse health effects (Bølling et al. 2009). Inflammation has been linked to, e.g., chronic pulmonary diseases, atherosclerosis and acute cardiac effects. Cytotoxicity has been linked to tissue damage in the lungs and other organs, and genotoxicity to carcinogenic risk (Figure 4.8). When studying the health effects of the particles, the markers are monitored both *in vitro* (using cultured cells) and *in vivo* (animal models and voluntary individuals) (Bølling et al. 2009, Kennedy 2007, Jokiniemi et al. 2012).

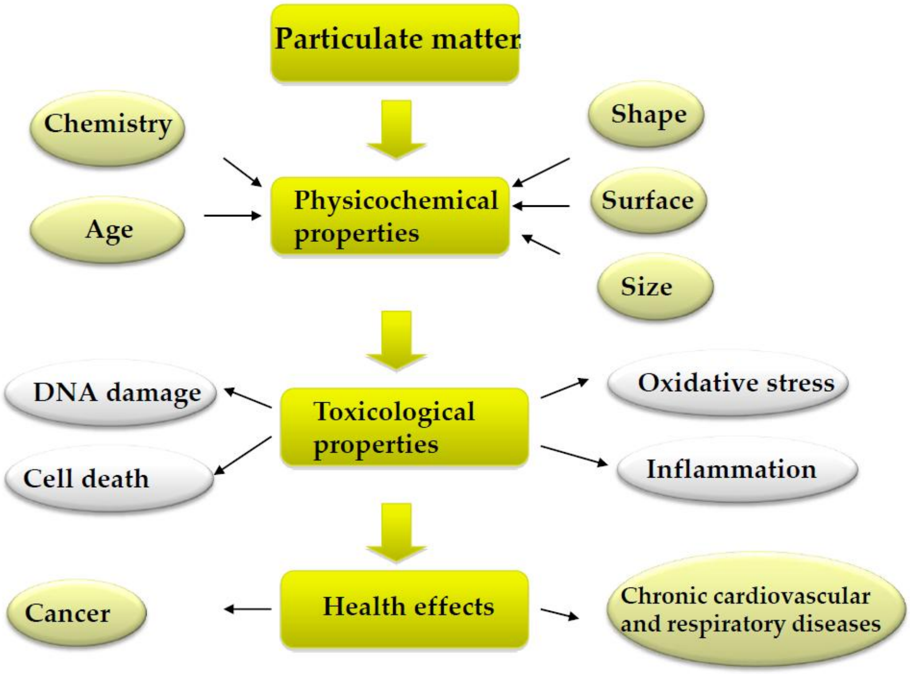

Figure 4.8. Identification of mechanisms behind the health effects (Jokiniemi et al. 2012)

4.5 Recent studies related to the health effects of fine particle emissions

In a recent BIOHEALTH study, several small-scale biomass combustion appliances, fuels and synthetically produced particle emissions and health-related responses were studied. The study concluded that toxicological responses induced by fine particles in biomass combustion emissions are strongly dependent on their chemical composition. The study indicates that the most harmful components of the particles are polycyclic aromatic hydrocarbons (PAHs), soot and zinc oxide (ZnO). Highly toxic responses were found for the combustion of fuels with a relatively high Zn concentration. PAH emissions seemed to be the most sensitive marker of combustion efficiency in relation to toxicity. Only pure potassium salts (K_2SO_4 in this case) were found to be non-toxic. PAHs and soot are produced during incomplete combustion conditions, but metals, such as ZnO and potassium salts, are produced during both efficient and incomplete combustion conditions. It was also found that ageing with ozone showed significant effects on the toxicological responses of wood-smoke particle emissions. Aged samples, especially from soot and PAH-rich combustion, had higher toxicological responses than samples without ageing (Tissari et al. 2013).

Kaivosoja et al. (2013) compared the use of fossil fuel oils against wood fuels on a small and medium scale with respect to their flue gas emissions and the cytotoxicity of the emissions. They found that the overall toxicological effects of oil combustion samples were greater than the corresponding samples from wood combustion. The PM_1 from wood combustion was composed mainly of alkali metals such as potassium, and low PM_1 emissions could be achieved by installing an efficient filtration system such as an ESP (electrostatic precipitator). However, the small number of particles passing through the ESP still evokes toxic effects. The authors propose that in the long term, in addition to the emission amounts, the toxicity of the emissions should be taken into account when regulating the emission limits for the plants.

Jalava et al. (2012) evaluated the toxicological effect of particulate emissions from different residential wood combustion furnaces: old batch combustion appliances, new batch combustion appliances and modern automated boilers. The results indicated that the combustion technology affected the emissions and toxicological responses. The modern automated boilers were usually the least potent inducers of most of the parameters while emissions from the old technology log wood boiler were the most potent. Correlation analyses showed that PAH and other organic and inorganic compositions affected the toxicological responses differently, e.g. PAH compounds were positively associated with the inflammatory activity in macrophages, and the elemental composition had a very limited effect on the cytotoxicity.

Happo et al. (2013) investigated the toxicological properties (pulmonary inflammation and tissue damage) of five modern and two old technology biomass heating appliances using mice lungs. They found that almost all the observed acute responses were at a very low level. They also found that although modern technology appliances had the lowest PM_1 emissions, they induced the highest inflammatory, cytotoxic and genotoxic activities. Increased inflammatory activity was associated with ash-related components, and a high PAH concentration was correlated with low responses, probably due to its immunosuppressive effect.

Jalava et al. (2010) investigated the effects of combustion conditions of batch combustion of wood on cytotoxicity and inflammation. The results showed that combustion conditions affect the toxic potential of emissions. Smouldering combustion, e.g., had higher inflammatory and cytotoxic potential than normal combustion, and the $PM_{1-0.2}$ emissions of the smouldering combustion induced more apoptosis than the respective normal combustion samples. PAH contents were similar in both combustion situations and may explain the very minor differences in their inflammatory potency. Differences in the cytotoxic and apoptotic responses may involve other organics, including reactive derivatives of PAHs, i.e. quinones or nitro PAHs. Metals may also contribute to the inflammatory responses.

Tapanainen et al. (2011) characterised *in vitro* immunotoxicological and chemical properties of PM_1 emissions from a pellet boiler and a masonry heater. The emissions from the masonry heater were three times more potent inducers of programmed cell death and DNA damage than the emissions from the pellet boiler. The emissions that induced extensive DNA damage also contained large amounts of PAH compounds. The authors concluded that the particles emitted from incomplete combustion are toxicologically more potent than those emitted from more complete combustion.

4.6 Highlights

- Evaluating the health effects of an individual emission source is difficult because of the large number of variables affecting the emissions and the health effects.
- The emissions of different combustion appliances and conditions can be compared by analysing the physical and chemical properties of the emission particles and analysing the toxicological responses they induced. According to these studies, the following can be concluded:
    - Toxicological responses induced by fine particles in biomass combustion emissions are strongly dependent on their chemical composition; though, the connection is still quite unclear.
    - PAH emissions are found to be a good marker of combustion efficiency in relation to toxicity.
    - ZnO has been found to cause toxicological responses.
    - Biomass combustion soot has been found to be harmful.
    - Inefficient combustion produces higher PM_1 emissions and higher PAH emissions than efficient combustion and also induces more toxicological effects; however, in some research, efficient combustion induced more toxicological responses, and metals, e.g. ZnO, are produced in both inefficient and efficient combustion.
    - Aging has been found to affect the toxicological responses of particle emissions.
- Research and test methods should be further developed, e.g., to
    - Clarify the links between toxicology and chemical and physical properties of particles
    - Clarify the effect of combustion conditions on health effects
    - Simulate atmospheric aging of emissions
    - Assess public health effects and give recommendations for future scenarios with increased biomass combustion

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5 Exposure to explosions and off-gassing accidents

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5.1 Self-heating and dust explosions

Several bulk fuels such as biomass, wastes and coal produce heat due to oxidation processes. Low-temperature reactions of organic substances with atmospheric oxygen lead to self-heating. With sufficient material volume and low heat conductivity, heat build-up and spontaneous ignition may occur (Wilén *et al.* 2013). Self-heating can be seen as the first step in the process. Babrauskas (2003) defines these steps as: 1) self-heating: an increase in temperature due to exothermal reactions in the fuel, 2) thermal runaway: self-heating that rapidly accelerates to high temperatures, and 3) spontaneous combustion: visible smouldering or flaming by thermal runaway (Koppejan *et al.* 2013).

Spontaneous heating and ignition phenomena are especially hazardous in storage bins and process equipment, as smouldering material deposits are potential sources of more extensive fire and dust explosions. When storing and handling biomass and other fuels, the tendency to spontaneous ignition and the temperature required for ignition should be known. Four main factors contribute to spontaneous ignition: oxidation tendency, ambient temperature, amount and characteristics of the material, and shape of the material storage vessel. The ambient temperature and amount and form of the stored material are important, as heat generation typically occurs in proportion to the volume and heat losses occur through the surface. As the volume increases according to the third power and the surface area according to the second one, there is a critical amount of material at which the generated heat is able to escape through the surface relatively quickly to prevent the temperature within the material from reaching the ignition point. The elevated pressure also affects the tendency to spontaneous ignition via oxidation and heat transfer (Wilén *et al.* 1999).

Dust explosions are always an actual risk in handling renewable fuels and fuel mixtures. The dusty nature and high reactivity of biofuels, combined with the generally needed thermal drying stage, emphasise the hazards of dust explosions. Dust explosion hazards in atmospheric pressure bins and handling equipment are usually provided by arranging the discharge of explosion pressure through explosion discs or relief vents and using explosion suppression systems (Wilén *et al.* 1999).

Knowledge of safety-technical basic characteristics of biomass and new fuels is essential when planning these safety measures and instructions, handling and feeding equipment, and evaluating fire and explosion hazards. Several safety-technical properties of the fuels with respect to their behaviour on hot surfaces and as dust clouds can be determined. The ignition sensibility of a substance can be evaluated through the determination of the minimum ignition temperature (MIT) and minimum ignition energy (MIE). MIT is the lowest temperature at which the ignition of a sample occurs. The test may be conducted using a sample in the form of a cloud (MIT_c) or a layer (MIT_l). MIE is the lowest energy stored in a capacitor that, upon discharge, is sufficient to produce ignition of the most easily ignitable dust mixture with air under specified test conditions. The self-ignition temperature is defined as the highest temperature at which a given volume of dust will not ignite (Wilén *et al.* 1999).

A dust explosion can be characterised as combustion of a dust cloud that results in a rapid build-up of pressure or uncontrolled expansion effects. The generation of a dust explosion requires the simultaneous occurrence of three particular conditions: combustible dust, dispersive air (oxygen) and an ignition source. The explosion severity is usually expressed in terms of maximum explosion over pressure, Pmax, and maximum rate of pressure rise (dP/dt)max or Kmax. These are the main indices influencing the assessment and design of different kinds of explosion relief venting and suppression. Limiting the oxygen concentration (LOC) in inertial cases indicates the maximum ambient oxygen content at which an explosion is prevented. The lower explosion limit (LEL) describes the minimum concentration of the dust in a dust cloud that may generate an explosion (Wilén *et al.* 2013).

5.2 The EU project 'Safe handling of renewable fuels and mixtures'

The EU project 'Safe handling of renewable fuels and fuel mixtures' of the Joule 3 Programme created new data on the safety-technical characteristics of renewable fuels (wood fuels and wood wastes, agricultural residues and energy crops), low-rank coals and mixtures of these (Wilén *et al.* 1999). The study included reactivity analyses, self-ignition tests and dust explosion tests.

Thermogravimetric analysis was used to study the reactivity of the fuels. The classification of the dust samples indicated that the low-grade coals are clearly more reactive than the biomass samples. The mixtures also showed higher reactivity than the pure biomass fuels. Higher reactivity of the samples was found at elevated pressures. Thermoanalysis appeared to be a fast and convenient means of classifying fuels according to their reactivity.

The self-ignition properties of the fuels were studied at normal and elevated pressures (1-25 bar). The self-ignition results were mainly in line with the reactivity tests. The lignites were the most reactive fuels both at ambient and elevated pressure. The pure wood fuels were least reactive with regard to spontaneous ignition. The wood wastes, bark and forest residues were more reactive than the agricultural straw residues. Increasing the pressure decreased the self-ignition temperature of the fuels. Partial inerting, i.e. decreasing the oxygen concentration of the ambient air atmosphere, increased the self-ignition temperature but to a rather low degree. To establish significantly safer conditions in fuel storage, an inert atmosphere with an oxygen content well below 7% is obviously required.

Dust explosion tests were performed both in normal conditions and at an elevated temperature and pressure. The dust explosion parameters were determined. The Pmax was directly proportional to the initial pressure and fell for all fuels by the same order of magnitude. In most cases, the LOC slightly increased with increasing initial pressure. It was suggested that for most cases, safe conditions can be obtained by reducing the oxygen content of the surrounding atmosphere to a level of approximately 11-15 vol%. In practice, a safety margin of 2 percentage units is usually recommended. The LOC decreased with an increasing initial temperature, by about 1-3 vol% per 100 °C temperature rise.

The dust explosion indices are essential to the design of protective measures. Generally, very little information existed earlier in the literature regarding the explosion properties of biomass fuels and, especially of explosion indices measured in elevated conditions. The knowledge created in this project was therefore considered unique.

5.3 Safety-technical properties of torrefied wood

The research project ‘Torrefaction of woody and agro biomasses as energy carriers for the European markets’ was carried out within the BioRefine programme by Tekes during 2010-2012 (Wilén *et al.* 2013). Within the project, a study on dust explosion and self-ignition characteristics of torrefied wood was carried out at the Laboratorio Oficial J.M. Madariaga (LOM) in Spain (Torrent 2011, Wilén *et al.* 2013).

The test material was torrefied pellets produced from whole tree wood chips at 245 °C with a pilot rig by the Energy research Centre of the Netherlands (ECN). The samples were pellets for the self-ignition tests and dust milled from the same pellets for the dust explosion and flammability tests. The dust explosion tests, carried out in a 20-litre sphere (Figure 5.1), were conducted over a dust concentration range (explosive range) of 125-2250 g/m^3. The optimum dust concentration was found to be 1250 g/m^3.

Figure 5.1. A 20-litre sphere used for dust explosion measurements (Wilén *et al.* 2013, Wilén *et al.* 1999) Photo: TNO

Table 5.1 shows the results obtained in these tests and, as a comparison, the corresponding values measured earlier for other fuel dusts (Wilén *et al.* 1999). The explosion class is defined as a function of the Kmax values. The torrefied wood dust was classified as an St1 dust (Kmax value ≤200 m*bar/s, explosion severity normal or low), like most fuel dusts. Table 5.2 summarises the interdependence between the size of the storage bin (cubic), storage temperature and induction time.

Table 5.1. Explosion parameters of different dusts (Wilén *et al.* 2013)

Sample	Explosion pressure Pmax (bar g)	Rate of pressure rise Kmax (m*bar/s)	Limiting Oxygen Concentration, LOC (%)
Torrefied wood dust	9.0	150	11
Wood dust	9.1-10.0	57-100	10-12
Peat dust	9.1-11.9	120-157	13.5
Lignite dust	9.4-11.0	90-176	13-15
Coal dust	8.9-10.0	37-86	14

Table 5.2. Influence of (cubic) storage size, temperature and time on the self-ignition behaviour of torrefied wood pellets (Wilén *et al.* 2013)

Storage size (m^3)	Temperature (°C)	Induction time
100	41.0	3.4 months
10	57.6	28 days
1	75.9	7.8 days
0.1	96.4	2.2 days

As with most of the dusts generated during biomass handling, pre-treatment and processing steps, dust and dust layers of torrefied biomass are susceptible to dust explosions and self-ignition. The safety-technical characteristics of the torrefied dust do not differ significantly from those of normal biomass dust but are clearly more reactive than coal dust. Torrefied wood pellets are drier and more brittle than conventional wood pellets. Severe dusting during the unloading and conveying of torrefied pellets has been observed. Due to the very fine particle size and almost zero moisture content, torrefied dust may ignite more easily and thus create a greater dust explosion risk than conventional biomass dusts and coal dust. The elimination of dust formation and ignition sources is therefore critical to the whole utilisation chain. The self-heating and spontaneous ignition behaviour of the torrefied wood pellets is more difficult to predict, partly because of the long time span that these reactions require, but these hazards cannot be neglected in large-scale storage of the fuel.

5.4 Self-heating, fire risks and off-gassing in pellet production and storage

The pellet production process includes raw material storage; crushing, grinding and drying of raw material; pelletisation; cooling; screening and pellet storage. Wood pellets are generally made from sawdust, which is first naturally dried and/or dried in a thermal dryer (from >50% moisture content to 10-15%) before pelletisation. It is quite common and will benefit the pellet quality to store the raw material, including fresh sawdust, wood chips and bark, outdoors for a period of time before pelletisation. This may, however, lead to self-heating processes (Koppejan *et al.* 2013).

The materials are generally porous and susceptible to heat-generating processes from biological metabolic reactions (microbiological growth), exothermic chemical reactions (chemical oxidation) and heat-producing physical processes (e.g. moisture absorption) and are thus prone to self-heating and spontaneous ignition. Cell respiration can continue for some time after harvesting, as an exothermic process. This process stops if the material is dried and will not restart when rewetted. Oxidation of fatty acids in sawdust and other moist fuels is accelerated by microbial activity with mesophilic bacteria and fungi up to approximately 40 °C and by thermophilic bacteria up to approximately 70 °C. Above this temperature, chemical oxidation becomes dominant and further raises the temperature. The domination of one or more of the heat-generating processes depends on several parameters, such as the temperature, moisture content and oxidation ability of the material (Lönnermark *et al.* 2008).

The hammer milling of the raw material during the manufacturing of pellets opens up the cell structure and exposes the cellulose, hemicelluloses, lignin and extractives to oxidation. Oxidation takes place above 5 °C and generates heat, non-condensable gases [mainly carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4)] and a number of condensable gases (e.g. aldehydes and ketones). The higher the temperature, the higher the rate of off-gassing becomes (Koppejan *et al.* 2013, Kuang *et al.* 2008).

Dry wood pellets like other dry solid biofuels require protected storage to retain the structure and low moisture content of the fuel. This can be done in silos or indoors (Koppejan *et al.* 2013). A number of serious incidents of self-heating and spontaneous ignition of wood pellets in storage have occurred. There are examples of fires caused by self-heating in silos and flat storage facilities. There is also a fire risk from various external ignition sources in storage and, especially, connected to the handling and transport of pellets (Lönnermark *et al.* 2008).

Due to the low moisture content of pellets and normally high temperatures in drying and pelletisation, microbial activities should be very limited in pellets during storage (Lönnermark *et al.* 2008). Self-heating of fuel pellets does, however, occur in large-scale storage and also in some cases in smaller piles stored at normal ambient temperatures. For wood pellets, the tendency of self-heating seems to vary between different qualities of pellets and is most pronounced relatively shortly after production. The temperature can vary, depending on the raw material, and is usually around 60 and 65 °C. The temperature increase can sometimes be higher (up to 90 °C), but at such temperatures the risk of a run-away temperature resulting in spontaneous ignition will increase, especially if the volume of the pile is large or the pellets are stored in a silo. The cooling after pellet production is very important. If the pellets are not cooled enough, the temperature in the storage can increase rapidly.

Part of the heat production is most probably due to low temperature oxidation of easily oxidised components in the material (Koppejan *et al.* 2013). It has been suggested that a high content of unsaturated fatty acids in the fuel increases the problem of low temperature oxidation and self-heating of wood pellets. The fatty acids in pellets are oxidised into aldehydes and ketones, accompanied by the generation of heat. Further oxidation will produce low molecular carboxylic acids. These volatile organic compounds have been detected during pellet storage. In addition, absorption of moisture in pellets is an exothermic process and generates heat. When pellets with a propensity to exhibit one or more of the heat-generating processes are stored in large volumes, the temperature will increase in the pile, which may lead to spontaneous ignition in pellet storage facilities.

The pelletisation process is subject to the Atmospheriques Explosives (ATEX) classifications and safety regulations. ATEX, based on the requirements of European directives (Initial Framework Directive, ATEX 100 Directive and ATEX 137 Directive), is the name commonly given to the framework for controlling explosive atmospheres and the standards of equipment and protective systems used in them.

In Sweden, the fire risks of wood pellets have been studied extensively by SP Technical Research Institute of Sweden and gas emissions by the Swedish University of Agricultural Sciences (SLU). In 2012, two projects were started on pellets and safety: the EU project SafePellets (Safety and quality assurance measures along the pellets supply chain) and a Swedish project financed by the Swedish Fire Research Board. In 2013, the first International Workshop on Pellet Safety was jointly organised by the European Pellet Council, the European Biomass Association and the Safe Pellets project.

Examples of real fires (Koppejan *et al.* 2013, Lönnermark *et al.* 2008) are listed below. They involve fires in wood pellets in silos and flat storage, and wet biofuel fires in heaps outdoors.

- A fire in a silo in Esbjerg, Denmark, in 1998. The fire started in a cell with wood pellets and lasted for nine months.
- In Härnosand, Sweden, in 2004, a concrete silo complex consisting of five separate silo cells was involved in a fire. The three silos, the building construction and conveyor system at the silo top were completely destroyed, and the silos were later demolished. Most of the pellets were destroyed as a result of the use of water.
- In Kristinehamn, Sweden, in 2007, auto ignition occurred in a silo (48 m x 8 m) filled to about 40 m with wood pellets.
- In Ramvik, Sweden, in 2005 a flat store containing 9000 tons of wood pellets ignited due to self-heating. The building and the pellets were destroyed.
- In Luleå, Sweden, in 2009, a fire incident occurred in a flat store containing 5000 tons of pellets at a pellet manufacturer.
- In Norrköping, Sweden, in 2008, a fire started in a large outdoor store of wood chips at a paper mill factory, due to self-heating.

In Copenhagen, Denmark, in 2012, a fire in a conveyor system caused a fire in two large silos (45 000 m^3 and 100 000 m^3) used for pellet storage at the Avedøre power plant.

The pellets and off-gassing can pose a safety and health threat to workers involved in production as well as personnel involved in handling the product in bulk (Melin 2011).

In Finland, several persons have died in the last years in transport and storage of pellets. In 2008, a maintenance man perished from CO formed in a wood pellet silo (TVL). He had worked alone and descended to the bottom of the silo. After four days he was found dead.

A number of serious accidents have occurred during ocean transportation of wood pellets (Svedberg *et al.* 2008). In 2002, one stevedore died and several other workers were injured in the Port of Rotterdam. In 2006, a fatal accident on board a vessel in the Port of Helsingborg occurred while the vessel was discharging wood pellets from Canada. One seaman was killed, a stevedore seriously injured and several rescue workers slightly injured after entering an unventilated staircase next to a cargo hold. The Wood Pellet Association of Canada (WPAC) has therefore studied the production of toxic emissions during ocean transportation of wood pellets (Lönnermark *et al.* 2008, Svedberg *et al.* 2008).

Ocean transportation of wood pellets in confined spaces can rapidly produce lethal levels of CO and an oxygen-deficient atmosphere that can leak into adjacent access spaces (Svedberg *et al.* 2008). The oxygen depletion and CO formation are probably caused by oxidative degradation of natural lipids and other organic materials naturally present in wood pellets. The measurement of both CO and oxygen levels is essential prior to entry into spaces with air communication with a cargo of wood pellets. Forced ventilation of staircases is necessary prior to entry in order to achieve safe entry conditions within a reasonable time. Svedberg *et al.* (2004) have already reported that high levels of hexanal and CO are strongly associated with the storage of wood pellets and may constitute an occupational and domestic health hazard. CO was postulated to be formed due to auto-oxidative degradation of fats and fatty acids.

Following the above fatal accidents with wood pellet shipments in the decade of 2000, industry and research institutions started to conduct in-depth investigations of wood pellet properties, including off-gassing and the influence of the storage parameters on it (Melin 2011). The work resulted in new industrial safety guidelines on the handling of raw material and finished products, and material safety data sheets (MSDS) were issued (Melin 2009[a,b]).

5.5 Highlights

- Self-heating and dust explosions are an actual risk of handling renewable fuels and fuel mixtures. Knowledge of the safety-technical characteristics of biomass fuels is essential when planning safety measures, handling and feeding equipment, and evaluating fire and explosion hazards.
- Torrefied dust may ignite more easily and create a greater risk of a dust explosion than conventional biomass dust and coal dust. The elimination of dust formation and ignition sources is critical to the whole utilisation chain.
- Self-heating and spontaneous ignition can occur in the storage and transport of wood pellets, and off-gassing can pose a safety and health threat to workers. High levels of CO and aldehydes may constitute an occupational and domestic health hazard. The measurement of both CO and oxygen levels is

essential prior to entry into spaces with air communication with a cargo of wood pellets.

5.6 References

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6 Studies on occupational health hazards in handling new biofuels

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The occupational health hazards of handling new biofuels were studied at VTT in the decade of 2000. The research was mainly funded by the Finnish Work Environment Fund, VTT and Finnish industry. The aims were to find out whether occupational health problems exist while working with new biofuels and to give instructions for safer working methods and the prevention of health hazards.

In the first project, in 2005-2006, a literature review on occupational studies of biofuels as well as field measurements were carried out (Ajanko and Fagernäs 2006, Fagernäs and Ajanko-Laurikko 2006, Ajanko-Laurikko and Fagernäs 2007). The work focused on logging residue bundles, stumps and reed canary grass bales. During 2007-2008, the research continued in another project and included additional measurements and suggestions for protective measures (Ajanko-Laurikko 2009).

6.1 Literature review of occupational studies of biofuels

Biofuels represent an important, sustainable energy source, but workers handling biofuels may be exposed to high levels of microorganisms and endotoxins (Madsen *et al.* 2004, Alvarez de Davila and Bengtsson 1993). From studies of farmers and refuse workers, it is known that exposure to microorganisms and endotoxins in dust from straw, grain, hay and garbage can cause respiratory diseases and eye irritation. Precautionary action should be taken to reduce dust exposure during the handling of biofuels.

Previous studies on the occupational health hazards of handling biofuels have been restricted, focusing on storing biomass. The studies have mainly been carried out in Sweden and Finland. During storage, wood fuels are subject to biological and chemical reactions and decomposition caused by fungi. Moist biomass releases heat, different humidity zones are formed in the storage and the mean moisture content of the fuel can change. The factors that cause most problems are heat development with the possible risk of self-ignition, losses of dry matter and energy value, and the potential health hazard from airborne microspores (Jirjis 1996).

Exposure by workers to dusts and microorganisms during production and handling of wood pellets and briquettes was studied by Alvarez de Davila (1993), Edman *et al.* (2003) and Madsen *et al.* (2004), and the dust concentrations in the air were found to be high, often exceeding the given limits many times over.

The microbiological properties during storage of forest residues have been studied by Jirjis (1996), Törnqvist and Jirjis (1990), Jirjis and Theander (1990), and Alvarez de Davila and Bengtsson (1993).

An earlier study by VTT (Fagernäs *et al*. 2003) reported a literature study of the behaviour of wood fuels in storage and carried out field tests on the chemical and biological changes that occurred in forest chips and sawdust during storage over a period of 7-10 months. Air samples were taken from the breathing air of workers and analysed for dust, endotoxins, microbes and VOC concentrations. The dust concentrations were low, 0.2-1.1 mg/m^3. In the handling of brown forest chips, the endotoxin concentrations varied greatly, <0.4-4800 EU/m^3 (EU = endotoxin unit, 0.1 ng), and the microbe concentrations were very high, even $3.0x10^6$ cfu/m^3 (cfu = colony forming unit).

During outdoor storage of forest residues, low volatile hydrocarbons, such as terpenes, are emitted into the air in the gas phase (Fagernäs *et al.* 2003, Rupar and Sanati 2005). The main compounds are α-pinene, β-pinene ja Δ^3-carene. Rupar and Sanati (2005) studied the emissions of terpenes from the bark/wood chips pile and the forest residue pile during storage from June through January. The emissions were high in the middle of the storage period and low in the beginning and end of the period. The emissions into the air increased when the temperature directly above the pile increased. In the storage tests by VTT (Fagernäs *et al.* 2003), the measured VOC concentrations were very low for brown forest chips at 14-38 µg/m^3 and green forest chips at 100-160 µg/m^3.

Jirjis (1996) studied the health risks during handling of stored wood fuel chips. The growth of fungi and bacteria usually takes place soon after building a pile of wood chips. Their numbers and growth depend on many internal and external factors. The internal factors include the moisture content of the chips, the fuel components, e.g. needles, bark or stem wood, and the particle size of the wood fuel. External factors that can affect the microbiological activity include the storage condition or treatment (ventilated, compacted or covered); length of the storage period; dimensions, form and location (indoors or outdoors) of the storage pile; and environmental conditions.

Many fungi require oxygen, moisture content above 20% and certain nutrients for growth. Different microorganisms have different requirements for optimal growth and sporulation. The various species of moulds can grow in a very wide range of temperatures, between 5 and 55 °C. Mould can usually tolerate a wide range of pH values with most species growing at pH values between 2 and 8. During storage, the pH value of the chips declines due to fungal activity. The most frequent microorganisms associated with the storage of wood chips are moulds and actinomycetes (Jirjis 1996).

When studying the handling of wood fuels and peat, Alvarez de Davila and Bengtsson (1993) found that the dust, microbe and endotoxin concentrations varied between different power plants and parts of the plants. The differences were affected by the fuel and its quality, the plant structure, and the handling methods of the materials. Mould and bacteria concentrations were higher for peat than for wood fuel.

With regard to logging residue bales, occupational studies were carried out by Jirjis (2003), Jirjis and Nordén (2005), and Hillebrand (2002). Storage of newly harvested logging residues in bales for ten months produced fuel of an acceptable quality but could lead to intensive microbial activity and, consequently, high substance losses and reduced total energy contents (Jirjis 2003). After storage, when the material was dry, strong dusting took place during handling and chipping of the bales. The dust contained fine wood particles as well as microbes. During the chipping and crushing of logging residue bales, microbe concentrations in the air of $1\text{-}2x10^6$ cfu/m^3 were obtained (Hillebrand 2002). When unloading the bales, a microbe concentration of $36x10^3$ cfu/m^3 was measured in the cabin.

When writing the review, occupational studies on handling stumps were not found in the literature.

6.2 Field measurements by VTT in 2005-2006

The measurements in the VTT project in 2005-2006 were carried out during loading of the biofuels from intermediate storage (Figure 6.1), and during unloading and crushing of the biofuels at power plants before feeding them into a boiler (Ajanko and Fagernäs 2006, Fagernäs and Ajanko-Laurikko 2006, Ajanko-Laurikko and Fagernäs 2007). The measurements for logging residue bundles stored for half a year and five years and for stumps stored for one year were made in the autumn. For reed canary grass bales, the measurements were made in the spring and during the harvesting of the reed canary grass. During the measurements, the bales were crushed with wet stumps. The study focused on biological exposures. Air samples were taken from the breathing air of workers and analysed for endotoxin, and microbe and dust concentrations. The sampling and analyses were carried out in co-operation with the Kuopio Regional Institute of Occupational Health.

Figure 6.1. Loading stumps into a truck (Ajanko-Laurikko & Fagernäs 2007) Photo: VTT

During the loading of the logging residue bundles the dust and endotoxin concentrations were low, while the microbe concentrations were high compared with those in other working environments (Figure 6.2). The total microbe concentration was $0.6x10^6$ cfu/m^3.

During the unloading of the logging residue bundles, stored for different times inside the power plant, considerably higher concentrations of endotoxins (770-1100 EU/m^3) and microbes ($6\text{-}9x10^6$) were observed (Figure 6.2). Of the microbes, mesophilic fungi, *Penicillium* and *Aspergillus niger*, dominated.

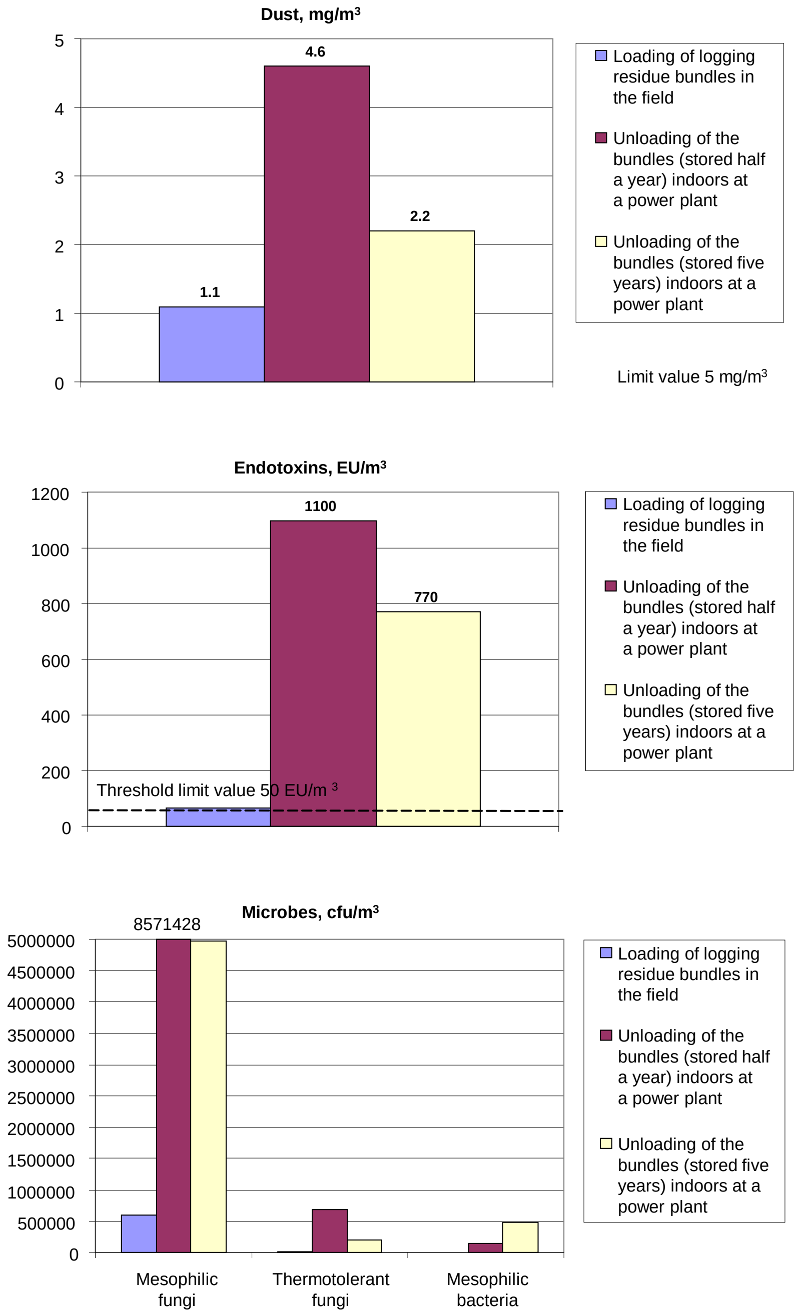

Figure 6.2. Concentrations of dust, endotoxins and microbes in the breathing air during the loading of logging residue bundles in the field and unloading of the bundles indoors at a power plant, EU=endotoxin unit, cfu=colony forming unit (Ajanko-Laurikko and Fagernäs 2007)

During the loading of the stumps stored for one year, the microbe concentration of the sample taken was high, $37x10^3$ cfu/m^3. *Penicillium* and *Trichoderma* species and mesophilic actino bacteria were dominant in the samples. During the unloading of the stumps indoors at a power plant, the dust concentration was higher than the limit value given, and the concentration of endotoxins was also high, 1300 EU/m^3. The concentrations of microbes ($0.8x10^6$ cfu/m^3) were significantly higher during unloading indoors than during loading in the field. *Penicillium* and mesophilic actino bacteria were also dominant.

In the measurements for reed canary grass bales, a high concentration of endotoxins was obtained for a worker at the crushing stage.

The results showed that workers handling biofuels are exposed to air impurities that can pose a risk to their health and welfare. Unloading of the biofuels indoors at a power plant was considered particularly harmful. Protective actions were recommended immediately. The exposure, however, is affected by many things, for example, the biofuel used and its storage conditions, the technical solutions at the workplace, and the health and physical condition of the workers. The risk of health hazards can be reduced by protection and avoidance measures, such as correcting working methods, using personal protection equipment, preventing contamination, focusing on sources of emissions, using air filtering and preconditioning, and installing detection and alarm systems.

6.3 Field measurements by VTT in 2007-2008

The research on occupational health hazards continued at VTT during 2007-2008 in the next project, which included additional measurements and suggestions for protective measures (Ajanko-Laurikko 2009). The study focused on mowing, baling and crushing reed canary grass (Figure 6.3), lifting stumps in a forest workplace (Figure 6.4), unloading stumps and logging residue bundles outdoors at a power plant (Figure 6.5), and unloading and crushing stumps indoors at another power plant.

Figure 6.3. Crushing reed canary grass bales (Ajanko-Laurikko 2009) Photo: VTT

Figure 6.4. Lifting stumps in a forest workplace (Ajanko-Laurikko 2009) Photo: VTT

Figure 6.5. Unloading logging residue bundles at a power plant (Ajanko-Laurikko 2009) Photo: VTT

During the different handling stages of reed canary grass, the dust concentrations measured were very low, <0.3-2.0 mg/m^3, while the endotoxin concentrations were relatively high, especially during mowing and baling, 4.1-110 EU/m^3. The microbe concentrations were high in crushing. The species *Aspergillus fumigatus*, *Penicillium* and actino bacteria were dominant among the microbes.

During the lifting of stumps at a forest workplace, the dust concentration was <0.3 mg/m^3 and the endotoxin concentrations were 1.6 and 3.9 EU/m^3. The microbe concentrations measured in the samples were very low.

During the unloading of the stumps at power plants, the dust concentrations were also very low, <0.5-7.3 mg/m^3. The endotoxin concentrations were high inside the power plant, 80-440 EU/m^3, but considerably lower, <0.3-25 EU/m^3, during unloading outdoors. The microbe concentrations were also high, 60-170x10^3 cfu/m^3, in the samples taken indoors but much lower, 2-18x10^3, when the unloading took place outdoors. Actino bacteria, in particular, were found in the samples taken indoors.

During the unloading of the logging residue bundles outdoors, the dust concentrations were also very low, <0.3-0.5 mg/m^3, and the endotoxin concentrations were relatively low, mainly 9.5-40 EU/m^3. The fungi concentrations were low, 3.8-13x10^3, in the samples taken in the winter, but many times higher in the samples taken in the autumn, 109x10^3. *Aspergillus fumigatus* and actino bacteria were found in the samples.

With regard to the unloading of biofuels indoors at a power plant, the results supported those obtained in the former project by VTT. Unloading of biofuels outdoors proved to be considerably less harmful to the workers. Many microbes found in the air samples taken from the different places contained fungi and actino bacteria that are harmful to health. Thus, their formation should be reduced, and protective and avoidance measures should be taken when handling biofuels.

6.4 Highlights

- Workers handling biomass fuels are exposed to air impurities that can pose a risk to their health and welfare. Exposure is affected by the biofuel used, its storage conditions, the technical solutions in the workplace, and the health and physical condition of the workers.
- Unloading the biofuels indoors at a power plant was considered especially harmful due to the endotoxins and microbes found.
- It is important to reduce the risk by protection and avoidance measures, such as correcting working methods, using personal protection equipment, preventing contamination, using air filtering and installing detection and alarm systems.
- Further studies should measure exposure at several points at power plants and during different seasons. As well as biomass fuels, other fuel types such as solid recovered fuel should be included.

6.5 References

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7 Multiple occupational exposure to gases in power plants

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7.1 Introduction

The combustion of fuels produces air pollution in the form of gases, organic compounds and particulate matter. The problems caused by power plant flue gases have been studied worldwide, as the components of these gases cause major harm to both human life and the natural environment. However, although the environmental aspect of these gases has been examined, workers' exposure to their components is a neglected issue. The purpose of this study was to measure workers' exposure to gases during the maintenance and ash removal tasks in eight biomass-fired power plants.

7.2 Materials and methods

All the air samples were collected from stationary sampling points during ash removal (Figures 7.1 and 7.2) and maintenance tasks (Figure 7.3). Concentrations of CO, NO, NO_2, SO_2, H_2S and NH_3 were measured using TSI and X-am 7000 gas monitors. We used the Mixie computer-based tool for evaluating the risks of the gases to the workers. The maximum concentrations of gases were used to obtain the worst-case exposure in the different work tasks in biomass-fired power plants. Our statistical analyses used SAS for Windows 9.2.

Figure 7.1. Ash removal using shovel

Figure 7.2. Ash removal using compressed air

Figure 7.3. Welding of superheater tubes

7.3 Results and discussion

Figure 7.4 presents the results of multiple exposures to gases. Multiple exposures to maximum concentrations of gases can affect the health of maintenance and ash removal workers negatively by causing disruption of oxygen transport, central nervous system disorders and upper respiratory tract irritation. When all these negative health effects were taken into account, the maximum concentrations of gases were significantly higher in peat-fired power plants (maintenance) than in other biomass-fired power plants $p<.0001$.

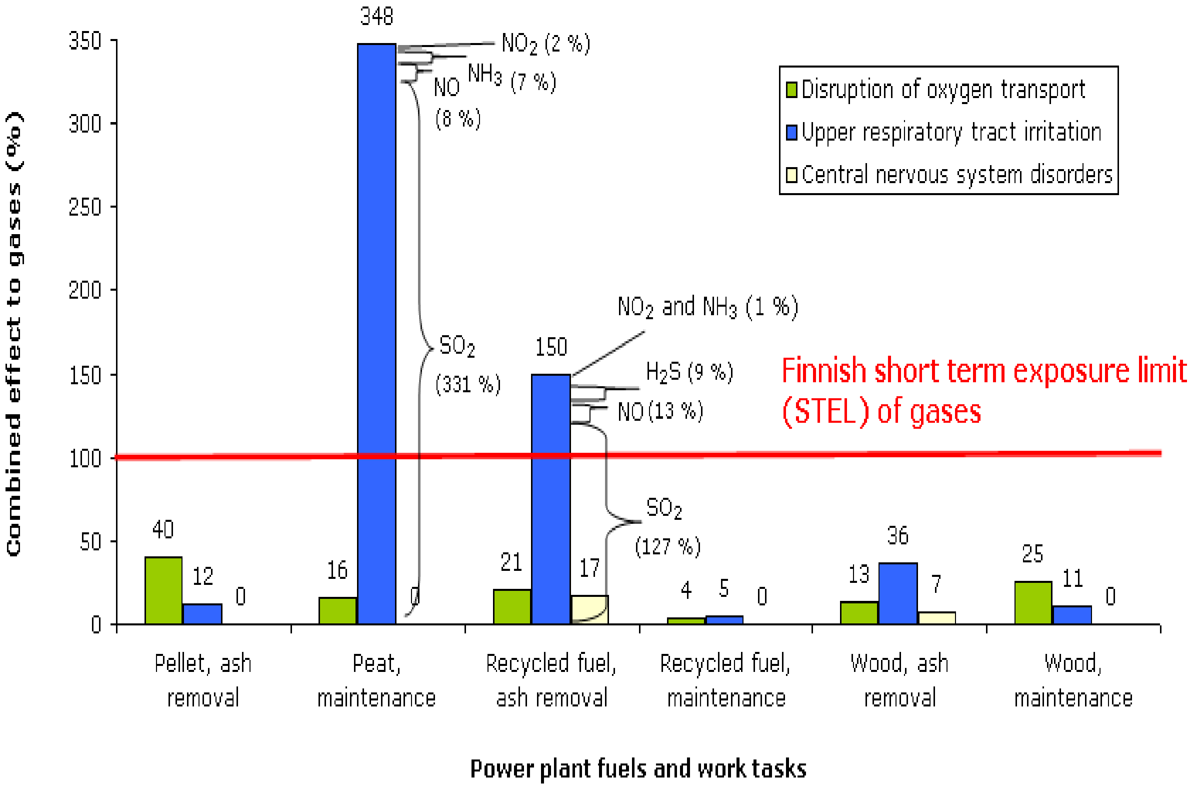

Figure 7.4. Multiple exposures to gases

7.4 Conclusions

Recording peak exposures was essential to be able to assess the real health risk to workers. In addition, workers were exposed to many gases simultaneously, so it was important to be aware of the possible combined effects of gases.

7.5 References

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8 Conclusions

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The use of bioenergy in Finland has increased during the last decade. In 2012, the total use of forest chips in heat and power plants was about 15 TWh and the use of by-products and residues from the wood processing industry about 17 TWh. Black liquor from the pulp industry was then at 38 TWh in energy production. In 2012, the total wood-based fuels used was 89 TWh including small-scale and recycled wood.

The Finnish national renewable energy action plan sets the 2020 target for the use of forest chips in the generation of heat and power at 25 TWh. Increasing the use of forest chips in multi-fuel boilers is the most central and cost-efficient way of increasing the use of renewable energy in the generation of power and heat.

With the increase in bioenergy production and use in Finland, the number of employees working with bioenergy will grow. It is therefore increasingly important to know the bioenergy production processes and the health and safety issues involved in the biomass supply chain. The possible exposure by inhabitants may also grow with the increase of bioenergy use.

The main solid wood fuels are forest chips (delimbed and whole trees, logging residues, tree stumps), bark and sawdust. Important work phases are harvesting, chipping, crushing and handling at the energy production plant. In most cases, forest energy procurement is combined with commercial roundwood harvesting. The most common chipping methods are roadside chipping, terminal chipping and chipping at a plant. In the future, the role of fuel terminals will grow. Fuel quality will also have a bigger role.

Based on the literature review, it was found that the occupational hazards of modern energy production that utilises renewable biomass have not been well studied. To assess health and safety hazards, more surveys and measurements need to be carried out.

Wood dust, inorganic dust, diesel exhausts and gases from the degradation process seem to be the most harmful chemical agents in the bioenergy supply chain and also in biomass-burning power plants. Similar biological agents are bacteria, fungi and zoonotic pathogens, which can easily spread to the air during heavy processes, such as chipping and crushing biomass. Woody and other biomass provide favourable substrate for micro-organisms due to their nutrients and moisture. There is little data on the dose-response relationship between humans and micro-organism. The general consensus is that exposure to high concentrations of micro-organisms should be avoided.

Workers can be exposed to many chemical compounds and biological agents at the same time when they work in the bioenergy supply chain and biomass-burning power plants. Multiple exposures by workers are dependent on many things, such as work tasks, the length of the work day, use of protective clothing and respirators, the fuels and chemicals used and the weather.

The exposure to chemical agents in power plants is at its highest when workers work inside the boilers. During the ash removal and maintenance tasks, the most commonly found gases are carbon monoxide, nitric oxide, ammonia, sulphur dioxide, nitrogen dioxide and hydrogen sulphide. In addition, a large number of polycyclic aromatic hydrocarbons have been found in the air and in fly ash particles. Heavy metals can be defined as individual metals and metal compounds that can affect human health. The form in which heavy metals exist in biomass combustion ashes and the kind of health effects they can cause have not been studied much.

Evaluating the health effects of the individual emission source in biomass combustion is difficult because of the huge number of variables affecting the emissions and the health effects. The research and development of test methods needs to clarify the links between toxicology and the chemical and physical properties of particles and to clarify the effect of combustion conditions on health effects.

The work tasks for which the gas, dust and bioaerosol concentrations are highest should be identified in order to determine what technological measures and protective equipment are needed to reduce the health risks.

The main physical factors involved in biomass work tasks are noise and vibration exposure. They arise in, for example, chipping and crushing. The use of stumps as a bioenergy source is increasing and the vibration caused when lifting stumps needs to be studied. More knowledge is needed about off-road machine operators’ exposure to impulse vibration and total long-term exposure to noise and vibration.

Self-heating and dust explosions are an actual risk of handling renewable fuels. Knowledge of the safety-technical characteristics of biomass fuels is essential when planning the safety measures. In the storage and transport of wood pellets, self-heating and spontaneous ignition can occur and off-gassing can pose a safety and health threat to workers.

Workers handling biomass fuels are exposed to air impurities that can pose a risk to their health and welfare. Previous studies on new biomass fuels (logging residue bundles, stumps and reed canary grass) have found high concentrations of microbes, actino bacteria and endotoxins. Exposure is affected by the biofuel used, its storage conditions, the technical solutions in the workplace, and the health and physical condition of the workers. It is important to reduce the risk through protection and avoidance measures.

In the future, it will be especially important to study biological exposure at biomass power plants as well as the health effects of combustion ashes. It will also be important to assess the public health effects and give recommendations for future scenarios with increased biomass use and combustion.