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Preface

This publication summarises the key properties of indigenous fuels used in Finland. The publication discusses the properties of wood, peat, energy crops, animal residues, solid recovered fuel, sludges, biogas, and fast pyrolysis oil. The data have been pooled from literary sources, research institutions and fuel producers and energy utilities, as well as VTT's laboratory analyses.

Definitions relating to properties have been compiled from sources such as quality standards for wood fuels, peat and solid recovered fuel, as well as the references listed at the end of this publication. The methods for analysing fuels have been described according to techniques generally used in the industry. The publication also lists the most important standards applicable to each fuel analysis.

Principal Scientist Eija Alakangas wrote all chapters and appendices with the exception of Chapter 5, which was written by Research Scientist Markus Hurskainen, and Sections 2.8, 8.5 and 12.5, which were written by Senior Scientist Jaana Laatikainen-Luntama. Research Technician Jaana Korhonen also contributed to the writing of Chapter 10 and Appendix D. Alakangas and Hurskainen compiled the terminology and Chapter 12.

Data from this publication are also used in the EU-funded FP7 projects: S2Biom "Delivery of sustainable supply of non-food biomass to support a "resource-efficient" bio-economy in Europe" property database and in the SECTOR "Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction" raw material potential and properties of Finland.

We would like to thank all researchers and industry representatives who provided information for the publication.

Jyväskylä, September 2016

Authors

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Abstract

Symbols, terminology and conversion factors

Symbols

d	dry, dry basis
daf	dry, ash-free
ad	analytical dry, air dry
ar	as received
A	ash content, A_d, w-%, dry basis
ρ	density, kg/m^3
BD	bulk density, kg/m^3
DE	gross density (as received), kg/dm^3
D	diameter, mm
DU	mechanical durability, w-%
E	energy density as received, E_{ar}, MWh/m^3 or kWh/loose m^3
F	fines (< 3.15 mm), w-%
L	length, mm or cm
m	mass, mg, g or kg
m^3	for wood, usually solid cubic metre
M	moisture content as received wet M_{ar}, w-%
MD	maximum dimension of a single particle and the sum of maximum dimensions, mm
OP	over-sized particles, w-%
w-%	weight-% (in this publication, key properties are given as weight percentages even where there is no 'w' or 'weight' before the percentage symbol)
P	designation for particle size or particle size distribution as received, based on the main fraction
$q_{\mathrm{p,net,\,d}}$	net calorific value at constant pressure on a dry basis, MJ/kg
$q_{\mathrm{V,gr,\,d}}$	gross calorific value at constant pressure on a dry basis, MJ/kg
Q	designation for net calorific value as received at constant pressure, $q_{\mathrm{p,net,ar}}$, J/kg or kWh/kg or MWh/t in the EN ISO 17225-1:2014 standard

VM	volatile matter, % on a dry basis
W	delivered energy, MWh or GJ
U	moisture content, percentage of moisture on a dry basis, U_d, w-%

Terminology

Acid number
Carboxylic acid number (CAN) expresses the amount of potassium hydroxide, which is needed to neutralise acids in one gram of oil. The carboxylic acid number does not differentiate between acids on the basis of their strength but indicates the total amount of carboxylic acids in a sample. However, the carboxylic acid number is not influenced by extremely weak acids with a dissociation constant (pKa) of less than 10^{-9}. Phenol number (PN) measures the acidity of phenolic compounds. Total acid number (TAN) is made up of both of these (CAN+PN). The use of the ASTM standard D664 (potentiometric) is recommended in pyrolysis oil acid number measurements.

Analysis sample
A sub-sample of a laboratory sample having a nominal top size of 1 mm or less and used for a number of chemical and physical analyses.

Angle of drain
See angle of repose.

Angle of repose (o)
Property describing the flowing ability of materials. Angle of drain indicates the angle relative to the horizontal plane on the slope face of a conical pile where matter will settle when flowing freely. Angle of descent means the angle to which the angle of drain is reduced when a pile at an equilibrium is shaken. Angle of flow is the natural angle, which is formed between e.g. contained material and the horizontal once the material has been released. A material's angle of slide is determined by tilting the board holding the material at a constant speed until the material begins to slide. Once this happens, the tilting is stopped and the angle determined.

Angle of slide
See angle of repose.

Animal residues and by-products (318)
Agricultural by-products or residues originating from animal husbandry, such as manure.

Ash
Inorganic matter, which is residue when a fuel sample is combusted completely in an oxidising gas atmosphere. Ash content (A_d) (%) is the weight percentage of ash in the weight of fuel on a dry basis. The main composition of ash is typically given as oxides: SiO_2, Al_2O_3, TiO_2, Fe_2O_3, CaO, MgO, Na_2O, K_2O, SO_3, and P_2O_5. The volume of ash is not directly equivalent to the volume of inorganic matter that fuel contains in its original state, as many minerals, for example, may break down or oxidise during combustion.

Ash melting behaviour, ºC
Changes in the form of ash as temperature is raised. Four different stages are distinguished in melting behaviour: deformation temperature (DT), sphere temperature (ST), hemisphere temperature (HT), and flow temperature (FT). For biofuels, shrinkage starting temperature (SST) can also be determined.

Bark (3121)
Bark residue derived from commercial timber by different debarking techniques.

Basic density
The dry mass of wood matter alone in its fresh state measured per unit of volume, i.e. basic density (kg/m^3), is dry mass (kg) divided by green solid volume (m^3).

Biobased content
A portion of fuel that originates from biomass, which is usually expressed as percentages of the total mass of the product.

Biodiesel
General name for biobased diesel fuel. Esterification of vegetable oil with alcohol produces fuel that can be used in normal diesel engines. Biodiesel can also be produced from wood-based fuels. Diesel oil (1133[1]) has an average biobased content of approximately 11% of volume.

Biogas (321)
Product of the anaerobic digestion of organic matter. The digesters are bacteria growing in an oxygen-free environment. The product is a solution containing digested biomass and large volumes of methane (55–75%) and carbon dioxide (45–25%).

Bio-oil (3221)
Oil made from plants (e.g. turnip rape, rapeseed, barley), wood, and forestry by-products.

Biomass
Material of biological origin excluding material embedded in geological formations and/or transformed to fossil. Biomasses include woody biomass, herbaceous biomass, fruit biomass, and aquatic biomass. EU Directives also include slightly varying definitions of biomass.

Biomass fuel
Fuel produced directly or indirectly from biomass.

Biosludge (3149)
Sludge produced by the biological treatment of wastewater. Forestry biosludge is comparable to common wastewater treatment sludge. In addition to microbial mass, it contains wood extractives, lignin compounds, and adsorbed chloro-organic compounds.

Black liquor (313)
Solution of high-lignin matter dissolved from wood in cellulose sulphate preparation and the cooking chemicals used in the process, which is recovered in connection with washing the mass, concentrated in an evaporation plant, and burnt in a recovery boiler to regenerate chemicals and produce energy. Approximately half of the dry mass of wood is dissolved to black liquor during boiling. Black liquor is classified as a wood-based fuel.

Blast furnace gas (123) and coke gas (124)
Gas generated by coke production or as a blast furnace by-product containing hydrogen, light hydrocarbons, and carbon dioxide. Also includes CO gas (126) generated by ferrochrome production, which is comparable to blast furnace gas.

Blend
Intentionally mixed solid biofuels with a known mixture ratio, based on either energy or weight. If the mixture ratio is defined based on volume, it must be converted to an energy-based ratio.

Brown chips, seasoned wood chips
Fuel chips made from dried and flushed logging residue (3113) or whole trees (3112). The raw material of the wood chips is dried in a pile for no less than six weeks between April and September, significantly reducing the amount of needles/leaves.

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[1] Classification number of Statistics Finland, see Appendix H

Bulk density, BD

The bulk density (unit weight) of homogeneous material is the mass of the fuel divided by the space it occupies (i.e. load volume).

By-products and residues from the wood processing industry (312)

Woody biomass residue from wood processing and the pulp and paper industry (bark, cork residues, cross-cut ends, edgings, fibreboard residue, fibre sludge, grinding dust, plywood residue, sawdust, cutting surfaces, slabs, and wood shavings). Statistics Finland and the Energy Authority classify wood chips or hog fuel made from industrial wood residues (wood strips, slabs, fibreboard industry plies, plywood edges, etc.) as well as undebarked or debarked wood chips and hog fuel generated as a by-product of the sawmill industry, which do not contain halogenated organic compounds, heavy metals or plastics, as category 3123 and as solid biofuels.

Calorific value (Q, MJ/kg)

Amount of heat generated by complete combustion per mass of fuel. Calorific value per volume, i.e. energy density, E (MJ/m^3 or MWh/m^3), is also often given. See also gross calorific value and net calorific value.

Charcoal, biochar, biocarbon, biocoke, biocoal (326)

Organic carbon, which is made by heating wood in an oxygen-free environment (by means of pyrolysis). Charcoal is a brittle, porous material, which has the original shape of wood and the microstructure of which retains its plant cell structure. Slow pyrolysis of wood produces gases, condensed liquids, and solid char. Charcoal is made using e.g. charcoal piles and retorts. Charcoal can also be produced by means of torrefaction, steam explosion, or hydrothermal carbonisation (HTC) for use as fuel in power plants.

Chemical treatment

Any treatment with chemicals (e.g. glue, coating, and paint) with the exception of air, heat, or water Chemical treatments are described in informative Annex C of the EN ISO 17225-1:2014 standard.

Chopped and split log (3111)

Chopped and split firewood between 25 and 50 cm in length used in domestic and agricultural central heating boilers and fireplaces. The term ‘smallwood’ can also be used to refer exclusively to pieces between five and 15 cm in length cut and split (diagonally or at right angles) from delimbed stem wood, which were used in wood gasifiers in vehicles during the 1940s.

Chlorine, Cl, % or mg/kg on a dry basis

Total chlorine contained in fuel.

Compressibility, %

Compressibility measures the difference between the densities of freely settled and condensed mass relative to the condensed value.

Combined sample

General term for a sample formed by combining the increments taken from a single batch of fuel. A combined sample can also be formed by combining the sub-samples separated from homogenised increments into a single sample.

Common sludge (325)

Sludges primarily originating from wastewater treatment plants. Especially larger treatment plants use a primary clarifier before biological treatment, in which case the wastewater treatment plant generates both primary sludge and biosludge. Cesspool and septic tank sludges, screen waste, and sand separator sludge are also generated.

Crown, tops (3113)

By-product of commercial felling, comprising treetops, branches, needles, and leaves. Crown mass is a synonym for treetops and branches.

Cutter chips, shavings (3124)
Wood residue from the planing of timber.

Debarking sludges (3149)
Sludges produced at a debarking plant, e.g. bark sludge, sand sludge from the sand separator, and sludge from the clarifier.

Degree of decomposition, degree of humification
Amount of amorphous humus in peat relative to plant tissue that has retained its original structure. The most common method of determining the degree of decomposition is the von Post scale. It determines the degree of decomposition by squeezing fresh peat in the hand and observing both the squeezed-out water and the peat mass remaining in the hand. The degree of decomposition is given as a so-called H value, which can vary between one and 10. An H value of 1 means that the peat is practically undercomposed, and an H value of 10 means that the plant matter that forms the peat has decomposed fully. The von Post scale can be used with wet peat in its natural state. The weakness of the method is its subjectivity. Other methods of determining the degree of decomposition include a centrifugal method and the so-called Pyatchenko method.

Deinking sludge (3234)
Generated by the deinking of recycled paper, which involves removing printing ink, fillers, and coatings from waste paper, leaving recycled fibre.

Delimbed stem wood (3111)
Delimbed trunk and logs that do not usually meet the requirements set for commercial timber. The term is primarily used for small-diameter timber.

Delivery lot
A wood fuel batch on which the essential, regularly monitored quality requirements for wood fuels are focused. The size of each delivery lot is agreed on a case-by-case basis. A delivery lot can be an individual delivery lot, which is an agreed quantity of fuel (e.g. a lorry load), or continuous delivery, where several loads are delivered to the end user during an agreed period of time (usually daily or weekly). If the delivery lot in continuous delivery is more than 1,500 to 2,000 loose m^3 in 24 hours, it is recommended that it should be divided into two or more sub-lots.

Demolition wood (3232)
Post-consumer wood (used wood) from the demolition of buildings or road and waterwork structures. Wood residue from corresponding new construction of sites is classified as recovered wood (315).

Density (ρ), kg/m^3
Mass of fuel per unit of volume. The density of indigenous fuels varies considerably. Density depends on both the amount of dry matter in the volume and moisture content. See also basic density, bulk density and particle density.

Solid cubic metre, m^3	Undebarked solid cubic metre
Bulk cubic metre, loose m^3	Loose cubic metre of wood chips or smallwood
Bulk density, kg/loose m^3	Mass and volume are measured as received
Stacked cubic metre, stacked m^3	Stacked formation of smallwood measuring 1 m^3

Dry fraction
Combustible waste that remains after biowaste, hazardous waste, and other recyclable waste have been separated from municipal solid waste.

Dry matter, d, TS
A portion of dry matter of the total amount of material as mass. This is the basis for reporting fuel and other analyses. The dry matter of fuel contains both combustible and non-combustible particles. Dry matter is

made up of carbon, hydrogen, oxygen, nitrogen, sulphur, and non-combustible inorganic matter, i.e. mineral matter (ash).

Edgings (3123)
The parts of woody biomass that are generated by the finishing of timber and which contain residues of the tree's original round surface (undebarked/debarked wood).

Elementary analysis, elemental analysis, w-%
Determination of the carbon (C), hydrogen (H), nitrogen (N), and sulphur (S) content of fuel by means of complete combustion. Oxygen can be measured, but typically oxygen (O) content on a dry basis is calculated as follows: 100% – CHNS and ash content on a dry basis (w-%).

Energy crops (31)
Energy crops grown in fields or bogs (317) (reed canary grass, oleiferous plants) or energy forest (willow 3115) as well as parts of cereal crops (straw) (3172), which can be used as fuel or turned into either solid or liquid fuels. Common reed also belongs to this group. The EN ISO 17225-1:2014 standard classifies willow as a wood fuel (3115).

Energy fraction
Combustible waste sorted at source for energy production.

Energy grain (3172)
Grain, which is used to produce energy.

Energy willow (3115)
Willow or willow biomass grown for energy use through short rotation forestry.

Extraneous ash
Matter that does not belong in fuel, which ends up in fuel in connection with harvesting, felling, processing, transport, storage, etc.

Fines (w-%)
Matter created during the production and processing stage and found among particular fuel, the percentage of which is determined by screening. The particle size of fines is less than 3.15 mm.

Fixed carbon
Fixed carbon on a dry basis is calculated as follows: 100% - volatile matter (w-% on a dry basis) - ash (w-% on a dry basis).

Fuel peat (21)
Peat product, which is designed for energy production.

Fuelwood
General term for all wood fuel, including wood, bark, and the green fraction. In statistics, the term 'firewood' is used to refer exclusively to domestic and agricultural wood fuels: billets and wood chips.

Flash point
Denotes the lowest temperature at which fuel oil has evaporated enough for the solution to ignite by an external spark.

Forest chips
Wood chips produced from forest wood biomass. In Finland, the term 'forest chips' is used as a general term, referring to delimbed stem (3112), whole tree (3112), and logging residue chips or hog fuel (3113) from stumps.

Forest residues
Branches, tops and stems left over from commercial timber harvesting and thinning in young forests. Depending on the drying of forest residues, they either do or do not contain the green fraction.

Forest wood (311)
Wood fuel produced with a mechanical process directly from wood raw material previously unused for any other purpose. See stump, logging residue, forest chips, thinning wood, and crown mass.

Fraction
Fraction, particle, granule. Cf. particle size.

Fuel powder (312)
Ground, pulverised solid biofuel with particles typically between one and five mm in size. For example, sawdust (3122) and grinding dust (3124).

Green chips
Fuel chips made from fresh logging residue or whole trees.

Grinding dust (3124)
Dust-like wood residues created by the grinding of timber and wooden board.

Gross calorific value, $q_{gr,V}$
Higher calorific value, which means the amount of heat that is released when one unit of mass of fuel burns completely and the water created during combustion or contained in the fuel remains liquid after combustion at the base temperature (+25 ºC). Gross calorific value is determined in a bomb calorimeter and the value is given on a dry basis at constant volume. See also calorific value, net calorific value, and net calorific value as received.

Halogenated organic compounds
Compounds that contain fluorine (F), chlorine (Cl), bromine (Br), or iodine (I). E.g. PVC compounds (PVC = polyvinyl chloride; in plastics) and PCB compounds (PCB = polychlorinated biphenyl; additive in e.g. PVC plastic before 1970). Furans (PCDF = polychlorinated dibenzofurans) and dioxins (PCDD = polychlorinated dibenzodioxins) can form when organic chlorine compounds are combusted under poor burning conditions.

Hazardous waste
Waste, which is flammable, explosive, or toxic, or that has another property that is dangerous to health or the environment, or another similar property (hazardous property).

Heavy metals
General term for substances that are toxic or harmful to humans and the environment. The most important include cadmium (Cd), thallium (Tl), mercury (Hg), antimony (Sb), arsenic (As), lead (Pb), chromium (Cr), cobalt (Co), copper (Cu), manganese (Mn), nickel (Ni), zinc (Zn), and vanadium (V).

Hog fuel
Wood fuel that has pieces of varying size and shape, produced by crushing with blunt tools such as rollers, hammers, or flails.

Hydrophilic
Material, which has a tendency to attract water.

Hydrophobic
Material, which has a tendency to repel water.

Hygroscopic
Material, which has a tendency to adsorb or absorb moisture from air.

Impregnated wood (3233)
Impregnated wooden products, such as pressure impregnated wood and electricity poles and telephone poles, as well as impregnated wood.

Impurity, foreign material
Particle, chemical, or other undesirable substance or object, which is not normally found in fuel. Impurities include stones, sand, metal, concrete, urethane foam, coating products, glues, plastics, and strings.

Increment
The smallest amount of fuel extracted in a single operation in order to form a combined sample.

Laboratory sample
A sub-sample formed from combined samples collected from a delivery lot or its part by homogenisation and division, delivered to a laboratory for analysis. For comparison purposes, several parallel laboratory samples may be formed from the same combined sample, for example for determining moisture content. Laboratory samples may be prepared by the supplier of the sample, or by the laboratory from the delivered combined sample.

Landscape management residues, landscape care wood or verge
Woody, herbaceous, and fruit biomass residues, which originate from landscape, park, or cemetery management. These residues include e.g. tree branches, roadside foliage, and wood matter from hedges.

Lignocellulose
Biomass on the cell walls of plants, which consists mostly of cellulose, hemicellulose, and lignin.

Logging residue (3113)
Woody residues left behind in the forest in connection with stem wood felling, such as branches and treetops, as well as small-diameter trees and rejects left at felling sites.

MCR, Micro Carbon Residue, %
Residue formed after the evaporation and pyrolysis of a sample under a nitrogen atmosphere. The result indicates the sample’s coke-forming tendencies. MCR is also determined for mineral oils.

Mechanical durability, DU, %
Durability of particular solid fuels against mechanical forces. The mechanical durability of briquettes and pellets is especially important. The most commonly used determination technique involves wearing a fuel in a rotating drum and measuring the change in the particle size distribution and the volume of fines by means of screening.

Milled peat (211)
Energy peat produced by milling peat from the surface of a peat bog and drying it. Peat is usually dried in situ by solar energy. Milled peat has an irregular particle size and mostly contains dust-like peat as well as peat granules of different sizes. In addition to peat, milled peat can also contain small amounts of undecomposed or poorly decomposed coarse plant pieces (bog wood, subshrubs, tussock cottongrass, etc.) as well as small amounts of impurities.

Minerals, major elements, minor elements
Primarily bound to the inorganic part of fuel. Major elements include aluminium (Al), calcium (Ca), iron (Fe), magnesium (Mg), phosphorus (P), potassium (K), silicon (Si), sodium (Na), and titanium (Ti). Minor elements include arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), mercury (Hg), manganese (Mn), molybdenum (Mo), nickel (Ni), lead (Pb), antimony (Sb), vanadium (V), and zinc (Zn). Mineral content depends on how and where the fuel was formed, which is why levels of minerals vary considerably.

Mixed waste (3238)
Unsorted municipal, industrial, or construction waste.

Mixture
Unintentionally mixed biofuels, the origins of which are known, but the precise mixture ratio is unknown.

Moisture, water, M, weight-%, w-%
Amount of water contained in fuel, which is given either on a wet or dry basis. *Moisture percentage*, i.e. moisture per wet weight, is the percentage of water in the total mass of a material. *Equilibrium moisture content* means the amount of water that a fuel is capable of retaining under certain conditions. *Delivery moisture content (as received)* is the name given to the moisture content that a fuel has when it is delivered to a consumer. *Operational moisture content* means the moisture content in a ready-to-use fuel. In the context of wood fuels, the term *fresh moisture content* is used, which means the moisture content of an undried fuel. *Moisture content* (U) is the ratio between the amount of water in fuel and dry matter. For more detailed information, see *Determination of properties* (Chapter 2). For oils, the term 'water content' is used.

Moisture sample
Sub-sample formed from a laboratory sample by homogenisation and division, which is dried to determine moisture content.

Municipal solid waste, MSW (3238)
Waste generated by households as well as waste with similar properties, composition and quantity generated by the industrial sector, commerce, or other similar activities.

Net calorific value as received, $q_{net,ar}$ or Q
The calorific value of fuel, delivered wet or as received, is calculated from the net calorific value of the dry matter with the help of moisture content (see also gross calorific value).

Net calorific value, dry basis, $q_{net, dry}$
Lower calorific value, which means the amount of heat that is released when one unit of mass of fuel is burnt when the water produced in connection with combustion – the volume of which depends on hydrogen content – is evaporated and cooled down to the initial temperature as vapour. Net calorific value is given on a dry basis (see also gross calorific value).

Nominal top size
The aperture of a sieve with round holes used in the determination of biomass particle sizes, where at least 95 w-% of the total weight of the material passes.

Non-woody biomass
Solid biofuel, which is made from herbaceous, fruit, or aquatic biomass, including mixtures and solutions. Fruit tree stems and woody energy crops such as poplars belong to woody biomass.

Organic compounds (OC, OM)
Compounds that contain carbon. However, not all carbon compounds are organic; e.g. carbon dioxide (CO_2), sodium carbonate (Na_2CO_3), and potassium cyanide (KCN) are inorganic compounds. Organic compounds are classified, e.g., as follows: alkanes, alkenes, aromatic hydrocarbons, alcohols, aldehydes, halogenated compounds, amides, amines, arenes, carboxylic acids, esters, ethers, ketones, nitriles, sulphides, and thiols. Volatile organic compounds (VOC) are compounds that have a high vapour pressure. Organic compounds make up a large proportion of the particulate mass of outdoor air.

Over-sized particles, coarse fraction
The portion of particles that exceed a certain threshold.

Particle density
Density of individual particles. The product of dividing the mass of fuel by the gross volume of the material, which excludes from the volume the volume of pores in the materials.

Particle size
Typical size of a particle of particular fuel. The particle size distribution (particle size distribution, granule size distribution, fraction distribution) of each fuel is determined by means of screening or using analysers (small particles). Sieve analyses are used to determine the weight percentage of samples with an equilibrium moisture content (20 w-%) that is left on sieves of different mesh sizes (see Chapter 2).

Peat (21)
Partially decomposed organic soil generated as a result of the slow decay of bog plants, which is stored in its natural habitat in wet conditions. Due to the lack of oxygen and high water content, plant residues are not broken down properly, which creates a growing layer of peat. The carbon content and calorific value of highly decayed peat make it suitable for energy production. The cell structure as well as the low pH and nutrient content of partially decayed sphagnum peat make it suitable for use as a bed for plant production.

Peat species
Peat is grouped into different peat species according to botanical composition.

Sphagnum peat (S)		S peat
		ErS peat
		CS peat
		LS peat
Carex peat (C)	SC peat	
		C peat
		LC peat
		BC peat
Woody peat (L)		SL peat
		CL peat
Bryales Carex peat (B)		B peat
		CB peat
Abbreviations	S	Sphagnum
	Er	Eriphorum vaginatum
	C	Carex
	L	Lignum, wood matter
	B	Bryales

In addition to these primary peat components, peat contains residues of many other plants.

Pour point, °C
Lowest temperature at which oil remains pourable.

Plywood residues (3123)
Ply, plywood, and other wood residues generated by the plywood industry (must not contain excessive quantities of glues).

Precision
The overall precision required for each significant characteristic of a delivery lot should be agreed between the parties. Should there be no such agreement, the values specified in this publication may be used (e.g. ± 2–4 percentage points for moisture). The overall precision must be achieved in sampling at a 95% confidence level. Furthermore, the authorities may lay down precision requirements in, for example, environmental and emission permits.

Primary biomass
Biomass, which is produced directly through photosynthesis and harvested or collected from the ground or the forest in which it grew. Examples include energy crops, perennial grasses and trees, plant residues, and logging residue.

Primary sludge
Sludge produced by settling during primary clarification. Primary sludges from the forest industry contain bark, fibres, bulking agents, additives, and pigments.

Proximate analysis
The analysis determines the moisture content and ash content of fuel and volatile matter. The percentage of fixed carbon in dry matter is calculated by adding up ash and volatile matter (w-% on a dry basis) and by deducting the sum from 100.

Pyrolysis oil (3222)
Dark brown liquid produced from wood or other biomass by means of fast pyrolysis, the properties of which differ from oil. Fast pyrolysis involves rapidly heating wood (moisture content < 10%) to a temperature of 500–600 °C in the absence of oxygen, which causes the majority of the wood material to turn into gases, which are liquefied in a gas condenser. Other products, uncondensed gases, and carbon residue are usually used as energy in the process. The typical liquid phase yield is approximately 70 w-% of the end products.

Pyrolysis solid
The pyrolysis solid of oil primarily consists of carbon residue elutriated from the cyclone with gas. It also contains sand and ash originating from the sand bed of the boiler or the feedstock. Pyrolysis solid is determined by a method based on the ASTM D7579 standard as matter that is insoluble in a solution of methanol-dichloromethane (1:1). Pyrolysis solid contains residues of organic matter, which are not soluble in the solvent in question.

Reactivity
Reactivity describes the gasification of char after the fuel pyrolysis stage. Reactivity shows how much time is required for achieving the final fuel conversion, i.e. how easily a fuel is gasified. Reactivity (%/min) is given as instantaneous reaction rate as a function of ash-free fuel conversion. Reactivity depends on multiple factors, e.g. the fuel itself, its chemical composition, temperature, pressure, and the gas atmosphere.

Recovered wood (315)
Clean wood residue classified as solid biofuel or used wood, which does not contain plastic coatings or halogenated organic compounds and heavy metals. For example, wood residue from new construction, pallets, wood packaging, etc.

Refuse derived fuel, RDF (3231)
Fuel produced from unsorted municipal solid waste (MSW) by means of mechanical processing.

Recovered fuel, REF or SRF (3231)
Fuel produced by mechanical processing from dry waste sorted and separately collected at source.

Reference material (RM)
Material or compound, which is sufficiently homogeneous with respect to one or more specific properties and which has been established to be fit for use in the calibration of equipment, assessment of a measuring technique, or agreed values for materials.

Sample
A quantity of fuel representing a larger quantity, the quality of which needs to be determined.

Sawdust (3122)
Small particles generated when wood is sawn. All three dimensions of the majority of the particles are in the range of a few millimetres with the exception of random longer particles, depending on the saw and the quality of the wood.

Sawmill chips (3123)
Undebarked or debarked wood chips generated as a by-product of the sawmill industry (3123).

Secondary biomass
Residues and by-products from food products, animal feed, wood and material processing plants (such as sawdust, black liquor, and whey), as well as manure.

Short rotation woody biomass (3173)
Woody biomass grown for raw material or energy usage in short rotation coppices with a five-to-eight-year rotation (e.g. energy willow).

Slabs (3123)
Parts of woody biomass created when cuts are made into the edges of logs and whereby one side shows the original rounded surface of the tree, either completely or partially, with or without bark. Approximate length is 200 to 800 cm.

Sod peat (212)
Energy peat produced by harvesting peat from a peat bog and turning it mechanically into pieces (e.g. cylindrical, cubical, or wave-like pieces). The pieces are primarily dried in situ by solar energy. The diameter and shape of sod peat are relatively consistent, but the length of the pieces may vary. Sod peat also contains varying quantities of fines, which are formed during the production and processing stages, as well as coarse particles and small amounts of impurities.

Solid density
Density of solid material excluding any interior pores. Solid density (“water density”) is calculated by dividing the mass of fuel by the volume that the fuel displaces when it is immersed in e.g. water.

Solid recovered fuel, SRF (3231)
Fuel made from combustible, dry municipal, industrial, and commercial solid waste sorted at source. See also RDF and REF.

Solid volume content
Ratio between the solid volume (solid m^3) and the bulk volume (loose m^3) of wood. For example, in wood chip measurements, solid volume (m^3) is determined with the help of a chip density conversion factor from the bulk volume (loose m^3) of the load. The weight of one cubic metre of wood chips depends on the density of the wood matter, the density of the wood chips, and the moisture content of the wood.

Stem wood (3111)
A delimbed part of a tree trunk.

Stump (3114)
Part of the stem below the felling cut, which comes up with the stump when the stump is removed.

Sub-sample, sub-lot
A portion of a lot for which a test result is required. Contracting parties may agree to divide a delivery lot into sub-lots in order to improve the assay precision or make the routines of the assay easier or quicker. NOTE: When determining the size of a sub-lot, the sample processing equipment must be taken into consideration, or its size must be separately agreed.

Tertiary biomass
End consumers’ residues and waste, such as lard, greases, oils, construction and demolition wood, as well as other wood residues from urban environments, along with packaging waste, municipal solid waste, and landfill gases.

Thinning wood (3112)
The part of a forest’s growing stock removed during thinning, timber harvested during thinning.

Trace elements, micronutrients
Substances the volume of which in plants and animals is low but that are vital for their normal development, e.g. magnesium (Mg), calcium (Ca), iron (Fe), zinc (Zn), selenium (Se), and chromium (Cr). See minerals.

Ultimate analysis, elementary analysis, elemental analysis
See elementary analysis.

Used wood (315)
Post-consumer wood that has been removed from its primary use. The term corresponds to the term 'recycled wood' (315) used in Finnish statistics.

Viscosity, mm^2/s
Temperature-dependent physical quantity used to measure the fluidity of a liquid. The old unit, centistoke (cSt), has the same numerical value. The viscosity or fluidity of heating oil depends on the temperature of the oil. The lower the temperature of oil, the less fluid it is, which means that it has high viscosity.

Volatile matter, %
Components and products releasing from the organic matter in fuel as gas when fuel is heated at 900 °C ± 10 °C for seven minutes in standardised conditions. The percentage of volatile matter is calculated as a loss of mass, after deducting loss of mass due to moisture. Volatile matter is given as weight percentages on a dry basis.

Waste
Substance or an object, which its holder has removed, intends to remove, or is obligated to remove from use.

Waste wood, used wood (315)
See wood waste.

Wood chip
Woody biomass chipped into pieces of a certain size with sharp blades. Wood chips are rectangular in shape, with their sides typically between five and 50 mm in length and their thickness small compared to the other dimensions.

Whole tree (3112)
Felled, undelimbed tree, excluding the stump and root system. Contains the stem with bark, branches, and needles/leaves.

Wood-based biomass
All solid biofuels that originate directly or indirectly from woody biomass.

Wood chips
General term for wood chips used in combustion or other energy production, produced with different techniques.

Wood briquette (316)
Wood briquettes are made from dry sawdust, grinding dust, or cutter shavings by means of compression. Binding agents are normally not used, as the natural components of wood keep the briquette in one piece. Wood briquettes are usually round or cubical. Each side or the diameter is between 50 and 80 mm long.

Wood chips from industrial wood residues (3123)
Chips from industrial undebarked and debarked wood residue (wood bars, slabs, etc.) that do not contain painted or otherwise treated wood.

Wood log (3111)
Split or round, delimbed logs of approximately one metre in length, which are intended for burning.

Wood pellet (316)
Cylindrical granules made from sawdust or cutter chips by means of compression. Pellets have a diameter of between six and 12 mm and they are between 10 and 40 mm long. Pellets can also be made from peat (213) and waste (3235).

Wood residue
Wood residue refers to wood generated during construction, demolition, and renovation activities (3129 or 3232) and wood generated by the wood processing industry that may contain glue, paint, preservatives, and other such substances. Chemically untreated wood residue is classified into class A, and chemically treated wood into class B (315), if it does not contain more halogenated organic compounds or heavy metals from treatments with wood preservatives or coatings than natural wood.

Wood waste, waste wood
Post-consumer wood generated during construction, demolition, and renovation activities (3232) and used wood generated by the wood processing industry (314, 315) that contains glue, paint, preservatives, and other such substances. Used wood or waste wood is classified as solid biofuel, if it does not contain more halogenated organic compounds or heavy metals from treatments with wood preservatives or coatings than virgin wood. Pressure impregnated wood (3233) is an exception, as it is classified as hazardous waste.

Woody biomass (31)
Biomass originating from trees and bushes. The definition covers forest and plantation wood (311), by-products and residues from the wood processing industry (312, 314), as well as used wood (315).

Other terms and classifications

In the European List of Waste (2000/532/EC), wood fuels delivered directly from the forest are classified as 02 01 07. Correspondingly, wood residues and by-products from the wood processing industry are classified as 03 01, the subclass 03 01 01 of which includes bark, and subclass 03 01 05 sawdust, shavings, cuttings, and particle board and plywood residue. Bark and wood residues from paper and pulp production are classified as 03 03 01. Wooden packaging is found in class 15 01 03, and demolition wood and wood residues from construction in class 17 02 01.

The EN ISO 16559 standard: Solid biofuels. Terminology, definitions and descriptions contains more term definitions relating to solid biofuels.

Conversion factors between different units of energy

	toe	MWh	GJ	Gcal
toe	1	11.63	40.868	10.0
MWh	0.0886	1	3.600	0.86
GJ	0.02388	0.2778	1	0.2388
Gcal	0.1	1.163	4.1868	1

Example: 1 toe = 11.63 MWh

100 ppm = 100 mg/kg = 100 µg/g = 0.01%

1 MJ/kg equals to 0.2778 kWh/kg

1 kWh/kg equals to 1 MWh/t and 1 MWh/t is 3.6 MJ/kg

1 g/cm^3 equals to 1 kg/dm^3

1. Introduction

This publication discusses the properties of fuels on the basis of literature and results of analyses carried out by VTT and fuel producers and energy utilities. The most important properties of fuels are

- calorific value,
- chemical composition (elementary analysis, e.g. alkalis and metals, non-metals, heavy metals, as well as trace elements),
- moisture content,
- ash content, ash composition, and ash melting behaviour, and
- density, grindability, viscosity, as well as other fuel handling properties.

The publication addresses the properties of different kinds of

- wood fuels (wood chips, smallwood, sawdust, bark, briquettes, pellets, and charcoal),
- black liquor,
- peat,
- energy crops (cereals, oleiferous plants and cereal seeds, straw, reed canary grass, and common reed) and animal residues,
- solid recovered fuels (waste wood, plastics, fibrous packaging, scrap tyres, industrial waste fuels),
- sludges (primarily forest industry sludges),
- fast pyrolysis oil, and
- process gases, as well as biogas.

Methods for determining fuel properties, sampling methods, and mathematical formulae are also presented at the beginning of the publication. The publication finishes with an analysis and descriptions of the effect of fuel properties on combustibility and gasification, as well as comparisons of fuel properties. The publication does not address transport fuels. Industrial process gases are touched upon briefly. With regard to indigenous fuels, fuel production technology and potential are also reported.

The publication is based on VTT Technology 258 (Alakangas et al. 2016). After the year 2012, the analytical methods used for solid biofuels have been updated to reflect EN standards or ISO standards. This publication is based on sampling and analytical methods that are compatible with new international standards.

2. Determination of properties and mathematical formulae

2.1 Methods for the determination of properties and quality classification

Quality is determined using the methods listed in Appendices A–D. This chapter describes the methods that are also used in heat and power plants. The mathematical formulae for determining the most important properties are also given. Data published before the year 2005 are based on the analytical methods referred to in the aforementioned VTT publication (Alakangas 2000, Alakangas 2005), and data as of the year 2005 are based on the methods discussed in this publication.

The methods used to analyse bio-oils are listed in Appendix D. Analyses for bio-oils and liquid fuels are described in more detail in VTT publications (Oasmaa & Czernik 1999, Oasmaa 2003, Lehto et al. 2013 & 2014).

All published EN and ISO standards are valid for five years from publication, after which they are reviewed. Always check the validity of standards online (e.g. www.cen.eu and www.iso.org).

The most important properties that are usually determined for fuels include proximate and elementary analyses, moisture content, calorific value, and ash melting behaviour (Alakangas 2016). Data are also often required about density, particle size distribution, and other fuel handling properties. Levels of different metals or non-metals either in the fuel or ash are also often determined for environmental or combustion-technical reasons. As regards dust-like fuels, data are also required on properties related to safety, e.g. on the temperature of spontaneous ignition and on dust explosion properties (Weckman 1986, Wilén et al. 1999, Wilén et al. 2013). In addition to all these, the reactivity of a fuel is an important property to know for evaluating/choosing gasification conditions fit for the fuel in question.

Proximate analysis of fuels comprises the determination of moisture content, volatile matter, fixed carbon, and ash. The proximate analysis is used for assessing the quality of fuels and, besides determinations of calorific value, as a basis for fuel trade (Ranta & Korhonen 1983).

Chemical analyses of fuels are given on a dry basis (dry, dry basis, Figure 2.1), in addition to which they can be calculated for dry, ash-free (daf) fuel. Bulk density and calorific value are given on as received / wet basis (ar) for the purposes of fuel trade. Table 2.1 shows mathematical formulae for converting results from one basis to another.

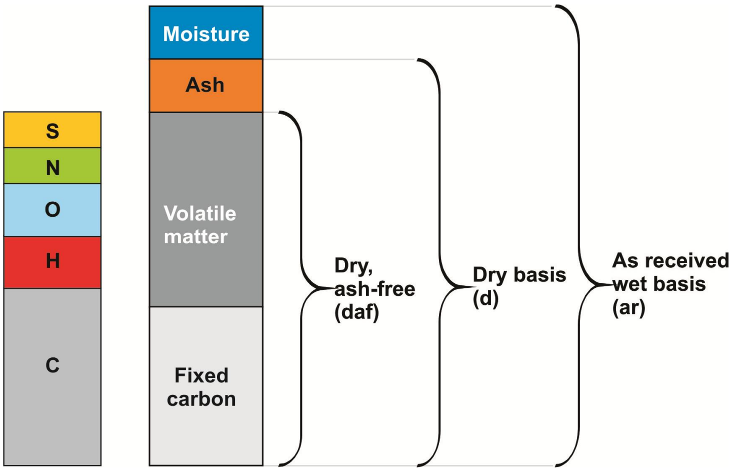


Figure 2.1. Different determination bases for fuels. Source: Alakangas & Selin 2006. Figure: VTT.

Table 2.1. Conversion of analytical results from one basis to another (EN ISO 16993:2016).

Source basis	**Target basis** **Analysed (air dry, ad)**	**As received (ar)**	**Dry basis (d)**	**Dry, ash-free (daf)**
Analysed (air dry, ad)		$\frac{100 - M_{ar}}{100 - M_{ad}}$	$\frac{100}{100 - M_{ad}}$	$\frac{100}{100 - (M_{ad} + A_{ad})}$
As received (ar)	$\frac{100 - M_{ad}}{100 - M_{ar}}$		$\frac{100}{100 - M_{ar}}$	$\frac{100}{100 - (M_{ar} + A_{ar})}$
Dry basis (d)	$\frac{100 - M_{ad}}{100}$	$\frac{100 - M_{ar}}{100}$		$\frac{100}{100 - A_d}$
Dry, ash-free (daf)	$\frac{100 - (M_{ad} + A_{ad})}{100}$	$\frac{100 - (M_{ar} + A_{ar})}{100}$	$\frac{100 - A_d}{100}$	
M = moisture content and A = ash content				

2.2 Determination of moisture content in solid biofuels

2.2.1 Determination of moisture content using the oven dry method

The moisture content of solid fuels is determined using the simplified oven dry method described in the EN ISO 18134-2:2015 standard. Other moisture content measurement methods (such as rapid moisture meters) can also be used, if their equivalence with the standard methods can be proven.

Solid biofuel samples are taken in accordance with the sampling standard (EN 114778:2012 / EN ISO 18135). The basic principle of sample reduction is that the composition of the sample must not change from the original during the different steps. The sample is divided in accordance with the sample preparation standard. The sample is mixed before division and weighed on a set of scales, which is accurate to at least 0.1 g. The empty tray (m_1) is also weighed. Figure 2.2 shows a drying oven in which fuels are drying.

Figure 2.2. Determination of the moisture content of fuel. Photo: Labtium Oy.

According to the EN ISO 18134-2:2015 standard for the determination of moisture content in solid biofuels, the moisture sample must weigh at least 300 g. With fine fuels (e.g. dust), a sample of 200 g can be used or, if the weighing accuracy is at least 0.01 g, a sample of 100 g can be used. The sample must not be too thick (1 g of material per cm^2). The particle size of the sample during moisture determination must be no more than 31.5 mm (nominal top size). Each sample must be uniquely labelled.

The following need to be given special attention:

- *Sample preparation* (particle size reduction and mixing) as well as weighing before drying samples must be carried out with care but quickly to prevent moisture loss (drying).
- *Particle size reduction* (crushing) must be carried out using equipment that prevents moisture from evaporating due to the heating of the device or strong air currents (priority must be given to slowly rotating crushing mills or crushers).
- If *moisture has condensed along the walls of the sample bag*, it must be rubbed into the sample before opening the bag. If condensed moisture cannot be rubbed into the sample, the empty sample bag must be dried and the moisture contained therein taken into account when calculating moisture content.

Samples are dried in a drying oven at 105 ± 2 °C. The air-conditioning valve (exhaust valve) of the drying oven must be open, and moist air must be allowed to leave the oven freely through it. Temperature must be monitored regularly. When wet samples are placed in a drying oven to dry, any dry samples that may already be in the oven must be removed.

Samples must be placed in the drying oven immediately after weighing (m_2). Care must be taken not to lose any of the sample material. Samples must not be placed too close together, against the walls, or on the bottom of the drying oven. When samples are taken out of the drying oven, oven gloves must be worn to prevent burns. Samples are dried until a stable weight is reached. A stable weight has been achieved when mass no longer changes by more than 0.2 w-% within 60 minutes. Samples must not be dried for more than 24 hours. In most cases, a drying time of 16 hours is sufficient, when the particle size of the sample is no more than 31.5 mm and the sample is not too thick. It is important to ensure the correct drying temperature and a sufficient drying time for reaching a stable weight for each type of fuel.

Samples must be weighed immediately after removal from the drying oven (m_3). Weighing after drying must be done quickly (within 10–15 s) to prevent moisture from the air in the laboratory from becoming absorbed in samples. The drying oven must then be switched off.

Moisture content (M_{ar}) is calculated from the wet weight using formula 2.1:

$$M_{ar} = \frac{(m_2 - m_3)}{(m_2 - m_1)} x\ 100 \tag{2.1}$$

in which

M_{ar}	moisture content as received, w-%
m_1	weight of the empty tray, g
m_2	combined weight of the tray and the sample before drying, g
m_3	combined weight of the tray and the sample after drying, g

The result is reported accurate to 0.1 percentage points.

Example 2.1:

$$M_{ar} = \frac{582.47 - 456.96}{582.47 - 281.13} x\ 100 = 41.7\ \%$$

Sawmill and wood processing industries also need to know the moisture content on a dry basis (moisture content per dry weight). The moisture content on a dry basis (U_d) is calculated using formula 2.2. Similarly, if U_d is known, moisture content can be calculated on a wet basis using formula 2.3.

$$U_d = \frac{M_{ar}}{100 - M_{ar}} x\ 100 \tag{2.2}$$

$$M_{ar} = \frac{U_d}{100 + U_d} x\ 100 \tag{2.3}$$

For liquid biofuels that are prone to forming a film, such as black liquor, dry matter can be determined by mixing a sample with a suitable amount of inert, fine matter, such as sand.

2.2.2 Determination of moisture content of firewood

The moisture content of firewood can be determined from sawdust from the cutting surface of the tree. A moisture sample is collected from the sawdust of one day of chopping so that each sample represents the same species of tree and the same batch of raw material. The sample must consist of sawdust collected at 30-minute intervals. The sawdust must be collected into a plastic container with a lid to prevent moisture from evaporating. The container must be sealed and kept away from direct sunlight between the taking of samples (Erkkilä 2012).

A combined sample is mixed from sawdust samples taken of one day's homogeneous sawdust samples, from which moisture content is determined. Three reserve samples are taken of each combined sample to analyse moisture content. Moisture content is determined using a moisture analyser from sawdust samples (Figure 2.3). The average of the moisture results of the three reserve samples is calculated.

Figure 2.3. Determination of moisture content from a smallwood unit using sawdust. Photos: VTT.

Moisture content is analysed using a set of rapid moisture meters. The mass of each processing unit is weighed empty and full of smallwood. The weighing method is chosen according to the processing unit in question. Different kinds of scales are available for weighing, such as beam scales, hook scales, and pallet truck scales. Each processing unit is numbered in connection with weighing to make it identifiable later. The results of weighing and the moisture content analysis are recorded in a table. Once the initial moisture content and wet weight are known, the delivery moisture content and energy content of the processing unit can also be calculated. Processing units are weighed in connection with delivery. The same scales can be used for weighing as for the initial measurements, or vehicle scales can be used.

Example 2.2:

The gross weight of a batch of wet firewood (including the cage) is 439 kg. The cage weighs 20 kg, which means that the wood weighs 419 kg and has a volume of 1 loose m^3. The moisture content of the sawdust is, based on the average of three samples, 44.5 w-%. At the delivery stage, the gross mass of the unit is 310 kg and the mass of the wood is 290 kg. The average value of 19.00 MJ/kg (5.28 kWh/kg) is used as the calorific value on a dry basis.

The mass of the batch of smallwood on a dry basis is

$$419\ kg\ x\ \left(\frac{100 - 44.5}{100}\right) = 232.5\ kg$$

The final moisture content (w-%) of the delivery lot is

$$\frac{290 - 232.5}{290}\ x\ 100 = 19.8\ \%$$

2.3 Determination of calorific values, energy density, and energy content

2.3.1 Overview

The net calorific value of the dry matter in solid biofuels, solid recovered fuel, peat, as well as bio-oil is determined in accordance with the standards listed in Appendices A–D. For packaging, calorific value can be determined in accordance with the EN 13431:2005 standard (Alakangas & Impola 2014, www.cen.eu, Lehto et al. 2013).

Gross calorific value, i.e. “higher calorific value”, denotes the amount of heat that is released when one unit of mass of fuel burns completely and the products cool down to a temperature of 25 ºC. When determining gross calorific value, the assumption is that both the water generated by the combustion of the hydrogen contained in the fuel and the water contained in the fuel (i.e. moisture) are liquid after combustion. However, in Finland, the calorific value of a fuel is usually given as its *net calorific value* (“lower calorific value”), which is calculated from the gross calorific value using conversion formula 2.4. Net calorific value takes account of the energy used for evaporating water during combustion.

The third calorific value that can be given is *net calorific value as received*. This calorific value is the lowest one, as both the energy used for evaporating the water contained naturally in the fuel and the water formed in combustion are deducted. Calorific values are usually given as megajoules per kilogramme of fuel (MJ/kg, 1 MJ = 0.2778 kWh).

2.3.2 Gross calorific value

Approximately one gram of an air-dry analysis sample (with an equilibrium moisture content) is weighed and then burnt in an oxygen atmosphere in a bomb calorimeter immersed in liquid, and the amount of heat released is measured. The moisture content of the analysis sample is determined at the same time, which can be used to convert the calorific value of the air-dry sample to represent the calorific value of an absolutely dry sample. The result is given as the average gross, i.e. higher, calorific value of two parallel measurements for an absolutely dry sample. The difference between the parallel measurements must not exceed 0.120 MJ/kg for sawdust or 0.140 MJ/kg for other solid biofuels. Calorific values are reported accurate to 0.01 MJ/kg.

2.3.3 Net calorific value on a dry basis

Once the gross calorific value has been determined, the net calorific value on a dry basis can be calculated using formula 2.4:

$$q_{p,net,d} = q_{V,gr,d} - 212.2\ x\ w(H)_d - 0.8\ x\ [w(O)_d + w(N)_d] \tag{2.4}$$

in which

$q_{p,\mathrm{net,d}}$	net calorific value on a dry basis at constant pressure, J/g or kJ/kg
$q_{V,\mathrm{gr,d}}$	gross calorific value on a dry basis at constant volume, J/g or kJ/kg
$w(\mathrm{H})_\mathrm{d}$	hydrogen content in dry biofuel (including the hydrogen contained in the water of hydration of the mineral matter and the hydrogen contained in the fuel), w-%
$w(\mathrm{O})_\mathrm{d}$	oxygen content in dry fuel, w-%
$w(\mathrm{N})_\mathrm{d}$	nitrogen content in dry fuel, w-%

Note: $\left[w(\mathrm{O})_\mathrm{d} + w(\mathrm{N})_\mathrm{d}\right]$ can be calculated by subtracting the ash, carbon, hydrogen, and sulphur content of the fuel on a dry basis (w-%) from 100 w-%.

When net calorific value on a dry basis is calculated according to formula 2.4, the result is given as J/g or kJ/kg. If the result needs to be given as MJ/kg, it must be divided by one thousand.

If no hydrogen, nitrogen, carbon, or sulphur content of the fuel has been determined, default values can be used in the calculation. Typical default values for hydrogen, $w(H)_d$, are 5.6% in peat, 6.2% in whole trees, 6.0% in logging residue, 5.9% in bark, and 6.0% in herbaceous biomass. The typical default value for $w(O)_d + w(N)_d$ is 35% in peat, 41% in whole trees, 41% in logging residue, 41% in bark, and 41% in herbaceous biomass. The default values for ash-free solid biofuels pursuant to the EN ISO 18125:2016 standard are given in Appendix H. The default values for hydrogen, $w(H)_d$, are 6.1–6.3% for wood-based fuels, 6.2–6.3% for herbaceous biomasses, and 6.6% for grains and seeds. The value for $w(O)_d + w(N)_d$ is 40.4–44.5% for wood-based fuels, 43.5–45.0% for herbaceous biomasses, and 46.0% for grains and seeds.

2.3.4 Net calorific value as received

a) Dry basis

Net calorific value (at constant pressure) as received (wet fuel) can be calculated on the basis of the net calorific value of the dry matter using the following equation (2.5).

$$q_{p,net,ar} = q_{p,net,d} \; x \left(\frac{100 - M_{ar}}{100}\right) - 0.02443 \; x \; M_{ar} \qquad (2.5)$$

in which

$q_{p,\mathrm{net,ar}}$	net calorific value (at constant pressure) as received, MJ/kg
$q_{p,\mathrm{net,d}}$	net calorific value (at constant pressure) on a dry basis, MJ/kg
M_{ar}	moisture content as received, w-%
0.02443 is	the correction factor for the enthalpy of vaporisation (at constant pressure) for water (moisture) at a temperature of 25 °C, MJ/kg per 1 w-% of moisture.

Net calorific value as received is denoted by the symbol Q in the quality classification standards for solid biofuels (EN ISO 17225 series). If the calorific value is converted into kWh/kg, the conversion should not be done until after the calculation.

Example 2.3:

The net calorific value of woodfuel in this example is 19.00 MJ/kg on a dry basis. The moisture content of the fuel is 19.8 w-%.

Net calorific value as received (Q)

$$Q = 19.00 \; x \left(\frac{100-19.8}{100}\right)\frac{MJ}{kg} - 0.02443 \; x \; 19.8 \; MJ/kg = 14.75 \; MJ/kg$$

If the net calorific value as received needs to be converted into kWh/kg, this can be calculated by dividing the result, 14.75 MJ/kg, by 3.6, which gives 4.10 kWh/kg. The energy content of the delivery lot in example 2.2 is 290 kg x 4.10 kWh/kg = 1,189 kWh. The volume of the delivery lot was one loose m^3, i.e. 1.2 MWh/m^3 in energy.

The calorific value of wood fuels per unit of volume can also be calculated with the help of basic density using formula 2.6.

$$q_{ar,V} = \frac{\rho}{1-\frac{M_{ar}}{100}}\, x\, q_{net,ar} \qquad (2.6)$$

in which

$q_{ar,v}$	net calorific value of wet fuel, MJ/m^3
ρ	basic density on a dry basis, kg/m^3
M_{ar}	moisture content of the fuel, w-%
$q_{net,ar}$	net calorific value of the fuel as received, MJ/kg (formula 2.5)

b) Dry, ash-free basis

The net calorific value (at constant pressure) as received (wet biofuel) can be calculated on the basis of the net calorific value of the dry, ash-free matter in the fuel using the following equation (2.7).

$$q_{p,net,ar} = [q_{p,net,daf}\, x \left(\frac{100-A_d}{100}\right) x \left(\frac{100-M_{ar}}{100}\right)] - 0.02443\, x\, M_{ar} \qquad (2.7)$$

in which

$q_{p\text{,net,ar}}$	net calorific value (at constant pressure) as received, MJ/kg
$q_{p\text{,net,daf}}$	net calorific value (at constant pressure in dry, ash-free fuel), MJ/kg
M_{ar}	moisture content as received, w-%
A_{d}	ash content in dry matter, w-%

0.02443 correction factor for the enthalpy of vaporisation (at constant pressure) for water (moisture) at a temperature of 25 °C, MJ/kg per 1 w-% of moisture

Calorific value can be determined for a specific batch, or a default value can be used:

1) If the ash content of a fuel is low and relatively constant (e.g. sawdust), the calculation can be based on the dry basis equation and the default net calorific value for dry matter ($q_{p\text{,net,d}}$).
2) If the ash content of a specific fuel (e.g. stump, straw) varies considerably (or is high), the ash-free fuel equation and the default net calorific value for dry, ash-free matter ($q_{\text{p,net,daf}}$) should be used instead.

The result is given rounded to the nearest 0.01 MJ/kg.

2.3.5 Energy density as received

The energy density of a delivery lot of solid biofuels as received (E_{ar}) is calculated based on the net calorific value as received and the bulk density as received using formula 2.8.

$$E_{ar} = \frac{1}{3600} \, x \, q_{p,net,ar} \, x \, BD_{ar} \tag{2.8}$$

in which

E_{ar}	energy content of biofuel as received, MWh/loose m^3
$q_{p,net,ar}$	net calorific value as received, MJ/kg
BD_{ar}	bulk density, i.e. volume weight of wood fuel as received, kg/loose m^3
$\frac{1}{3600}$	conversion factor for units of energy from MJ to MWh

2.3.6 Delivered energy

Delivered energy, W (MWh), is calculated using formula 2.9.

$$w = \frac{Q}{3.6} \, x \, m \tag{2.9}$$

in which

$\frac{Q}{3.6}$	conversion of the net calorific value as received (MJ/kg) into MWh/t
m	mass of the delivered fuel, tonnes

For small lots and random use, the procedure described above may be too cumbersome; for example, smaller plants may not always have weighbridges available. In such cases, the energy content of a fuel delivery lot can be determined as follows:

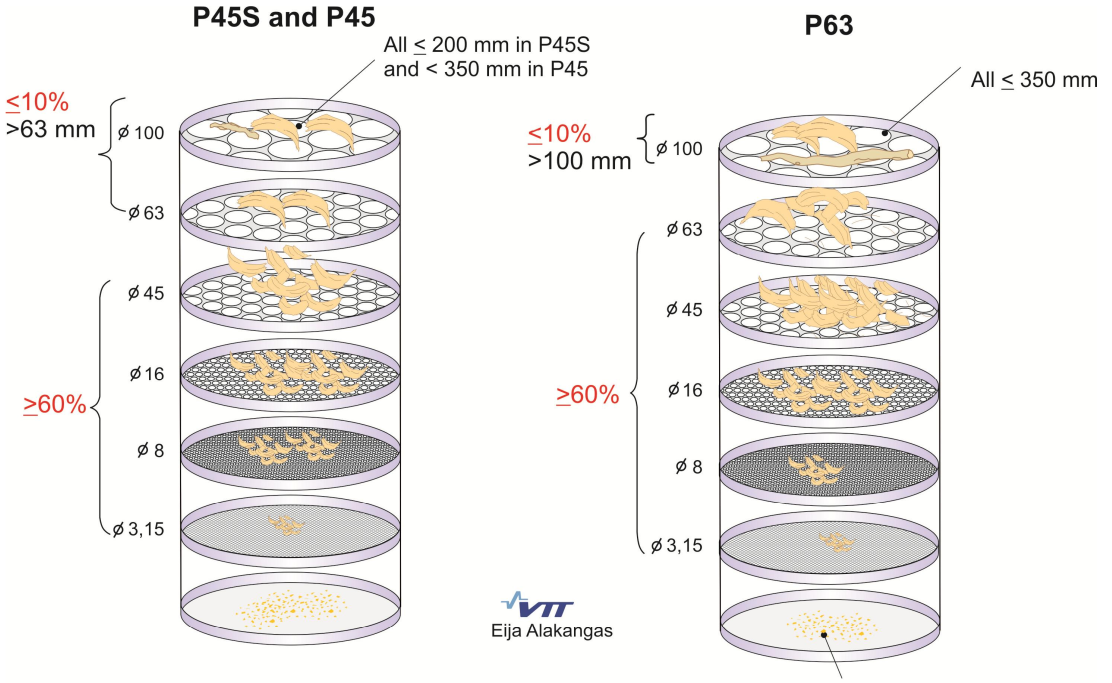
- Measure the volume of the delivered fuel lot in accordance with the Finnish Timber Measurement Act (141/2013).
- Determine the bulk density of the fuel (BD).
- Based on sampling, determine the moisture content (M) and net calorific value (Q) of the fuel, or determine the moisture content but use a commonly agreed, typical wood fuel species specific net calorific value on a dry basis.

The energy content of a delivered fuel lot can be determined at small plants on the basis of the amount of energy produced and the efficiency of the boiler (EN 12952-15:2003 Water-tube boilers and auxiliary installations. Part 15: Acceptance tests).

2.4 Determination of particle size

Sample taking for sieve analyses is carried out in accordance with the sampling standard for solid biofuels. The required sample size is at least eight litres. Screening is carried out using sieves with round holes. The apertures to be used are 3.15 mm, 8 mm, 16 mm, 31.5 mm, 45 mm, and 63 mm as per the ISO 3310-2:2013 standard. Particle size distribution is determined on the basis of the EN ISO 17827-1:2015 standard. The sample is screened through horizontally oscillating sieves to mechanically sort the particles into descending size classes (Figure 2.4), i.e. the largest aperture is at the top and the smallest at the bottom. The sample is screened at less than 20% moisture, and the screening time is 15 minutes. The screening direction is reversed from time to time. If necessary, the sample can be dried in accordance with the instructions given in the sampling standard. The material left on each sieve and in the bottom container is weighed accurate to 0.1 g. All particles over 100 mm in size are picked out by hand. Particle size analyses should ideally be outsourced to specialist laboratories.

The names of the particle size classes in the EN ISO 17225-1:2014 and EN ISO 17225-4:2014 fuel specification and classes standards refer to the main fraction (60% of the weight remaining on each sieve). With P31, for example, the combined weight of the material left on the 3.15 mm, 8 mm, 16 mm, and 31.5 mm sieves counts towards the 60 w-% main fraction. The maximum allowed amount of particles over 45 mm in size is 10 w-%, which makes the maximum amount of fines 30 w-% (F30). If the amount of fines is smaller, the main fraction comprises over 60 w-% of the material, as indicated by the example in Figure 2.4. The particle size categories for wood chips are explained in “Quality guidelines for wood fuels” (Alakangas & Impola 2014, Alakangas & Impola 2015).



Fines (< 3,15 mm) to be stated according to the following classes F05, F10, F15, F20, F25, F30, F30+
In P45S a cross sectional area of largest piece of wood should be ≤ 6 cm^2

Figure 2.4. Determination of particle size and quality requirements for classes P45S, P45, and P63. Source: Alakangas & Impola 2015. Figure: VTT.

In Figure 2.4, the letter S after the particle size class means ‘small’, and this particle size class is intended for small-scale appliances. The cross-section area is also determined for class S wood chips in accordance with the Quality guidelines for wood fuels (Alakangas & Impola 2015).

The informative annex of the EN ISO 17827-1:2016 particle size determination standard describes the procedure for determining the median for particle size distribution (d50). It is a value that divides the distribution into two equally sized parts and is graphically the intersection point of the cumulative size distribution curve at the 50% horizontal line.

Example 2.4:

The following masses of stem wood chips have been measured from sieves complying with the ISO 3310-2:2013 standard:

Fraction	**Sieve size, mm**	**Volume, w-%**	**Measured fraction (requirement pursuant to the EN ISO 17225-1:2014 standard)**	**Class[1]**	**Cumulative amount**
Fines	< 3.15	1.8	1.8% (F05)	F05	3.7
Main fraction	3.15–8	7.7	89.5% (≥ 60%)	P31	9.5
	8–16	5.0			14.5
	16–31.5	78.7			93.2
	31.5–45	4.2	Belongs to the main fraction	P31	97.4
Coarse fraction	45–63	2.1	3.6% (≤ 6% more than 45 mm) All under 150 mm		99.5
	63–100	0.5		P31	100
	< 100	0			100

[1] Select the smallest particle size class that meets the quality requirements. When 60% of the combined mass is achieved using sieves of 3.15–31.5 mm, the matter in the 31.5–45 mm sieve belongs to the main fraction, as only matter of more than 45 mm (2.1% + 0.5% = 3.6%) is included in the coarse fraction. Example 2.4 fulfils the particle size requirements for P31 and F05 as well as the P31S requirement.

2.5 Determination of bulk density

Bulk density as received (BD_{ar}) is obtained by dividing the weighed mass of a load by its volume (formula 2.10). The weighing and volume measurement are carried out in the manner agreed by the supplier and user in the delivery contract.

The bulk density of fuel can also be determined for wood chips and hog fuel using a 50-litre container and for pellets using a five-litre container according to the EN ISO 17828:2015 bulk density determination standard. The determination of bulk density for wood chips is described here, and in more detail in Figure 2.5.

For wood chips and hog fuel, the ratio between the container height and diameter must be between 1.25 and 1.50. A so-called large container with a volume of 50 litres (0.05 m^3) is used for wood chips and hog fuel. Samples are weighed on a set of scales, which is accurate to at least 10 g. The empty vessel is also weighed. Sample taking and preparation are carried out according to the relevant standards. The moisture content of a sample as received is determined in accordance with the EN ISO 18134-2:2016 standard immediately after the determination of bulk density. This allows for combining the determination of bulk density and moisture content.

Bulk density (BD) is calculated using the following formula (2.10):

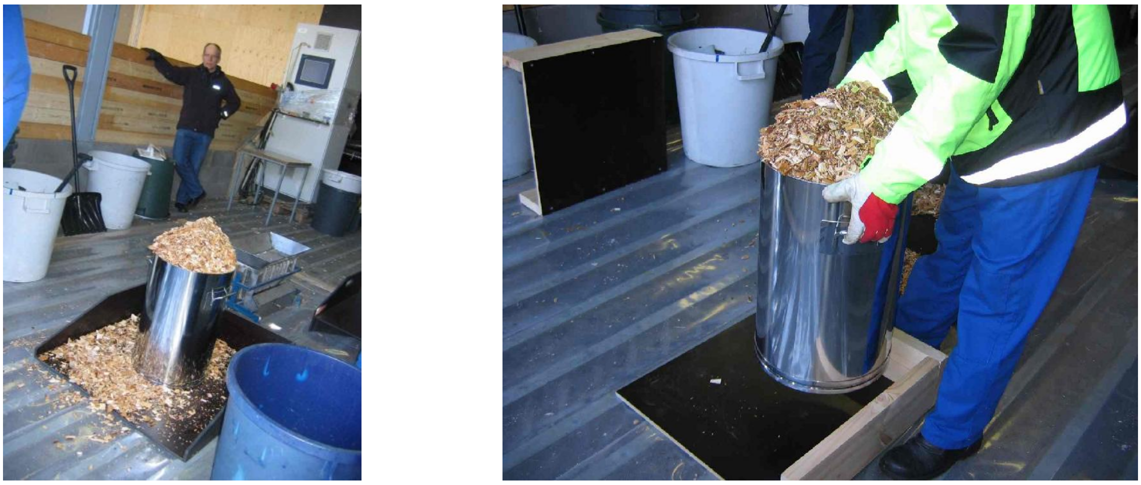
$$BD_{ar} = \frac{m_2 - m_1}{V} \tag{2.10}$$

$$BD_d = BD_{ar} \times \frac{100 - M_{ar}}{100}$$

in which

BD_{ar}	bulk density as received, kg/m^3
BD_d	bulk density on a dry basis, kg/m^3
m_1	weight of the empty container, kg
m_2	weight of the filled container, kg
V	net volume of the measuring container, m^3
M_{ar}	moisture content as received (on wet basis), w-%

The results of individual determinations are given accurate to 0.1 kg/m^3, and the average of two individual results is rounded to the nearest 10 kg/m^3.



The sample is mixed (sample amount just under 70 litres). The container is filled by pouring from 20–30 cm above the top edge of the container until the highest possible heap has formed.

The filled container is jolted three times by letting it drop freely from a height of 15 cm onto a wooden board. It is important to ensure that the container hits the wooden board vertically. The empty space created in the container is refilled.

Any excess material is removed by swinging a small scantling over the container. If the sample contains coarse matter, all particles preventing the scantling from moving freely must be removed by hand. If the removal of large particles makes largish pits in the levelled surface, they must be filled and the removal of excess material repeated.

The filled container is then weighed. The used sample is combined with unused sample material and the procedure repeated at least once.

Figure 2.5. Determination of the bulk density of wood chips. Photos: Eija Alakangas, VTT.

Example 2.5:

The task is to calculate the bulk density of wood chips using a 50-litre container, which weighs 3.160 kg when empty and 18.845 kg when filled. The moisture content of the wood chips has already been measured as 41.7 w-% (see Example 2.1).

$BD_{ar} = \frac{18.845-3.160}{0,05} = 313.7\ \text{kg/m}^3$

$BD_{d} = 313.7 \text{ x } \frac{100-41.7}{100} = 182.9\ \text{kg/m}^3$

2.6 Determination of mechanical durability of pellets and briquettes

Mechanical durability refers to the ability of pellets and briquettes to endure shocks and/or wear during handling and transport. The method and equipment for determining mechanical durability are described in the EN ISO 17831-1:2016 standard for pellets and in the EN ISO 17831-2:2016 standard for briquettes.

The pellet sample is subjected to controlled shocks in a rotating chamber by the collision of the pellets against each other and the walls of the chamber. Durability is calculated from the sample mass that remains after the removal of ground and broken down particles (“fines”). Pellets are tested in a dust-tight container. The container must be made from a rigid material (e.g. stainless steel plates) with smooth and flat surfaces. The container must measure 300 x 300 x 125 mm, and a metal sheet of 230 mm in length should be fixed symmetrically to a diagonal of one 300 x 300 mm side of the box. Figure 2.6 shows a testing device with two boxes.

The ground fines are screened using a 3.15 mm sieve according to the ISO 3310-2:2013 standard. The recommended sieve diameter is no more than 400 mm, and the volume of sample on the sieve is 0.8 g/cm^2. The fines must be sifted by hand (5–10 rotating motions) prior to screening. The required sample size is one kilogram, divided into two sub-samples of 500 ± 10 g. The sample is weighed to an accuracy of 0.1 g. The sample is tumbled at a speed of 50 ± 2 revolutions per minute for a total of 500 revolutions. The sample is removed and screened by hand as before the test. The material remaining on the sieve is weighed. The weight percentage of whole pellets remaining on the sieve (particles remaining on the 3.15 mm sieve) is then calculated. The mechanical durability of pellets is determined using formula 2.11.

$$DU = \frac{m_a}{m_e} x\, 100 \tag{2.11}$$

in which

DU	mechanical durability of pellets, w-%
m_e	mass of pre-screened pellets before the tumbling process, g
m_a	mass of the screened pellets after the tumbling process, g

Figure 2.6. Tester for the mechanical durability of pellets. The device consists of two drums. Photo: Labtium Oy.

The test must be repeated or a device be used that allows both sub-samples to be tested at the same time (Figure 2.6). The result is calculated to two decimal places, and the mean of the two samples rounded to the nearest 0.1% for reporting.

The testing equipment for briquettes consists of a cylindrical steel drum with a nominal volume of 160 litres. A metal wire cloth sieve complying with the ISO 3310-1:2000 standard is used for screening, the aperture size of which is chosen so that it equates to approximately 2/3 of the diameter or diagonal of the briquettes, but amounts to no more than 45 mm. The total sample size is 25 kg, divided into four sub-samples of at least five kilograms each. Two sub-samples (of at least 2 kg ± 0.1 kg) are used to determine moisture content and two for the tumbling test. The sample must not contain broken particles. The sample is tumbled at a speed of 21 ± 0.1 rpm for five minutes or for 105 ± 0.5 revolutions. After tumbling, the sample is sifted and the material remaining on the sieve is weighed. The mechanical durability of briquettes is calculated using formula 2.11 as with pellets.

2.7 Ash melting behaviour

Ash-melting behaviour depends on the composition of ash, which varies from one fuel to the next. Ash melting during combustion causes several undesirable phenomena, such as slagging and fouling of heat transfer surfaces.

Ash melting behaviour is determined for solid biofuels according to the CEN/TS 15370-1:2006 / EN ISO 21404 standard. The determination method for peat is described in the ISO 540:2008 standard. The ashing temperature is 550 °C for solid biofuels and 815 °C for peat. In the EN ISO 21404 standard, which is under preparation, the ashing temperature is proposed to be 710°C ± 10 °C. If ashing is done at 550 °C, carbonates in Ca-rich solid biofuels, especially calcium carbonate, will mainly contribute to SST since decomposition of calcium carbonates occur from approximately 600 °C. It may be more difficult to determine DT due to strong shrinkage of test pieces. The difference is primarily due to the breakdown of carbonates into carbon dioxide at a higher temperature. The ash is ground to a particle size of 0.075 mm. Prior to the year 2005, the ashing temperature for solid biofuels was 815 °C, which is why ash content can be lower than the results achieved with the new method.

A cylindrical sample of a height and diameter of 3–5 mm is formed from the ash of solid biofuels. For coal, a cubical sample of a height and diameter of 3–7 mm is formed. A conical sample can also be formed for coal.

Four different stages are usually distinguished in melting behaviour: deformation temperature (DT), sphere temperature (ST), hemisphere temperature (HT), and flow temperature (FT). For solid biofuels, shrinkage starting temperature (SST) can also be determined, but no sphere temperature. Figure 2.7 shows the ash melting behaviour of solid biofuels.

According to the solid biofuels quality requirements standards (EN ISO 17225 series), ash melting behaviour is determined in an oxidising atmosphere using a solution of air and carbon dioxide. Ash melting can also be determined in a reducing atmosphere. The temperature of the sample is raised at a set speed while monitoring the transformation of the test piece as a function of temperature by means of photography. For biofuels, the sample is heated to 550 °C at a rate of 3–10 °C per minute. The sample is photographed at intervals of 10 °C, and the temperatures shown in Figure 2.7 (SST, DT, HT, and FT) are given to an accuracy of 10 °C.

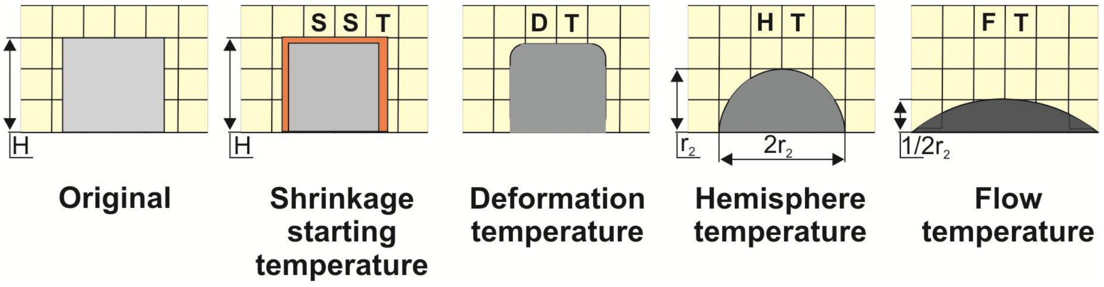


Figure 2.7. Ash melting behaviour of solid biofuels. Figure: VTT.

2.8 Fuel reactivity

In addition to general fuel properties (chemical composition), information is also needed on the fuel reactivity and the ash-sintering and melting behaviour for evaluating the suitable gasification conditions.

Reactivity describes the gasification of char after the fuel pyrolysis stage. Reactivity shows how much time is required for achieving the final fuel conversion, i.e. how easily a fuel is gasified. Reactivity (%/min) is given as instantaneous reaction rate as a function of ash-free fuel conversion. Reactivity depends on multiple factors, e.g. the fuel itself, its chemical composition, temperature, pressure, and the gas atmosphere (Moilanen 2006).

Reactivity is determined by measuring the weight of a fuel sample as a function of time in a pressurised thermogravimetric analyser. The method was developed to simulate actual gasification conditions and especially fluidised bed gasification. Figure 2.8 shows a diagram of VTT's pressurised thermogravimetric analyser (PTGA). The sample is lowered quickly into a hot reactor with constant conditions (temperature, pressure, gas atmosphere). Moisture is first removed from the sample, followed by pyrolysation. The remaining carbon is gasified, leaving residual ash. The mass change of the sample is determined as a function of time keeping microbalance at a constant temperature. The mass change can be used to calculate the reactivity of the sample (char) during gasification, and the sintering degree can be inspected from the residual ash. Reactivity profiles (instantaneous reaction rate vs fuel conversion) are biomass-specific: reactivity increases or decreases as conversion increases. Figures 2.9 and 2.10 illustrate the determination of reactivity in more detail.

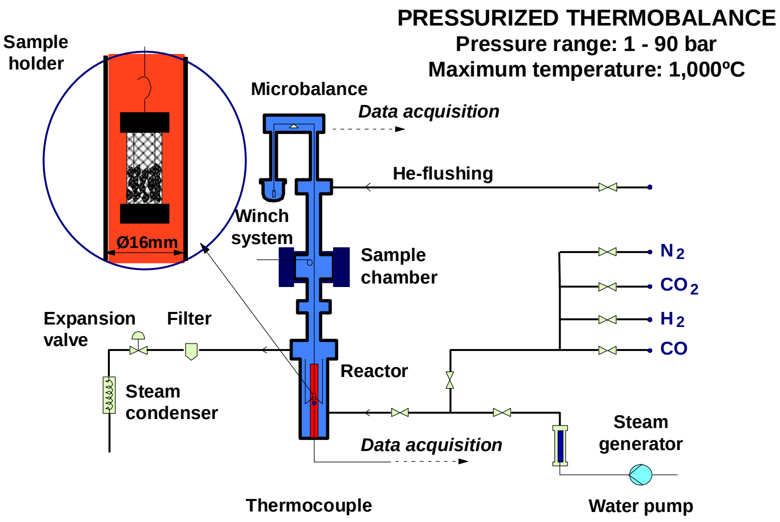


Figure 2.8. Diagram of a pressurised thermogravimetric analyser. Figure: VTT.

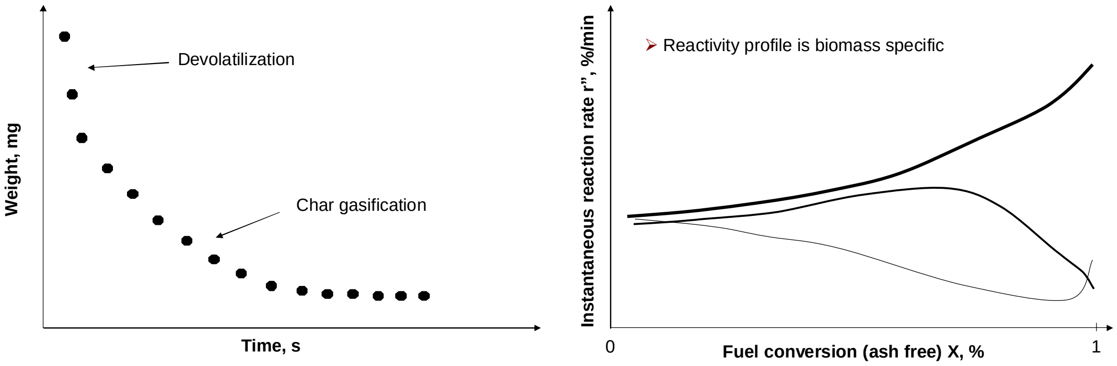


Figure 2.9. Typical change in mass as a function of time (left) and examples of biomass reactivity profiles (right). Figure: VTT.

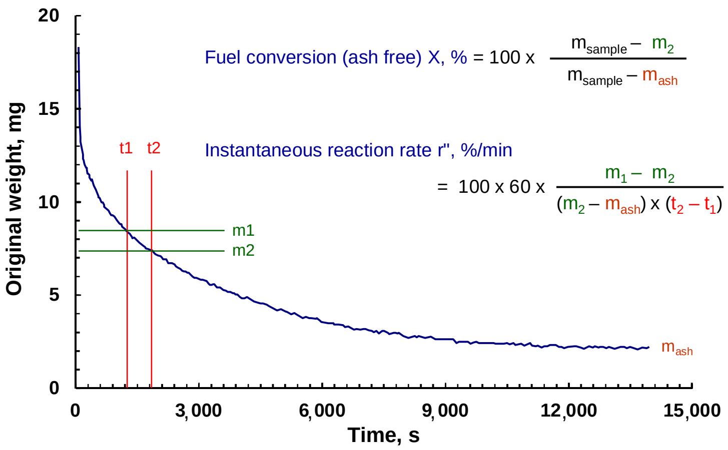


Figure 2.10. Calculating the fuel reactivity from the results of thermogravimetric analyses. Figure: VTT.

After the reactivity measurements, the residual ash is inspected under a microscope to detect whether the ash has sintered. The sintering degree is given as asterisks (VTT's method, Moilanen 2006) on the basis of the following classification criteria (Figure 2.11):

1. If ash has not sintered, the symbol 'o' is used.
2. If ash has sintered partly and/or clear signs of fused ash can be observed, one or two asterisks (* or **) are used.
3. If ash has sintered completely or almost completely, or if the ash has melted, three asterisks (***) are used.

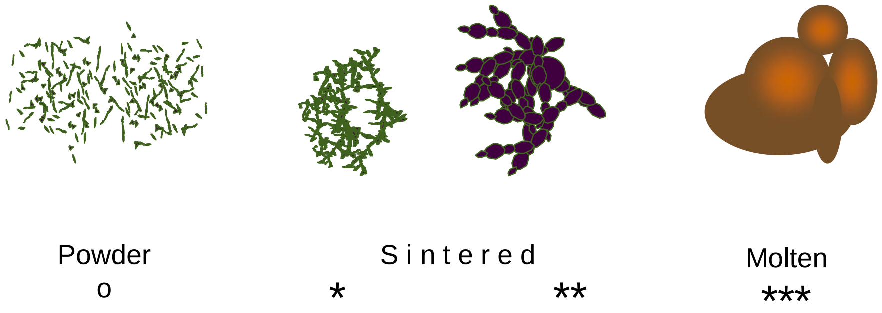


Figure 2.11. Ash sintering degrees. Figure: VTT.

The following conclusions can be drawn from the fuel reactivity and ash behaviour:

- Reactive biomass with no ash melting (high ash melting point) → easy to gasify
- Reactive biomass with ash melting (low ash melting point) → lower gasification temperature
- Not very reactive biomass and signs of ash melting → challenging fuel to gasify

2.9 Calculation of emission factors

'Emission factor' refers to the amount of carbon dioxide generated by the oxidation of carbon in a certain volume of fuel, energy, or raw material, in the use of a certain volume of raw material, or in the production of a certain volume of a product. For fuel blends, emission factors are determined using the EN 15440:2011 standard. The standard also includes a description of a method for determining ^{14}C.

Appendix H lists the emission and oxidation factors of different fuels as published by Statistics Finland, as well as their default calorific values.

Calculation of the carbon dioxide emission factor of fuels (Energy in Finland 2004):

$$CO_2 \left[\frac{g}{MJ_{pa}}\right] = F \; x \; \frac{m_c}{m_{pa}} \; x \; \frac{M_{CO_2}}{M_c} \; x \; 10^3 x \; (1 - M_{ar}) \; x \; \frac{1}{q_{net,ar}} \qquad (2.12)$$

in which

m_c/m_f	carbon content of fuel
M_{CO2}	44.01 kg/kmol
M_C	12.01 kg/kmol
M_{ar}	moisture, w-%
$q_{net,ar}$	net calorific value as received, MJ/kg
F	oxidation factor

Example: Calculation of the CO_2 factor of peat using the typical values for milled peat:

- The carbon content of peat is 54.5 w-% on a dry basis.
- The net calorific value on a dry basis is 21.00 MJ/kg.
- Moisture content as received is 46.5 w-%.
- The net calorific value as received ($q_{net,ar}$) is 10.10 MJ/kg.

One kilogram of milled peat at the moisture level of 46.5 w-% contains (100.0−46.5)/100 x 1,000 g = 535 g of dry peat with a carbon content of 54.5% x 535 g = 292 g.

The amount of carbon dioxide produced is

$$\frac{292\ g}{12.01\ \mathrm{g}/mol}\ x\ 44.01 \frac{g_{CO_2}}{mol} = 1\,070\ g_{CO_2}$$

The CO_2 emission factor is $\frac{1\,070\ g/kg}{10.10\ MJ/kg} = 105.9\ g_{CO_2}/MJ$

3. Sampling and preparation

3.1 Overview

This chapter discusses the general principles of sampling that are suitable for many solid fuels. The sampling of solid biofuels and especially wood fuels at heat and power plants is examined in more detail (Järvinen & Impola 2012, Järvinen 2012). General guidelines are given for taking and preparing samples of solid biofuels in accordance with the EN 14778:2012 / EN ISO 18135 and EN 14780:2012 / EN ISO 14780 standards, which can be used to draw up plans and instructions on a case-by-case basis. The guidelines are based on the Quality guidelines for wood fuels (Alakangas & Impola 2015). The sampling of ash is described in VTT Research Notes 2141 (Laine-Ylijoki et al. 2002). Sampling standards for solid and recovered fuels are listed in Appendices A and B.

Sampling refers to extracting and separating a specific batch suitable for analysis from a larger volume in such a manner that the sample and the original lot of materials are identical with regard to the desired properties. In fact, representative sampling means the reduction of both systematic and random errors. It has been estimated that approximately 80% of the errors in the results of analyses are attributable to sampling, 15% to sample preparation, and 5% to the analysis itself.

The simplified principles of good sampling and sample preparation are as follows:

- The sampling location must be as close as possible to the receiving station of the fuel.
- Samples must be taken from freely moving fuel, for example from a falling fuel stream.
- The entire fuel stream or the majority of it must be subjected to sampling.
- Several smaller increments must be taken from the fuel stream.
- Continuous sampling from a partial stream must be avoided.
- The preparation and division of samples must not change the properties analysed.

The basic principle of good sampling is to obtain a representative sample of the entire fuel lot being tested. Every particle in the lot or sub-lot that the sample represents should have an equal probability of being selected as part of the sample. The purpose of sample preparation is to reduce the sample while maintaining its representativeness. In order to ensure this, a sampling scheme is required; it is recommended to include a sampling and sample preparation diagram in the scheme.

We recommend preparing a detailed sampling scheme for each plant that is approved by both the fuel supplier and the heat or power plant (buyer of the fuel) when making the deal, and which can form a part of the delivery contract for the fuel deal in the future. Emissions trade also requires a plant-specific sampling scheme. When the scheme is being prepared, plant-specific issues to be taken into consideration include fuel delivery logistics, vehicle unloading methods, and the requirements and limitations placed by the plant's reception and handling system on the best possible and reliable sampling and sample preparation method. Safety issues must also be taken into consideration. Summarised and simple sampling instructions are also prepared based on the scheme to be followed by the sample collectors, who are usually the vehicle drivers in Finland, during unloading.

With each heat or power plant (fuel buyer), the following are agreed in the contract:

- The sampling location and method best suited for reception
- The sampling devices and equipment to be used
- The number and volumes of increments
- The preparation, storage, and labelling of samples, and documentation of the sampling process
- Fault case management

3.2 Sampling location and method

With fuel deliveries, the primary sampling location is the fuel's handover location. In practice, this is often the receiving station, where increments are taken during unloading from the fuel stream falling from the load, or immediately afterwards from the receiving hopper, the conveyor leaving the receiving station, or the fuel stream falling off the conveyor. The sampling location should be chosen so that a representative sample of the fuel lot can be obtained most reliably and at a reasonable expense. A representative sample can be most reliably taken from a moving, falling fuel stream.

Based on current experience, the recommended order for the incremental sampling of fuels is as follows:

- Moving, continuous fuel stream, primarily at a receiving station, but also during the loading or load transfer stages, for example at terminals
- Mechanically directly from the load using samplers drilling through the load
- At the receiving station during unloading or immediately afterwards, either from the receiving hopper or the fuel storage yard
- At the loading stage from the bucket of the loader or the working face of the stockpile
- Collecting samples from large wood fuel stockpiles or stacks for commercial purposes is not recommended, because obtaining a representative sample is uncertain and requires an undue amount of work.

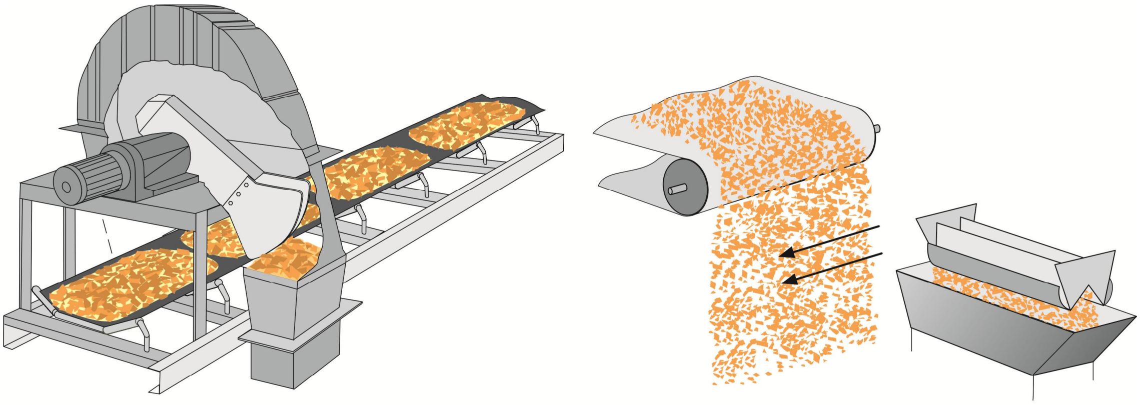
The sampling stage is where the most inaccuracies originate with respect to the results of analyses. For this reason, particular attention must be paid to sampling, and it must be done in a systematic and careful manner. The best precision can be achieved when sampling is mechanical, which is possible when collecting samples from a continuous stream of fuel.

Due to the non-homogeneous nature of solid biofuels, it is often difficult to collect increments in a manner that meets the principle of good sampling, according to which each individual particle should have an equal probability of being selected for the final sample. This is the case particularly when collecting samples from stationary fuel that is often segregated according to particle size, such as stockpiles, silos, receiving hoppers, or loads. Collecting increments is easier and more reliable when the fuel is moving, for example directly from a conveyor or a fuel stream falling off the conveyor, and during the unloading or loading of fuel.

Samples should be collected from a moving, preferably falling fuel stream, if at all possible.

3.3 Mechanical sampling

According to the basic principle of mechanical sampling, increments are collected in such a manner that the fuel stream's entire cross section is represented in the sample in accordance with the principle of averages. This is easiest to implement by collecting the samples either directly from the conveyor belt, cutting a part of the entire fuel stream or the fuel stream falling off at the end of the conveyor into the sample (Figure 3.1). This is usually done by the sampling container moving at a constant speed across the entire fuel stream, cutting the sample from the entire stream. There are several alternative methods for the mechanical sampler's movement solutions. In both cases, the sampler's aperture must be at least 2.5 times the nominal top size of the material (the round apertures of the sieve where at least 95% by mass of the fuel passes). The sampling container must be large enough. The fill rate of the sampling container should be designed to be 2/3 (around 67%) of the volume of the entire container in accordance with the standard.



Sampling by cross-belt cutter

Falling stream sampler

Figure 3.1. Sampling from a conveyor belt on the left and from a falling fuel stream on the right. Figure: VTT.

Mechanical sampling can also be implemented from grag chain conveyors and screw conveyors. Sample increments can be collected from such intermittent fuel streams by opening the bottom of the conveyor across its entire width so that the entire intermittent lot of fuel is collected in the sample, for example the fuel lot between grag chains.

When selecting the sampling location on a conveyor line, attention must be given to ensuring that fuels from different loads and different suppliers remain separate at the sampling location. Similarly, the sampling interval must be chosen according to the unloading and conveyor capacity so that the planned number of increments per load can be collected and representatively spread over the length of the entire load.

Increments can also be collected at the receiving station directly from the fuel stream falling off the load using screw samplers. In mechanical sampling, increment volumes are large, which is why sample crushing, mixing, and division equipment are also usually incorporated into the automated systems. They produce a relatively small load-specific sample in a supplier-specific collection bin. After mixing and division, these combined samples provide a date-specific laboratory sample for analysis.

As plants receive loads that are from different suppliers and contain different fuel grades, it must be ensured that the sampler and sample preparation equipment used are always cleaned after a load-specific sampling sequence. Similarly, it must be guaranteed that the entire sample lot collected (also including the fines and the largest particles) is included in the sample.

When mechanical sampling and sample preparation equipment are used, their reliability must be tested, mainly in order to detect and eliminate any systematic errors. Additionally, the parties must approve their use for the sampling on which fuel pricing is based.

3.4 Manual sampling

At most plants, the quality and pricing of fuel are based on manual sampling. Increments are most commonly taken during unloading either from the fuel stream falling from a rear dump vehicle or immediately after unloading, for example from a load-specific fuel pile, receiving hopper, or the fuel storage yard.

Manual sampling can be implemented from conveyor systems using the same principles as the mechanical sampling methods described above. When implemented correctly, however, they are cumbersome for continuous use, because, when collecting samples directly from a belt conveyor for instance, the conveyor must be stopped for the duration of sampling.

A sampling scoop with a long handle (Figure 3.2) must be used in manual sampling. The diameter of its aperture in both directions must be at least 2.5 times the nominal top size.

Figure 3.2. A three-litre sampling scoop with a long handle, which is ideal for forest chip sampling. Photo: Ismo Tiihonen.

When samples are collected directly from a fuel stream falling from a load, the sampling interval is determined so that a sufficient number of increments per load can be collected evenly from different parts of the load. Samples should be collected from different parts of the fuel stream in the lateral direction as well. Collecting samples from, for example, the very first particles falling off a rear dump vehicle and the last scraps should be avoided. Safety must also be taken into consideration during sampling with regard to the fuel stream falling from vehicles. We recommend arranging sampling from “behind a glass” from a space that is as clean as possible using a sampling scoop with a long handle. Indeed, this has been implemented successfully at many plants.

When collecting samples from a receiving hopper, for example after the unloading of a side dump vehicle, the sample collector must walk around the entire hopper and collect samples from different parts of the hopper while taking safety issues into consideration, so that the sampling is done evenly from different parts of the entire load.

In many cases, fuel loads need to be unloaded in a fuel storage yard. In these cases, samples can be collected from the fuel stream falling from a rear dump vehicle in the manner described above. However, it is not always possible to collect increments from a falling stream, and instead samples need to be collected after unloading from a load-specific pile. In these cases, too, a sampling scoop must be used, and the samples must be collected from different parts of the pile in such a manner that the sampling is done as evenly as possible from different parts of the dumped load. Fuel is almost always segregated during dumping, with the coarsest particles settling to the ground around the edges of the pile and the finest matter remaining in the middle and top of the pile. For this reason, samples must also be taken at regular intervals in the vertical direction of the pile. Collecting samples from the very top of the pile and from the very bottom and edges of the pile should be avoided (Figure 3.3). A sampling scoop should be used to dig samples from beneath the surface layer.

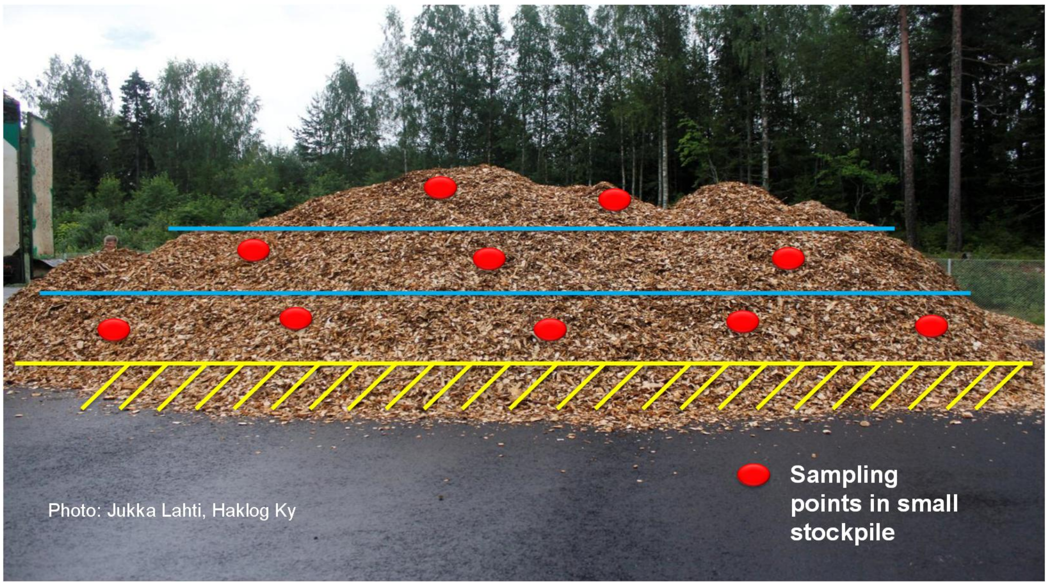


Figure 3.3. The location of sampling points in a small pile of fuel. No samples must be collected from the zone marked in yellow. Photo: Haklog Ky.

In manual sampling, the purpose is to be as systematic as possible when collecting load-specific increments. The main principle is that the samples should represent the entire load uniformly, with no kind of segregation or selection taking place during sampling. The sample collector must not make a selection with regard to, for example, particle size; instead, even the largest particles and any impurities collected must be included in the load-specific combined sample.

3.5 Number and size of increments

The most important factors affecting the number of increments are the actual deviation of a certain property, such as moisture, in the lot (load) being sampled, the precision requirement, and the number of loads belonging to the delivery lot. As moisture deviation increases, the precision requirement will easily raise the number of increments unreasonably high. Moisture deviation in loads depends on the fuel type, but also on the load filling method. For example, when wood is chipped with a wood chipper directly into a load, there will be segregation into different parts of the load. In Finland, the moisture deviation of non-homogeneous logging residue and whole-tree chips is larger than that of stem wood chips and hog fuel from stumps.

If sampling is done by fuel load, at least two increments per 50 loose m^3 of fuel must be taken during continuous fuel deliveries.

The minimum numbers of increments for different load volumes of wood and peat are as follows:

- Lorry (tractor)	minimum of two samples
- Semi-trailer (< 100 m^3)	minimum of four samples
- Tractor-trailer (100–160 m^3)	minimum of six samples (two from tractor + four from trailer)
- Container combinations	minimum of two samples/container

Using these numbers of samples with delivery lots comprising between three and five loads, a precision requirement of around ± 3 percentage points can be achieved for moisture, and in deliveries comprising more than six loads, the precision improves to around ± 2 percentage points. (Järvinen & Impola 2012, Järvinen 2012).

As some forest fuels have large in-load moisture deviation, the number of increments must be at least doubled with small delivery lots (less than 200 loose m^3) and when determining load-specific properties. For the majority of wood fuels in Finnish conditions, a precision of around ± 4 percentage points can be achieved in moisture analyses in this way. If the average amount of peat delivered is less than 250 tonnes (approximately 700 m^3 or six lorry loads) per month, double the number of increments must be taken.

The volume of increments of solid biofuels is based on the particle size of the fuel in question as per the EN 14778:2012 / EN ISO 18135 sampling standard. The minimum volume of an increment is calculated using formula 3.1:

$$\begin{aligned} Vol_{incr} &= 0.5 && \text{when } d_{95} < 10 \\ Vol_{incr} &= 0.05 \times d_{95} && \text{when } d_{95} \geq 10 \end{aligned} \tag{3.1}$$

in which

Vol_{incr}	minimum increment volume, litres
d_{95}	nominal top size, mm (diameter of apertures in a sieve with round holes where at least 95% of the mass of the fuel passes)

If the nominal top size of wood chips (d_{95}) is 100 mm, a minimum of five litres must be collected for an increment, and if the nominal top size is 63 mm, a minimum of three litres. In practice, the latter particle size is the most typical for wood chips in Finland.

Note: Although the calculation gives 2.25 litres as the minimum increment sample volume for a particle size of 45 mm, a sample size of three litres should be used for it, too. The nominal top size of hog fuel from stumps is larger than that of wood chips, giving an increment volume of five litres.

Table 3.1. Increment volumes for fuels of different particle sizes (Alakangas & Impola 2014, NT ENVIR 009 2005).

Fuel	**Increment volume, litres**
Sawdust	0.5
Forest chips	3
Hog fuel (stump) and sod peat	5
Bark	5
Milled peat and pellets	1 (2)

In many cases, tens of litres of samples might need to be collected per load when mechanical sampling is used. After a sample has been divided, the excess sample material is returned to the feed line. The size of the final sample is close to the size of an increment collected manually. The sample must be properly divided to ensure that a representative sample is obtained from each load. Separate testing approved by both the fuel supplier and the user/buyer is recommended in order to ensure that the mechanical sampling process operates reliably and that representative samples are obtained.

3.6 Sample preparation and processing

The sampling standard describes both methods that can be used to reduce combined samples into laboratory and analysis samples, and equipment and methods suitable for mixing and dividing samples.

Certain basic principles must be followed in the reliable processing of samples:

- The basic principle of division is that the composition of the sample must not change from the original during the different processing steps;
- Careful mixing of the samples improves the reliability of division;
- When the particle size of wood fuels is being reduced (by crushing or grinding), no moisture changes or loss of fines may occur;
- The heating and drying of samples must be prevented during processing and storage; and
- The sampling and sample preparation equipment and methods used for commercial determination of quality must always be tested in a jointly agreed manner.

Combined samples are formed from delivered fuels for the determination of their properties, primarily for the purpose of determining the price, but also for emissions trading and other separately defined purposes. Combined samples are usually analysed for the moisture content of the fuel and dry matter properties (ash, calorific value, etc.). Combined samples are formed supplier-specifically and, if necessary, fuel type or delivery location specifically and always covering a specific period of time.

The length of such a period is usually

- one day, or one delivery lot for moisture. With large deliveries, e.g. over 2,000 loose m^3, it is recommended to form sub-lot-specific combined samples.
- no more than one month for dry matter properties (such as calorific value and ash content).

One of the following methods can be chosen when forming combined samples and laboratory samples:

- All delivery lot specific increments are put directly into a single container forming a combined sample that is sent to a laboratory, where a laboratory sample is prepared from it.
- The increments are mixed together, forming a combined sample from which a laboratory sample is prepared after mixing and division.
- Each increment is put into a separate container or bag and sent to a laboratory. The laboratory combines the samples forming a laboratory sample.

A combined sample for determining dry matter properties is usually formed from the dried part of each moisture determination sample. The dry matter tonnage represented by the sample is proportioned according to the amount of dry matter in the fuel delivery lot used for the combined sample (Example 3.1). A corresponding sample can also be extracted from wet fuel lots proportionally to the size of the delivery volume represented by the sample. In Example 3.1, a combined sample has been formed from two weeks of moisture samples for the purpose of a calorific value analysis.

Example 3.1: Formation of a combined sample weighted by delivery lot size. Source: Labtium Oy.

Date	Delivery volume, tonnes	Moisture, w-%	Dry matter volume, tonnes	Percentage of total dry matter volume, w-%	Amount weighed for the combined sample, g
01/08/2015	40.20	48.34	20.77	6.402	38.41
02/08/2015	40.60	44.49	22.54	6.947	41.68
03/08/2015	40.00	47.49	21.00	6.475	38.85
04/08/2015	40.50	51.20	19.76	6.093	36.56
05/08/2015	40.40	47.83	21.08	6.497	38.98
06/08/2015	41.20	55.15	18.48	5.696	34.18
07/08/2015	39.30	51.68	18.99	5.854	35.12
08/08/2015	81.70	49.87	40.96	12.625	75.75
09/08/2015	41.30	50.18	20.58	6.343	38.06
10/08/2015	38.90	48.01	20.22	6.234	37.41
11/08/2015	39.80	48.86	20.35	6.274	37.65
12/08/2015	41.50	49.62	20.91	6.445	38.67
13/08/2015	39.90	49.40	20.19	6.224	37.34
14/08/2015	39.00	54.45	17.76	5.476	32.86
15/08/2015	40.90	49.13	20.81	6.414	38.48
Total	645.20		324.39	100.000	600.00

With large deliveries, supplier-specific and, if necessary, fuel type-specific samples are collected from each delivery into a large combined sample container, from which a sample is obtained for moisture determination once a day after mixing and division. With smaller deliveries, load-specific samples can be collected in their own plastic bags or containers that are then sent for moisture analysis. With wood fuels, the large volumes of increments are a problem, which means that load-specific combined samples must be divided so as to make them smaller before delivery to a laboratory.

Combined samples must be stored carefully throughout the entire duration of sample collection in lidded, airtight containers in a space that is as cool as possible. It is also important to ensure that the moisture content of combined samples collected for moisture determination does not change during storage.

Figure 3.4 shows the steps involved in sample size reduction according to the EN 14778:2012 / EN ISO 18135 and EN 14780:2012 / EN ISO 14780 sampling standards and sample volumes at different stages of the process.

The number of increments for solid biofuels is calculated using formula 3.2:

$$n = \frac{4V_l}{NP_L^2 - 4\,V_{PT}} \tag{3.2}$$

in which

n	minimum number of increments
P_L	desired overall precision including sampling, preparation, and determination (analysis) at a 95% statistical confidence level
V_l	primary increment variance (= square of internal deviation, s_d^2)
N	number of sub-lots, i.e. number of loads
V_{PT}	variance of preparation and testing

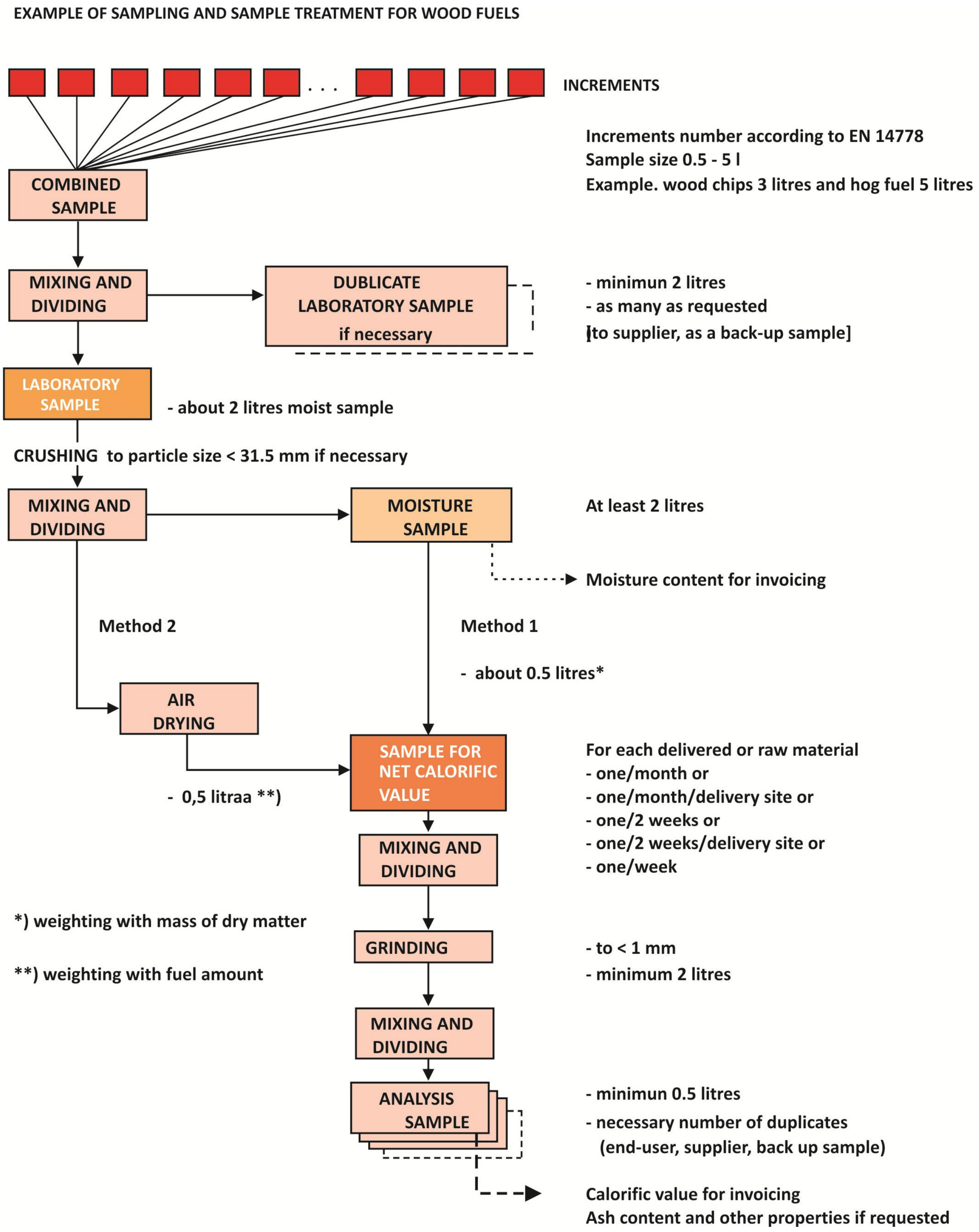


Figure 3.4. Sample preparation diagram. Figure: VTT (Alakangas & Impola 2014).

Figure 3.5 shows the dependence of overall precision (P_L) on the number of increments (n) in the case of logging residue.

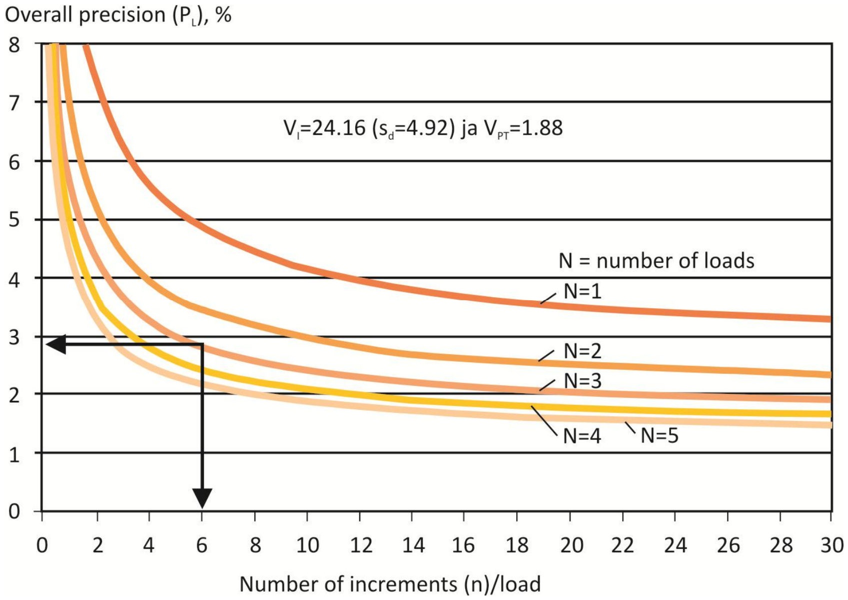


Figure 3.5. Dependency of the number of logging residue increments (n) on the desired overall precision (P_L) with the number of loads (N) as parameters using average seasonal deviation.
Figure: VTT (Alakangas & Impola 2015).

When six increments are taken from a logging residue load, the overall precision is just under ± 3 percentage points, when the delivery lot comprises three loads. Precision increases to close to ± 2 percentage points with delivery lots comprising five loads. The changes in overall precision are large with small delivery lots (1–2 loads), and the number of increment samples must be doubled in order to keep the overall precision tolerable. Variations in internal deviation do not affect the shape of the graphs; with larger deviations, the family of curves in the figure moves upwards, i.e. sampling precision decreases.

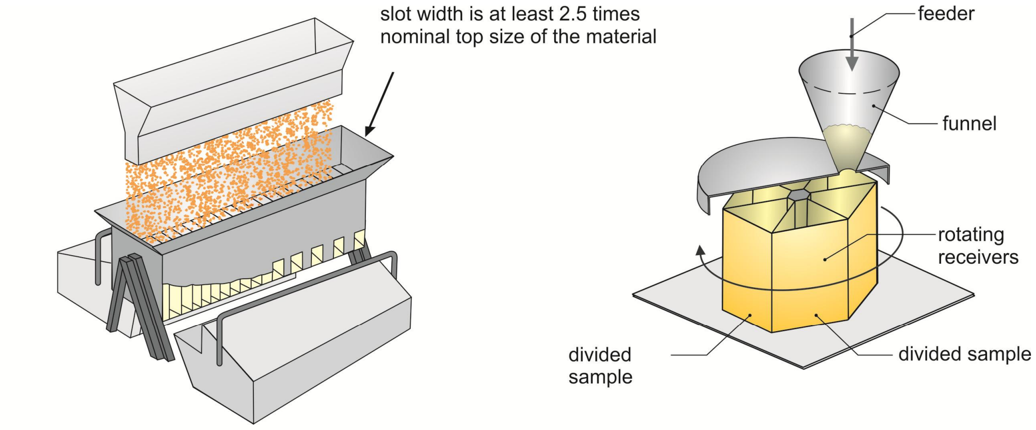
Combined samples are divided into laboratory samples of the required or desired size; with solid fuels, the volume is at least two litres. The minimum volume is usually determined by a moisture content analysis performed in accordance with the EN ISO 18134-2:2015 moisture standard, which requires a sample size of at least 300 g of wet material (see Section 2.2.1). If other fuel properties are also to be determined, a larger sample is required. Table 3.2 shows minimum sample volumes for different analyses.

Table 3.2. Sample volumes for typical analyses (Alakangas & Impola 2015).

Analyses	**Sample volume**
Basic analyses (calorific value (Q), ash (A), sulphur (S), carbon (C), hydrogen (H), and nitrogen (N))	Approximately two litres per analysis (can also be formed from a moisture content analysis sample)
Moisture, M	At least 300 g of wet sample, i.e. approximately two litres per analysis
Bulk density, BD	Approximately 70 litres per analysis, when bulk density is determined using a 50-litre container (e.g. wood chips), or seven litres per analysis, when bulk density is determined using a five-litre container (e.g. pellets)
Particle size distribution	Approximately eight litres per analysis at 20% moisture content

3.7 Division of samples

Large combined samples can be mixed and divided using various sampling methods, such as the coning and quartering method, descriptions of which are included in the sampling standard. Before a combined sample is divided, it must be mixed well. After mixing, combined samples can be divided using suitable equipment; see Figure 3.6 for examples of dividing equipment complying with the EN 14780:2012 / EN ISO 14780 standard. Figure 3.7 shows an example of the division of a wood chip sample using a riffle divider. As the particle size of wood fuels increases, the dimensioning of riffle dividers must take into consideration the fact that the aperture must be large enough for the divider to operate reliably, i.e. 2.5 times the nominal top size. Particularly when dividing wet fuels, the use of such mechanical dividers requires a significant amount of work and great care in cleaning and drying the device before preparing the next sample.



Riffle box

Rotating sample divider

Figure 3.6. Example of a riffle box and a rotating divider. Figure: VTT.

Figure 3.7. Division of a wood chip sample using a riffle box. Photo: Eija Alakangas, VTT.

Figure 3.8. Division of a sample using the coning and quartering method. Figure and photos: Eija Alakangas, VTT.

If a sample divider is not available, samples can also be divided manually using the coning and quartering method shown in Figure 3.8. The sample is mixed carefully all the way to the bottom, after which the entire sample is poured onto a table or a suitable board with a reasonably rapid motion so as to form a conical pile. The pile is then evened out. The sample is split into four equal parts using a suitable tool. Two quarters are selected for the sample in accordance with Figure 3.8 (diagonally opposite quarters) and the other two quarters are rejected. The remaining segments can also be quartered again, if the remaining sample volume is too large after single quartering. In such cases, the sample must be carefully mixed before the second quartering.

In Figure 3.8, bulk density has been determined first, after which a moisture content sample has been formed from the bulk density sample by means of division. Combining the methods is a suitable alternative for small plants that trade in units of volume and have no vehicle scales. Bulk density, moisture content, and net calorific value on a dry basis can be used to determine the energy content of a delivery lot (Section 2.3.4).

4. Wood fuels

4.1 Properties of wood and wood parts

The forest cover in Finland is more extensive than in any other European country. Three quarters of the land area, some 26.2 million hectares (77%), is forest. The average increment of growing stock in southern Finland, 6.4 solid m^3 per hectare per year, is twice as much as in northern Finland, and average annual increment is 4.6 solid m^3 per hectare. The net annual increment of forest land is 104 million m^3 solid (over bark) and total growing stock is 2,357 million m^3 solid (only stem part of tree). (Statistical Yearbook of Forestry 2014).

Biomass is generated by the photosynthesis of plants. Green leaves use the energy of the sun to convert the carbon dioxide in the atmosphere and the water in the soil into simple sugars. The living cells of plants turn them into more complex compounds, which consist of carbon (C), oxygen (O), and hydrogen (H). Biomass also contains small amounts of nitrogen (N) and different kinds of minerals.

In other words, forests use photosynthesis to capture carbon from the atmosphere while simultaneously converting energy from the sun into chemical energy. When a tree or a part of a tree dies, its biomass breaks down by an oxidation process during which the bonds of carbon and hydrogen are broken and energy is released. In nature, this breakdown either takes place slowly through the natural decomposition of wood or rapidly during a forest fire. If the combustion process is moved into a “contained space”, the energy released can be recovered and used to produce heat, steam, or electricity.

The most voluminous component of biomass is cellulose, which is the most abundant of all organic compounds found on Earth. In woody plants, it accounts for 40–50% of dry mass, with broad-leaf trees having higher cellulose content than coniferous trees. Cellulose consists of glucose molecules ($C_6H_{12}O_5$), which are joined through oxygen atoms to form long-chain molecules ($(C_6H_{12}O_5)_n$). In addition to cellulose, tree biomass contains hemicellulose, the chain molecules of which consist of several different sugars. Table 4.1 shows the cellulose, hemicellulose, lignin, and extractives contents of different species of tree. Coniferous trees have higher lignin content than broad-leaf trees. Lignin binds wood fibres together and gives trees the mechanical durability they need. Lignin contains high volumes of carbon and hydrogen, substances that produce heat. Wood also contains extractives (terpenes, fats, and phenols), which are compounds that can be extracted from wood using neutral organic solvents. The volume of extractives is higher in broad-leaf trees than in coniferous trees. Wood resin, for example, is composed of these substances. (Jensen 1977, Hakkila & Heiskanen 1978, Kärkkäinen 1971 & 2007, Sjöström 1978, Verkasalo 1988, Hakkila & Verkasalo 2009).

Wood has high volatile matter content. This makes it a fuel with tall flames, which requires a large space to burn (Kytö et al. 1983). Figure 4.1 illustrates the composition of wood.

The division of the biomass of a tree into stem, bark, branches, and leaves (needles) varies considerably depending on the species and age of the tree. In the boreal region, i.e. in northern coniferous forests, the stump and roots account for 30% of stem wood on a dry basis, for 25% of the whole tree, and for 20% of the whole tree including the root system and stump. The harvestable quantity of stump wood amounts to 20–24% of stem wood mass (Hakkila & Verkasalo 2009). Table 4.2 shows the percentage of crown mass in pine and spruce stem wood.

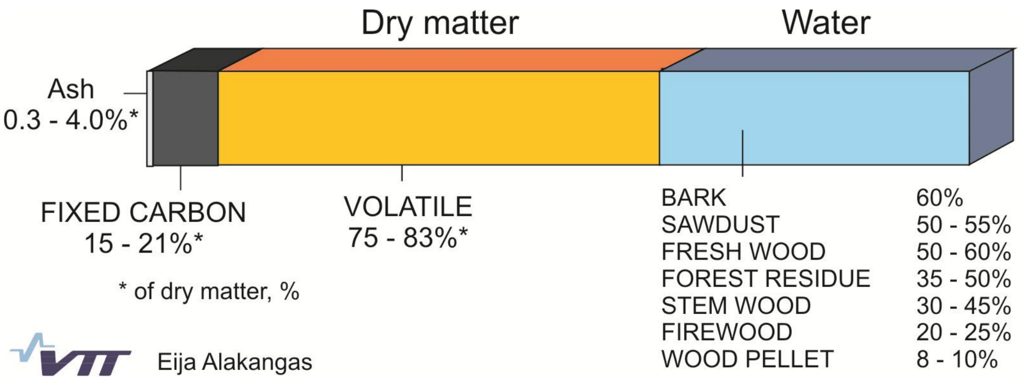


Figure 4.1. Composition of wood (Alakangas et al. 2016).

Table 4.1. Chemical composition of different species of tree (Hakkila & Verkasalo 2009, Nurmi & Brännström 2014).

Species	Dry basis, w-%				
	Cellulose	Hemicellulose	Lignin	Extractives	Other substances
Siberian larch (Larix sibirica)	41.4	29.6	26.8	1.8	0.4
Norway spruce (Picea abies)	41.7	28.3	27.4	1.7	0.9
Stem wood	42.0 (1.2)	27.3 (1.6)	27.4 (0.7)	2.0 (0.6)	not reported
Bark	26.6 (1.3)	9.2 (1.1)	11.8 (0.9)	32.1 (3.8)	
Branches	29.0	30.0	22.8 (1.7)	16.4 (2.6)	
Needles	28.2	25.4	8.4 (2.1)	43.3 (2.3)	
Stump	42.9	27.9	29.4 (1.8)	3.8 (0.2)	
Roots	29.5	19.2	25.5	15.7	
Scots pine (Pinus sylvestris)	40.0	28.5	27.7	3.5	0.3
Stem wood	40.7 (0.7)	26.9 (0.6)	27.0 (0.0)	5.0 (1.0)	not reported
Bark	22.2 (3.2)	8.1 (0.4)	13.1 (5.4)	25.2 (5.2)	
Branches	32.0	32.0	21.5 (5.9)	6.9 (0.8)	
Needles	29.1	24.9	6.9 (0.8)	39.6 (1.3)	
Stump	36.4	28.2	19.5	18.7	
Roots	28.6	18.9	29.8	13.3	
Silver birch (Betula pendula)	41.0	32.4	22.0	3.2	1.4
Downy birch (Betula pubescens)	43.9 (2.7)	28.9 (3.7)	20.2 (0.8)	3.8 (1.3)	not reported
Stem wood	10.7 (0.3)	11.2 (0.5)	14.7 (3.9)	25.6 (1.1)	
Bark	33.3	23.4	20.8 (3.9)	13.5 (3.0)	
Branches	not reported	not reported	11.1 (0.0)	33.0 (0.0)	
Needles	29.5	19.4	13.4	4.7	
Stump	26.0	17.1	27.1	13.5	
Roots					

The figures in brackets denote deviation.

Table 4.2. Percentage of crown mass relative to the volume of pine and spruce stem wood at different stages of development (Hakkila & Verkasalo 2009).

Stage of development	**Pine**	**Spruce**
	Crown ratio, %	
First thinning	57	78
Later thinning	43	67
Regeneration felling	45	75
Average stock	54	79

The elementary composition of wood mostly comprises carbon, hydrogen, and oxygen (Table 4.3). These account for approximately 99% of tree mass on a dry basis. Nitrogen accounts for 0.5–2.3%, and alder has the highest nitrogen content. Pine and spruce have a nitrogen content of approximately 0.05%, birch 0.08–0.1%, aspen 0.06%, and grey alder 0.19%. Wood generally contains less than 0.05% sulphur (Tables 4.3 and 4.4). The elementary composition of different species of tree varies only little (Moilanen et al. 1996, Laine & Sahrman 1985, Wilén et al. 1996, Nurmi 1993).

Table 4.3. Element content of different wood fuels (Moilanen et al. 1996, Taipale 1996, Wilén et al. 1996, Tahvanainen et al. 1995, Pesonen et al. 2014).

Wood fuel	Elementary analysis, w-%, dry basis					
	C	H	N	O	S	Cl
Wood, in general	48–50	6.0–6.5	0.5–2.3	38–42	0.05	< 0.01
Whole-tree chips, pine	51.8	6.1	0.3	41.2**	0.01	0.0042
Forest residue chips	51.3	6.1	0.4	40.8**	0.02	0.0076
Softwood chips					0.02–0.045	0.011–0.031
Hardwood chips					0.02–0.09	
Sawdust, pine, debarked	51.0	6.0	0.08	42.8**	0	< 0.0050
Salix myrsinifolia, willow, undebarked	47.8	5.7	0.2		0.03	0.005-0.022
Salix myrsinifolia, willow, debarked	47.6	6.2	0.1		0.015	< 0.0005
Salix schwerini, willow, undebarked	47.7	6.1	0.2		0.025	0.005–0.022
Salix schwerinii, willow, debarked	47.6	6.1	0.1		0.013	< 0.0005
Klara, willow, undebarked	47.5	6.0	0.1		0.027	
Klara, willow, debarked	47.4	6.0	0.2		0.016	
Willow in general	49.7	6.1	0.4	42.6**	0.03–0.05	0.0037
Pine bark*	52.5	5.7	0.4	39.7**	0.03	0.0085
	54.5	5.9	0.3	37.7		
Spruce bark*	49.9	5.9	0.4	41.4**	0.03	0.0279
	50.6	5.9	0.5	40.2		
Birch bark	56.6	6.8	0.8	34.2		

* Values from two different sources. ** Oxygen calculated as a difference

Table 4.4. Sulphur content of different parts of coniferous and broad-leaf trees on a dry basis (Hakkila & Kalaja 1983).

CONIFEROUS TREES	**Sulphur content, w-%**	**BROAD-LEAF TREES**	**Sulphur content, w-%**
Stem wood	0.0116	Stem wood	0.0090
Stem wood bark	0.0343	Stem wood bark	0.0341
Branches	0.0203	Branches	0.0218
Needles	0.0673	Leaves	0.0965
WHOLE TREE	0.0236	WHOLE TREE	0.0212

Tables 4.5 and 4.6 show major and minor elements of wood fuels.

Table 4.5. Mineral content of different parts of coniferous and broad-leaf trees on a dry basis (Hakkila & Kalaja 1983).

Species/part	**Major elements, w-%**				**Minor elements, ppm (mg/kg)**				
	P	**K**	**Ca**	**Mg**	**Mn**	**Fe**	**Zn**	**B**	**Cu**
CONIFEROUS TREES									
Stem wood	0.01	0.06	0.12	0.02	147	41	13	3	2
Stem wood bark	0.08	0.29	0.85	0.08	507	60	75	12	4
Branches	0.04	0.18	0.34	0.05	251	101	44	7	4
Needles	0.16	0.60	0.50	0.09	748	94	75	9	6
WHOLE TREE	0.03	0.15	0.28	0.05	296	85	30	6	4
BROAD-LEAF TREES									
Stem wood	0.02	0.08	0.08	0.02	34	20	16	2	2
Stem wood bark	0.09	0.37	0.85	0.07	190	191	131	17	13
Branches	0.06	0.21	0.41	0.05	120	47	52	7	4
Leaves	0.21	1.17	1.10	0.19	867	135	269	21	10
WHOLE TREE	0.05	0.21	0.25	0.04	83	27	39	6	5

1 ppm = 0.0001%

The levels of heavy metals in willow on a dry basis (mg/kg) are as follows: As < 4, Cd 0.7–2.9, Cr < 2.5, Cu 2.5–3.8, Pb < 4, Zn 11–64, and Ni < 1.5 (Pesonen et al. 2014).

The volumes of ash-forming substances in different species and parts of the tree have been studied at Åbo Akademi University (Werkelin 2008). In the study, levels of ash-forming substances were analysed from four different species of tree (spruce, pine, birch, and aspen) and their different parts (stem, bark, branches, tops, shoots, leaves, and needles). Trees were felled in both summer (140 samples) and winter (70 samples). Table 4.6 shows the results for 18 samples.

Table 4.6. Levels of ash-forming substances on a dry basis, mg/kg (Werkelin 2008).

Element/ species		Wood	Bark	Branches	Needles	Shoots	Leaves
Si	Spruce	59	171	982	6,640	300	
	Pine	123	60	312	549	747	
	Birch	77	114	69			318
	Aspen	63	94	188			133
Al	Spruce	2	98	221	83	27	
	Pine	4	908	332	374	331	
	Birch	2	19	23			40
	Aspen	6	20	35			20
Fe	Spruce	4	39	167	45	43	
	Pine	8	52	73	40	113	
	Birch	6	24	40			83
	Aspen	5	27	35			56
Ca	Spruce	724	8,350	4,320	8,030	1,670	
	Pine	641	6,350	5,300	4,140	2,370	
	Birch	636	7,860	4,730			9,120
	Aspen	998	11,700	10,400			9,800
Mg	Spruce	95	865	909	1,050	907	
	Pine	189	874	715	804	1,020	
	Birch	92	323	448			2,030
	Aspen	286	1,370	644			2,940
Mn	Spruce	98	714	496	1,390	245	
	Pine	81	343	244	839	193	
	Birch	102	534	354			1,600
	Aspen	49	256	183			667
Na	Spruce	6	26	97	48	13	
	Pine	15	22	40	28	36	
	Birch	4	14	43			32
	Aspen	15	12	19			9
K	Spruce	215	2,030	3,560	4,270	14,600	
	Pine	407	3,180	3,040	4,770	8,790	
	Birch	315	1,710	3,020			9,420
	Aspen	1,370	4,730	5,870			24,000
P	Spruce	4	452	1,080	1,540	3,830	
	Pine	41	1,260	848	1,270	2,590	
	Birch	49	428	820			3,140
	Aspen	191	663	708			5,140
S	Spruce	50	367	776	704	1,320	
	Pine	94	311	587	845	1,250	
	Birch	82	329	493			1,690
	Aspen	125	520	479			2,560
Cl	Spruce	51	260	317	504	1,090	
	Pine	85	147	200	407	538	
	Birch	40	149	120			181
	Aspen	35	40	87			511

Ash content of wood is shown in Table 4.7. The ash content of debarked stem wood is usually 0.3–0.7 w-%. The inorganic matter in wood is in the form of extractives. Young trees have a higher ash content than more mature trees. Broad-leaf trees contain more ash than coniferous trees. Compositions of wood ash are given in Table 4.8. Coniferous trees in the boreal region have low ash content. The average ash content of the four species of tree studied in Finland (birch, pine, spruce, aspen) is 0.46% in stem wood, 2.97% in bark, 1.52% in undebarked branches, and 4.97% in leaves. Wood ash does not contain chlorine or nitrogen, as these are volatile and escape with flue gases during combustion. The magnesium and calcium in ash are effective in neutralising acidic soils. The primary component of wood ash is calcium, and especially ash from bark contains high levels of calcium. The ash content of wood is usually lower than that of other solid fuels, which makes the handling of the ash easier and cheaper. (Kytö et al. 1983, Wilén et al. 1996)

Table 4.7. Ash content of wood on a dry basis (Taipale 1996, Wilén et al. 1996, Tahvanainen 1995, Pesonen et al. 2014).

Wood fuel	**Ash content, w-%**
Billets and chopped and split logs (firewood)	0.5/1.2
Whole-tree chips, pine / whole-tree chips, mixed	0.6/0.5
Birch chips	0.4–0.6
Logging residue chips	1.33
Logging residue chips, spruce	2.0–6.0
Hog fuel from stumps	0.50
Willow chips	0.44–1.39
Sawdust, undebarked / sawdust, pine, debarked*	1.1/0.08
Cutter shavings	0.40
Pine bark	1.70
Spruce bark*	2.34/2.8
Birch bark	1.60

* Two different values from literature

Table 4.8. Ash composition (w-%) of certain wood fuels as oxides of the main components (Taipale 1996, Kytö et al. 1983, Moilanen et al. 1996).

Species	**CaO**	**K_2O**	**P_2O_5**	**MgO**	**Fe_2O_3**	**SO_3**	**SiO_2**	**Na_2O**	**Al_2O_3**	**TiO_2**
Birch*	57.8	11.5	7.7	7.7		3.8	3.8	7.7		
	46.0	15.0	14.9	11.6	1.3	2.6	0.9	8.6		
Pine	42.0	15.2	1.0	16.0	5.5	4.5	4.6	3.0		
Spruce	36.7	29.6	1.0	10.0	8.5	4.2	1.0	3.2		
Willow	30.8	26.5	4.8	5.1	0.2	2.1	0.4	0.3	0.3	0.02
Pine bark*	40.0	3.3	2.6	2.6	5.0	3.7	14.5	2.0		
	40.6	7.6	4.8	4.5	0.3	2.0	1.3	0.5	5.3	0.10
Spruce bark	50.5	3.5	2.6	4.2	1.8	1.6	21.7	2.8		
Birch bark	60.3	4.1	3.5	5.9	1.0	4.8	3.0	0.7		
Sawdust, pine	41.8	12.3	5.2	11.8	1.9	1.9	8.3	0.2	2.0	0.10

* Kytö et al. 1983 gives two values.

Table 4.9. Wood ash melting behaviour (Wilén et al. 1996).

Fuel	**Ash melting temperature, °C**							
	Oxidising atmosphere				**Reducing atmosphere**			
	DT	**ST**	**HT**	**FT**	**DT**	**ST**	**HT**	**FT**
Whole-tree chips, pine	1,210	1,250	1,250	1,275	1,230	1,240	1,245	1,290
Forest residue chips	1,175	1,205	1,230	1,250	1,175	1,225	1,245	1,260
Sawdust, pine	1,150	1,180	1,200	1,225	1,135	1,165	1,185	1,205
Bark, spruce	1,405	1,550	1,650	1,650	1,565	1,580	1,650	1,650
Bark, pine	1,340	1,525	1,650	1,650	1,375	1,504	1,506	1,507
Willow	1,490			1,580	1,570			1,580

DT = deformation temperature
ST = sphere temperature
HT = hemisphere temperature
FT = flow temperature

Wood ash sintering begins at a temperature of 900–1,000 °C (Solantausta & Asplund 1979a). Depending on the source, the deformation temperature (DT) is 1,150–1,490 °C, the sphere temperature (ST) 1,180–1,550 °C, the hemisphere temperature (HT) 1,200–1,650 °C, and the flow temperature (FT) 1,225–1,650 °C (Kytö et al. 1983, Wilén et al. 1996) (Table 4.9).

Table 4.10 includes examples of heavy metals formed by wood and willow combustion in the bottom ash and fly ash.

Table 4.10. Heavy metal contents of ash formed by wood and willow combustion (Taipale 1996, Pesonen et al. 2014).

Element	**Wood ash, mg/kg**		**Willow (aged 2–4 years) ash, mg/kg**
	Bottom ash	**Fly ash**	
As, arsenic	0.2–3.0	1–60	< 20–40
Cd, cadmium	0.4–0.7	6–40	< 0.4
Co, cobalt	0–7	3–200	
Cr, chromium	60.0	40–250	< 2.5–8.9
Cu, copper	15–300	200	< 2.5–14
Hg, mercury	0–0.4	0–1	
Mn, manganese	2,500–5,500	6,000–9,000	45–5,000
Ni, nickel	40–250	20–100	< 20–49
Pb, lead	15–60	40–1,000	< 20–40
Se, selenium		5–15	
V, vanadium	10–120	20–30	
Zn, zinc	15–1,000	40–700	25–4,797

The moisture content of fresh wood is usually 40–60% (Tables 4.11 and 4.12). Moisture content depends on the growth site, the species of tree, and the age of the tree. Moisture content also varies in different parts of the tree. The moisture content of growing broad-leaf trees varies seasonally. Birch has a moisture content of 45% in the winter, when the tree is leafless and resting. In the spring, moisture content rises to 48% when the tree is still leafless but the roots are active in moving water into the stem. Moisture content drops to 38% in the summer, when evaporation from the leaves is at its peak, and rises to 45% again in the autumn, when the tree drops its leaves. The variation in coniferous trees is less dramatic (Table 4.11).

In a living tree, the cell wall is saturated with water, and the cell lumen and spaces are filled with water. When wood is dried, "free water", i.e. the water in the lumina, escapes first. Bound water, i.e. the water in the cell wall, is the last to escape. The physical properties of wood begin to change as soon as this bound water begins to escape, i.e. the saturation point of wood cells is surpassed. At room temperature, the saturation point is reached at a moisture level of 24–32%. The moisture content of wood varies according to the relative humidity of the air and the ambient temperature. Once wood reaches a stable moisture level in certain conditions, the term 'equilibrium moisture content' is used. Equilibrium moisture content is 11–13% when wood is kept outdoors protected against moisture but just 4–8% in a heated indoor space. The volume of wood shrinks during drying. The volume of softwood is reduced by 8–13% and the volume of hardwood by 11–17% when wood dries from fresh to oven dry. (Hakkila & Verkasalo 2009.)

Table 4.11. Moisture contents of different parts of coniferous trees (Kytö et al. 1981, Pellikka & Saviharju 1983, Taipale 1996).

Part of tree	**Moisture content, w-%**	
	Pine	**Spruce**
Stem wood	45–50	40–60
Branches	50–56	42–46
Crown/Top	60	60 (50*)
Bark:		
Outer bark	36–60	38–58
Other bark	53–67	47–63

* spruces from Northern Finland

It is usually the intended use of wood fuels that determines how moist the wood can be. Larger plants can use moist fuels, while e.g. households require dry wood. Households and farms normally dry firewood prior to use. An old method of drying is to fell trees in early summer and leave them in the stand to season, making use of the evaporation capacity of leaves and needles. Trees can also be stacked for drying, delimbed or limbed. Logs and smallwood are also dried in piles. The moisture content of fuel burnt in fireplaces should be 15–20%. In central heating boilers, the storage moisture content of chips should not exceed 25%. If wood chips are used in plants of less than 1 MW_{th}, their moisture content should not exceed 40% (Laine & Sahrman 1985, Linna et al. 1983, Linna & Järvinen 1983, Siltanen & Rantasalo 1984, Simola & Mäkelä 1976).

Wet fuel (with a moisture content of up to 50%) can be used in plants that are equipped with a flue gas condenser, which is capable of condensing the moisture in flue gases and recovering the thermal energy.

Storing wet wood increases the loss of dry matter. A project called INFRES (Routa et al. 2015, Erber et al. 2014) studied the dry matter loss from logging residue and stem wood during storage. The experiments revealed that the dry matter loss from logging residue was 9–18% over 9–12 months of storage. Previous Swedish studies have shown a dry matter loss rate of 1–3% per month for logging residue. The dry matter loss from pine stems was 5% over 14 months of storage. The average dry matter loss rate was less than 2.9% per month.

Table 4.12. Moisture contents of wood fuels (Pellikka & Saviharju 1983, Immonen & Seppälä 1984, Taipale 1996, Tahvanainen 1995).

Wood fuel	**Moisture, w-%**
Logs and smallwood, freshly chopped	45
Logs and smallwood, stored over one summer	25
Logs and smallwood, stored over two summers	20
Stem wood chips, fresh	50
Stem wood chips, seasoned	40
Stem-wood chips, air dry, stored for more than one year	25–30
Forest residue chips, pine, fresh	60
Forest residue chips, spruce, fresh	50–57
Forest residues, branch chips, fresh	50
Hog fuel from stumps	35
Willow chips	35–40
Wood chip screening residue	50–55
Sawing residue	5–10
Sawdust and chips, undried	50–55
Sawdust from dried timber	5–15
Slab chips	15
Grinding dust	5–10
Grinding dust, dry	15–20
Cutter dust, dry	5–10
Cutter dust, air dry	15–20
Carpentry residue	5–10
Carpentry residue, air dry	15–20
Plywood residue	35–50
Plywood slabs	5–10
PULPWOOD BARK	
Softwood, dry transport • Dry debarking • Wet debarking, uncompressed • Wet debarking, compressed	 40–50 60–70 55–62
Softwood wet transport or storage in water • Uncompressed • Compressed	 70–85 55–62
Birch • Wet debarking, uncompressed • Wet debarking, compressed • Dry debarking	 65–70 55–62 40–50
ROUNDWOOD BARK, softwood, dry treatment wet treatment	40–50 60–80
ROUNDWOOD BARK, birch	35–50

The energy content of a fuel depends on its chemical composition, i.e. the amount of solar energy bound to carbon and hydrogen compounds. The higher the carbon and hydrogen content, the higher is the fuel's energy content**.**

The net calorific value of wood on a dry basis is 18.3–20.0 MJ/kg. The calorific value of tops, branches, and small trees is slightly higher than that of the whole tree (Kytö et al. 1983, Nurmi 1993, 1997, and 2000). For example, the calorific value of pine branches is 19.99 MJ/kg and that of the stem 19.55 MJ/kg (Nurmi 2000). The greatest differences between different parts of trees have been measured for alder and aspen. The calorific value of wood is low compared to that of other solid fuels, which sets requirements for wood handling and combustion equipment. Wood fuels also usually require more storage space than other solid fuels. (Figure 12.1, Laine & Sahrman 1985, Wilén 1996). Tables 4.13–4.15 illustrate variations in the net calorific value of wood.

Table 4.13. Net calorific values of different parts of tree on a dry basis (MJ/kg) by species of tree (Nurmi 1993 and 2000).

Species	Stem wood	Bark	Whole stem	Crown	Leaves/ needles	Whole tree	Stump
Scots pine (Pinus sylvestris)							
young tree	19.31	19.53	19.33	20.23	21.00	19.53	
mature tree			19.55	20.09	21.04	19.63	22.36
Norway spruce (Picea abies)							
young tree	19.05	18.80	19.02	19.77	19.22	19.29	
mature tree			19.16	19.41	19.19	19.24	19.18
Downy birch (Betula pubescens)							
young tree	18.62	22.75	19.19	19.94	19.77	19.30	
mature tree			19.06	19.33	19.36	19.09	18.61
Silver birch (Betula pendula)							
young tree	18.61	22.53	19.15	19.53	19.72	19.21	
mature tree			18.96	19.61	19.76	19.05	18.50
Grey alder (Alnus incana)							
young tree	18.67	21.57	19.00	20.03	20.57	19.18	
mature tree			19.14	19.74	20.54	19.22	19.27
Common alder (Alnus glutinosa)							
young tree	18.89	21.44	19.31	19.37	20.08	19.31	
mature tree			18.90	19.47	19.78	19.00	18.91
Common aspen (Populus tremula)							
young tree	18.67	18.57	18.65	18.61	19.18	18.65	
mature tree			18.62	18.96	19.02	18.66	18.32

Table 4.14. Net calorific values of different parts of branches and tops on a dry basis, MJ/kg (Nurmi 1997).

Species	Wood			Bark				Leaves/ needles	Crown without leaves/ needles	Crown with needles
	> 5 mm	< 5 mm	Whole branch	Inner bark	Outer bark	< 5 mm	Whole bark			
Pine	20.01	19.96	19.99	19.28	20.36	31.39	20.30	21.04	20.09	20.33
Spruce	19.36	19.23	19.30	17.87	20.77	20.27	19.60	19.19	19.41	19.33
Downy birch	18.68	18.57	18.64	18.49	28.53	20.58	21.03	19.36	19.33	
Silver birch	18.53	18.65	18.57	19.07	29.87	20.13	21.78	19.76	19.61	
Grey alder	18.83	19.11	18.88	20.11	25.15	21.85	21.69	20.54	19.74	
Common alder	18.48	18.66	18.51	19.55	23.92	21.76	21.29	19.78	19.47	
Aspen	18.76	19.00	18.81	18.46	20.48	19.69	19.20	19.02	18.96	

Table 4.15. Net calorific values of different wood fuels on a dry basis (Pellikka & Saviharju 1993, Hakkila et al. 1978, Laine & Sahrman 1985, Tahvanainen 1995, Taipale 1996, Wilén 1996, Pesonen et al. 2014).

Wood fuel	**Species**	**Net calorific value, MJ/kg**
Pulpwood with bark	Pine	19.3
	Spruce	19.1
	Birch	19.5
Whole-tree chips from young stands	Pine	20.5
	Spruce	19.6
	Birch	19.6
Whole-tree chips from thinning	Pine	19.6
	Spruce	19.2
	Birch	19.0
Logging residue chips without needles	Pine	20.4
	Spruce	19.7
	Birch	19.7
Logging residue chips with needles	Pine	20.5
	Spruce	19.8
Forest residue chips		19.3
Hog fuel from stumps and roots	Pine	19.5
	Spruce	19.1
Sawdust	General	18.9
	Pine, debarked	19.0
Cutter shavings		18.9
Bark	Pine	20.0
	Spruce	18.6
	Birch	22.7
Wood chips	Willow	16.2–18.9

The density of wood (basic density) can vary according to growth site, genotype, and age, and there may even be differences in the stem wood densities of the same species of tree in the same growth site (Table 4.16). Aspen has a basic density of 400 kg/m^3, while the basic density of rowan is 540 kg/m^3, oak is 600 kg/m^3, ash is 590 kg/m^3, maple is 550 kg/m^3, and juniper is 510 kg/m^3 (Kytö et al. 1983, Björklund 1984, Björklund & Ferm 1982, Hakkila et al. 1978, Tahvanainen 1995, Pesonen et al. 2014). More basic densities are listed in Tables 4.17 and 4.18.

Table 4.16. Variations in basic density in different parts of various species of tree (Kytö et al. 1983).

Species	**Basic density, kg/m^3**				
	Whole tree	**Stem wood**	**Branches**	**Stump**	**Bark**
Pine	385	390–410	450	450	300
Spruce	400	380–400	610	410	340
Birch	475	490	530	510	550
Alder	370	360–430	405–440		
Aspen	385	360	450		
Beech		575–625	750		

Table 4.17. Average basic densities of different timber categories (Hakkila et al. 1978).

Timber category	**Species**	**Basic density, kg/m^3**
Pulpwood with bark	Pine	390
	Spruce	380
	Birch	490
	Alder	360
Whole-tree chips from thinning	Pine	385
	Spruce	400
	Birch	475
	Alder	370
Logging residue chips without needles	Pine	405
	Spruce	465
	Birch	500
Logging residue chips with needles	Pine	395
	Spruce	425
Sawing residue with bark	Softwood	415
Stumps and roots	Pine	475
	Spruce	435

Table 4.18. Basic density, moisture percentage, and bark ratio of willow saplings of different ages in winter (Hytönen & Ferm 1984, Pesonen et al. 2014).

Age (years)	Basic density, kg/m^3	Moisture, %	Bark, %
1	284	64	34
2	356	57	22
4	360	57	13
5	382	56	11
2–3	295–408 whole tree 299–437 timber		

Wood fuels can be classified according to quality or traded form (chips, bark, chopped and split logs, refined wood fuels, such as pellets, briquettes, and charcoal), or their origin, as e.g. the FAO Forestry Department classifies solid biofuels (FAO 2004).

- "Primary": solid, liquid, or gaseous wood fuels ("direct wood fuels") are fuels made from trees or parts of trees grown in forests or fields.
- "Secondary": solid, liquid, or gaseous wood fuels ("indirect wood fuels") are wood fuels generated as by-products in industrial processes or wood residues.
- "Recovered wood fuels" are wood fuels made from used wood products.

The solid biofuels standard (EN ISO 17225-1:2014) divides wood fuels (1 Woody biomass) into the following sub-categories:

- 1.1 Woody biomass from forests and plantations, and other virgin wood
- 1.2 By-products and residues from the wood processing industry
- 1.3 Used wood

In this publication, wood fuels are described on the basis of both their raw material and quality.

Figure 4.2 shows the classification of wood fuels according to the EN ISO 17225-1:2014 standard, and examples of more detailed classifications are given below:

- Fresh/green logging residues, spruce – 1.1.4.2
- Stumps/roots, spruce – 1.1.5.2
- Stem wood, mixture of broad-leaf and coniferous (majority broad-leaf) – 1.1.3.1 & 1.1.3.2
- Sawdust, spruce – 1.2.1.4
- Cutter shavings, pine – 1.2.1.4
- Bark, spruce – 1.2.1.5
- Blend of cutter shavings, sawdust, and bark – 50 vol-% 1.2.1.4 (cutter shavings) and 50 vol-% 1.2.1.5 (bark)

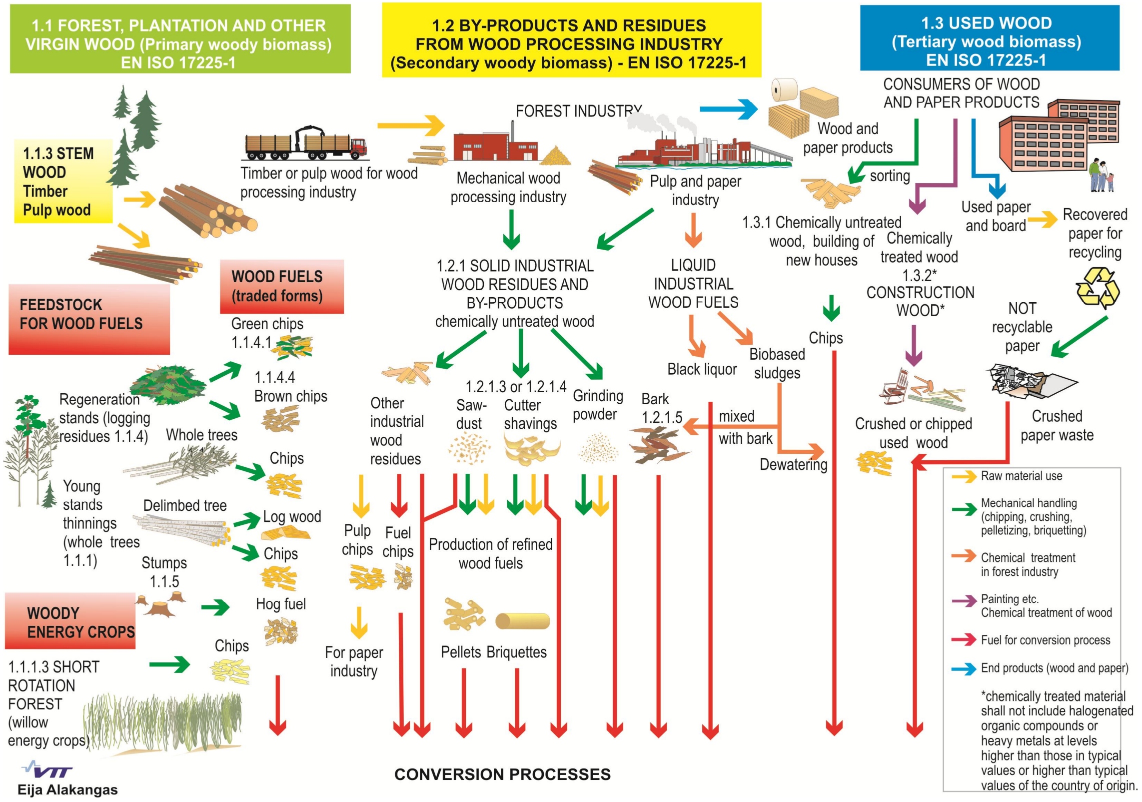


Figure 4.2. Classification of wood fuels according to the raw material classes. Figure: VTT.

4.2 Wood chips and hog fuel

4.2.1 Overview

Wood chips are a fuel made from whole trees, stem wood, forest residues, or other wood matter by chipping. Hog fuel is produced either using a mobile or stationary crusher at a power plant. Whole-tree chips are made from undelimbed trees and stem wood chips from delimbed stems. Logging residue, i.e. tops, branches, and small-diameter timber, is turned into logging residue chips, and stumps into stump hog fuel. Sawmill chips are a by-product of sawing (Hakkila 1992).

Stumps, recovered wood, and plywood residues are processed in a crusher. A crusher in forestry science publications is known as a grinder. Figure 4.3 shows differences between the particle sizes of wood chips and hog fuel.

The maximum sustainable commercial timber felling volume is almost 73 million m^3 solid per year, and the energy wood felling potential is 21 million m^3 solid per year. Of energy wood, branches and leaves would account for 7.8 million m^3 solid, stumps and roots for 6 million m^3 solid, and stem wood for 7.2 million m^3 solid. Of stem wood that is categorised as energy wood, 5.8 million m^3 solid corresponds to commercial timber by its dimensions (Härkönen 2014).

In Pöyry's and Metsäteho's report on the estimated forest chip potential in 2020, the domestic commercial felling potential was assumed to be 56.6 million m^3 solid, with the maximum scenario being based on a volume of 67.9 million m^3 solid. In the basic scenario, the theoretical forest chip harvesting potential was 105 TWh (378 PJ), while the techno-ecological potential was 43 TWh (155 PJ) and the techno-economical potential was 27 TWh (97 PJ). In the maximum scenario, the potentials were 115 TWh (414 PJ), 48 TWh (173 PJ), and 29 TWh (104 PJ) respectively. The techno-economical potential of smallwood was

6.4–7.4 TWh (23–28 PJ), the potential of crown mass was 10.3–12.8 TWh (37–46 PJ), and the potential of stumps was 9.2–10.1 TWh (33–36 PJ) (Kärhä et al. 2010).

In the estimate of Anttila et al. from 2014, the technical harvesting potential of crown mass is 6.6 million m^3 solid (13.2 TWh / 47.5 PJ), if the commercial timber yield remains around the average of the years 2008–2012 in terms of species of tree and the area used for regeneration felling. The potential of stumps is 7.1 million m^3 solid (14.2 TWh / 51.1 PJ). If the volume of commercial timber harvesting were to rise to the maximum sustainable level, the potential of crown mass/tops would be as high as 11.6 million m^3 solid (23.2 TWh / 83.5 PJ) and that of stumps as high as 12.0 million m^3 solid (24 TWh / 86.4 PJ). The smallwood harvesting potential is 6.2–8.3 million m^3 solid (12.4–16.6 TWh / 44.6–59.8 PJ) (Anttila et al. 2014).

Figure 4.3. Wood chips and hog fuel. Figure: VTT.

Wood chips are used in the heating boilers of buildings, in heating plants, and in industrial heat and power plants. This is why moisture content is the most important quality criterion for combustible wood chips, and the average target length of wood chips is usually 30–40 mm (particle size class P31 or P45). Hog fuel is usually used in heating plants and in industrial heat and power plants.

When moisture content is known, the most significant factor of uncertainty is solid volume content (solid/loose m^3 ratio), which varies, as it depends on the technology used to produce and transport the fuel. The solid volume content of wood chips indicates the ratio between particle density and bulk density, i.e. how many solid cubic metres there are in one bulk cubic metre. The most important factors affecting solid volume content are particle size, particle shape, species of tree, branches, moisture content, time of year, loading method, and settling (Hakkila 2000).

The particle size of wood chips is not uniform, and smaller particles fill the spaces between larger ones during loading and transport. Wood chips made from whole trees and logging residue contain a higher level of fines than e.g. the more homogeneous pulpwood chips, which usually makes the fuel slightly more compact. Density can be increased considerably by mixing sawdust with the chips. The higher the ratio between the diagonal of a chip surface and thickness, the lower is the solid volume content is (Hakkila 2000).

Wood chips made from brittle species of tree, such as grey alder, contain higher levels of fines, which make the fuel more compact. Fresh branches, especially the bendy branches of broad-leaf trees, produce over-sized particles, which lower the density of the fuel. Fewer over-sized particles are produced by brittle and dry raw material, which is why drying makes wood chips more compact. Frozen raw material is brittle and produces more fines by chipping, which is why wood chips made from frozen wood are usually more compact than normal (Hakkila 2000).

A more compact load is achieved by discharging wood chips through the chipper chute than by chips falling freely off a conveyor, a tip trailer, a front-loader bucket, or a silo. However, the outcome depends on the discharge capacity of the chipper and the arc and distance of the stream of chips. A more compact load is achieved when using a chipper chute that discharges chips from the top than from the rear. Spaces between larger particles are filled with smaller particles during transport, causing the load to become more compact and settled. Settling depends on the initial solid volume content, the transport distance, the road surface, and any freezing of the wood chips (Hakkila 2000).

Settling occurs at a faster rate at the beginning of the journey, but the rate stabilises within the first 20 kilometres. If the factor restricting the size of the load is the volume of wood chips rather than their mass, from the perspective of the economy, the significance of the initial density is greater than the final density. However, if the load is measured upon receipt on the basis of the space it occupies, it is the final density that determines the measuring results. The effects of different factors on the density of wood chips are not always easy to predict, as they also depend on the equipment used. Wood chips usually have a solid volume content of 0.37–0.45 and bark hog fuel a solid volume content of 0.3–0.4. As a rule, 0.4 can be applied for wood chips (Hakkila 2000).

Quality guidelines have been drawn up for the unambiguous determination of the quality of wood fuels (Alakangas & Impola 2014, 2015), which are based on European or international solid biofuel standards (Appendix A). The guidelines lay down the procedure to be followed in reporting and determining the quality and energy content of wood fuels – wood chips, sawdust, and bark – unambiguously and expeditiously. The guidelines and the quality classification of wood fuels are primarily used in the wood fuel trade as an appendix to supply contracts. Other parties that make use of the quality guidelines include plant and equipment engineers and fuel producers. Quality assurance ensures that the particle size and moisture content of wood chips meet the requirements of individual plants: Wood chips may not contain parts of the forest undergrowth (moss, humus), stones or metals, long sticks or twigs (Impola 1995 and 1998, Alakangas & Impola 2014, 2015).

4.2.2 Logging residue

Logging residue offers a usable and quantitatively significant stock of raw material for wood fuel production. The volume and composition of logging residue produced during commercial timber felling varies by logging site. Logging residue produced by the first thinning of birch stands mostly consists of tops below the commercial timber size and branches, and the yield is relatively low. Regeneration felling in spruce stands, on the other hand, produces considerably higher volumes of logging residue, mostly consisting of branches and needles as well as a significant number of refused logs, if there is butt rot in the stand. This is why logging residue produced by regeneration felling in spruce stands is the category of forest chips with the highest potential for producing thermal energy at competitive prices (Alakangas et al. 1999, Hakkila 2000, Hakkila & Alakangas 2000).

Logging residue can be harvested either fresh with needles immediately after felling, or dry at the end of the summer season, when a considerable percentage of needles and a small amount of bark and thin branches will be left in the forest. The yield and profitability are lower when logging residue is harvested dry, but the nutrients are left in the forest (Alakangas et al. 1999, Hakkila 2000, Hakkila & Alakangas 2000). In Finland, logging residue is usually left to dry in situ for between two and six weeks, allowing the majority of needles to be shed (Routa et al. 2013).

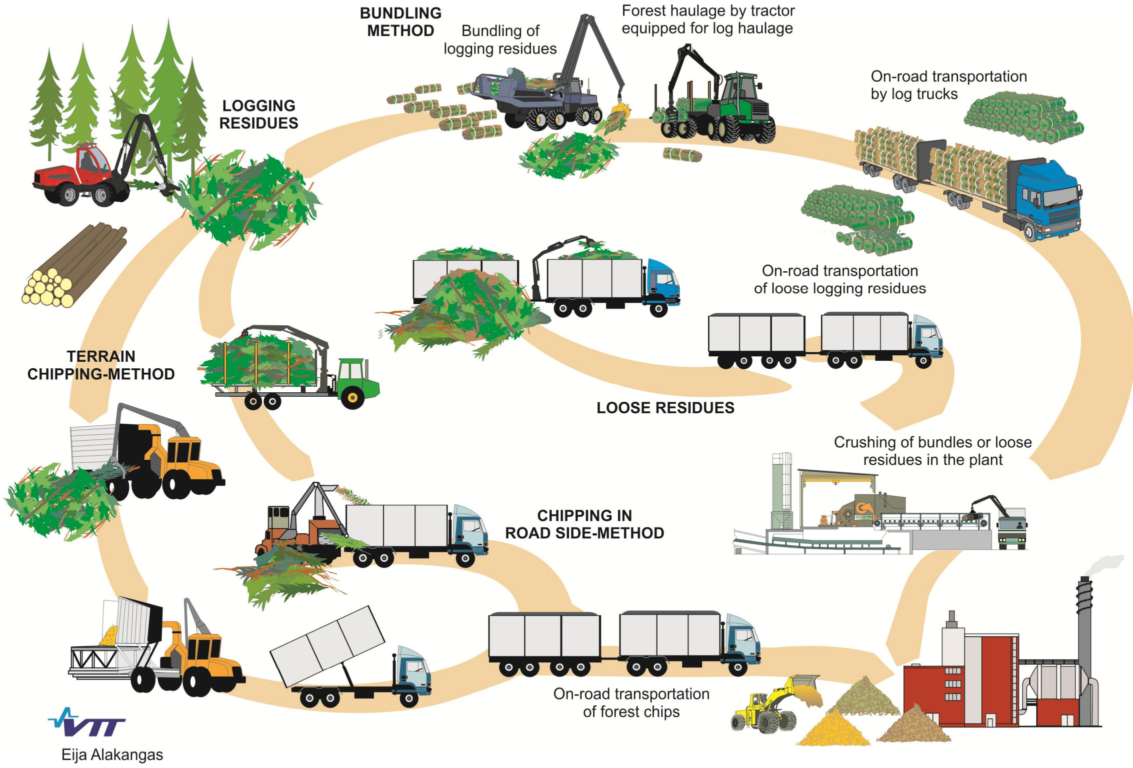


Figure 4.4. Logging residue harvesting techniques. Figure: VTT.

The most commonly employed technique for harvesting logging residue in Finland (almost 76%) is a production technique based on chipping logging residue by the side of the road (Figure 4.4). The technique involves piling forest residues on site in connection with commercial timber harvesting. The logging residue piles are transported to a roadside storage area, from where they are chipped directly into a wood chip transport vehicle and transported to a plant. Logging residue can also be chipped using an on-site chipper or a multi-purpose chipper on site, or using a chipper or a crusher at the place of use. Alternatively, logging residue can be bundled and commercial timber harvesting machinery used for forwarding and transporting. Logging residue is bundled to make bundles of 450–550 kg, which makes it more compact. The bundles are transported to a plant and crushed. Bundling represents a small percentage of logging residue harvesting (Alakangas et al. 1999, Hakkila 2000).

Logging residue is primarily harvested in areas where the forest is mature and the dominant species of tree is spruce. This is why Central and Southern Finland yield the most logging residue.

The volume of logging residue left in a logging site depends on the species of tree, the number of trees, the size of stems, and the volume of branches, as well as the amount of rot. Spruce stands produce more than twice the amount of logging residue than pine and birch stands (Figure 4.5). Logging residue formed from mature trees contains more branches than logging residue from smaller trees. If there is rot in the stand, a considerable number of refused logs may accumulate. The amount of logging residue left in a typical regeneration felling site in spruce stands in Southern Finland is 100 m^3/ha with a commercial timber harvesting volume of 200–250 m^3/ha. The volume of recoverable logging residue usually accounts for 25–30% of the volume of stem wood harvested from spruce stands. Each solid cubic metre of stem wood from regeneration felling sites produces crown mass with an energy potential of 0.4 MWh (1.4 GJ) for pine and 1.0 MWh (3.6 GJ) for spruce (Figure 4.6). Figure 4.6 shows the volume of logging residue relative to the volume of stem wood.

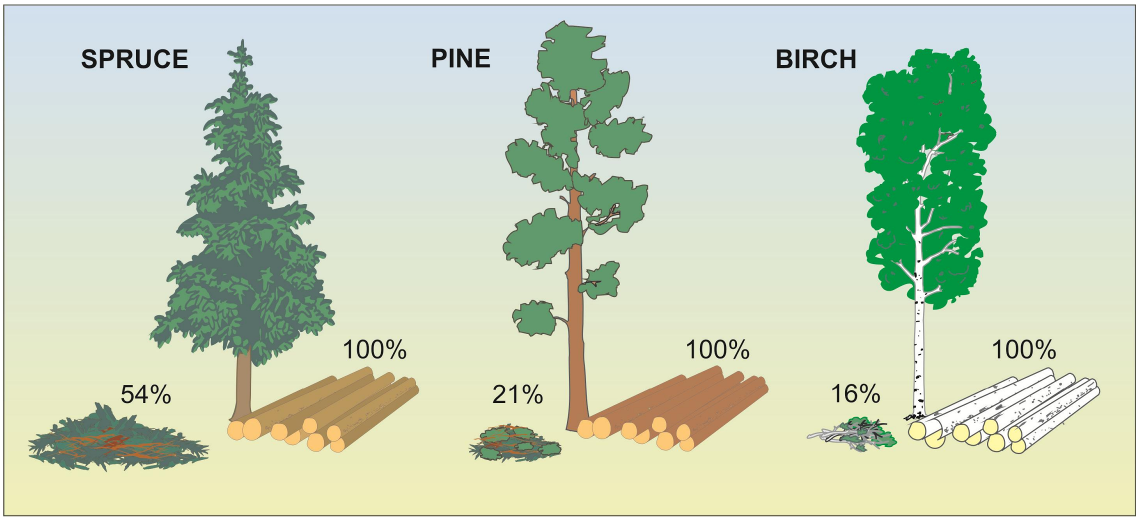


Figure 4.5. Biomass yield of regeneration felling stands (crown mass / stem wood mass, %) Source: Hakkila 1992. Figure VTT.

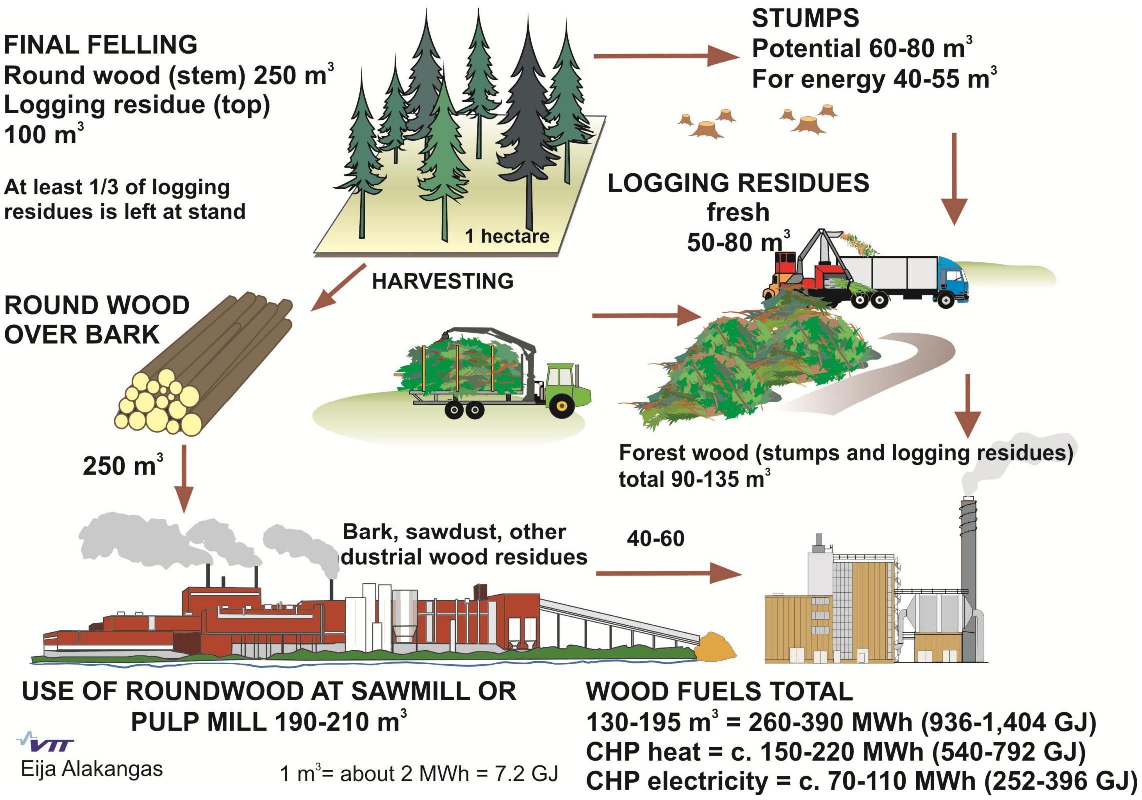


Figure 4.6. Average volumes of commercial timber and energy wood yielded by regeneration felling in spruce stands per hectare. Figure: VTT.

If logging residue is left to dry in situ for a couple of summers, its moisture content drops from 50–60% to as low as 20–30%. Drying causes needles to fall, thin branches to break off, and even some of the bark to come loose. The wood content of logging residue increases and its moisture content drops, but, on the other hand, the volume of logging residue that can be harvested decreases by as much as 20–30% primarily due to the shedding of needles. The recovery yield is also lower than with fresh logging residue. The recovery yield of dry logging residue is 45%.

Figure 4.7 shows the compositions of fresh and dry spruce logging residue (Alakangas et al. 1999).

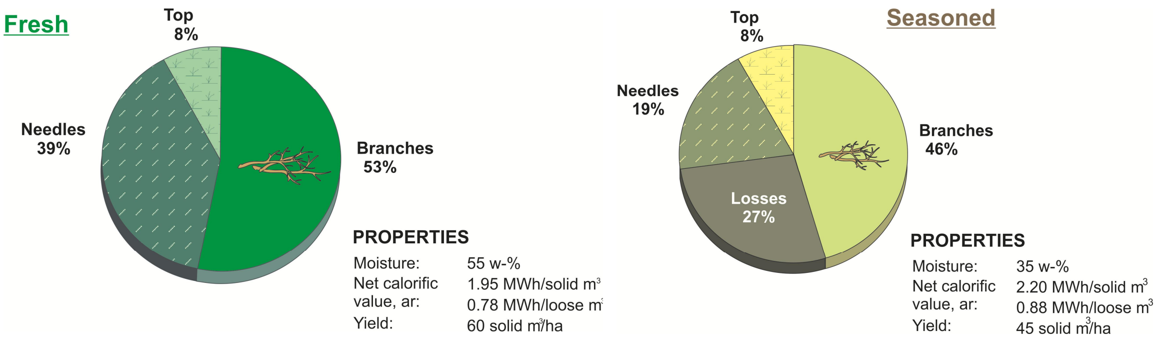


Figure 4.7. Composition of fresh (left) and dry (right) spruce logging residue. Figure: VTT.

The most significant operational properties of logging residue chips are dry mass per bulk cubic metre, as well as moisture content, net calorific value at the plant, and particle size distribution. Moisture content affects the net calorific value, as water evaporation requires energy. The higher the proportion of dry mass in each cubic metre of chips and the lower the moisture content, the higher is the energy yield achievable at a plant (Figure 4.7).

Crown mass is mostly composed of leaves or needles. Needles account for 26% of pines and for 39% of spruces in regeneration felling sites in Southern Finland. The net calorific value of pine branches without needles on a dry basis is 20.09 MJ/kg and that of spruce is 19.41 MJ/kg (see Tables 4.13–4.14). The net calorific values for needles are 21.04 and 19.19 MJ/kg respectively. In other words, the net calorific value of pine needles is higher than that of the rest of crown mass, while the difference between spruce needles and branches is small. The fall off of needles therefore has a greater impact on the average net calorific value of pine than of spruce. This leads to a conclusion that, although the net calorific value of logging residue decreases with the fall of needles, rotting, and the release of extractives, the average net calorific value on a dry basis remains the same, as the ratio between carbon and hydrogen also remains relatively unchanged during storage. Moisture content is, therefore, the only factor of significance to the net calorific value (Hakkila et al. 1995, Nurmi 1993, Nurmi 1999).

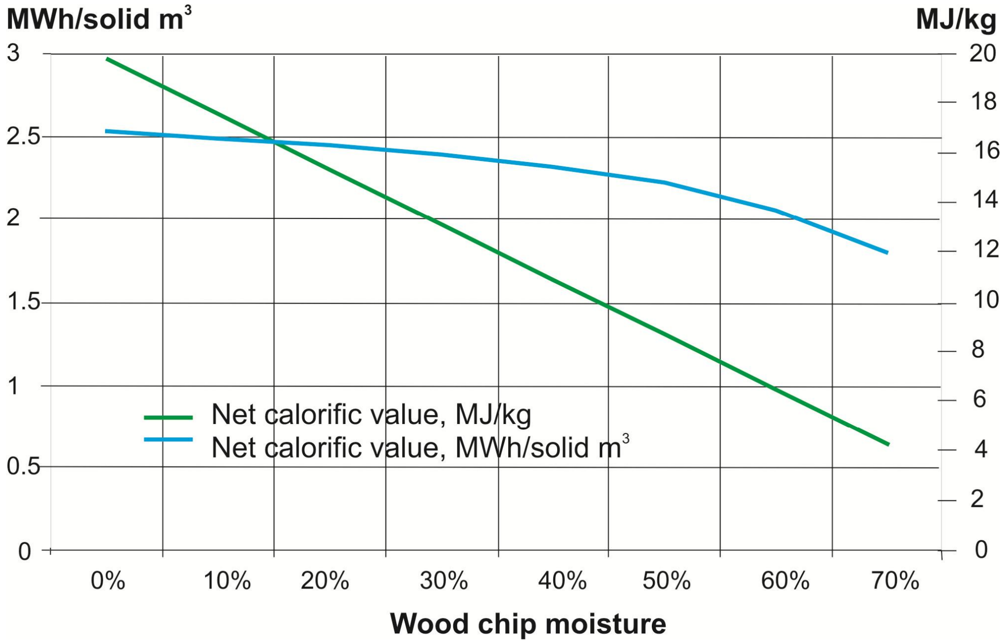


Figure 4.8. Dependence of the net calorific value of logging residue chips on moisture content (MWh/solid m^3 or MJ/kg). Figure: VTT.

The dry matter content of each bulk cubic metre of wood chips varies considerably. It is dependent on the basic density of wood and the compactness of the wood chips. The average basic density of spruce logging residue without the green fraction is 465 kg/m^3, and the average basic density of spruce logging residue chips with the green fraction is 425 kg/m^3 (Hakkila 1985).

The density of wood chips depends above all on the technical properties of the chipper: uniformity of the particle size distribution, discharge capacity of the chipper, and the method of loading. The drying time and settling of logging residue during transport over long distances also affect density. Solid volume content (solid/loose m^3 ratio) needs to be known to convert bulk values into solid values for determining chipping and transport costs, for example. A factor of 0.40 is usually used for the solid/loose m^3 ratio, as it represents a workable average. Table 4.19 lists solid volume content figures for logging residue chips (Uusvaara & Verkasalo 1987, Hakkila 2000).

Table 4.19. Solid volume contents of logging residue chips (solid m^3/loose m^3) at different times of year (Verkasalo 1988).

Chipper type and loading method	Time of year	Fresh	Seasoned for over one year
Drum chipper, rear discharge	Summer Winter	0.36 0.38	0.39 0.41
Crusher, belt conveyor	Summer Winter	0.39 0.39	0.39 0.39

Needles reduce the solid volume content of wood chips, which is why logging residue chips that have been allowed to dry for more than a year are more compact than chips made from fresh logging residue. This is also partially due to the higher fines content of logging residue chips that have been left to season (Uusvaara & Verkasalo 1987, Hakkila 2000).

Logging residue chips are non-homogeneous by particle size and moisture content. The particle size ranges from dust-like needle and bark matter to wooden blocks and twigs (Table 4.20). Particle size depends on the feedstock, the chipper or crusher, the condition of the chipper blades, and the mesh size of the screen. The more stem wood there is in the feedstock, the more homogeneous is the particle size distribution of the wood chips. Wood chips produced using crushers are coarser than those produced using chippers (Alakangas et al. 1999, Alakangas 2012). Table 4.20 shows the quality classes of particle sizes (P) and fines (< 3.15 mm, F).

Table 4.20a. Particle size analyses for logging residue chips, mass remaining on sieve, w-% (Alakangas 2012).

Sieve, mm	Fresh logging residue, mass remaining on sieve, w-%								
	1	2	3	4	5	6	7	8	9
< 3.15	19.5	25.6	33.7	28.3	32.8	24.2	25.1	6.9	6.0
3.15–8	11.2	21.4	18	21.6	24.4	34.2	27.9	22.8	19.6
8–16	12.0	18.8	22	26	21.8	29.8	24.4	8.9	19.2
16–31.5	13.4	25.7	17.2	17.2	12.8	8.3	16.8	7.5	39.6
31.5–45	10.5	4.8	2.9	1.7	4.7	0.7	3.4	4	8.6
45–63	6.3	3.7	1.7	5.2	0	2.8	2.3	1.2	5.1
63–100	1.9	0.1	4.6	0.0	4.1	0	0.1	48.7	2.8
> 100	25.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Quality class	No	F30 P31	F30+ P63	F30 P31	F30+ P31	F25 P31	F30 P31	F10 P63	F10 P31

No = Quality class could not be assigned, as the wood chips do not comply with the criteria for any P class. The quality requirements are based on Alakangas & Impola 2014, 2015.

Table 4.20b. Particle size analyses for logging residue chips, mass remaining on sieve, w-% (Alakangas 2012).

Sieve, mm	**Seasoned logging residue**				**Bundles**	
	1	**2**	**3**	**4**	**1**	**2**
< 3.15	30.5	41.9	20.4	22.2	20.7	30.0
3.15–8	18.1	30.9	31.4	32.6	11.8	17.6
8–16	23.1	17.8	31.3	29.7	12	12.3
16–31.5	0	0	0	0	21.3	10.5
31.5–45	26.4	7.8	16.1	15	8.4	7.4
45–63	0	0.2	0.4	0.4	15.2	0.0
63–100	1.8	1.5	0.5	0	1.7	0.1
> 100	0.0	0.0	0.0	0.0	8.8	22.2
Quality class	F30.5; P45	No	F25, P16	F25, P16	F25, P63	No

No = Quality class could not be assigned, as the wood chips do not comply with the criteria for any P class. The quality requirements are based on Alakangas & Impola 2014, 2015.

The moisture content of fresh logging residue is 50–60 w-% of the total mass of wood chips. However, the moisture content of the wood chips produced from the logging residue is 25–65%. Moisture content depends on factors such as the time of year and storage. Moisture content values of less than 30% can be achieved in the summer, when the raw material of wood chips is left to dry in situ, but similarly moisture content values as high as 65% can be measured in the winter, when snow and ice are mixed with the wood chips (Figures 4.9 and 4.10). Moisture has a considerable impact on the energy density of wood chips. In practice, the energy content of logging residue chips is 0.6–1.0 MWh/m^3 loose (2.16–3.6 GJ/loose m^3) (Alakangas et al. 1999, Hakkila et al. 1998, Uusivaara 1984).

Covering stockpiles with kraft paper developed for this specific purpose is relatively common. The paper protects the piles from getting wet, which means that chipping can be carried out even in poor weather conditions. The kraft paper can be put through the chipper with the logging residue so that it will not remain at the storage site. Figure 4.9 shows an example of VTT's research into the moisture content of logging residue at a logging site, in a covered and uncovered stockpile. Moisture contents are given both as weight percentages and as kg(H_2O)/loose m^3. Based on the results, the moisture content of logging residue stored in covered stockpiles was 7–10 percentage points lower than in uncovered stockpiles. According to VTT's research, the drying of logging residue was most efficient at the beginning of the storage period, as logging residue dried by 14–20 percentage points during the first two months. Evaporation exceeded rainfall by more than 100 mm during this period. The moisture contents began to increase in October due to higher rainfall (Hillebrand & Nurmi 2000, Raitila et al. 2014, Figure 4.9).

Wood chips should not be stored in small (< 200 loose m^3), uncovered stockpiles except for short periods of time, as they can become completely saturated with water as a result of rain. However, relatively dry (< 30 w-%) wood chips can be stored for the entire heating season, if they can be placed in a covered stockpile (Raitila et al. 2014, Röser et al. 2010).

The fuel reception, conveyance, and combustion equipment of different heat and power plants differ from each other. This is why the site of use sets certain quality requirements for wood chips, the most important of which are moisture content and particle size distribution. Any long sticks among wood chips can cause arching or blockages (bridging) in the equipment. The handling properties of homogeneous, relatively fine logging residue chips do not differ significantly from those of sawmill by-products, i.e. dust and bark.

Wet logging residue chips can be used in large multi-fuel power plants throughout the year, as long as the plant is designed to run on wet wood fuel. For example, logging residue chips cannot be the only fuel used in district heating plants that are designed to run on fuel peat in the winter, as not high enough an output can be achieved in the boiler with chips alone. Moreover, wet logging residue may freeze in the winter, or become bridged in silos and conveyors. Moisture can also interfere with mixing. For example, warm peat and cold, wet wood chips do not mix easily. Smaller plants are usually only able to run on wet logging residue in the summer, when they are not operated at full capacity and there is no risk of freezing (Impola 1995).

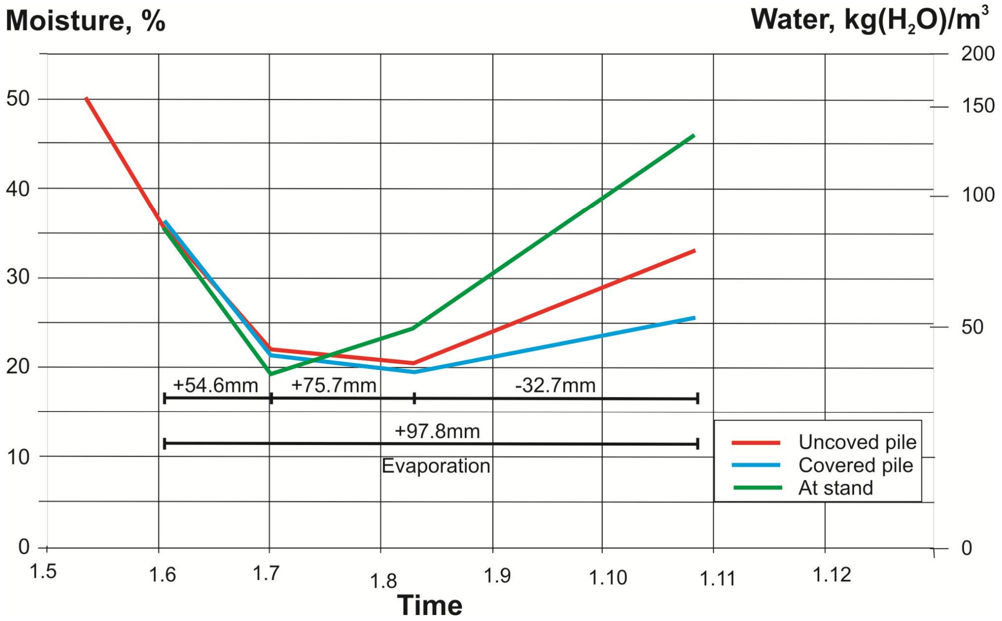


Figure 4.9. Moisture content of logging residue at a logging site, in uncovered and covered stockpiles (the line graph shows the evaporation/rainfall ratio, mm). Source: Hillebrand & Nurmi 2000. Figure: VTT.

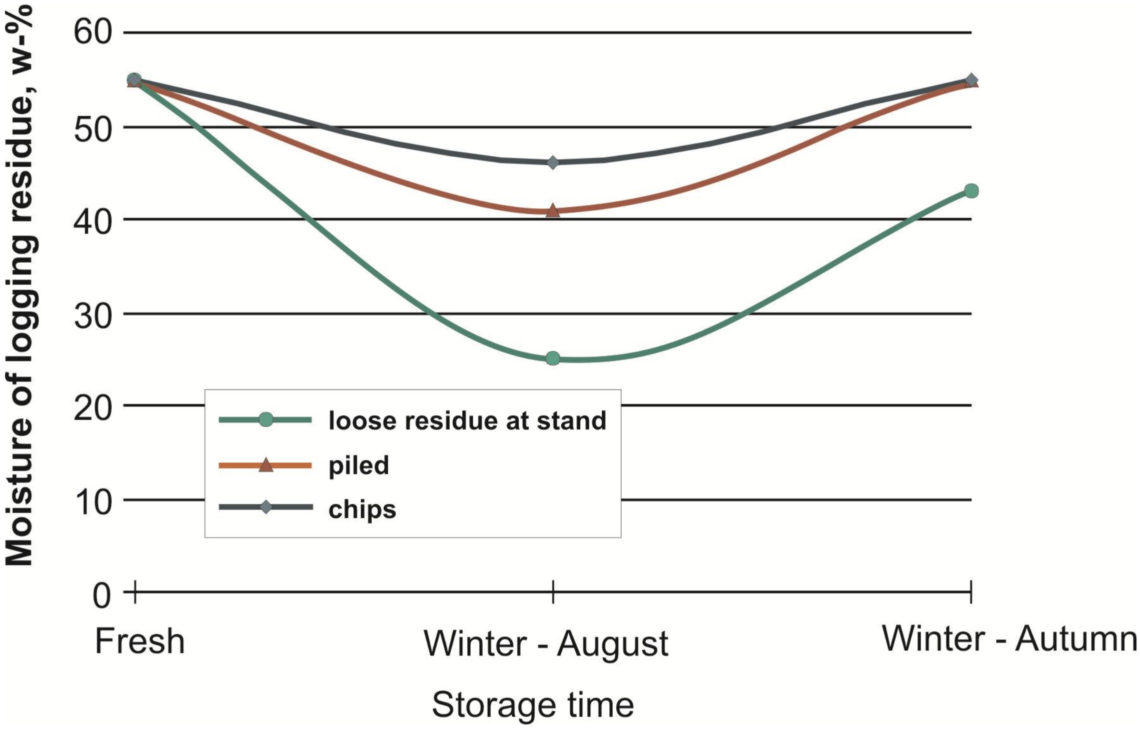


Figure 4.10. Moisture content of logging residue at a logging site, in stockpiles, and as wood chips. Figure: VTT.

The ash content of the wood matter in spruce stems and branches accounts for 0.30–0.63% on a dry basis. Undebarked branches have an ash content of 1.9% and bark of 3.0%. The ash content of needles is even higher (4.2–5.1%). The ash content of spruce logging residue is 2–2.5%. The ash content of both needles and logging residue increase with longer interim storage, and amounts to 4.5–5% in the longest stored stockpiles. Covered stockpiles also contain less ash than uncovered stockpiles (Nurmi 1999).

Ash melting behaviour is of significance especially for combustion techniques in which ash melting can prevent e.g. the circulation of air. It is also useful to know a fuel's ash melting behaviour in order to prevent boiler fouling resulting from ash deformation. Ash melting behaviour depends on the composition of the ash, the combustion equipment, and combustion conditions. Although the sphere temperature of forest residue chips is high, sintering, i.e. the agglomeration of ash particles, begins at much lower temperatures in the case of wood fuels.

Nutrient content lowers the ash melting temperature of logging residue chips compared to bark and peat ash. The highest nutrient contents are found in needles and leaves. Needles account for a considerable proportion of logging residue. Needles represent approximately 35% of the dry crown mass of regeneration-ready spruce stands and 30% of the dry logging residue mass. The corresponding figures for pine are 23% and 20%. The fall off of needles requires drying. This is why the majority of fall off occurs in the summer (Nurmi 1999).

Nutrients also include chlorine (Cl), which can cause high-temperature corrosion in steam boiler superheaters. This problem does not occur in lower-output boilers, as the temperatures are lower. From the perspective of combustion, it is beneficial for forest residues not to contain needles or leaves, as this lowers the levels of chlorine and potassium considerably compared to chips with high green matter content. Compared to undebarked stem wood, spruce needles, for example, contain many times the levels of nitrogen, potassium, phosphorus, and calcium per one unit of dry mass. Spruce needles have a sodium content of 0.020–0.040% and a chlorine content of < 0.4%. Pine needles have an extremely low sodium content and a chlorine content of < 0.2%. Figure 4.11 shows the nutrient contents of the biomass fractions of regenerated pine and spruce stands.

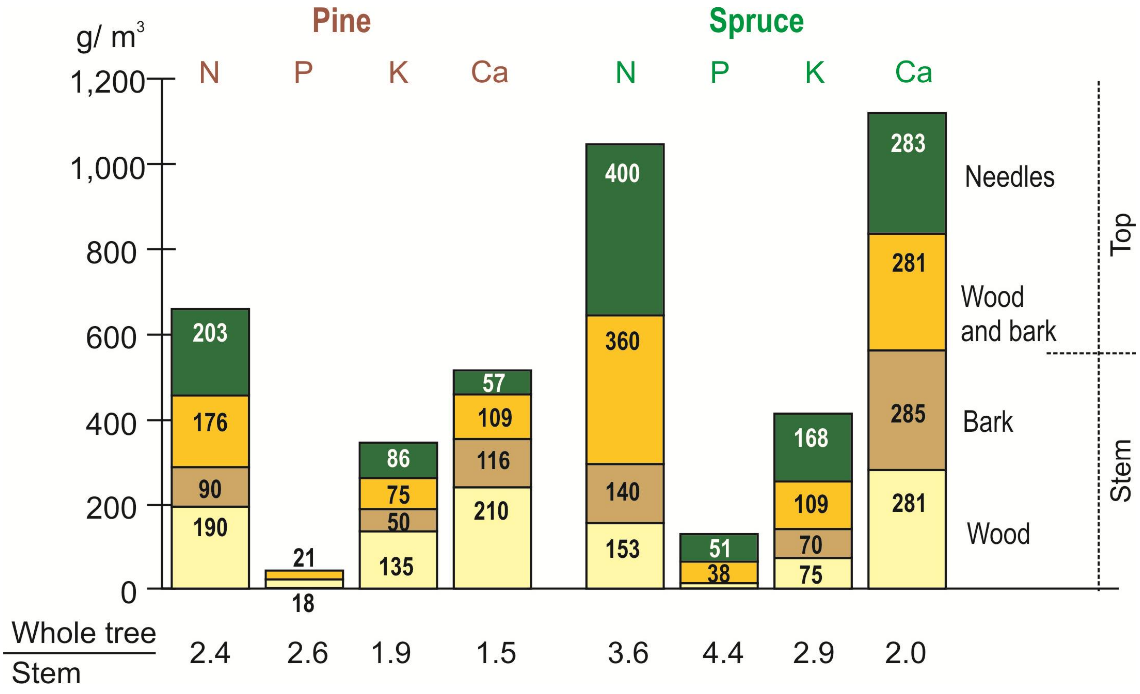


Figure 4.11. Nutrient contents (g/m^3) of the biomass fractions of regenerated pine and spruce stands per one cubic metre of undebarked stem (Mälkönen 1974 & 1977).

4.2.3 Whole-tree and stem wood chips

Whole-tree and stem wood chips are used in smaller heating stations and in residential and agricultural heating boilers. The chips are made from undelimbed stems, which are either refused stem wood or stems too small for industrial use (e.g. underproductive forests, sapling stands, first thinning). Stem wood chips are made from delimbed stem wood, and they represent comfortably the largest source of small-size wood chips. Refused stem wood generally consists of undebarked stem wood left in the forest in connection with felling and forest management. Delimbed stem wood chips are currently mostly used to heat homes and in smaller district heating stations, where the quality requirements of fuel are stricter than at larger plants. The moisture content of wood chips used at heating plants must be lower (less than 35%) and the particle size more uniform than with fuels used in larger heating stations. The energy production technology also sets limitations on particle size, e.g. in the case of small gasification plants. Whole-tree chips are produced by means of multi-tree handling and by manual methods, whereby forestry workers cut and stack small trees using the so-called felling-piling technique (Figure 4.12). Small trees are primarily (66%) turned into wood chips at the roadside.

To increase productivity and ergonomics, a felling frame is attached to the chainsaw. The cut trees are stacked near the road and stored in stem wood stockpiles for later chipping and transport to users. Mechanical harvesting is based on multi-tree handling, which involves bundling several trees before depositing them at the logging site (Figure 4.12).

Tables 4.21–4.24 list some of the most important properties of small trees, including calorific values, elemental analysis, and ash content. The properties of whole-tree chips have mostly been studied in first thinning pine stands (Tables 4.25–4.27), and Tables 4.28–4.31 list factors that affect the solid volume content (solid/loose m^3 ratio) of whole-tree chips, particle size distributions, as well as angles of slide and friction coefficients.

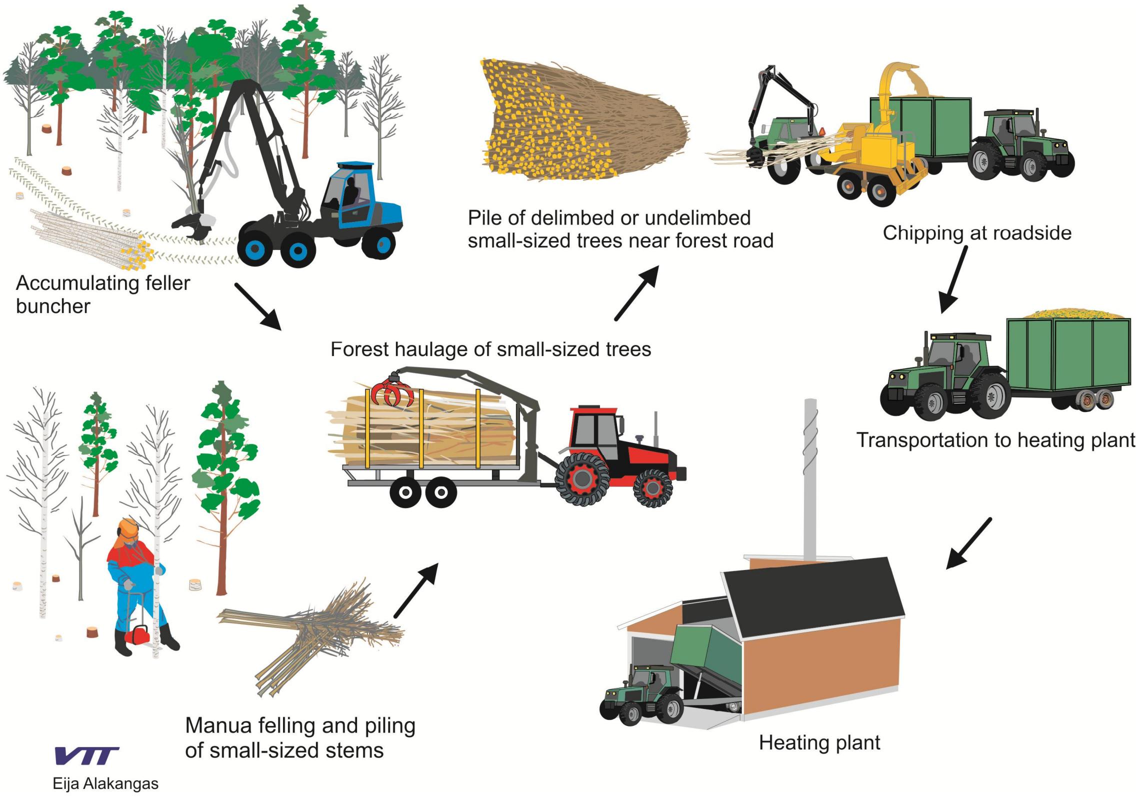


Figure 4.12. Whole-tree or stem wood chip harvesting. Figure: VTT.

Table 4.21. Net calorific value of stem wood and whole trees on a dry basis for different species of tree (Nurmi 1993).

Species	**Net calorific value on a dry basis, MJ/kg**	
	Stem wood	**Whole tree**
Pine	19.33	19.53
Spruce	19.02	19.29
Downy birch	19.19	19.30
Silver birch	19.15	19.21
Grey alder	19.00	19.18
Common alder	19.31	19.31
Aspen	18.65	18.65

Table 4.22. Elemental analysis of different parts of small-diameter trees on a dry basis (Nurmi 1993).

ELEMENT/ SPECIES	WOOD			INNER BARK		OUTER BARK		BARK	Needles/ leaves
	Stem	Branches		Stem	Branches	Stem	Branches	Branches	
		> 5 mm	< 5 mm		> 5 mm		> 5 mm	> 5 mm	
CARBON CONTENT, w-%									
Pine	52.34	53.53	50.83	40.83	52.33	55.75	56.35	54.99	52.20
Spruce	52.43	53.36	50.37	49.70	50.20	55.56	56.10	54.02	51.30
Downy birch	50.97	50.97	48.39	52.20	52.49	72.64	68.37	57.82	49.12
Silver birch	47.43	48.67	48.05	48.00	48.60	66.71	64.34	50.24	48.68
Grey alder	49.09	48.21	49.17	49.67	48.34	64.09	60.58	51.53	49.75
Common alder	46.64	47.90	48.45	50.29	50.09	58.52	62.06	53.97	50.95
Aspen	46.21	46.84	50.23	48.95	47.81	52.71	52.94	48.05	48.23
HYDROGEN CONTENT, w-%									
Pine	6.09	6.03	5.23	6.17	6.36	5.68	6.12	6.70	6.82
Spruce	5.86	5.61	5.14	5.59	5.62	5.85	5.77	5.95	6.28
Downy birch	5.86	5.80	5.15	5.79	6.10	9.37	8.43	6.55	6.13
Silver birch	5.22	5.25	5.18	5.10	5.01	9.41	8.40	5.33	6.08
Grey alder	5.77	5.16	5.71	6.15	5.94	8.59	7.66	6.48	6.22
Common alder	5.01	5.84	5.89	5.77	5.57	6.37	7.56	6.23	5.90
Aspen	4.98	5.09	5.98	5.74	5.73	6.42	6.18	5.77	5.95
NITROGEN CONTENT, w-%									
Pine	0.08	0.10	0.19	0.48	0.55	0.15	0.38	0.68	0.88
Spruce	0.01	0.03	0.14	0.47	0.52	0.33	0.43	0.74	0.79
Downy birch	0.12	0.18	0.28	0.63	0.86	0.28	0.47	12.0	1.73
Silver birch	0.07	0.18	0.28	0.33	0.65	0.79	0.59	0.74	1.59
Grey alder	0.44	0.59	0.83	1.49	1.74	1.28	1.23	1.72	2.79
Common alder	0.20	0.46	0.62	1.06	1.26	1.15	1.06	1.33	2.22
Aspen	0.15	0.29	0.61	0.84	1.30	0.59	0.88	1.00	2.50

Table 4.23. Volume of clean ash in fuel chips produced from freshly felled small trees (Hakkila & Kalaja 1983).

Raw material	**Ash content on a dry basis, w-%**				
	Birch	**Alder**	**Aspen**	**Pine**	**Spruce**
Delimbed stem	0.68	0.92	0.92	0.74	1.04
Whole tree without leaves/needles	0.79	1.08	1.09	0.80	1.25
Whole tree with leaves/needles	0.98	1.25	1.30	0.86	1.56

Table 4.24. Ash content of different parts of small trees on a dry basis (Voipio & Laakso 1992).

Species	Stem 20%			Stem 80%			Branches > 5 mm			Branches < 5 mm		Needles/ leaves
	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	Inner bark	Outer bark	Wood	Outer bark	
Pine	0.3	1.2	1.0	0.3	1.8	1.2	0.4	1.9	1.5	0.7	1.8	2.2
Spruce	0.3	3.5	3.3	0.5	3.0	2.6	0.5	5.1	3.9	1.0	2.9	4.2
Silver birch	0.3	2.7	0.7	0.4	2.3	0.6	0.7	4.6	2.0	1.1	3.4	4.9
Downy birch	0.3	2.0	0.5	0.4	1.8	0.5	0.5	3.2	0.9	0.7	2.4	4.2
Grey alder	0.4	3.2	2.4	0.6	3.2	1.7	0.7	2.9	2.0	1.0	2.2	5.4
Common alder	0.3	2.5	1.4	0.4	2.1	1.5	0.5	2.0	1.5	0.7	2.1	4.8
Aspen	0.4	5.0	11.1	0.5	4.9	10.2	0.7	5.5	6.8	2.0	5.2	8.7

Table 4.25. Net calorific value and ash content of different parts of first thinning pine (Hakkila et al. 1995, Nurmi 1993).

Part of tree	**Net calorific value**			**Ash**	
	Dry basis, MJ/kg	**At 40% moisture, MWh/m^3**	**At 50% moisture, MWh/m^3**	**%, dry basis**	**kg/m^3 of wood**
STEM					
Debarked	19.31	1.95	1.86	0.40	1.6
Bark	19.53	1.32	1.26	2.55	6.8
Undebarked	19.33	1.86	1.78	0.62	2.3
BRANCHES					
Undebarked	20.23	1.97	1.89	1.03	3.9
Needles	21.00	2.01	1.92	2.35	8.8
Living crown	20.49	1.99	1.90	1.48	5.6
Whole crown	20.38	2.02	1.93	1.25	4.9
WHOLE TREE	19.56	1.89	1.81	0.76	2.9

Table 4.26. Average masses and basic densities of different parts of first thinning pine in Southern Finland (Hakkila et al. 1995).

Part of tree	Mass, %	Basic density, kg/m^3
STEM		
Wood	89.5	395
Bark	10.5	266
Wood + bark	100	376
LIVING BRANCHES		
Wood	9.2	424
Bark	5.4	311
Wood + bark	14.6	382
Needles	7.5	373
Living crown	22.1	379
Dead branches	5.9	424
Whole crown	28.0	388
Whole tree	128.0	379

Table 4.27. Average properties of stem wood in standing first thinning pine in Southern Finland (Hakkila et al. 1995).

Property	Whole stem	Stem		Refused tops, cm		
		> 6 cm	> 8 cm	6–8	4–6	1–4
BARK VOLUME						
Thickness, mm	4.5	4.6	5.0	2.4	2.3	1.8
Volume, %	15.4	15.2	15.6	13.5	17.4	25.5
Dry matter, %	10.1	9.8	9.8	10.5	13.9	21.4
BASIC DENSITY, kg/m^3						
Debarked	395	397	399	377	371	365
Undebarked	376	377	379	361	352	340
Bark	267	266	265	275	274	278
WATER, UNDEBARKED TREE, w-%						
Moisture	59	58	58	61	62	63
Moisture ratio (U)	141	140	138	158	164	170
COMPOSITION, kg/m^3						
Wood without extractives	327	329	331	312	293	258
Acetone extractive in wood	11	11	11	11	10	9
Bark	38	37	37	38	49	73
Water	530	528	523	570	577	578
Total = fresh density	906	905	902	931	929	918
ENERGY DENSITY, MWh/m^3 loose , fresh (1 MWh = 3.6 GJ)						
Undebarked	1.85	1.85	1.86	1.78	1.73	1.67
Debarked	1.94	1.95	1.96	1.85	1.82	1.79
Bark	1.18	1.17	1.17	1.21	1.21	1.23
ASH, UNDEBARKED TREE, kg/m^3	2.3	2.3	2.3	2.3	2.5	2.9

Table 4.28. Solid volume content (solid/loose m^3 ratios) of whole-tree chips (Uusvaara & Verkasalo 1987).

Wood chip category	Disc chipper, rear discharge Summer/winter	Disc chipper, top discharge Summer/winter	Disc chipper, tipping Summer/winter	Drum chipper, top discharge Summer/winter	Drum chipper, tipping Summer/winter
Whole-tree pine chips	0.47/0.50	0.48/0.49	0.45/0.48	0.46/0.49	0.41/0.44
Pine stem wood chips		0.49/0.50	0.42/0.42		
Whole-tree birch chips	0.44/0.46	0.45/0.50	0.38/0.43	0.43/0.44	0.40/0.42
Birch stem wood chips	0.44/0.44	0.43/0.46	0.46/0.46	0.43/0.44	
Whole-tree spruce chips	0.44/0.44	0.44/0.44	0.39/0.39		
Whole-tree alder chips		0.54/0.54	0.48/0.48		0.52/0.53
Alder stem wood chips		0.56/0.56			

Table 4.29. Particle size distributions of whole-tree chips (Alakangas 2012).

Sieve, mm	Mass remaining on sieve, w-%											
	1	2	3	4	5	6	7	8	9	10	11	12
< 3.15	2.8	8.1	45.6	23.5	6.2	17.9	8.9	10.8	5.1	8.8	10.8	16.1
3.15–8	3.6	11.0	22.9	25.9	13.0	22.5	11.7	13.0	12.7	21.2	21.4	18.5
8–16	27.8	14.4	17.7	23.9	30.1	31.5	25.7	22.8	26.9	38.7	32.3	28.2
16–31.5	40.8	19.3	10.1	13.8	37.2	22.5	39.4	40.0	38.4	0	35.6	0
31.5–45	12.8	12.4	1.2	2.7	9.3	5.5	13.3	8.2	13.3	31.3	0	31.1
45–63	5.8	25.4	0	1.9	3.0	0	0.9	5.1	3.5	0	0	3.4
> 63	0	9.5	2.5	0.3	1.3	0	0	0	0.1	0	0	2.8
> 100	0	0	0	8.1								
Quality class	F05, P31	F10, P63	No	F25, P31	F10, P31	F20, P31	F10, P31	F15, P45	F10, P31	F10, P45	F15, P31	F20, P45

Table 4.30a. Particle size distributions of delimbed stem wood chips (samples 1–12) (Alakangas 2012, Laitila & Routa 2015).

Sieves, mm	Mass remaining on sieve, w-%											
	1	2	3	4	5	6	7	8	9	10	11	12
< 3.15	11.9	2.1	8.4	2.8	6.3	3.8	5.0	9.13	6.4	6.8	5.8	5.0
3.15–8	26.8	7.3	13.6	3.6	9.9	15.5	14.6	20.2	16.4	22.2	20.1	17.1
8–16	30.1	27.4	46.2	27.8	4.4	14.1	17.4	19.8	10.4	14.8	15.75	7.7
16–31.5	22.7	44.5	18.2	40.8	73.8	62.3	54.9	47.2	62.5	52.5	51.4	62.7
31.5–45	2.5	10.8	18.2	12.8	3.3	2.3	5.1	2.9	1.9	3.7	4.45	5.6
45–63	2.3	6.1	5.1	5.8	1.4	2.0	2.7	0.9	2.4	0	2.5	1.9
> 63	3.7	1.7	8.5	0	0.8	0	0.4	0.0	0	0	0	0
> 100	0	0	17.8									
Quality class	F15, P31	F05, P31	No	P05, P31	F10, P31	F05, P31	F05, P31	F10, P31	F10, P31	F10, P31	F10, P31	F05, P31

No = Not compliant with the quality requirement for chip particle size. The quality requirements are based on Alakangas & Impola 2014, 2015.

Table 4.30b. Particle size distributions of delimbed stem wood chips (samples 13–23) (Alakangas 2012, Laitila & Routa 2015).

Sieves, mm	Mass remaining on sieve, w-%										
	13	14	15	16	17	18	19	20	21	22	23
< 3.15	4.2	5.1	5.4	6.5	4.6	5.4	5.0	5.5	6.2	6.9	9.7
3.15–8	9.3	12.9	11.6	16.9	13.9	17.7	16.5	13.9	11.5	11.7	16.7
8–16	5.7	5.3	6.0	21.9	5.8	5.8	13.1	6.0	29.1	28.4	31.7
16–31.5	69.0	72.6	67.5	48.8	69.8	65.2	55.2	66.6	40.1	42.1	36.4
31.5–45	8.5	3.9	8.5	5.7	5.5	4.5	5.6	8.1	8.7	10.8	5.7
45–63	3.3	0.3	1.1	0.2	0.4	1.3	2.8	0	1.0	0.2	0
> 63	0	0	0	0	0	0	1.8	0	1.0	0.2	0
> 100	0	0	0	0	0	0	0	0	3.4	0	0
Quality class	F05, P31	F10, P31	F10, P31	F10, P31	F05, P31	F10, P31	F05, P31	F10, P31	F10, P31	F10, P31	F10, P31

No = Not compliant with the quality requirement for chip particle size. The quality requirements are based on Alakangas & Impola 2014.

Table 4.31. Angles of slide and friction coefficients for whole-tree chips on different surfaces (at 5–55 mm particle size and 9.2% moisture content) (Rautalin et al. 1986).

Surface	**Angle of slide**		**Friction coefficient**	
	Average	**Deviation**	**Average**	**Deviation**
Steel plate, Fe 37, unpainted	24.4	1.28	0.48	0.02
Painted plate, “Miranol”	23.5	2.17	0.43	0.04
Water-resistant plywood	21.9	1.72	0.40	0.03
Painted plate, “Inerta 51 HB”	23.5	1.13	0.43	0.02
Painted plate, “Inerta 160”	27.0	1.90	0.51	0.03
Glass plate	29.4	3.06	0.56	0.05
Acrylic plate	28.4	1.77	0.54	0.03

4.3 Bark and stumps

Wood bark consists of outer bark and inner bark, or phloem. The layer of cambium between bark and wood grows inwards to produce wood and outwards to produce phloem, through which the tree transfers photosynthesis products from the top to the trunk and the roots. Bark accounts for 10–20% of stem wood, but can account for as much as 60% in small branches. Bark content is calculated from the total volume or total mass of undebarked wood. It can be determined using e.g. callipers, a xylometer, or a gauge punched through the bark. The volume of bark left in the forest has been estimated at approximately 1 million m^3 solid (Hakkila et al. 1995, Leino 1975, Impola et al. 2000).

As bark contains a significant amount of lignin, its calorific value is high and almost constant at different heights of the stem. However, the calorific values of bark in different species of tree vary considerably: In broad-leaf trees, the calorific value of bark is generally considerably higher than in coniferous trees. Aspen is an exception, as the calorific value of aspen bark is actually lower than that of pine bark and of the same magnitude as that of spruce bark. The calorific values of outer bark are considerably higher than the calorific values of inner bark in broad-leaf trees: The calorific values of inner bark are 19–20 MJ/kg on average and those of outer bark are 20–32 MJ/kg. The net calorific value of bark is higher in the bark of the stem than of the branches. The calorific value also varies by species of tree and by the size of the tree. Greater variations are found in smallwood than in stems. The calorific value of the dry matter of pine bark in first thinning stands is 1.2 MWh/solid m^3 (4.3 GJ/solid m^3) fresh and 1.3 MWh/solid m^3 (4.7 GJ/solid m^3) at 40% moisture content due to its low basic density. The growth site also affects the calorific value of bark (Nurmi 1993 and 2000, Hakkila et al. 1995).

In practice, high moisture and ash contents reduce the fuel value of bark considerably. Wood bark is usually used to fuel boilers in forestry plants and heating stations. The majority of bark generated as a by-product of the wood processing industry originates from coniferous trees. What makes bark difficult to process is its non-homogeneity, in addition to which bark mixed into fuel blends can cause problems in fuel handling and feeding equipment.

The fuel properties of bark can be improved e.g. by compressing, drying, or mixing it with other fuels. Bark can be dried by means of heat or mechanically using a bark press. The bark of coniferous trees cannot always be compressed successfully, and its dry matter content often remains at less than 40%. When screening bark, it is worth separating large particles from the oversized flow and small particles from the undersized flow to avoid problems caused by large particles during the compression process. The final dry matter content depends on both the temperature and the particle size of the bark. Drying by means of heat is a less commonly employed technique and requires large plants. Heat drying is based on cheap waste heat or flue gases. The tables in Section 4.1 as well as Tables 4.32–4.35 contain more information about bark properties (Juvonen & Johanson 1986, Öhman 1980, Impola et al. 2000, Alakangas 2013).

The quality of bark fuel can be improved considerably by mixing e.g. cutter shavings in with bark, which improves the value and usability of both fuels. This can even help to prevent the need for drying bark. (Juvonen & Johanson 1986)

Table 4.32. Typical bark analyses, % on a dry basis (Leino 1975).

Bark	Carbon, C	Hydrogen, H	Oxygen, O + Nitrogen, N	Ash content
Pine	54.4	5.9	38.0	1.7
Spruce	50.6	5.9	40.7	2.8
Birch	56.6	5.9	35.0	1.6

Table 4.33. Basic densities of bark in certain species of tree, kg/m^3 (Kärkkäinen 1985).

Species	Basic density	Species	Basic density
Pine, regular bark	300	Bay willow	358
Pine, outer bark	310	Mountain birch	560
Spruce, regular bark	365	Dwarf birch	545
Spruce, outer bark	410	European larch, outer bark	285
Silver birch, roundwood	560	Siberian larch, outer bark	325
Downy birch, roundwood	530	Walnut	280
Downy birch, small-diameter pulpwood	500	Douglas fir	310
Downy birch, branches	505	Poplar	410
Grey alder, small-diameter pulpwood	390	Oak	425
Grey alder, branches	425	Ash	455
Downy birch, year-old sapling	535	Silver fir	460
Willow, year-old sapling	490	Maple	530
Pussy willow	408	Beech	580

Table 4.34. Bark ash melting behaviour, °C (Leino 1975).

Bark	Deformation temperature (DT)	Sphere temperature (ST)	Hemisphere temperature (HT)	Flow temperature (FT)
Pine	1,010	1,240	1,385	1,400
Spruce	1,020	1,250	1,400	1,420
Birch	935	1,180	1,440	1,460

Table 4.35. Ash content of bark in different species of tree on a dry basis and the elementary composition of ash, w-% (Raiko et al. 2002, Alakangas 2000).

Species	Ash	SiO_2	Fe_2O	P_2O_5	CaO	MgO	Na_2O	K_2O	SO_3
Pine	1.8	14.5	3.8	2.7	40.0	5.1	2.1	3.4	3.7
Spruce	3.4	21.7	1.8	2.7	50.5	4.2	2.8	3.5	1.6
Birch	1.6	3.0	1.0	3.0	60.3	5.9	0.7	4.1	4.8
Oak	1.5	11.1	3.3		64.5	1.2	8.9	0.2	

Stumps are sometimes found among peat or in the residues collected from roadworks and building sites and also extracted from regeneration felling sites for use in energy production (Figure 4.13). Stumps are difficult to feed into a chipper, which is why they are usually crushed. Stumps can be crushed in a terminal (45%), at the place of use (40%), or at the roadside (15%). Hog fuel made from stumps usually has a moisture content of approximately 35%, and its ash content can be 3.8–13% if there is soil in the mix. Based on measurements taken by VTT, the net calorific value of hog fuel made from stumps was on average 19.3 MJ/kg on a dry basis, the density of the dry matter was 182 kg/loose m^3, the average moisture content was 34%, and the ash content was 0.2%. Pine stumps have the highest net calorific value (22.36 MJ/kg, Table 4.36), as the organic matter in the stumps contains a high amount of extractives (18–20%). According to Laitila & Nuutinen's 2015 publication, the moisture content of spruce stumps was 17.9–36.7 w-% and that of pine stumps was 20.9–33.7 w-%. The basic density of spruce stumps varied between 409 and 466 kg/m^3 and that of pine stumps between 417 and 446 kg/m^3. The net calorific value on a dry basis was 17.9–19.9 MJ/kg, and ash content was 0.4–2.3 w-%.

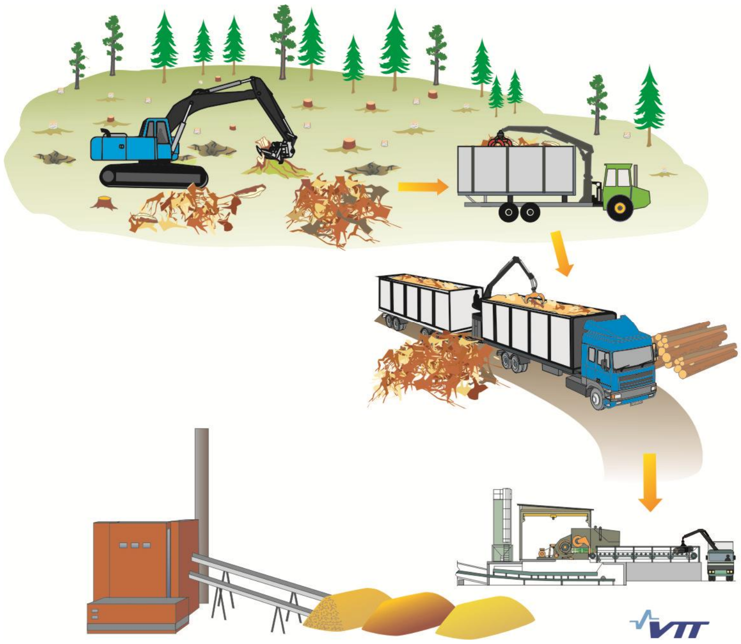


Figure 4.13. Harvesting of stumps for energy production, crushing at the end-use facility. Figure: VTT.

Table 4.36. Net calorific values of different parts of roots and stumps on a dry basis, MJ/kg (Nurmi 1997).

Species	Wood in roots	Root bark	All roots	Stump	Roots and stump
Pine	19.32	20.43	19.51	22.36	21.02
Spruce	19.33	19.55	19.38	19.18	19.32
Downy birch	18.60	19.65	18.84	18.61	
Silver birch	18.50	20.18	18.97	18.50	
Grey alder	18.83	20.38	19.28	19.27	
Common alder	18.93	19.66	19.17	18.91	
Aspen	18.30	19.73	18.78	18.32	

Hog fuel made from stumps typically contains thick pieces: 34.3% of the pieces in hog fuel produced using the largest sieve had a diameter of more than 8 mm (i.e. pieces left on 45 mm and 8 mm sieves), while the figure was 44.1% in hog fuel produced without a sieve (Pulkkinen 1996). Particle size distributions of hog fuel made from stumps are shown in Tables 4.37 and 4.38 (Laine & Sahrman 1985, Pulkkinen 1996, Alakangas 2012).

Table 4.37. Particle size distributions of hog fuel made from stumps (7 samples) (Alakangas 2012).

Sieve, mm	Mass remaining on sieve, w-%						
	1	2	3	4	5	6	7
< 3.15	20.7	9.0	11.0	9.7	20.7	24.4	7.7
3.15–8	11.8	10.5	18.0	25.8	11.8	14.0	27.6
8–16	12.0	15.8	31.0	34.0	12.0	16.1	37.4
16–31.5	21.3	16.7	28.5	23.8	21.3	15.3	0
31.5–45	8.4	11.3	10.9	3.4	8.4	17.1	26.0
45–63	15.2	5.0	0.6	1.4	15.2	7.2	1.3
63–100	1.7	4.6	0	2.0	1.7	0	0
> 100	8.8	27.1	0	0	8.8	5.8	0
Quality class	F25, P63	No	F15, P31	F10, P31	F25, P100	F25, P45	F10, P16

No = Not compliant with the quality requirement for hog fuel particle size. The quality requirements are based on Alakangas & Impola 2014, 2015.

Table 4.38. Average particle size distributions of hog fuel made from bark and stumps (Laine & Sahrman 1985).

Sieves, mm	100	78	45	40	25	20	10	6	4	Bottom
BARK HOG FUEL										
Mass remaining on sieve, %		1.7		13.0		24.5	23.3	2.9	0.8	33.8
Standard deviation, %		2.0		10.6		6.0	4.4	4.6	1.3	19.9
STUMP HOG FUEL										
Mass remaining on sieve, %	1.6	2.8	10.2		20.9		35.1	8.5		20.9
Standard deviation, %	1.9	2.4	1.0		1.4		2.2	1.0		4.8

4.4 Sawdust and cutter shavings

Sawdust used as fuel is obtained as a by-product of timber sawmills. Cutter shavings are residue from mechanical planing. Sawdust is usually wet and airy. However, its moisture content can vary considerably (from air dry to 70%). Sawdust is burnt with other fuels in boilers at forestry plants and heating stations. Cutter shavings are usually too dry and lightweight to burn on their own, which is why they are mixed with other, heavier and wetter fuels. Forestry plants and heating stations use cutter shavings in the same way as sawdust. Sawdust and cutter shavings can also be turned into compressed fuels: pellets and briquettes. Average properties of sawdust and cutter shavings are listed in Tables 4.39–4.41.

Table 4.39. Average properties of sawdust and cutter shavings (Hakkila et al. 1978, Laine & Sahrman 1985).

Property	**Sawdust**	**Cutter shavings**
Typical moisture, %	50–55	5–15
Net calorific value on a dry basis, MJ/kg	18.9–19.2	18.9
Basic density, kg/m^3	380–480	380–480
Density of wet fuel, kg/loose m^3	250–300	80–120
Energy density, MWh/loose m^3	0.4–0.7	0.5
Ash content, w-%, dry basis	0.4–1.1	0.4

Table 4.40. Sawdust particle size distribution (Laine & Sahrman 1985, Vapo Oy 2015).

Sieves, mm	40	15	10	8	4	2	1	0.5	0.25	Bottom
Mass remaining on sieve, w-%	2.0	3.2	5.9	3.7	13.8	19.2	30.3	14.4	4.9	2.6
Sieves, mm				> 4	3.15–4	2–3.15	1–2	0.5–1	< 0.5	
Mass remaining on sieve, w-%*				3.7	3.7	13.5	45.9	26.4	6.7	

* 37.7 w-% moisture content and 222 kg/m^3 bulk density. Q50 = 1.367 and Q90 = 2.926.

Table 4.41. Angle of slide and friction coefficient of sawdust (fraction remaining on a 4.0 mm sieve at 10% moisture content) (Rautalin et al. 1986).

Surface	**Angle of slide**		**Friction coefficient**	
	Average	**Deviation**	**Average**	**Deviation**
Steel plate, Fe 37, unpainted	37.1	0.90	0.77	0.02
Painted plate, “Miranol”	30.25	1.64	0.58	0.03
Water-resistant plywood	33.02	0.68	0.65	0.01
Painted plate, “Inerta 51 HB”	32.71	0.50	0.64	0.01
Painted plate, “Inerta 160”	27.71	1.42	0.53	0.02
Glass plate	32.37	0.79	0.63	0.01
Acrylic plate	28.17	3.33	0.54	0.06

4.5 Firewood

More than 6.7 million solid cubic metres (m^3) of firewood was used in Finland in 2014 (Torvelainen 2009). One solid cubic metre of wood equates to 1.5 cubic metres of stacked billets or chopped and split logs and to just under 2.5 cubic metres of loose chopped and split logs (Pirinen 1987, 1995 & 1997). The most popular species of tree was birch, of which 2.2 million m^3 was used. At least one million cubic metres of other broad-leaf trees, pine, and spruce were also used. The majority of firewood was made from stem wood. Approximately 20% of firewood was bought from firewood suppliers. Figure 4.14 illustrates different firewood production techniques.

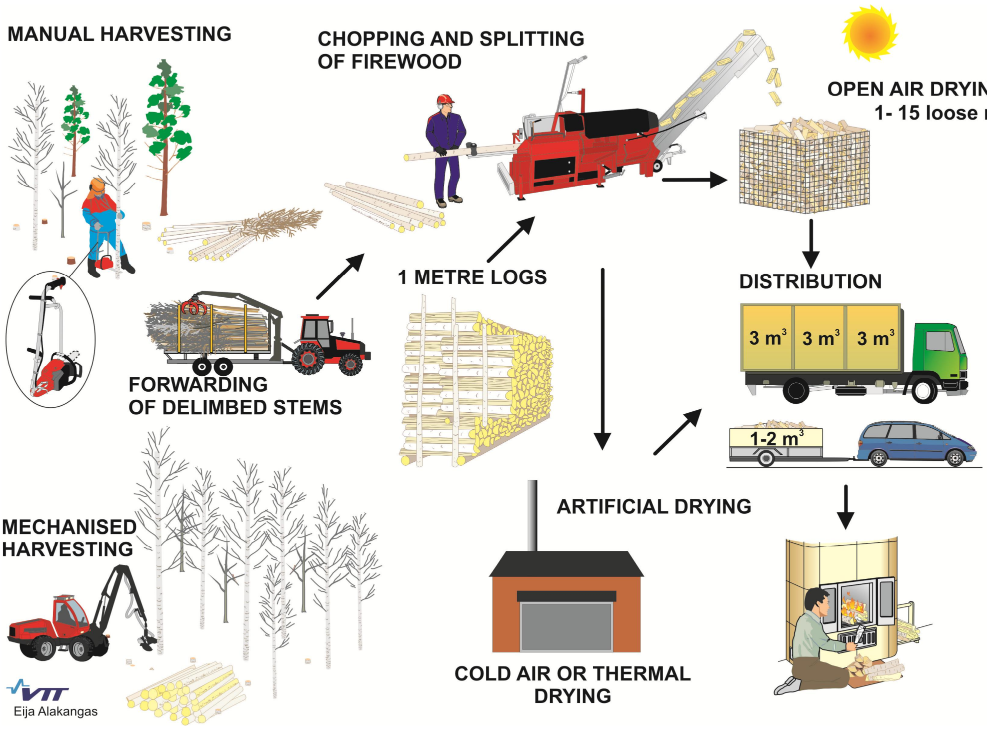


Figure 4.14. Firewood production and distribution chain. Figure: VTT.

Billets are split or round, delimbed blocks of wood measuring approximately one metre in length, which are intended for burning. Billets are made either exclusively from birch or from a mixture of different species of tree. Billets are burnt in top feed and underfeed boilers as well as in fireplaces. (Immonen & Seppälä 1984)

Chopped and split logs are 25–50 cm long. Using chopped and split logs as fuel requires manual work, as they cannot be fed automatically. It is somewhat easier to use them if the fireplace or boiler has a storage bin into which enough fuel for e.g. one day can be placed. Chopped and split logs are primarily a fuel for small-scale heat consumption and recreational use (Virtanen et al. 1984, Immonen & Seppälä 1984).

During the war, the term ‘chopped and split logs’ was used for pieces of wood 50–150 mm long, chopped with an axe or a chipper. They were used in the wood gas generators of cars during the war. In this publication, the term ‘chopped and split logs’ refers to pieces of wood 25–50 cm long.

International quality classes have been laid down for commercially sold firewood. Firewood requires its own quality standard, as trade in ready-to-use wood has increased considerably. Quality classes for firewood are laid down in the EN ISO 17225-5:2014 standard, and they are A1, A2, and B. Sellers must show the quality class of their wood in their product declarations. The requirement applies to both wood burnt in fireplaces and wood burnt in log wood boilers. The most important properties to be determined for firewood are the source of the raw material, the species of tree, dimensions, moisture content, and volume. Chopped and split logs are divided into three quality classes in the EN ISO 17225-5:2014 standard. The quality class of a batch of chopped and split logs depends e.g. on

- length (L),
- diameter (D),
- moisture content (M),
- quality of the cut surface,
- presence of rot and mould, and
- wood species.

The highest quality class for firewood intended for fireplaces is A1, which is made from stem wood. Class A2 and B firewood can also be made from whole trees, logging residue, or industrial wood residues.

The standard stipulates that 85% of the firewood in a batch must comply with the declared diameter class. For class A1 firewood, at least 90% of the number of individual trees must be split, i.e. every tenth tree can be unsplit. The length categories for firewood range from L20 (less than 20 ± 2 cm long) to one metre. The most common quality class is L33 (less than 33 cm long), as firewood is made from one-metre billets in many countries. Chopped and split logs of 25 cm and 33 cm in length are mostly used in fireplaces and ovens, while chopped and split logs that are 50 cm long are suitable for central heating boilers and baking ovens. If firewood is placed horizontally in an oven as recommended, firewood of 25 cm in length is usually suitable for smaller fireplaces. Firewood can include 15% shorter pieces. The cut surface must be smooth in class A1 firewood (Alakangas et al. 2008).

The energy content of a batch of firewood in kilowatt-hours depends mostly on the moisture content of the wood. When the moisture content, weight, and calorific value of firewood on a dry basis are known, its energy content can be calculated using a formula given in an appendix to the standard. Energy density can be determined using a technique developed by VTT (Erkkilä et al. 2012), which involves first determining the initial moisture content of a batch of wood during chopping and weighing the batch in a wire cage, for example, before drying. The initial moisture content of a batch of wood is determined from sawdust samples (see Section 2.2.2). All the firewood must be from the same species of tree and from the same batch of raw material. Moisture content can also be measured from a dried batch of wood using the oven dry method or with a rapid moisture meter (if a degree of imprecision is acceptable). For example, if the desired moisture content of a delivery batch is 19%, the software developed by VTT can be used to calculate how much the batch of wood should weigh at this moisture level and the drying process monitored on that basis. The energy content of a dry batch of fuel is calculated on the basis of its mass and moisture content as delivered, as well as the calorific value of the wood on a dry basis.

The thickness of firewood refers to the largest diameter of chopped and split logs (Figure 4.15). The guideline value for the minimum thickness of chopped and split logs is 4 cm, and the maximum thickness, depending on the quality class, is 10–15 cm. If the diameter of the stem or the logs is more than 10 cm, the wood is split into four pieces and, if the diameter is less than 10 cm, the wood is cleaved in two. Smaller logs of 4–5 cm in thickness can be left unsplit as long as they are stripped on both sides.

The diameter classes (thickness classes) for firewood in quality classes A1 and A2 are D2 (less than 2 cm, kindling), D5 (2–5 cm diameter), and D15 (5–15 cm diameter). Kindling can consist of debarked, mechanically shaved feather sticks of less than 2 cm in diameter. Figure 4.16 shows different types of typical Finnish kindling. (Alakangas et al. 2008).

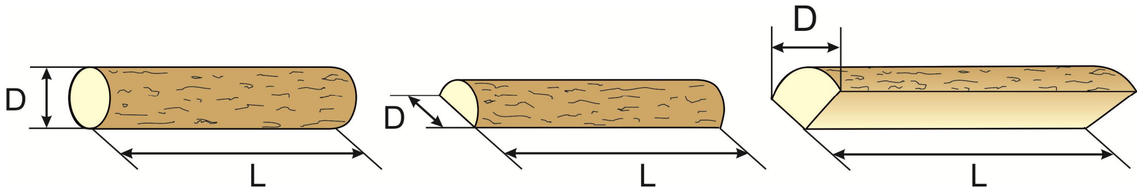


Figure 4.15. Measuring the diameter and length of firewood. Figure: VTT.

Figure 4.16. Kindling. Wood used as kindling has a diameter of approximately 2 cm.
Figure: Eija Alakangas, VTT.

Bulk measuring is a commonly employed method of measuring chopped and split logs. The method involves measuring logs relative to each other in a random order in a box or stack of certain dimensions. A measuring box or pallet of 1–3 m^3, such as a trailer, is usually used. The logs can be loaded into the box either manually or e.g. using a loader attached to a tractor. A traditional way of measuring firewood is to measure it as one-metre billets in a stack. The procedure is based on the same principle as the stacked measurement of pulpwood. (Kouki 1997, Pirinen 1995 and 1996).

A common requirement for all quality classes is sufficiently low moisture content. The moisture classes are M20 (water accounting for no more than 20% of the total weight of the wood) and M25 (no more than 25% water). Firewood suppliers should aim to dry their wood to the M20 class, as moisture content usually increases during storage. This also helps to prevent mould growth and to lower emissions during the combustion stage. The recommended moisture content for firewood is 15–20%. A lower or higher moisture content increases emissions and especially dust emissions. Class A1 firewood must not have visible rot or mould. Class M20 moisture content is achieved by storing logs over one summer. Table 4.42 lists calorific values of chopped and split logs at different moisture content levels.

The drying of chopped and split logs depends on the initial moisture content, the storage location, and weather conditions. The most important climatic factors include relative atmospheric humidity, rainfall, temperature, and wind conditions. During a normal summer, the drying of chopped and split logs made from fresh timber (40–50% moisture content) to the combustion moisture content level takes at least two months outdoors, under a cover. This amount of drying achieves a moisture content of 20–25%. Fresh chopped and split logs shrink by 6–7%. Shrinking only begins at a moisture level of 23–25%, i.e. at the so-called fibre saturation point. Storing wood over the winter e.g. in a woodshed does not lower the moisture content of wood significantly, as the most favourable time for drying wood is the summer season from April to the beginning of September (Figures 4.17–4.20).

Table 4.42. Net calorific values at the operational moisture level and energy densities of chopped and split logs made from different species of tree and mixtures of species (Pirinen 1997).

Species	Net calorific value at operational moisture, kWh/kg	Moisture, %	Energy density	
			kWh/loose m^3	kWh/stacked m^3
Pine	4.15	20	810	1,360
Spruce	4.10	20	790	1,320
Birch	4.15	0	1,040	1,750
		10	1,030	1,730
		20	1,010	1,700
		30	990	1,660
		40	970	1,620
		50	930	1,550
Alder	4.05	20	740	1,230
Aspen	4.00	20	790	1,330
Mixed broad-leaf trees		0	790	1,330
		10	780	1,310
		20	760	1,280
		30	740	1,250
		40	720	1,200
		50	680	1,140
Mixed coniferous trees		0	830	1,380
		10	810	1,360
		20	800	1,340
		30	780	1,310
		40	760	1,270
		50	720	1,200

Mixed broad-leaf trees are assumed to consist of 50% alder and 50% aspen, and mixed coniferous trees are assumed to consist of 50% pine and 50% spruce.

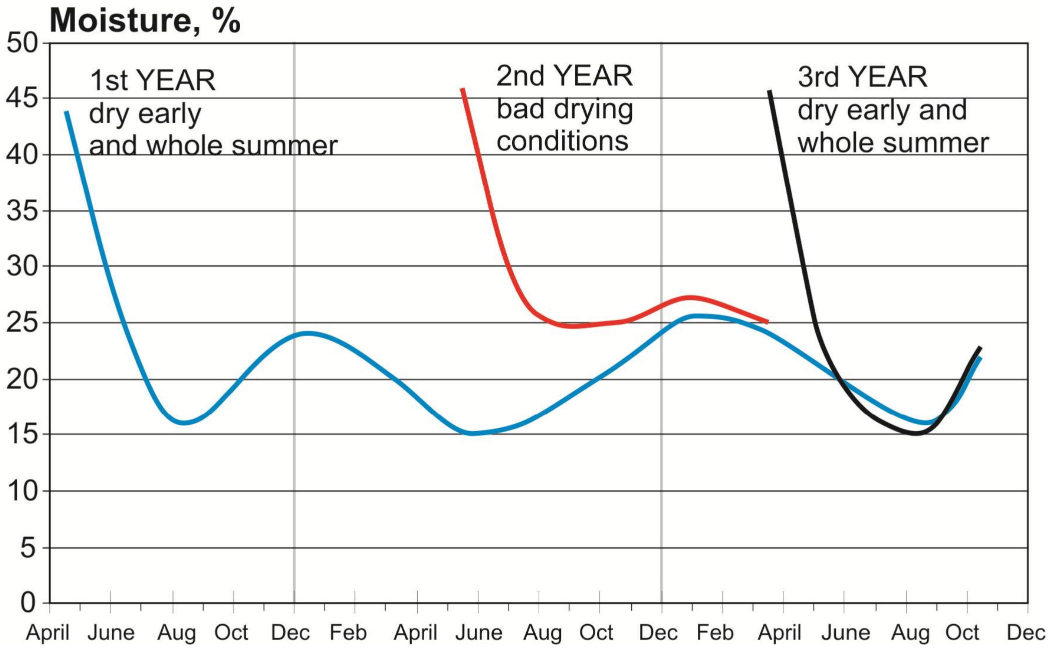


Figure 4.17. Chopped and split logs drying outdoors in a covered wire cage, and seasonal variation in moisture content (Alakangas et al. 2008). Figure: VTT.

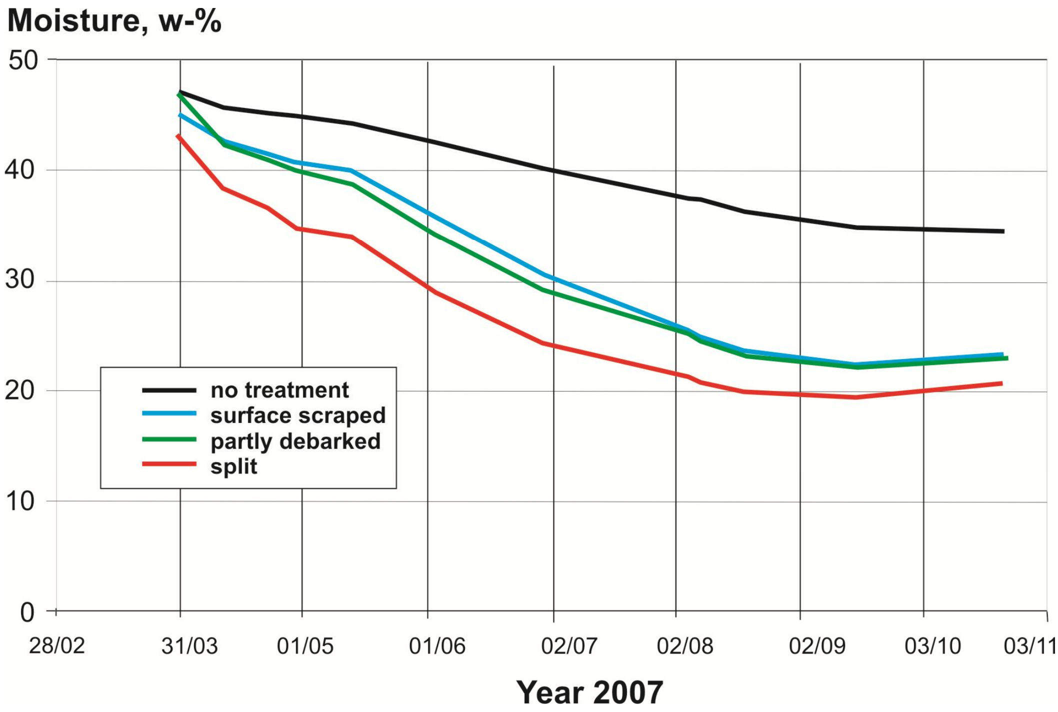


Figure 4.18. Effect of bark breaking on the drying of bundles of birch stems in a covered stockpile in 2007. Source: Erkkilä et al. 2012. Figure: VTT.

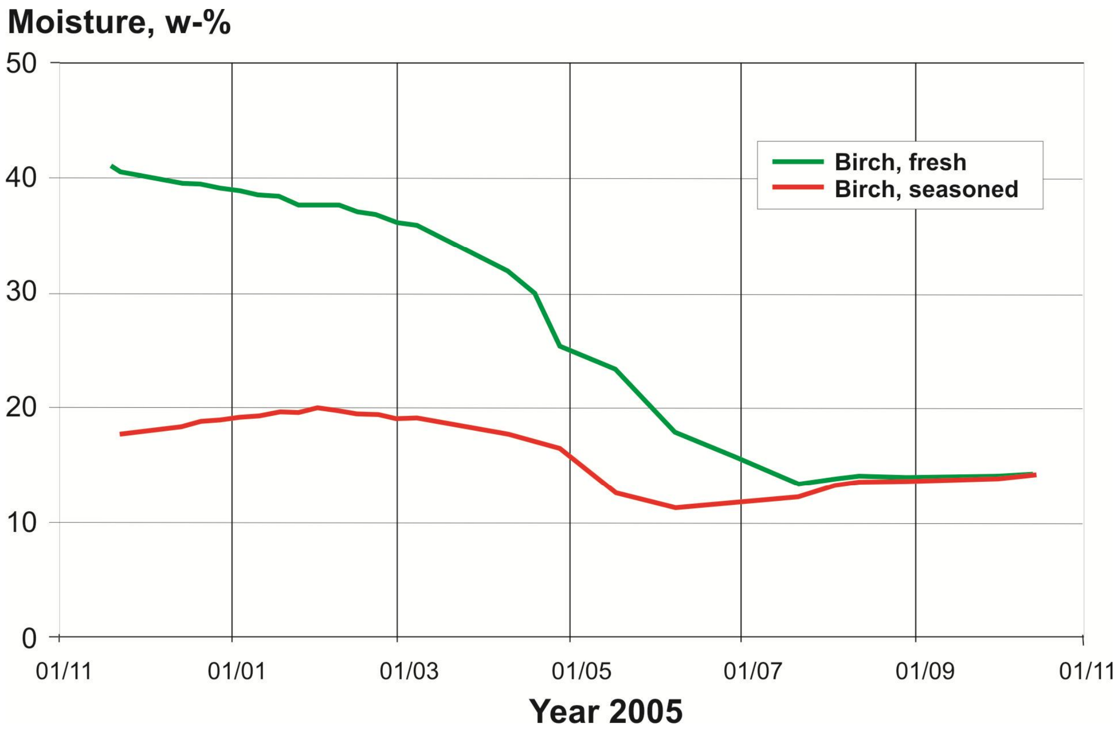


Figure 4.19. Moisture content of fresh and dried chopped and split birch logs outdoors under a cover in 2005. Source: Hillebrand & Kouki 2006. Figure: VTT.

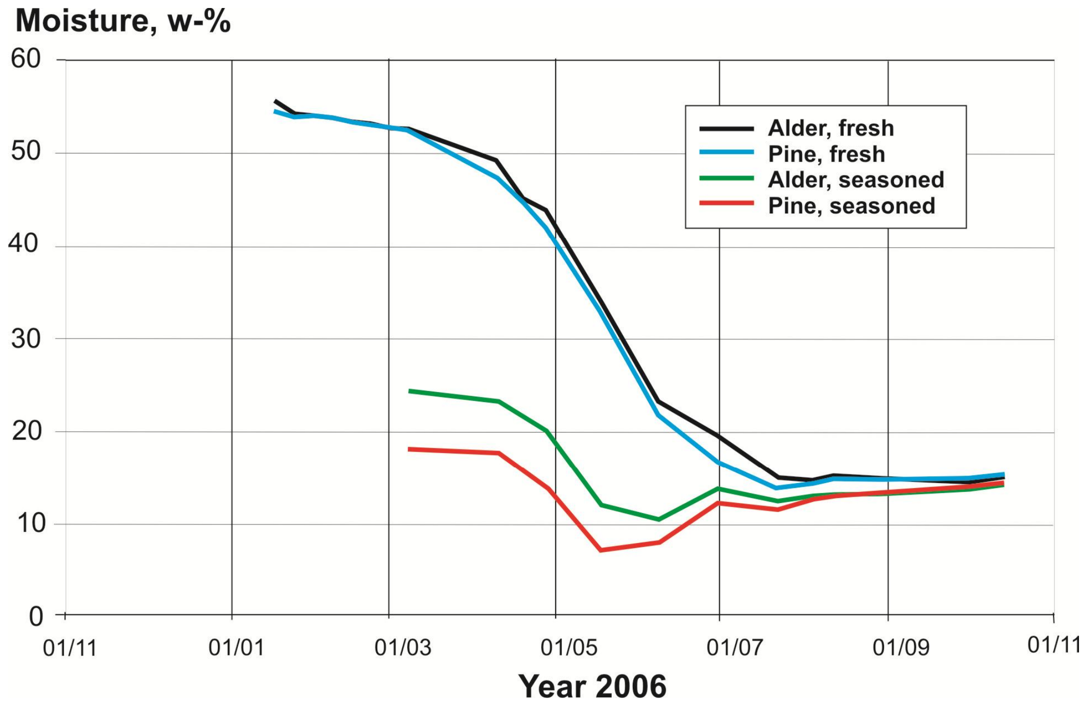


Figure 4.20. Moisture content of fresh and dried chopped and split alder and pine logs outdoors under a cover in 2005. Source: Hillebrand & Kouki 2006. Figure: VTT.

Table 4.43 shows conversion factors measured by the TTS Work Efficiency Institute for converting one solid cubic metre into 2.5 bulk cubic metres. E.g. one loose cubic metre of chopped and split logs contains 0.40 solid cubic metres, i.e. 400 litres, of wood.

Table 4.43. Conversion factors for units of measurement for chopped and split logs (Pirinen 1995 and 1996).

Unit of measurement	Loose m^3	Stacked m^3	Solid m^3
Loose cubic metre, chopped and split logs (33 cm)	1	0.60	0.40
Stacked cubic metre, chopped and split logs (33 cm)	1.68	1	0.67
Stacked cubic metre, billets (100 cm)	1.55	1	0.62
Solid cubic metre	2.50	1.50	1

In VTT's studies, the average net calorific value of billets and chopped and split logs on a dry basis was 18.73 MJ/kg (standard deviation 0.67 MJ/kg), volatile matter accounted for 78.3% (standard deviation 3.9%), and ash content was 1.2% (standard deviation 0.8%) (Alakangas 2000).

VTT studied the drying of chopped and split logs (Erkkilä et al. 2012, Tables 4.44 and 4.45). The logs were chopped fresh. The bulk density at delivery moisture content does not factor in shrinkage or compacting resulting from the moving of pallets. The range is 2.15–2.48 bulk cubic metres per one solid cubic metre (Erkkilä et al. 2006).

Table 4.44. Measurements relating to chopped and split log production in 2010 (Erkkilä et al. 2012).

Property	Pallet 8	Pallet 9	Pallet 10	Pallet 11	Average	Standard deviation
Solid volume, dm^3	661	697	643	604	651	38
Number of stems	24	21	19	25	22	2.8
Average diameter, cm	10.6	11.6	11.6	9.9	10.9	0.8
Average size, dm^3	28	33	34	24	30	4.6
Bulk volume, dm^3	1,500	1,500	1,500	1,500	1,500	0
Loose m^3 / solid m^3	2.27	2.15	2.33	2.48	2.31	0.14
Wood mass, kg	567	542	518	506	533	27
Moisture, w-%	43.1	43.1	40.9	40.9	42.0	1.3
Gross density, kg/m^3	858	778	806	837	820	35
Basic density, kg/m^3, dry basis	488	443	476	495	475	23
Bulk density, kg/m^3	378	361	345	337	356	18

Table 4.45. Drying data on chopped and split birch logs left to dry naturally in net sacks in 2011 (1.5 loose m^3 net sacks on pallets). Initial moisture contents were measured from sawdust samples.

Sack No	Chopping and splitting date	Sampling date	Initial moisture content of sacks, w-%	Moisture content of chopped and split logs, w-%		Number of sample logs
				Average	Deviation	
Drying under a cover since production						
37	20 March	12 August	44.5	14.6	0.6	15
62	20 March	12 August	44.5	13.6	0.5	15
Drying outdoors, brought in in June						
138	4 March	8 September	45.2	18.1	1.3	14
144	5 April	8 September	43.7	17.3	2.3	15
143	5 April	20 September	43.7	16.4	1.0	15
158	5 April	20 September	42.9	14.9	0.4	16
201	8 April	8 September	43.4	16.9	1.0	15
Drying outdoors, stored outdoors under a tarpaulin						
628	30 June	20 September	30.1	17.0	1.1	16
629	30 June	8 September	30.1	20.3	1.1	15

The cut surface of class A1 chopped and split logs must be even and smooth. In practice, this requires the use of a circular saw or a chainsaw. Machines that operate on a guillotine principle always leave the ends of logs uneven, which is why logs chopped and split in this way are categorised as either class A2 or class B.

No plastic, soot, metals, pesticides, or other harmful substances are permitted among chopped and split logs. Nor are snow and ice permitted. First-class chopped and split logs must contain no mould. The logs must have the colour of healthy wood. Cut surfaces must not be blackened or have other colour defects that lower usability. Using the colour of wood as a quality criterion mostly relates to chopped and split logs burnt in clean indoor environments for atmospheric reasons. Any rot in chopped and split logs lowers the calorific value of wood and damages its appearance. The volume of combustible matter and therefore the energy content are lower in decayed wood than in healthy wood.

Chopped and split logs are categorised according to the principle species of tree in each batch. No other species of tree are allowed among chopped and split birch logs. No softwood is allowed among chopped and split logs made from broad-leaf trees. There are no restrictions on hardwood among chopped and split logs made from coniferous trees.

4.6 Wood briquettes

Wood briquettes are made from dry sawdust, grinding dust, or cutter shavings by means of compression. Binding agents are normally not used, as the natural components of wood (lignin) keep the briquettes in one piece. Wood briquettes are usually round or cubical. Briquettes are larger than pellets, and the smallest dimension is usually 50–75 mm. Briquettes are made by compressing them into a cylindrical or brick-like shape. The energy content of briquettes per unit of mass is similar to that of wood pellets. Briquettes are also supplied in bulk and in packages. In Finland, briquettes have mostly been used in heat plant grate boilers. Briquettes are also used in fireplaces. When using briquettes, attention must be paid to the fact that the energy content of briquettes is more than double that of birch firewood per unit of volume (Kallio & Alakangas 2002).

Round briquettes may have a hole of 10–20 mm in diameter in the middle. Almost all dry, combustible substances with a moisture content of less than 15 w-% can be turned into briquettes. The moisture content of the wood matter is less than 10% during pressing. The dry matter mass of wood briquettes is more than 1,000 kg/m^3, and their bulk density is 650 kg/ m^3. Compared to other fuels, briquettes are heavy and dry. Analysis results for briquettes are listed in Table 4.46.

Table 4.46. Properties of cylindrical wood briquettes made from sawdust (Laine & Sahrman 1985, Bioklapi Oy).

Properties	**VTT**	**ENAS (Bioklapi Oy)**
Calorific value, MJ/kg		
* Net, dry basis	18.93 (0.19)	19.42
* Gross		20.79
* Net, as received		17.36
Moisture content during production, %	5.4 (0.4)	9.4
Volatile matter (dry basis), %	83.6 (0.7)	
Ash content (dry basis), %	0.3	0.6
Bulk density, kg/m^3		1,111
Dry basis, w-%		
Carbon, C		52.1
Hydrogen, H		6.3
Nitrogen, N		< 0.2
Sulphur, S		0.09
Chlorine, Cl		0.002
Dry basis, mg/kg		
Chromium, Cr		< 0.5
Copper, Cu		2.3
Nickel, Ni		< 0.5
Zinc, Zn		10
Arsenic, As		< 0.5
Cadmium, Cd		0.12
Lead, Pb		< 0.5
Mercury, Hg		< 0.05

The figures in brackets denote deviations in the analysis results.

Some factories in the mechanical forest industry have small-scale briquette presses that can be used to make disc-shaped briquettes. The net calorific value of briquettes as received is approximately 4.8 kWh/kg (17.3 MJ/kg), their moisture content approximately 6 w-%, and their ash content less than 0.7 w-%. Disc-shaped briquettes are not as durable as cylindrical briquettes. Other properties depend on the properties of the raw material (usually debarked softwood). Wood briquettes are governed by the international standard EN ISO 17225-3:2014. The standard lays down three quality classes for briquettes: A1, A2, and B. The quality classes determine the shape, dimensions, moisture content, ash content, and elementary compositions of briquettes. The elementary analhysis of briquettes is similar to that of wood pellets. Briquettes made from energy crops are governed by the EN ISO 17225-7:2014 standard, which lays down two quality classes: A and B.

4.7 Wood pellets

Wood pellets and briquettes are a form of compressed, cylindrical wood fuel usually made from by-products of the mechanical forest industry. In most cases, the raw material consists of dry sawdust, grinding dust, and cutter shavings, although pellets and briquettes can also be made from fresh biomass, bark, and forest chips, in which case the raw material needs to be not just crushed but also dried before pressing.

When turning wood into pellets, the ideal moisture content from the perspective of power demand, strength, and equipment capacity is 10–15%. Softwood is a slightly better raw material for wood pellets than hardwood due to its higher lignin content. Lignin is a natural binding agent in wood fibres, which also helps to bind pellets.

Pellets made from a raw material that contains bark have a higher calorific value. The amount of raw material needed to make one tonne of pellets (Kytö & Äijälä 1981) is

- approximately 7 loose m^3 of sawdust (at 50–55% moisture content) or
- approximately 10 loose m^3 of cutter shavings (at 10–15% moisture content).

No drying is necessary if the raw material is cutter shavings or dry sawdust. However, if wet sawdust is used, it must be dried before grinding using e.g. a drum dryer.

The grinding stage sees the raw material being ground down to at least the grain size equivalent of the pellet diameter. However, the ground wood dust must not be too fine to eliminate the larger fibres that help to bind pellets together. Grinding is most commonly carried out using a hammer mill to achieve a homogeneous raw material for the press (Alakangas & Paju 2002).

Grinding and raw material drying can be combined if drying is required. In a grinding dryer, the crusher changes the grain size of the dust. Grinding facilitates the drying process considerably: The particle size becomes homogeneous and the moisture content of all particles becomes relatively uniform. With moisture distributed evenly across all particles, the pellets produced are stronger and hold their shape better. Drying is most commonly carried out using a hot gas generator, with a burner that burns any dust left over from the production process. The gas formed mostly consists of carbon dioxide, water, and nitrogen.

Pellets are pressed using flat or vertical mounted ring dies. No additives are normally used when pressing wood pellets, and instead the pellets are held together by the cohesion of their inner surfaces, the fibrous parts of the particles, and above all the adhesion resulting from the softening of lignin in response to the heat generated by compression. In a pellet press, the temperature of the wood matter increases, and the natural binding agent, lignin, melts and keeps the pellet in shape as it cools. In other words, pellets only achieve their strength once they have cooled down. The die is always chosen on a case-by-case basis depending on the properties of the raw material (hardness, moisture content, composition). The success of pelletisation is indicated by the amount of fines left among the pellets after pressing.

Cooling is an extremely important stage in the process. After pressing, the temperature of the pellets is high, normally approximately 90 ºC. The moisture released during pressing leaves the product with heat. Cooling stabilises the pellets and hardens the molten lignin on the surface of the pellets, helping them to keep their shape.

Screening is carried out to separate the formed pellets from the raw material dust mixed in with them, which is returned into the pelletising process. This is usually done using a vibrating screen. The process helps to produce a homogeneous product, which does not cause problems in transport and combustion equipment. Finally, the pellets are sent to a warehouse or placed in sacks or bags to await transport to users (Alakangas & Paju 2002). Figure 4.21 illustrates the pellet production and distribution chain.

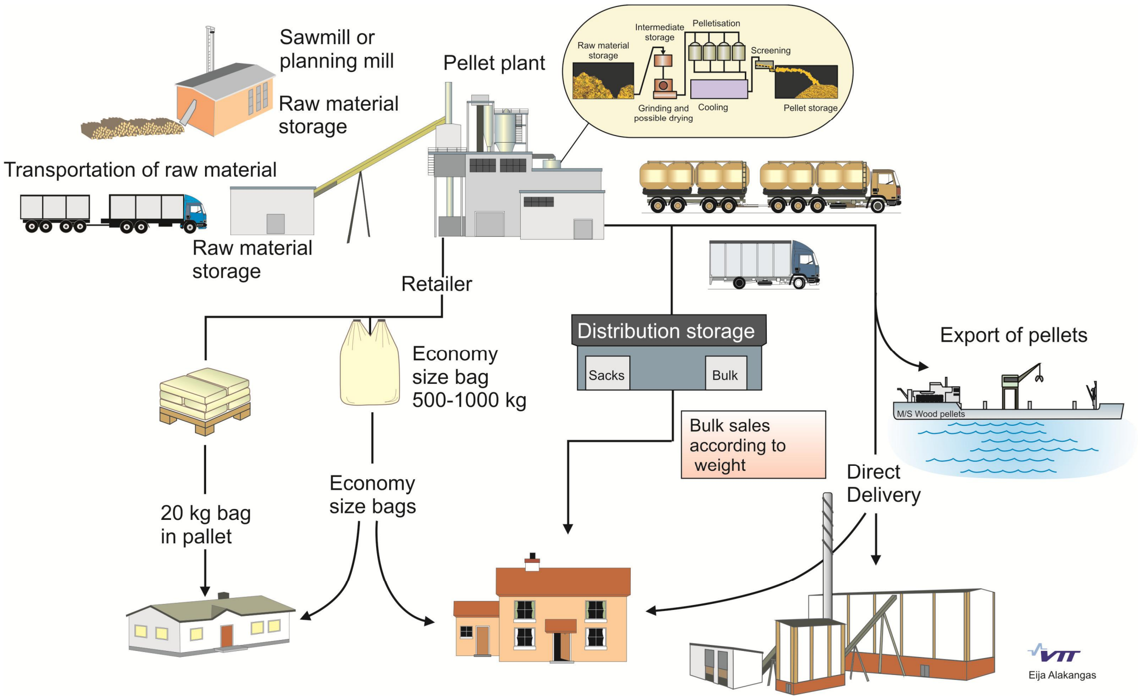


Figure 4.21. Pellet production and distribution chain. Figure: VTT.

The diameter of pellets produced in Finland is usually 8 mm and their length 10–30 mm. The moisture content of pellets is low: 6–10%. Their ash content is also low at approximately 0.5%. One bulk cubic metre of pellets weighs 640–690 kg. Their particle density is 1,100–1,500 kg/m^3. The calorific value as received of one kilogram of pellets is 14.0–17.5 MJ (4.7–5.0 kWh). One cubic metre of pellets therefore has an energy content of 3,000–3,300 kWh. One tonne of pellets contains 4,700–5,000 kWh of energy and takes up approximately 1.5 m^3 of storage space. When coming into contact with water, wood pellets get wet, swell, and break down. Their ability to withstand actual moisture is low. Average properties of pellets and comparisons of the same are shown in Table 4.47.

Wood pellets can be used to heat homes, farms, and large properties. Special equipment is required for burning wood pellets. Large heat and power plants crush pellets before feeding them e.g. into pulverised combustion boilers. In Finland, the maximum wood pellet production capacity is approximately 630,000 tonnes and the annual production volume approximately 300,000 tonnes.

Wood pellets are governed by an international standard (EN ISO 17225-2:2014), which lays down quality requirements for pellets (Alakangas & Valtanen 2015). The wood pellets standard covers both smaller-sized pellets (quality classes A1, A2, and B) and pellets for industrial use (quality classes I1, I2, and I3). The most important quality properties of pellets are moisture content, mechanical durability, and a low volume of fines. Class A1 pellets must have a moisture content of ≤ 10 w-%, mechanical durability of 97.5 w-% and no more than 1 w-% of fines (< 3.15 mm).

Table 4.47. Average properties of Finnish pellets (Tuomi 2001).

Property	Product 1	Product 2	Product 3	Product 4	Product 5
Moisture, w-%	5.2	6.6	9.1	8.5	9.7
DRY BASIS, w-%					
Ash	0.28	0.30	0.25	0.24	0.37
Carbon, C	49.80	49.70	49.72	49.39	49.12
Hydrogen, H	6.12	6.11	6.13	6.10	6.03
Nitrogen, N	0.16	0.16	0.05	0.07	0.08
Sulphur, S	0.005	0.006	0.004	0.005	0.007
DRY BASIS, mg/kg					
Cadmium, Cd	0.06	0.08	0.07	0.11	0.06
Chromium, Cr	0.48	1.59	0.36	0.48	0.31
Zinc, Zn	7.83	0.04	7.55	7.56	8.00
Copper, Cu	1.14	2.76	1.02	1.22	1.10
Nickel, Ni	0.26	0.26	0.24	0.21	0.30
Iron, Fe	9.28	8.19	8.79	7.59	29.79
Chlorine, Cl	6.88	5.82	6.85	5.73	7.38
Sodium, Na	61.52	30.32	15.23	7.78	53.35
Manganese, Mn	64.42	65.74	62.02	85.43	67.21
DRY BASIS, mg/g					
Calcium, Ca	0.57	0.59	0.54	0.62	0.64
Potassium, K	0.31	0.35	0.35	0.26	0.46
Magnesium, Mg	0.11	0.12	0.13	0.09	0.12
Phosphorus, P	0.02	0.03	0.03	0.02	0.03
Diameter, mm	8	8	8	8	8
Average length, mm	16	14	19	7	14
Minimum	10	7	8	4	6
Maximum	22	25	37	10	25
Number of pellets per 100 g	110	120	110	300	140
Pellet hardness test (Amandus Kahl), kp/kg	21	20	21	17	19
Minimum	20	18	20	9	17
Maximum	21	21	21	21	21
Mechanical durability, fines (ASTM E 1288–89, < 2.36 mm), %	1.8	1.1	1.3	1.9	2.6
Bulk density, kg/loose m^3					
As received	690	680	630	600	560
Dry basis	655	635	575	550	505
Net calorific value, MJ/kg					
Dry basis	19.0	18.9	19.0	18.8	18.7
As received	17.9	17.5	17.0	17.0	16.7
Net calorific value, MWh/t					
Dry basis	5.28	5.26	5.28	5.23	5.20
As received	4.98	4.87	4.74	4.73	4.63
Energy density, MWh/loose m^3	3.43	3.31	2.98	2.84	2.59

4.8 Charcoal and thermally treated densified biomass fuels

4.8.1 Charcoal

There are currently a few dozen charcoal producers in Finland. Charcoal is often produced on a small scale in metal or brick-built kilns.

In most cases, the term ‘charcoal’ refers to barbecue charcoal used by households. However, the industrial use of charcoal is relatively common worldwide, especially in the steel industry and silicon manufacturing. Fine charcoal can also be used to produce cement and more generally as a source of energy in its dust or sludge form. In the 1930s and 1940s, charcoal was used in wood gas generators. Wood and other organic materials are more common and cleaner alternatives for producing activated carbon.

Charcoal can be made from all species of tree and parts of plants. The properties of the final charcoal depend both on the properties of the raw material and on the production process. If necessary, charcoal can be turned into briquettes with the help of a binding agent. In most cases the requirement is that the charcoal does not break down very easily and that it is easy to light and burns for as long as possible. Hardwood is generally considered a cleaner raw material of charcoal (Ranta 1994).

Tables 4.48 and 4.49 list properties of charcoal. As carbonisation progresses, the carbon content of charcoal increases and the percentage of volatile matter decreases. Charcoal with a carbonisation temperature of 475 ºC is ideal for use in barbecues, as it has a low ash content and a fixed carbon content of more than the 75% required under the EN ISO 17225-1:2014 standard.

Table 4.48. Charcoal properties (Fagernäs et al. 2014).

Property	**Raw material, birch**	**Charcoal carbonisation temperature**		
		Low 300 ºC	**Medium 375 °C**	**High 475 °C**
Particle surface area, m^2/g		2.2	6.4	43.5
Moisture, w-%	10–12	0.2	0.5	0.0
Gross calorific value, MJ/kg, dry basis	20.1	27.2	30.1	33.1
Net calorific value, MJ/kg				
Dry basis	18.8	26.1	29.3	32.4
As received	17.3	26.0	29.1	32.4
DRY BASIS, w-%				
Volatile matter	84.6	48.0	30.0	17.2
Fixed carbon	15.0	51.5	69.3	81.8
Carbon, C	49.9	71.6	80.3	88.5
Hydrogen, H	5.9	4.9	3.9	3.1
Nitrogen, N	0.1	0.2	0.3	0.3
Sulphur, S	0.01	0.01	0.01	0.01
Oxygen, O (difference)	44.0	23.0	15.0	7.0
Ash	0.4	0.5	0.7	1.0

Table 4.49. Charcoal properties (Fagernäs et al. 2012).

Property	Raw material	Charcoal	Raw material	Charcoal	Raw material	Charcoal	Raw material	Charcoal
	A1 Undebarked hardwood		A2 Debarked hardwood		B Undebarked hardwood		C Undebarked hardwood	
Raw material length, cm	5–10		15					
Moisture, w-%	14.7	1.3	13.8	4.9	14.5	2.8	7.6	0.9
Gross calorific value, MJ/kg, dry basis		33.2		33.4		33.8		33.4
Net calorific value, MJ/kg								
Dry basis		32.5		32.6		33.1		32.3
As received		32.0		30.9		32.1		32.0
DRY BASIS, w-%								
Volatile matter	84.5	19.6	83.0	19.9	84.5	18.4	72.2	17.1
Fixed carbon	14.9	79.6	15.9	78.7	14.9	80.6	27.5	81.9
Carbon, C	40.7	87.1	50.0	86.4	49.8	87.2	50.3	88.0
Hydrogen, H	6.1	3.3	5.9	3.3	6.0	3.3	6.0	2.9
Nitrogen, N	0.1	0.3	0.1	0.1	0.1	0.2	0.1	0.2
Sulphur, S	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.01
Oxygen, O (difference)	44.1	9.0	42.9	9.0	43.5	8.0	43.3	8.0
Ash	0.6	0.8	1.1	1.4	0.6	1.2	0.3	0.9

The density of charcoal depends on the density of the raw material and the particle size. Beech charcoal has a density of 190–200 kg/m^3, birch charcoal of 160–170 kg/m^3, pine charcoal of 130–140 kg/m^3, and spruce charcoal of 110–120 kg/m^3.

Charcoal usually has a moisture content of less than 5%, and volatile matter accounts for less than 20%. Households tend to prefer a high percentage of volatile matter, as it makes charcoal easier to light, while nevertheless simultaneously producing a higher amount of harmful gases. Charcoal has an ash content of 0.5–1.4%, but it is not uncommon for impurities (e.g. soil) to raise the ash content to as high as 10% and beyond (Ranta 1994).

The EN ISO 17225-1:2014 standard lays down two moisture classes for charcoal: M8 and M10. The ash content classes are A5, A8, and A8+ (more than 8 w-% of ash on a dry basis). The fixed carbon classes are C60 and C75. The bulk density classes are BD130 and BD150. The particle size is P150, with 75 w-% of particles measuring 16–150 mm, and the coarse fraction is defined as follows: no more than 10% of particles above 100 mm and all particles below 150 mm. Fines of less than 10 mm must not account for more than 7 w-%.

4.8.2 Thermally treated densified solid biofuels

There are several techniques for producing thermally treated densified fuels, i.e. pellets and briquettes. Finland has focused on the development of torrefaction, steam explosion, and hydrothermal carbonisation. Hydrothermal carbonisation of peat was studied especially in the 1970s and 1980s.

The torrefaction process uses dried biomass, such as wood chips, forest chips, or agricultural residues, as the raw material. Torrefaction involves treating biomass in a reactor in the absence of oxygen under atmospheric pressure, at a temperature of approximately 250–280 ºC. After the torrefaction stage, the biomass is usually turned into pellets, resulting in a brown, compact pellet that resembles a bark pellet. Torrefied biomass typically contains 60–70% of the original mass of the raw material and 90% of the original net calorific value. The gases and steam produced by torrefaction are usually burnt and the heat generated used to dry biomass and as a source of heat for the torrefaction process (Figure 4.22).

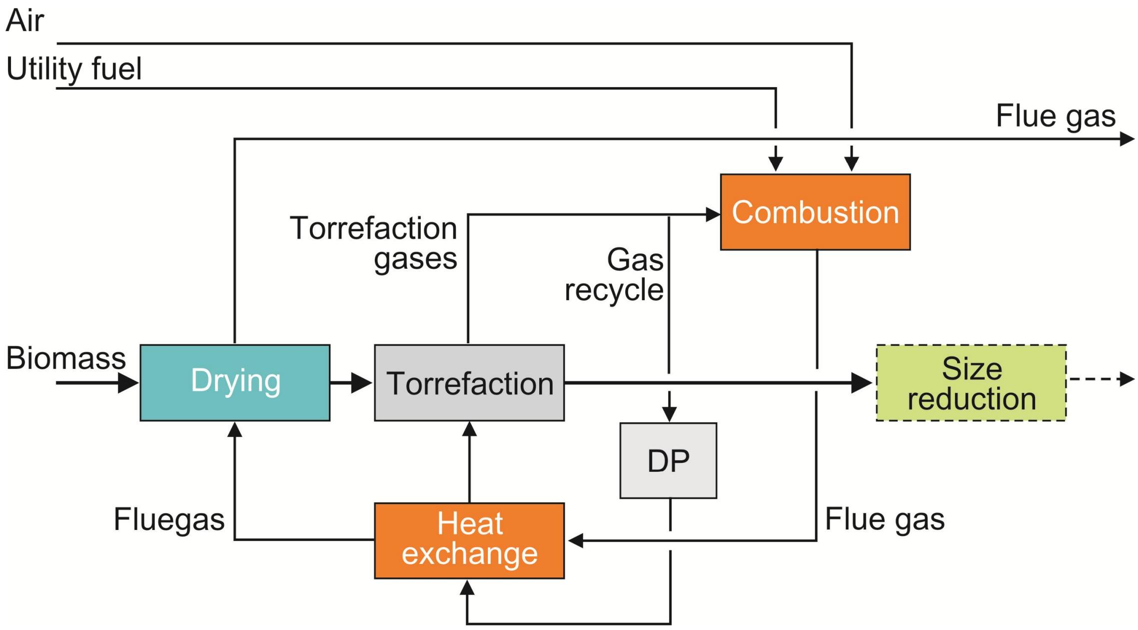


Figure 4.22. Wood torrefaction process. Figure: VTT.

Hydrothermal carbonisation is a thermochemical process typically used to treat wet biomasses, such as common sludge, manure sludge, digestion waste from biogas plants, black liquor, peat sludge, algae, food waste, brewery sludge, or sludges from the timber and paper industries. Hydrothermal carbonisation takes place in water at a temperature range of 180–250 ºC and at an autogenic pressure of 2–5 MPa, and the reaction time is typically a few hours. The reaction pH is approximately 7, and the reactions generate heat. An organic catalyst, such as citric acid, can be used in hydrothermal carbonisation. The main product is fixed carbon with a mass yield of 35–70 w-% on a dry basis. The calorific value of the carbon produced is typically 25–30 MJ/kg. The product can be used to produce energy, in different kinds of biochar applications, as a soil conditioner, or as a fertiliser. Organic products are also dissolved during the water phase of hydrothermal carbonisation. The volume of reaction gases is typically low, with carbon dioxide being the most abundant. Hydrothermal carbonisation occurs at relatively high temperatures, which helps to destroy bacteria contained in biosludges, pathogens, and harmful organic impurities, such as pharmaceutically and hormonally active substances. In Germany, hydrothermal carbonisation processes are being introduced to industrial users as one technique for processing biosludges.

Suitable raw materials for steam explosion include not just wood and forest chips but also agricultural residues, such as wheat straw. The steam explosion technique involves feeding wood biomass into a pressurised reactor and heating it up to a saturation point using steam (Figure 4.23). The reactor pressure is 0.7–5 MPa and the temperature 160–250 ºC depending on the application. The reaction time varies from a few seconds to dozens of minutes. Steam explosion can be used for wood pulping or as a pretreatment stage in the production of bioethanol. Steam explosion is usually carried out on a batch basis. A new and contemporary application is the production of steam-exploded pellets. This is a competitive alternative for pellets produced by means of torrefaction. Wood biomass can be dried before steam explosion to a moisture content of approximately 8 w-%, in which case no drying is required after the steam explosion process. The dried raw material can be ground using a hammer mill, for example, before feeding it into the steam explosion reactor. The reactor pressure is 1.5–2.5 MPa (temperature under 210 ºC), and the reaction time for wood mass is typically less than 20 minutes. The hot and softened biomass is extracted from the reactor through a valve, which causes the water in the mass to boil as a result of the drop in pressure. This forces the biomass to break down mechanically. The biomass is then turned into brown or black pellets. The energy yield of steam-exploded pellets is typically more than 90% based on the net calorific value, and their energy density is of the same magnitude as that of torrefied pellets.

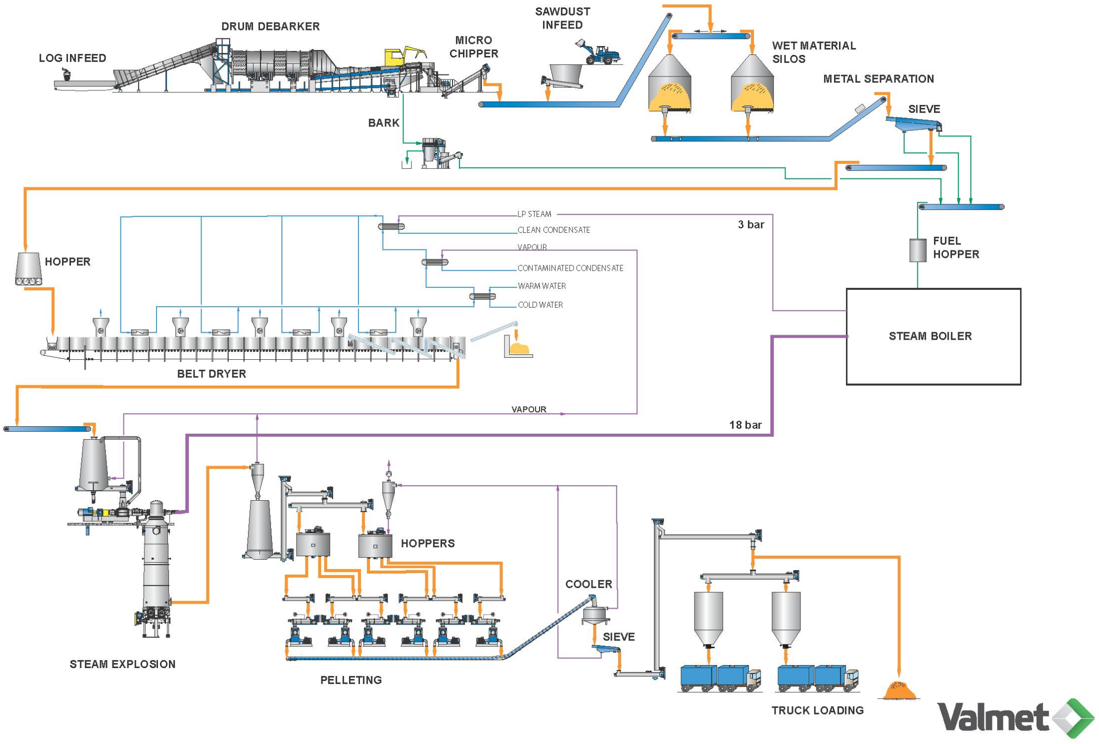


Figure 4.23. Steam explosion process. Figure: Valmet

Table 4.50 lists properties of pellets torrefied in the Netherlands using Finnish raw material.

The raw materials were as follows:

- Delimbed trees from thinning sites (primarily pine, including some bark)
- Logging residue composed of different species of tree, with a particle size of 8–32 mm
- Stem wood chips, pine
- Crushed spruce bark
- Willow chips

The raw material was predried to a moisture content of 20 w-%, placed in 20-kg sacks, and shipped to ECN for torrefaction. The torrefaction temperature was optimised for these materials with the help of TGA analyses, and it was 250–260 °C. The experiments produced a mass yield of 81–88 w-% and an energy yield of 88–91 w-%. Tables 4.51 and 4.52 list more properties of torrefied pellets produced from different raw materials, and Table 4.53 lists explosion properties of different kinds of dust.

Table 4.50. Properties of torrefied pellets and their raw materials (Wilén et al. 2013).

Raw material / fuel	Moisture, w-%	Property on a dry basis, w-%							Calorific value, MJ/kg, dry basis	
		Ash	Volatile matter	Fixed carbon	C	H	N	O	Gross	Net
DELIMBED TREES FROM THINNING SITES										
Raw material	0.5	0.5	83.2	15.8	49.5	6.2	0.17	43.6	19.97	18.62
Torrefied 235 ºC	< 0.1	0.5	80.4	19.1	51.5	6.1	0.19	41.8	20.99	19.66
Torrefied at 245 ºC	< 0.1	0.7	77.9	21.4	52.2	6.0	0.23	45.9*	21.01	19.70
Torrefied at 255 ºC	< 0.1	0.7	74.4	23.9	53.6	5.9	0.30	39.5	21.59	20.59
LOGGING RESIDUE										
Raw material	0.3	1.3	80.5	17.9	49.8	6.2	0.3	42.9	20.21	18.86
Torrefied at 245 °C	< 0.1	1.2	77.1	21.7	52.2	6.0	0.31	40.4	20.96	19.65
Torrefied at 255 ºC	< 0.1	0.8	76.3	22.9	53.2	6.0	0.22	44.3*	21.35	20.05
CRUSHED SPRUCE BARK										
Raw material	3.6		69.4	27.0	51.9	5.7	0.45	41.0	20.46	19.22
Torrefied at 255 ºC	4.2		62.4	33.4	56.7	5.2	0.52	38.7	21.99	20.86
STEM WOOD CHIPS, PINE										
Raw material	0.3		83.2	16.6	50.9	6.6	0.09	43.6	20.34	20.34
Torrefied at 255 ºC	0.3		78.8	20.9	53.3	6.4	0.09	41.4	21.21	19.82
WILLOW CHIPS										
Raw material	1.8		79.8	16.0	49.0	5.8	0.53	43.1	19.86	18.59
Torrefied at 255 ºC	2.0		73.5	24.5	53.1	5.7	0.59	38.8	21.37	20.13

* outlier in analysis

Table 4.51. Properties of torrefied pellets (Wilén et al. 2013).

Sample	Moisture, w-%	Gross calorific value, MJ/kg	Bulk density, kg/m^3	Energy density, GJ/m^3, dry	Mechanical durability, w-%	Hardness (Amandus Kahl), kp/kg
Torrefied pellets made from stem wood chips, 235 °C	1.4	19.20	556.6	10.69	80.0	18.5
Torrefied pellets made from stem wood chips, 245 °C	2.1	20.02	633.1	12.67	92.0	20.8
Torrefied pellets made from stem wood chips, 255 °C	1.6	20.27	633.8	12.85	88.0	20.8
Torrefied pellets made from logging residue, 240 °C	2.8	19.67	681.3	13.40	89.0	17.5
Torrefied pellets made from logging residue, 250 °C	1.0	20.19	643.2	12.99	87.0	9.5
Wood pellets	6.9	17.68	678.5	12.00	98.0	20.5

Table 4.52. Properties of torrefied pellets (Föhr et al. 2015).

Property	Raw material					
	Mixed broad-leaf trees	Birch	Spruce	Pine	Spruce ply	Birch ply
Length, mm	17.1	10.8	10.3	9.1	8.0	13.1
Diameter, mm	8.0	8.0	8.0	7.9	8.0	8.0
Fines, w-%	0.2	0.6	0.1	0.9	0.8	0.2
Mechanical durability, w-%	96.6	97.4	96.8	91.8	92.6	96.8
Moisture, M_{ar}, w-%	6.6	6.4	4.4	6.8	8.6	5.0
Bulk density, g/m^3	700	680	700	680	650	700
Ash, w-%	1.3	1.2	1.4	1.3	0.9	1.2
Net calorific value, MJ/kg, dry basis	19.91	19.37	18.47	19.96	20.53	19.88
Net calorific value as received, MJ/kg	18.44	17.96	17.53	18.43	18.56	18.77
Energy density, MWh/loose m^3	3.61	3.38	3.40	3.49	3.34	3.64

Table 4.53. Comparison of explosion properties of different kinds of dust (Wilén et al. 2013).

Dust	Explosion pressure, P_{max}, bar g	Rate of pressure rise, K_{max}, m x bar/s	Limiting oxygen concentration, LOC, %	Minimum ignition temperature, ºC	
				In a cloud of dust	On a layer
Torrefied wood dust (stem wood chips, 245 ºC)	9.0	150	11	460	330
Wood dust	9.1–10.0	57–100	10–12	420	340
Cereal dust	9.2	131		510	300
Peat dust	9.1–11.9	120–157	13.5	470–590	305–340
Coal dust	8.9–10.0	37–86	14	590–760	270–450

The explosion classes of different kinds of dust are as follows: St0 (non-explosive), when $K_{max} = 0$; St1 (weak/normal explosion), when $K_{max} \leq 200$; St2 (strong explosion), when $K_{max} = 201–300$, and St3 (violent), when $K_{max} > 300$. The types of dust listed in Table 4.53 belong to explosion class St1.

A water absorption test was carried out in which steam-exploded pellets were submersed for 15 minutes in a filter bag in a vessel that contained 10 times more water than pellets. After submersion, the pellets were left to drip for 15 minutes, after which their moisture content and mechanical durability were measured from a wet sample (Korpijärvi et al. 2014). Table 4.54 lists results of the experiments conducted using VTT's method (Björklund 2014).

The most important properties of thermally treated biomass fuels are a high energy density, grindability (ability to use coal mills), mechanical durability (transport, lower dust generation), and hygroscopy (less water absorption). The moisture content of pellets varies 1–9 w-%. The mechanical durability of torrefied pellets produced from Finnish raw materials is 80–97.4 w-%. The mechanical durability of steam-exploded pellets is 98.0 w-% and only slightly lower after the submersion test. The energy density of thermally treated pellets is 3.0–4.1 MWh/loose m^3 (Tables 4.52 and 4.54). A special technical specification, ISO/TS 17225-8:2016, is published for thermally treated densified biomass fuels.

Table 4.54. Properties of steam-exploded pellets before and after the water absorption test (Björklund 2014).

Pellet raw material	Softwood pellets	Steam-exploded, softwood	Steam-exploded, forest chips
Mechanical durability before water absorption test, DU, w-%	98.0	98.0	98.0
Bulk density, BD, kg/m^3	617	739	746
Energy density, E, MWh/m^3	3.0	3.7	4.1
Moisture content before water absorption test, w-%	5	5	5
Ash, w-%, dry basis	0.4	0.5	4.9
Mechanical durability after water absorption, w-%	98.0	94.0	97.0
Moisture content after water absorption, w-%	72	14	12

4.9 Recovered wood

Approximately one million solid cubic metres of recovered wood is used in Finland each year. Special quality guidelines were drawn up for used wood, i.e. so-called recovered wood (Figure 4.24), in 2008 (Alakangas & Wiik 2008), which were updated in 2014 (Alakangas 2014). The quality guidelines for recovered wood cover chemically treated industrial wood residues, wood residues from construction and waste management, and roadside trees. Chemical treatments include e.g. painting, coating, glueing, and laminating. Treatment using heat, air, or water does not constitute chemical treatment.

'Cascading use', which involves first turning wood into a wood product, which is then recycled or reused after it has served its original purpose, is also a hot topic in the EU (Sokka et al. 2015, Alakangas et al. 2016, Vis et al. 2016). This is designed to increase the value added of wood. When a wood product can no longer be recycled or reused, it can be used to produce energy. Several definitions have been formulated for cascading use. From Finland's perspective, it is important also to include the use of residues and by-products for energy production, and the definitions vary with regard to the energy use of residues and by-products, for example. A large proportion of the Finnish wood processing industry's products are exported, which reduces their cascading use in Finland.

Figure 4.24. Recovered wood at a waste management plant. Figure: VTT.

This so-called used wood is categorised as either A, B, C, or D according to the guidelines shown in Table 4.55. Solid biofuels are divided into two classes – A and B – and they are governed by the EN ISO 17225-1:2014 standard and excluded from the scope of the Government Decree on Waste Incineration. Chemically untreated wood residue is classified as class A, and chemically treated wood as class B (315), if it does not contain more halogenated organic compounds or heavy metals from treatments with wood preservatives or coatings than virgin wood. Class C includes wood waste that contains more halogenated organic compounds and heavy metals than virgin wood but no wood preservatives (pressure impregnated wood). This kind of wood waste is classified as solid recovered fuel (EN 15359:2013) and governed by the provisions of the Government Decree on Waste Incineration (151/2013). Class D includes wood treated with wood preservatives, which is categorised as hazardous waste.

Impurities in used wood can be categorised into mechanical and chemical impurities. Mechanical impurities include, for example, soil, stones, plastic, metals, concrete, and glass. They can typically be separated from the raw material by means of sorting or during the fuel production process. For example, metals can be removed using a metal separator (magnet) and stones by screening. Chemical impurities are almost invariably integral to the wood material, which makes them extremely difficult to separate and remove. Paints, coatings, protective agents, and glues are examples of chemical impurities found in used wood.

Table 4.55. Categorisation of recovered wood into different quality classes (Alakangas 2014, Alakangas et al. 2016).

Class	Raw materials of used wood (EN ISO 17225-1:2014)	Applicability of the Government Decree on Waste Incineration (151/2013)
A	1.1 Woody biomass from forests and plantations, and other virgin wood 1.2.1 Chemically untreated industrial wood residues 1.3.1 Chemically untreated used wood 1.1.7 Segregated wood from landscape management, parks, gardens and orchard pruning, as well as drift wood from fresh-water	Not applicable
B	1.2.2 Chemically treated wood, wood by-products, residues, fibres and wood constituents 1.3.2 Chemically treated used wood	Not applicable
C	Contains wood with coatings or protective agents that contain halogenated organic compounds (e.g. PVC) but no wood preservatives (not pressure impregnated) or whose origin is difficult to verify. Demolition wood also belongs to this category unless proven otherwise (e.g. by means of analyses).	Applicable
D	Hazardous waste contains wood that has been treated with wood preservatives.	

Table 4.56 and the text discuss methods for determining each class of fuel. The normative properties are mandatory and the informative properties are voluntary. Minimum requirements only include normative properties. Demolition wood belongs to class C, unless it can be proven by means of a quality management system or property data that the wood is chemically untreated (e.g. wood frames of houses, beams). Figure 4.25 shows a diagram of the logic for classifying wood residues.

Analysing physical and chemical properties is not necessary, if the required properties are known sufficiently well. Sufficient knowledge may be: information about the origin or processing of the fuel, the governing quality management system, or the manufacturing method. Examples include wood products and residues originating from the mechanical forest industry, such as plywood, particle board, and MDF, as well as other similar glued, painted, or coated boards. In these cases, the analyses listed in Table 4.56 are carried out, if the product is being used as fuel for the first time, or if the raw material or additives in the wood change.

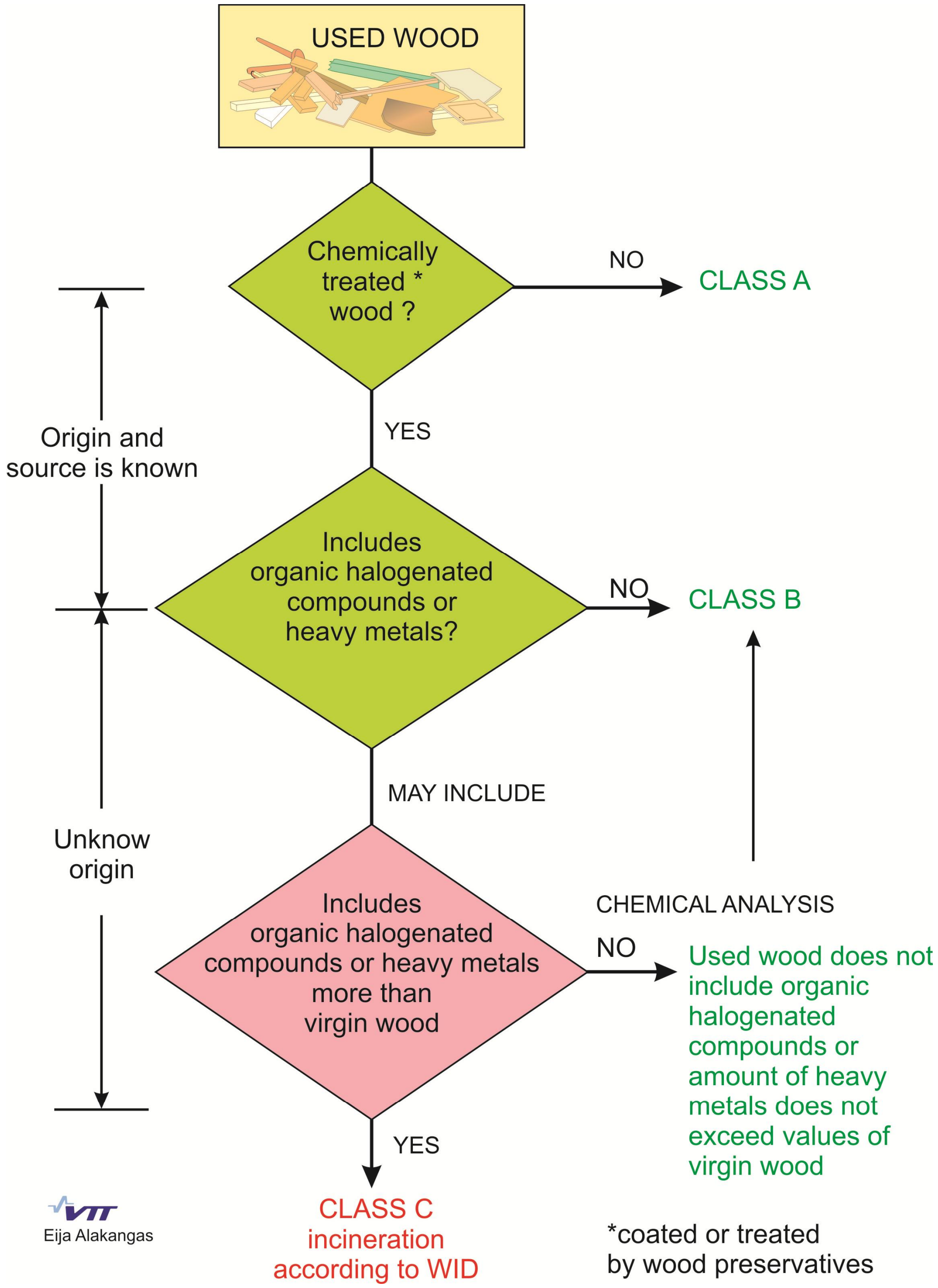


Figure 4.25. Flowchart for verifying classes A, B, and C. Source: Alakangas 2014, Alakangas et al. 2016.

The recommendation for class B wood is to analyse nitrogen, sulphur, and chlorine content as well as heavy metal concentrations (Table 4.56) from one-month combined samples at least once every six months. Analyses should be carried out at least four times during the first year of operation. If the analysed content in the combined sample is more than 20% higher than the limit value for the combined arsenic, chromium, and copper content and the cadmium content shown in Table 4.56, the exceedance is considered to be significant. In these circumstances, analyses must be carried out more frequently during the following six months (at least four times) and the quality management system improved to ensure the quality of used wood in the future. The same procedure can also be followed in the case of mechanical impurities.

The quality guidelines for wood fuels (Alakangas & Impola 2014, 2015) can be used to categorise the properties of class A and B fuels and to denote origin. The quality guidelines for wood fuels contain tables showing the quality classes of wood chips and hog fuel. Wood chips and hog fuel are divided into two groups, based on which nitrogen, sulphur, and chlorine contents are also mandatory information to be reported for chemically treated wood (class B). Table 4.56 also lists other chemical elements for which limit values have been set. The limit values shown in Table 4.56 are only applicable to chlorine, nitrogen, sulphur, and heavy metals. The normative properties are mandatory and the informative properties are voluntary. The values given for potassium and sodium are recommendations (informative).

Table 4.56. Limit values for class A, B, and C wood (Alakangas 2014).

Property		Limit value on a dry basis	Natural wood on which the limit value is based	Class A		Class B		Class C
				Normative	Informative	Normative	Informative	Limits for reclassification to class B
	Sulphur, S	≤ 0.2 w-%	bark, hardwood		X	X		X
	Nitrogen, N	≤ 0.9 w-%	bark, hardwood		X	X		X
	Potassium, K	≤ 5,000 mg/kg (0.5 w-%)	bark, hardwood				X	
	Sodium, Na	≤ 2,000 mg/kg (0.2 w-%)	bark, softwood				X	
	Chlorine, Cl	≤ 0.1 w-%	[2]		X	X		X
Heavy metals	Σ Arsenic [1] + Chromium + Copper, As + Cr + Cu	≤ 70 mg/kg	bark, softwood Σ 74 mg/kg			X		X
	Cadmium, Cd	≤ 1 mg/kg	bark, softwood			X		X
	Mercury, Hg	≤ 0.1 mg/kg	bark, softwood			X		X
	Lead, Pb	≤ 50 mg/kg	bark, softwood			X		X
	Zinc, Zn	≤ 200 mg/kg	bark, softwood			X		X

[1] In class B wood, arsenic content must not exceed 10 mg/kg at a measuring accuracy of ± 30%.

[2] Virgin wood ≤ 0.05 w-%

Class A recovered wood can be used in all boiler plants, including small ones. Class B recovered wood can be used in boiler plants with advanced combustion technology and equipment (sufficient retention time and temperature, control of combustion air, and flue gas cleaning) and where the efficiency of combustion can be monitored. Class B wood is recommended for use as a blended fuel primarily in boiler plants of at least 20 MW_{th}. Current Finnish legislation (act No 750/2013) also stipulates the same standard of combustion technology for new smaller plants of more than 5 MW_{th}. Plants of more than 50 MW_{th} are governed by the Government Decree on the limiting of emissions from combustion plants of at least 50 megawatts (93/2013).

Appendix F lists properties of recovered wood. Properties of board products are listed in Table 4.57 and those of furniture wood in Table 4.58. Table 4.59 compares the properties of recovered wood against those of virgin wood. The properties vary according to the origin of the wood residues.

Table 4.57. Properties of recovered wood (Linna & Kolsi 1992, Vesterinen 1995, and industry data).

Property	Glued laminated timber	Particle board	Plywood edges			MDF	Creosote-impregnated wood	CCA-impregnated recovered wood**
			1	2	3			
Moisture, w-%	13.5		21.9	8.6		4.7		
Net calorific value, MJ/kg, dry basis	18.3	18.6	19.1	19.08		18.7	19.8	18.9
CONTENT ON A DRY BASIS, w-%								
Ash	1.8	1.6	0.96	1.2	1.6	0.3	4.0	1.4
Carbon, C	48.6	48.8	50.6	50.9			52.3	50.4
Hydrogen, H	6.1	5.9	5.9	5.9			5.9	6.1
Nitrogen, N	3.0	0.31*	0.10	0.2	< 0.2		0.19	0.13
Sulphur, S	0.05	0.02	0.01		< 0.02	0.03	0.07	0.02
Chlorine, Cl	0.011		0.01	0.003	0.009		0.008	0.009
Fluorine, F	< 0.002							
CONTENT ON A DRY BASIS, mg/kg								
Calcium, Ca			3,069					
Iron, Fe			30.5					
Potassium, K	593		297	900	700		829	198
Manganese, Mn	81		71.8				115	81
Sodium, Na	568		2,349	5,100	3,100		717	68
Arsenic, As	< 2			< 0.5	< 0.5		5.5	2,022
Cadmium, Cd	0.12			0.05	0.05		< 0.1	0.31
Chromium, Cr	17			0.98	0.51		22	5,272
Copper, Cu	4.6			0.87	0.97		6.1	1,911
Mercury, Hg	< 2			< 0.5	< 0.05		0.13	0.15
Nickel, Ni	9.6						7.8	3.6
Lead, Pb	4.4			< 0.5	< 0.5		2.4	1.8
Zinc, Zn	80			8.2	9.7		19	12

* Modern particle board is estimated to contain a 10-fold amount of nitrogen

** CCA: copper, chromium, arsenic (preservative)

Table 4.58. Furniture wood analyses (Larjava et al. 1995).

Fuel sample	Sawdust containing particle board	Particle board dust	Mixture of cutter shaving dust
Moisture, %	7.5	5.8	22.2
Net calorific value, MJ/kg, dry basis	18.4	18.6	19.0
CONTENT ON A DRY BASIS, w-%			
Ash	0.75	1.64	0.42
Carbon, C	48.8	48.8	49.9
Hydrogen, H	5.84	5.87	6.02
Nitrogen, N	0.54	0.31	0.2
Sulphur, S	0.02	0.02	0.02

Table 4.59. Summary of the properties of recovered wood and virgin wood on a dry basis (Alakangas & Wiik 2008, VTT, and industry data).

Property	**Recovered wood**	**Virgin wood**
Net calorific value, MJ/kg	18.6–20.7	17.1–20.6
CONTENT, w-%		
Ash	0.3–10.6	0.2–10.0
Carbon, C	48.1–50.4	47–55
Hydrogen, H	5.8–6.5	5.3–7.0
Nitrogen, N	0.23–2.86	<0.1–1.2
Sulphur, S	< 0.02–0.08	< 0.01–0.20
Chlorine, Cl	0.02–0.16	< 0.01–0.01
Fluorine, F	< 0.01	< 0.0005–0.002
CONTENT, mg/kg		
Aluminium, Al	100–600	10–3,000
Iron, Fe	350–1,070	500–2,000
Potassium, K	240–900	200–5,000
Magnesium, Mg	not available	100–3,000
Manganese, Mn	72–115	9–840
Sodium, Na	200–5,100	10–2,000
Phosphorus, P	26–340	50–1,300
Silicon, Si	not available	2–20,000
Titanium, Ti	not available	1–50
Arsenic, As	< 0.1–54	< 0.1–4.0
Cadmium, Cd	0.12–0.94	< 0.05–5.0
Chromium, Cr	0.2–81.0	0.2–40.0
Copper, Cu	5.5–47.0	0.5–400.0
Mercury, Hg	< 0.03–0.14	< 0.02–2.0
Nickel, Ni	1.0–19.0	< 0.1–80.0
Lead, Pb	1.7–150.0	< 0.5–50.0
Vanadium, V	0.5–13	0.7–3.0
Zinc, Zn	27–230	5–200
Tin, Sn	0.42–6.0	
Thallium, Tl	< 0.01–1.0	
Cobalt, Co	0.4–2.7	
Antimony, Sb	0.5–8.0	
Barium, Ba	24–120	

Appendix E lists more properties of recovered wood.

5. Black liquor

The kraft process is currently the most significant method used to make chemical pulp. The process involves using inorganic cooking chemicals (sodium hydroxide NaOH and sodium sulphide Na_2S) to remove the majority of the lignin that binds the cellulose fibres of wood together in strongly basic conditions. However, this does not occur completely unselectively, and instead some of the cellulose and the other carbohydrate components of wood (glucomannans and xylan) are simultaneously converted into aliphatic carboxylic acids. Due to the yield losses relating to the carbohydrates, approximately half of the dry mass of the wood is dissolved into the cooking liquid. The solids in the cooking liquid, which is known as black liquor, therefore contain not just inorganic matter but also broken down lignin and carbohydrate-based carboxylic acids (Table 5.1). Black liquor also contains traces of extractives. The chemical composition of black liquor (especially the share of inorganic matter) and its properties nevertheless vary considerably and are affected by e.g. its dry solids content, the type of raw material (softwood and hardwood chips), the cooking modification applied, and the degree of recycling of the plant's process waters. (Raiko et al. 2002)

Table 5.1. Composition of typical sulphate-based pine and birch black liquors on a dry basis, w-% (Raiko et al. 2002).

Component	Pine	Birch
Organic matter	**67**	**67**
- Lignin	31	25
- Aliphatic carboxylic acids	29	33
• *Formic acid*	*6*	*4*
• *Glycolic acid*	*4*	*8*
• *Acetic acid*	*2*	*2*
• *Lactic acid*	*3*	*3*
• *2-hydroxybutyric acid*	*1*	*5*
• *3,4-dideoxypentonic acid*	*2*	*1*
• *3-deoxypentonic acid*	*1*	*1*
• *Xyloisosaccharinic acid*	*1*	*3*
• *Glucoisosaccharinic acid*	*6*	*3*
• *Others*	*3*	*3*
- Other organic matter	7	9*
• *Extractives*	*4*	*3*
• *Poly- and oligosaccharides*	*2*	*5*
• *Others*	*1*	*1*
Inorganic matter	**33**	**33**
- Inorganic compounds	22	22
- Organically bound sodium	11	11

* Change compared to original source: 7 → 9.

The dry solids content of the black liquor separated from fibres after boiling is only approximately 15 w-%, which is when it is termed “weak black liquor”. The dry solids content is raised in special evaporation units, after which the dry solids content is approximately 60–85 w-% (“heavy black liquor”). The black liquor, at approximately its boiling point, is then pumped into a recovery boiler, in which the cooking chemicals are regenerated and steam simultaneously produced for electricity production and the plant’s processes. Heating is necessary, as heavy black liquor is a highly viscous liquid which cannot be pumped at room temperature. (Raiko et al. 2002)

Figure 5.1 shows basic fuel properties of black liquor typical of Finnish pulp mills. Modern Finnish recovery boilers burn black liquor at a high dry solids content, approximately 75–85 w-% (Figure 5.2). As recently as in the early 1980s, a typical dry solids content was 65 w-%. Increasing the solids content increases the efficiency of the boiler, lowers sulphur emissions, and enables smaller boilers to be used – or alternatively capacity to be increased. Factors limiting the increase in dry solids content include e.g. the rise in viscosity, fouling of the evaporation unit, and the challenge of maintaining sufficient char bed inventory in the boiler (Vakkilainen 1993 and 2000).

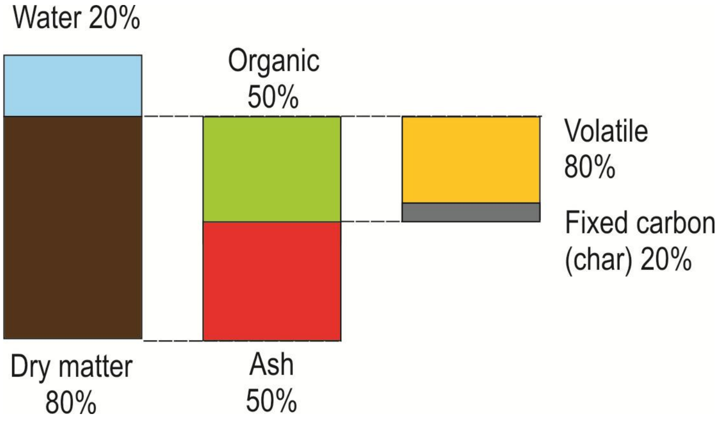


Figure 5.1. Basic fuel properties of black liquor (Raiko et al. 2002, some of the figures have been updated). Figure: VTT.

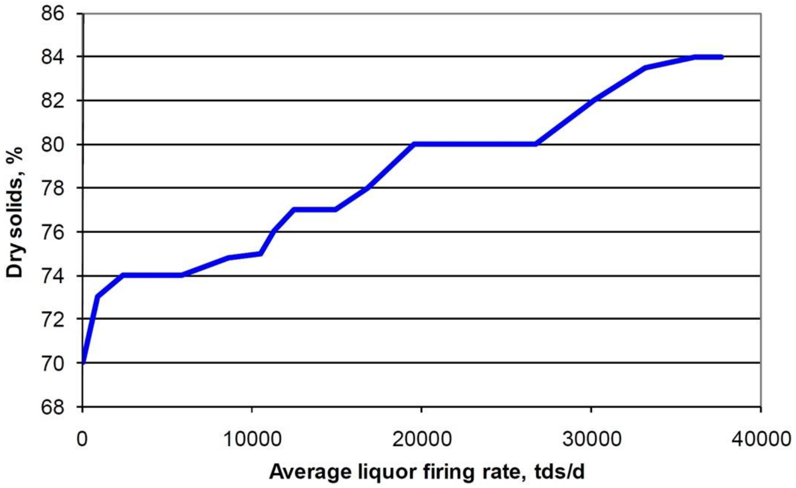


Figure 5.2. Dry solids contents of black liquor burned in Finnish pulp mills in 2004 (Finnish Recovery Boiler Committee 2010).

Approximately half of the dry solids are ash-forming and primarily consist of the cooking chemicals (Table 5.2) and the other half are organic, combustible matter. Approximately one fifth of the combustible matter is fixed carbon, and the rest is volatile matter (Raiko et al. 2002). However, the percentage of volatile matter in black liquor is not often analysed, and there is no widely employed standardised method (Vakkilainen 2000). The gross calorific value of black liquor on a dry basis is typically 13–15 MJ/kg (Tables 5.2–5.3).

Table 5.2. Typical properties and ranges of dry solids in Nordic black liquors (Vakkilainen 2000).

	Gross calorific value, MJ/kg		**Ash content, w-%**		**Sulphidity, $Na_2S/(Na_2S+NaOH)$, mol/mol**	**Volatile matter*, w-%**
	Typical	**Range**	**Typical**	**Range**	**Typical**	
Softwood	14.2	13.3–14.8	49	46–52	35	28
Hardwood	13.5	13.0–14.3	51	48–54	37	30

* Experimental method

Table 5.3. Average dry solids contents and calorific values of liquors burnt in certain Finnish recovery boilers (Juvonen 2004).

Boiler	**Liquor category**	**Dry solids content, w-%**	**Gross calorific value, MJ/kg, dry basis**
A	Softwood	80	13.5
B	Softwood	80	13.5
C	Mixed wood	80	12.5
D	Mixed wood	74	13.7
E	Mixed wood	74	13.7
F	Softwood	80	13.3
G	Mixed wood	77	13.0
H	Mixed wood	77	13.0
I	Softwood/birch/mixed	77	13.2
J	Softwood	78	13.0
K	Softwood/mixed	82	13.7
L	Softwood/birch/mixed	70	13.7
M	Softwood/birch/mixed	80	13.7
N	Softwood	75	14.1

Elementary compositions of black liquor are listed in Tables 5.4–5.6. Due to the cooking chemicals, the chemical composition of black liquor differs substantially from that of other wood fuels. This is manifested by a high share of inorganic matter with an unusual composition. The combined sodium, potassium, sulphur, and chlorine content is typically 25–29 w-% on a dry basis (Vakkilainen 2000). The main inorganic components of black liquor are Na_2CO_3, Na_2SO_4, Na_2S, $Na_2S_2O_3$, NaOH, and also NaCl in cases where there is chlorine in the recovery system (KnowPulp 2013).

Due to its unusual ash composition, black liquor ash has a low melting temperature, approximately 750 °C. This causes fouling and corrosion on the heat transfer surfaces of boilers. The presence of foreign substances – primarily chlorine and potassium – has a crucial impact on ash melting behaviour. Both potassium and chlorine lower the melting temperature range of dust particles, and chlorine in particular accelerates corrosion significantly. Increasingly efficient recycling of wastewater (closed process) has increased the concentration of foreign substances, and it is possible that new stages will be added to the process in the future to enable these foreign substances to be removed from circulation. (Raiko et al. 2002)

Table 5.4. Composition of Nordic pine-based and birch-based virgin black liquor as weight percentages on a dry basis (Vakkilainen 2000).

	Pine		Birch	
	Typical	**Range**	**Typical**	**Range**
Carbon, C	35.0	32–37	32.5	31–35
Hydrogen, H	3.6	3.2–3.7	3.3	3.2–3.5
Nitrogen, N	0.1	0.06–0.12	0.2	0.1–0.2
Oxygen, O	33.9	33–36	35.5	33–37
Sodium, Na	19.4	18–22	19.8	18–22
Potassium, K	1.8	1.5–2.5	2.0	1.5–2.5
Sulphur, S	5.5	4–7	6.0	4–7
Chlorine, Cl	0.5	0.1–0.8	0.5	0.1–0.8
Inert matter	0.2	0.1–0.3	0.2	0.1–0.3
Total	100		100	

Table 5.5. Results of analyses carried out on black liquors of Finnish plants according to Åbo Akademi University's database.

Property	**Hardwood (1999)**	**Softwood (1999)**	**Mixed wood (2009)**	**Mixed wood (2009)**	**Mixed wood (2009)**
Dry solids, w-%	74.5	77.9	81.3	80.8	82.2
DRY BASIS, w-%					
Carbon, C	32.5	32.2	31.4	32.2	31.0
Hydrogen, H	3.2	3.3	3.1	3.3	3.1
Nitrogen, N	0.08	0.04	0.11	0.09	0.10
Sodium, Na	20.7	20.7	21.6	21.4	21.8
Potassium, K	2.3	2.7	2.4	2.4	2.3
Sulphur, S	7.4	6.3	6.6	6.4	6.6
Chlorine, Cl	0.3	0.2	0.4	0.3	0.3
Gross calorific value, MJ/kg	12.74	13.01	12.85	13.17	12.81

Table 5.6. Black liquor composition on a dry basis (Söderhjelm et al. 1989).

Property	**Plant 1**	**Plant 2**	**Plant 3**	**Plant 4**	**Plant 5**	**Plant 6**
Liquor category	**Hardwood**	**Softwood**	**Hardwood**	**Softwood**	**Hardwood**	**Hardwood**
Target Kappa number	~20	30–32	~22	~34	~20	~15
Gross calorific value, MJ/kg, dry basis	-	14.1	11.9	15.4	13.2	13.2
CONTENTS, w-%						
Ash (700 ºC)	50.3	47.9	55.8	44.8	51.8	48.9
Carbon, C	32.8	35.8	30.5	37.8	33.3	33.4
Hydrogen, H	3.3	3.5	3.4	4.2	3.6	3.9
Nitrogen, N	0.2	0.1	0.2	0.2	0.2	0.1
Sulphur, S	4.6	4.1	6.4	4.8	5.4	4.4
Sodium, Na	20.7	19.9	21.0	17.9	19.9	20.7
Potassium, K	-	1.1	1.1	1.2	1.5	1.7
Calcium, Ca	-	0.006	0.02	0.007	0.02	0.01
Chlorine, Cl	-	0.2	0.7	2.9	0.6	0.25
Silicon, Si	-	0.03	0.05	0.04	0.03	0.08
Sodium hydrosulphide, NaHS	4.3	5.3	4.2	5.5	3.8	3.2
Sodium hydroxide, NaOH1)	1.8	6.3	2.0	4.3	3.0	2.4
Sodium sulphate, Na_2SO_4	-	2.3	-	2.3	5.8	3.4
Sodium carbonate, Na_2CO_3	12.5	8.0	12.3	5.1	8.9	10.0
Effective alkalis 1,2)	4.9	10.0	5.0	8.2	5.7	4.7
Tall oil	0.26	-	0.22	0.45	0.88	1.6
Lignin	36.0	-	31.2	-	29.7	33.7
Carboxylic acids	9.4	-	8.7	-	7.8	-
Lignin-carbohydrate complex, w-%	11.0	7.0	10.0	9.0	13.0	-
Polysaccharides, w-%	5.0	2.8	3.6	2.2	1.6	-
High-molar-mass fraction of lignin3), w-%	5	-	5	11	4	3
TGA (thermogravimetric analysis)						
- Transition temperature, ºC	789	757	785	740	801	781
- Loss of ignition, %	16.8	18.8	16.4	23.4	23.5	15.5
- Loss prior to ignition, %	25.0	23.7	20.1	24.6	24.5	23.2
Viscosity, mPa·s	430	365	215	200	~30	90

1) The values are high, but comparable. 2) Calculated as NaOH. 3) Percentage of compounds with a molar mass of more than 10,000 g/mol of total lignin.

In addition to chemical properties, the combustibility of black liquor also depends on several physical properties, such as density, viscosity, thermal conductivity, specific heat, and surface tension. In practice, the most important physical property is viscosity, which affects not only pumpability but also e.g. heat transfer and evaporation speed in the evaporation rate, as well as droplet formation in liquor nozzles. Viscosity must be kept at below 0.5 Pa·s by means of heating or otherwise (Raiko et al. 2002). In addition to temperature, the viscosity of black liquor is also highly dependent on the dry solids content. The composition of liquor and any pre-treatments (heat treatment, pre-oxidation) also play a role. Hardwood liquor, which in Finland is usually birch liquor, has a higher viscosity than softwood liquor. The viscosity of liquor made from mixed wood is also often higher than that of softwood liquor. (Juvonen 2004)

Methods of determining the physical properties of black liquor still require more research (Raiko et al. 2002). The physical properties of black liquor can also often be estimated sufficiently accurately on the basis of dry solids content, composition, and temperature (Figure 5.3) (KnowPulp 2013).

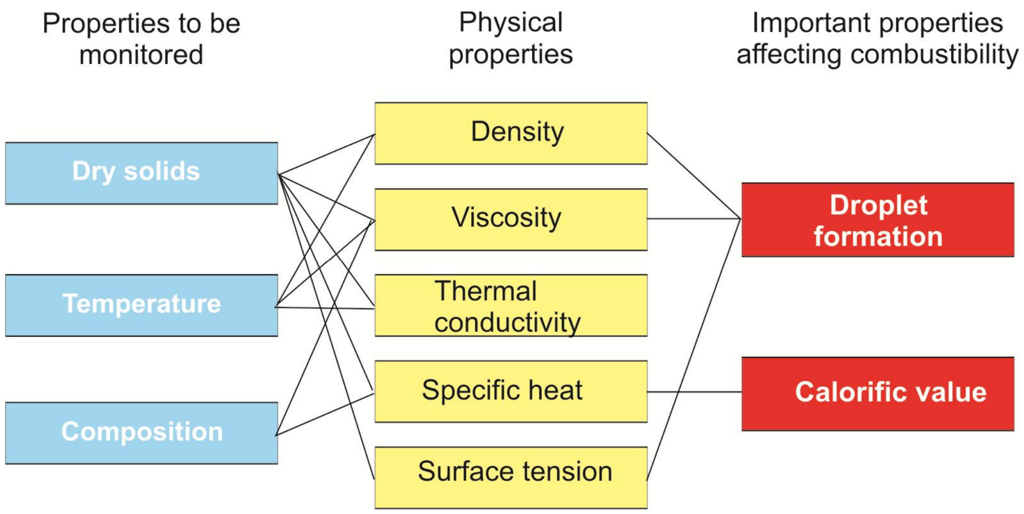


Figure 5.3. Interconnections between the most important physical properties of black liquor and properties that are typically monitored at pulp mills, and key properties affecting combustion.
Source: KnowPulp 2013. Figure: VTT.

6. Peat

6.1 Peat reserves and consumption

Finland's peat reserves inventory is done by the Geological Survey of Finland and Natural Resources Institute Finland. Data on peat reserves vary slightly depending on the source. According to the 2014 Statistical Yearbook of Forestry, peatlands account for approximately 8.8 million hectares of forestry land, in addition to which there are 0.25 million hectares of peatlands in agricultural use, and 0.06 million hectares of peatlands in production of horticultural and fuel peat. Finland has 3.91 million hectares of pristine peatlands, of which 1.2 million hectares have been designated as conservation areas (http://www.ym.fi/en-US/Nature/Biodiversity/Nature_conservation_programmes, Mire Conservation Programme, 2014), and 4.68 million hectares are used for forestry purposes (drained). (Ministry of the Environment, Environmental Permit Register). Most of the peat production area is used to harvest fuel peat. The production area of peat other than fuel peat accounts for just below 10% (The Bioenergy Association of Finland). Peat production has been discontinued across an area of 2,000–3,000 hectares in recent years, and 1,000–2,000 hectares of new production areas have been legalised (The Bioenergy Association of Finland).

Approximately 4.1 million hectares, i.e. 34.1%, of the total area of peatlands, have been drained. In forest statistics, 'peatland' refers to an area where there is peat and/or where bog plants account for more than 75% of ground cover (biological bog). Based on this definition, the area of land classified as peatland cannot remain constant, and instead, over time, some peatlands become forests, e.g. when bog vegetation decreases as a result of drainage (Vasander 1998, Statistical Yearbook of Forestry 2014, Leinonen 2010).

In the 1920s, Finland had 12 million hectares of land biologically classified as bog, and the figure given by an inventory carried out in the 1950s was 10.4 million hectares. Some peatlands have been transformed and been reclassified according to the latest surveys. Geological bogs, i.e. bogs of more than 20 hectares with a 0.3 metre layer of peat, amount to 5.1 million hectares in total. The amount of carbon stored in bogs of more than 20 hectares is estimated at 3.2 billion tonnes. The energy content of bogs suitable for peat production now amounts to approximately 6,400 TWh (23,000 PJ), of which approximately 500–700 TWh (1,800–2,500 PJ) may already have been used, which would make the maximum energy content remaining approximately 5,800 TWh (20,900 PJ). One cubic metre of bog produces approximately 0.54 MWh (1.9 GJ) of energy on average. The amount of peat in Finnish bogs amounts to approximately 69.3 billion bog-m^3, of which dry matter accounts for 6.3 billion tonnes (87 kg of dry matter/bog-m^3). Bogs that are more than two metres deep contain 34.08 billion bog-m^3 of peat, and bogs that are larger than 50 hectares and two metres deep contain 23.7 billion bog-m^3 of peat. Bogs that are larger than 50 hectares and more than two metres deep amount to approximately one million hectares in total. The average depth of bogs is 1.4 metres. The area of bogs that are technically suited for peat production stands at 1.2 million hectares. Taking account of current conservation programmes and environmental legislation, approximately half of the peat reserves are estimated as being available for peat production (Lappalainen & Hänninen 1993, Selin 1999, Statistical Yearbook of Forestry 2014, Alakangas et al. 2012, Virtanen et al. 2003, Leinonen 2010, Virtanen 2011).

The suitability of bogs for peat production depends on the following factors (Alakangas et al. 2011):

- Peat thickness
- Peat species
- Subsoil type
- Surface and base height
- Peat properties (density, calorific value, ash and sulphur content, and heavy metal content)

In the 2010s, peat consumption has been 14.4–26.3 TWh (51.8–94.7 PJ) per year. Peat consumption has been within the limits permitted by environmental targets, and the target consumption rate has been set at approximately 20 TWh (72 PJ). Peat pellets, peat coke, and peat briquettes were produced in Finland in the 1980s. Peat pellet production amounted to 18,000 tonnes in 2013 (85 GWh / 306 PJ), but the production of peat coke and peat briquettes has been discontinued in Finland (Statistical Yearbook of Forestry 2014).

6.2 Milled peat

Milled peat accounts for more than 90% of all fuel peat production. The main phases of the milled peat production technique are milling, harrowing, ridging, and collecting (Figure 6.1). What distinguishes different production techniques from each other is the collecting phase. Milling involves detaching a thin layer of peat from the surface of the bog and leaving it to dry in the sun. The drying process can be accelerated by favouring a large particle size during the milling phase. Harrowing the milled layer also accelerates drying (Figure 6.2).

Production techniques include the so-called Haku method, the mechanical harvester method, and vacuum harvester method. The Haku method involves using a belt loader to load the dry ridge of peat onto tractor-drawn trailers for transport to a stockpile. When using the vacuum harvester and mechanical harvester methods, the same vehicle is used to collect the dried peat and transport it to a stockpile. Vacuum harvesters collect milled peat from fields into tanks pneumatically.

The Haku method accounts for just under half of all milled peat harvesting these days, while the mechanical harvester method accounts for approximately half and the vacuum harvester method for approximately one tenth. The Haku method allows several milled layers to be ridged and loaded simultaneously. This means that dry, sunny spells can be made more efficient use of in drying the peat, and loading and stockpiling can be carried out during less favourable weather conditions (Alakangas et al. 2012). The harvester methods are preferred over the Haku method especially in smaller bogs and in bogs that are less homogeneous due to the layer of peat having become shallow.

Milled peat is used in district heating plants and in communal and industrial CHP plants. In recent years, peat consumers have increased their consumption of wood fuels, and peat has begun to play a more important role as a fuel to be blended with wood or solid recovered fuels.

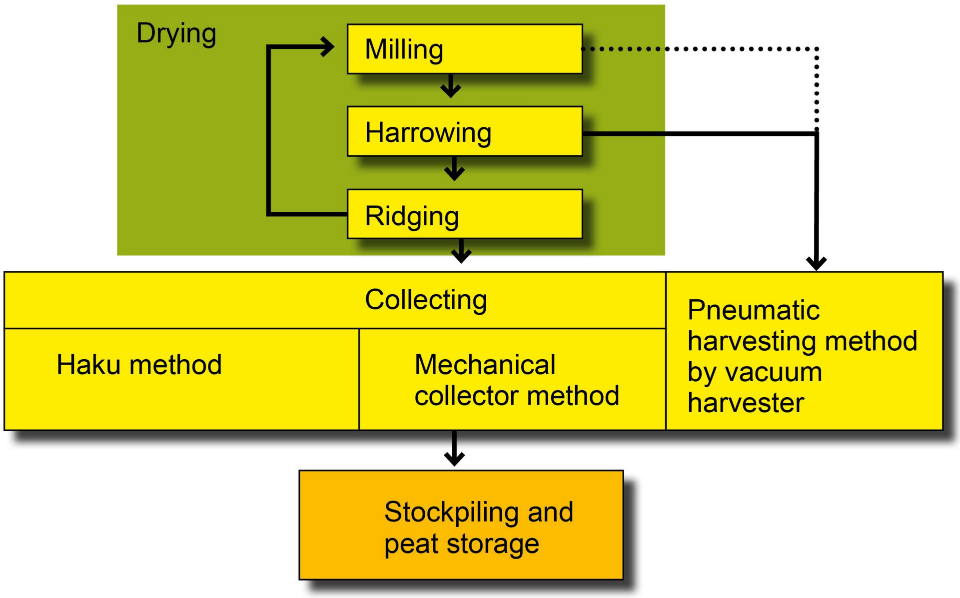


Figure 6.1. Milled peat production methods (Alakangas et al. 2012).

Figure 6.2. Harrowing of milled peat. Figure: Vapo Oy.

6.3 Sod peat

The first phase of the sod peat production method (Figure 6.3) is to mill a narrow slit into the field and to shape, compress, and extrude the extracted peat through a nozzle into sods that are left to dry on the surface of the field. Milling is carried out using either a cutting disc or an extraction auger, usually to a depth of approximately 0.5 metres. The sods are usually either cylindrical or wave-like in shape (Alakangas et al. 2012).

Depending on the production technique, the sods are either harrowed to accelerate drying in the field or ridged while semi-dry and dried in ridges to the target moisture content. Sod peat is usually dried to at least 35% moisture content, but there are also consumers who need their sod peat to be even drier. Dry sod peat is stockpiled with the help of a sod peat loader and trailers or a harvester. The stockpiles are shaped and covered.

Sod peat production is less affected by weather than milled peat production. The method of drying peat in ridges makes sod peat production more successful in changeable weather conditions.

The sod peat technique typically yields between one and three harvests per summer, depending on the weather. The size of the sods also affects the number of harvests. Larger sod sizes lead to higher field loading and larger yields per harvest. Smaller sods dry faster than large sods. Yield rates are also affected by the loss of peat that occurs at every phase of processing. Sod peat yield per harvest is 150–300 m³/ha.

Sod peat is used to fuel houses, district heating stations, and large power plants alike.

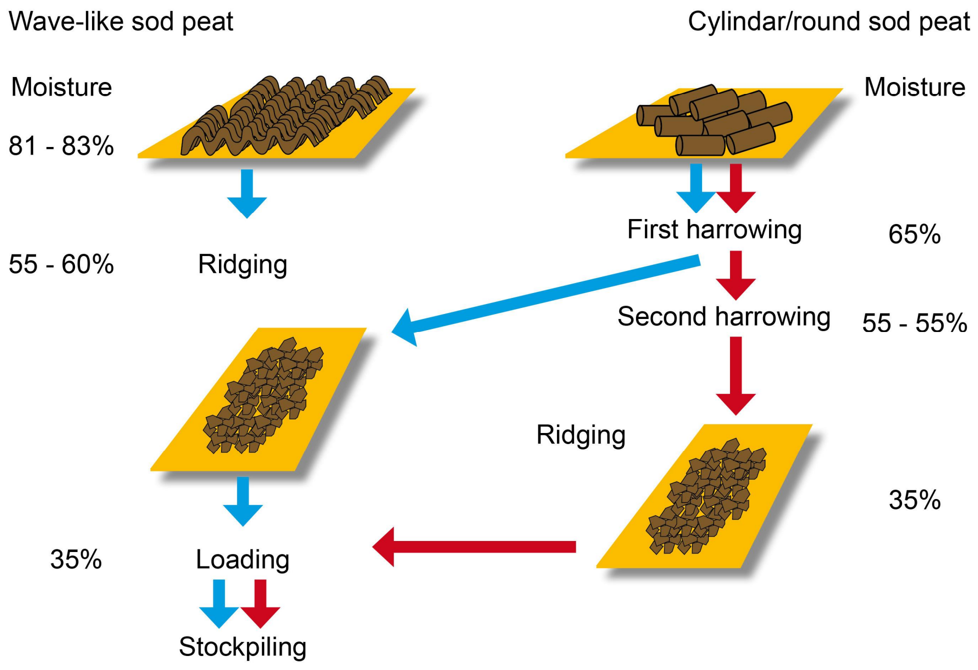


Figure 6.3. Sod peat production methods (Alakangas et al. 2012).

6.4 Peat as fuel

Peat is a material generated by the decay of pieces of dead plants in wet conditions. Due to the lack of oxygen and high water content, plant residues are not broken down properly, which creates a growing layer of peat. Peat contains varying amounts of undecomposed or poorly decomposed coarse plant pieces (bog wood, subshrubs, etc.).

Knowing the physical and chemical properties of peat is important for using it as a source of energy. The most important properties are calorific value and moisture content, as well as fuel handling properties, such as density and particle size. In large-scale fuel trade, the most important properties are determined by means of laboratory tests. For small-scale trade, properties can be estimated on the basis of existing tables and graphs depicting the average properties of the fuel and dependencies between properties. A quality classification system for peat is laid down in the Nordtest NT ENVIR 009:2005 method and in Appendix G.

Optimal transport, handling, and storage techniques have a tremendous impact on the quality of fuel peat. They can also ensure that the fuel is stored in optimal conditions. All parties in the fuel supply chain must avoid actions that could degrade fuel quality (including the end user with regard to final storage), such as impurities, over-sized particles, or an increase in the volume of fines. Examples of impurities include stones, soil, pieces of metal, plastics, ice, and snow. Quality can also suffer if moisture is absorbed into sods and pellets.

The size and traded form of commercial fuel peat vary. Size and traded form affect fuel handling and combustion properties. Some of the commercial product names of fuel peat are listed in Table 6.1.

The weight of the fuel is primarily determined using vehicle scales at CHP plants, and moisture content is analysed from fuel samples. In peat production, the volume of fuel is given as cubic metres in a stockpile (Fagernäs et al. 1980, Impola 1983, Impola et al. 1986).

Figure 6.4 shows the average composition of fuel peat. The composition and structure of peat vary considerably depending e.g. on the composition of plant species and the degree of decomposition. In Finland, peat is grouped into the following primary peat species according to botanical composition: Sphagnum peat (S), Carex peat (C), and Bryales Carex peat (B). These plants can form a peat species on their own. However, peat species often consist of two primary peat species. One of the most important properties of peat is its degree of decomposition. The degree of decomposition is given as a so-called H value, which can vary between one and 10. H1 refers to practically undecomposed peat and H10 to fully decomposed peat (von Post 1922). Table 6.2 lists the cellulose, hemicellulose, and lignin contents of peat as well as other contents according to degree of decomposition.

Table 6.1. Major traded forms of fuel peat (NT ENVIR 009:2005).

Fuel	Typical shape and particle size	Common preparation method
Briquettes	Diameter or smallest dimension > 25 mm	Mechanical compression
Pellets	Ø < 25 mm	Mechanical compression
Sod peat	Ø < 80 mm, cylinder, cubic, or wave-like sod	Cutting, maceration, pressed into pieces of sods, harrowing, ridging, collecting, and stockpiling
Milled peat	Ø < 25 mm	Milling, harrowing, ridging, collecting, and stockpiling

The majority of peat is carbon (46–59%). Carbon content varies according to the peat species and degree of decomposition (Table 6.2). Carbon content usually increases as peat decomposes. Moderately decomposed peat contains 53.8% carbon on average. Sphagnum peat has a high cellulose and hemicellulose content. Carex peat contains more lignin than Sphagnum peat. The amount of lignin increases with the degree of decomposition, but cellulose and hemicellulose contents decrease. Peat contains 5–6.5% hydrogen, 30–40% oxygen, less than 0.3% sulphur, and 0.2–3.1% nitrogen. Peat usually contains 0.1–0.2% sulphur. In some areas, especially North Karelia and Western Lapland, sulphur content can be comfortably over 0.3%. Due to the high carbon content, peat burns “more slowly” than wood (Berggren et al. 1980, Blomqvist et al. 1984, Impola 1983 and 1986, Moilanen & Ranta 1983, Herranen 2009) (Tables 6.2 and 6.3).

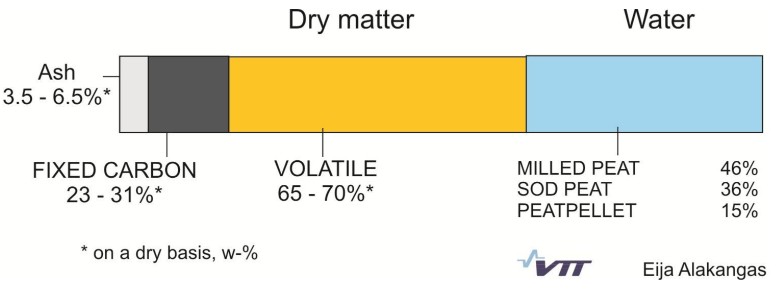


Figure 6.4. Composition of peat (* dry basis) (Alakangas et al. 2012).

Table 6.2. Effect of the degree of decomposition on the composition of peat and on carbon, hydrogen, nitrogen, and oxygen content on a dry basis, w-% (Arpiainen et al. 1986, Seppälä et al. 1982, Taipale 1996).

Component	**Poorly decomposed H1–2**	**Moderately decomposed H5–6**	**Fully decomposed H9–10**
Cellulose	15–20	5–15	-
Hemicellulose	15–30	10–25	0–2
Lignin and similar substances	5–40	5–30	5–20
Humic substances	0–5	20–30	50–60
Bituminous substances (waxes and resins)	1–10	5–15	5–20
Nitrogen-containing substances (as protein)	3–14	5–20	5–25
Carbon, C	48–50	53–54	58–60
Hydrogen, H	5.5–6.5	5.0–6.0	5.0–5.5
Nitrogen, N	0.5–1.0	1.0–2.0	1.0–3.0
Oxygen, O (calculated)	38–42	35–40	30–35

Peat contains less volatile matter than wood, 56–74%. Due to the aforementioned reasons, on a dry basis peat has a higher net calorific value than wood. Net calorific value on a dry basis also depends on the degree of decomposition, the peat species, and carbon and ash content. The calorific value of peat increases with the degree of decomposition. However, ash content usually also increases with the degree of decomposition, which, at least in theory, lowers the calorific value. The net calorific value of peat on a dry basis is approximately 19.0–22.6 MJ/kg (Table 6.3).

The samples in Table 6.3 were taken in connection with deliveries during or immediately after unloading (2/3 of samples) at the receiving station (manually or automatically), and 1/3 of the samples were taken as quality control samples during production (e.g. from each harvest of stockpiled peat using a shovel or a 1.5 or 3 metre auger) or from completed stockpiles using an eight-metre auger. The table also includes test samples from production, stockpiles, deliveries, etc. Vapo Oy performed the analyses until 2005 and ENAS Oy (now Labtium Oy) between 2006 and 2011.

Table 6.3. Chemical properties of peat on a dry basis in 2001–2011 (Lehtovaara & Salonen 2012).

Property	Ash		Calorific value, MJ/kg		Chemical analyses, w-%					
	815 °C	550 °C	Gross	Net	Volatile matter	H	C	H	N	S
Method	ISO 1171	EN 14775	ISO 1928 EN 14918		EN 15148	Empirical calculation*	EN 15104			ASTM D 4239 or EN 15289
Number of analyses	21,686	51	20,008	20,027	666	655	1,229	67	662	19,745
Average	5.63	5.75	22.00	20.78	67.85	5.52	53.84	5.64	1.63	0.213
Median	5.0	5.5	22.04	20.83	68.0	5.53	53.8	5.70	1.59	0.20
Deviation (std)	3.2	2.0	0.89	0.89	2.5	0.13	1.6	0.25	0.38	0.11
Variance	10.4	4.0	0.80	0.80	6.0	0.02	2.4	0.06	0.14	0.01
Maximum	39.9	14.9	25.42	24.20	74.5	5.8	59.4	6.20	3.25	3.01
Minimum	0.5	2.4	13.68	12.46	56.6	4.7	46.3	4.90	0.19	0.01
95% confidence level, maximum**	12.1	9.7	23.78	22.56	72.8	5.77	57.0	6.14	2.39	0.43
95% confidence level, minimum**	-	1.8	20.21	18.99	62.9	5.26	50.7	5.13	0.88	-

* In 1989–1991, hydrogen content was calculated using the following formula: 3 + 0.001672 x volatile matter x gross calorific value (Nordin 1924).

** The 95% confidence level for the minimum and maximum values was calculated as follows: average ± deviation x 2.

Chemically speaking, peat is highly reactive. This property of peat is useful e.g. in the gasification of peat and in the production of peat ammonia. The peat char produced by coking is also highly reactive and can be used to reduce metals and ores. On the other hand, its reactivity makes peat highly flammable, and, as it is a dry and finely grained material, explosive, which is why the use of peat carries a risk of fire and dust explosion. Peat is also acidic (the pH of Finnish peat is 5–6) and therefore corrosive.

Compositions of milled peat and sod peat are listed in Table 6.4. Table 6.5 lists averages of the most commercially relevant properties of milled peat and sod peat.

Table 6.4. Elemental analysis of milled peat and sod peat (%, dry basis) (Vapo Oy, internal peat database 2001–2015).

Fuel	**Carbon, C**	**Hydrogen, H**	**Nitrogen, N**	**Oxygen, O**	**Sulphur, S**
Milled peat	53.73	5.58	1.69	32.97	0.22
Sod peat	55.70	5.80	2.18	32.53	0.18

Table 6.5. Average properties of milled peat and sod peat (Taipale 1996, Electrowatt-Ekono 1999 a and b, 2005, Vapo Oy's data on the properties of peat delivered in 2010–2014, and internal peat database of 2001–2014).

PEAT	MILLED PEAT			SOD PEAT		
Source	VTT	Ekono	Vapo	VTT	Ekono	Vapo
Moisture, w-%	48.5	47.1	45.9	38.9	39.5	35.3
Density as received, kg/m^3		330	313		385	346
Net calorific value as received, MJ/kg	9.6	9.9	9.8	11.9	11.9	11.9
CONTENT ON A DRY BASIS						
Ash, w-%	5.1	5.8	6.3	4.5	4.8	3.5
Volatile matter, w-%	68.6		67.7	68.9		69.2
Gross calorific value, MJ/kg	22.1		21.8	22.5		22.6
Net calorific value, MJ/kg	20.9	20.8	20.6	21.3	21.2	21.3
Density, kg/m^3		175			233	
Energy density, MWh/m^3		0.91	0.85		1.27	1.15

The heavy metal contents of fuel peat are listed in Tables 6.6 and 6.7, and alkali metal and halogen contents in Table 6.8. Table 6.9 illustrates the particle size distribution of milled peat.

Electrowatt-Ekono (now Pöyry Consulting) also monitored the quality of delivered peat by collecting feedback on usability and quality from peat consumers in 1985–2005. No statistics exist for the year 1993. No more statistics have been compiled since 2005, when the energy market was opened to competition. Appendix F lists averages of the properties of milled peat and sod peat reported by peat consumers during these years.

Table 6.6. Heavy metal contents of fuel peat on a dry basis (mg/kg) (Vähä-Savo et al. 2016, cobalt based on Vapo's earlier surveys from 1996–2013).

Property	**Average**	**Median**	**Standard deviation**	**Minimum**	**Maximum**
Arsenic, As	3.3	3.1	1.4	0.5	6.9
Cadmium, Cd	0.13	0.12	0.04	0.06	0.2
Cobalt, Co	1.29	1.1	0.74	0.3	8.8
Chromium, Cr	6.14	5.5	3.18	0.82	15.0
Copper, Cu	7.7	6.95	3.4	2.1	18.0
Nickel, Ni	4.37	4.0	2.1	0.94	13.0
Lead, Pb	3.74	3.4	2.11	0.5	11.0
Zinc, Zn	7.5	7.23	2.7	2.1	16.0
Mercury, Hg	0.056	0.05	0.019	0.05	0.20
Vanadium, V	8.7	8.3	4.1	1.2	20.0
Molybdenum, Mo	1.07	1.0	0.52	0.5	3.4

Table 6.7. Heavy metal contents of fuel peat on a dry basis (mg/kg) (Taipale 1996, Vapo Oy).

	Arsenic, As	Cadmium, Cd	Cobalt, Co	Chromium, Cr	Copper, Cu	Nickel, Ni	Lead, Pb	Zinc, Zn
Average	2.2	0.12	1.4	5.9	6	3.9	4.6	9.0
Standard deviation	1.2	0.025	0.61	2.78	2.61	1.66	1.48	3.54
Minimum	0.2	0.03	0.1	0.9	1.4	0.8	0.6	2.8
Maximum	9.3	0.2	3.7	24.9	16.5	16.7	9.9	36.5

Table 6.8. Alkali metal and halogen contents of fuel peat on a dry basis (Vähä-Savo et al. 2016).

	Chlorine, Cl	**Fluorine, F**	**Bromine, Br**	**Sodium, Na**	**Potassium, K**
Unit	**w-%**			**mg/kg**	
Average	0.023	0.0028	0.0015	607	734
Median	0.024	0.0020	0.0010	575	730
Standard deviation	0.004	0.0018	0.0006	457	484
Minimum	0.011	0.001	0.001	33	89
Maximum	0.035	0.01	0.003	2,600	2,700

Table 6.9. Particle size distribution of milled peat (w-%) based on screening (Vapo Oy).

Particle size and sieves, mm	**Number of samples**	**Mean**	**Median**	**Maximum**	**Minimum**
Average particle size	26	3.56	3.37	6.34	2.18
D50	43	1.28	1.31	3.17	0.34
31.5	37	100.0	100.0	100.0	100.0
16	18	96.3	97.4	100.0	85.4
10	18	90.5	91.5	98.6	77.1
4	18	74.4	72.6	91.5	57.0
2	18	60.8	59.2	82.5	40.2
1	18	47.7	46.0	70.7	28.2
0.63	18	39.6	38.1	62.4	22.6
0.5	18	38.3	35.2	58.3	20.2
0.25	18	26.0	24.0	45.4	9.7
0.125	18	15.9	14.4	30.8	3.0
Bottom	18	11.0	9.1	22.9	1.7

Table 6.10 lists peat pellet properties and compares them against the requirements of the NT ENVIR 009:2005 Nordtest method.

Table 6.10. Peat pellet properties (Vapo Oy & NT ENVIR 009:2005).

Property	NT ENVIR code	Typical value	Range
Dimensions	D12, diameter (D), mm and length, mm	≤ 12 mm ± 1 mm 5 x D	
	D15, diameter (D), mm and length, mm	≤ 15 mm ±1 mm 5 x D	
Moisture, M, w-%	M20	15 w-%	13–20 w-%
Mechanical durability, DU	DU95	≥ 95%	≥ 95%
Bulk density, BD	BD700	700 kg/loose m^3	± 50 kg/ loose m^3
Net calorific value as received, Q	Q16.2	4.7 kWh/kg ≥ 16.9 MJ/kg	4.4–5.0 kWh/kg 15.1–18.0 MJ/kg
Energy density, E		≥ 3.3 MWh/ loose m^3	2.05–3.60 MWh/ loose m^3
Volatile matter, VM_d (dry basis)		69%	67–73%
Ash (550 ^oC) (dry basis)	A6.0	3%	1.1–6.0%
Ash melting behaviour	Hemisphere temperature, HT	1,160 ^oC	1,130–1,390 ^oC
Sulphur, S (dry basis)	S0.15	0.12%	0.04–0.30%
Nitrogen, N (dry basis)	N1.5	1.20%	0.7–1.7%
Chlorine, Cl (dry basis)	Cl 0.03	< 0.03%	0.0235–0.027%
Cadmium, Cd (dry basis)	Cd 0.01	≤ 0.01%	
Carbon, C (dry basis)		54%	49–56%
Emission factor, as received	-	97–99 g CO_2/MJ	97–99 g CO_2/MJ
Caesium, Cs-137 Bq/kg (dry basis)	-	< 80	10–340

The ash content of peat refers to the total amount of inorganic mineral nutrients, alluvial sediments, and chemical sediments contained in peat. In Finland, the ash content of peat is usually 3–10% on a dry basis. The quantity and quality of inorganic matter in peat depend on the conditions that prevailed while it was formed, the peat-forming plant species present, and the degree of decomposition (Mäkilä 1994, Virtanen et al. 2003, Tables 6.3 and 6.5).

Ash can be divided into primary and secondary ash based on its origin. Primary ash originates from peat-forming plants. Secondary ash consists of minerals that were carried into the peat with e.g. dust or flooding as the bog developed (Mäkilä 1994).

Minerals in peat are typically finely grained and, in Finland, mostly comprised of e.g. quartz, feldspar, amphiboles, and mica.

Sphagnum-dominated peat usually has lower ash content than Carex-dominated peat. The average ash content of Sphagnum-dominated peat in Finland is 2.5% and that of Carex-dominated peat 4%. The ash content of peat typically increases with the volume of nutrients in the bog and the degree of peat decomposition (Virtanen et al. 2003).

With the increasing popularity of multi-fuel boilers, the majority of ashes are mixtures – most commonly mixtures of peat ash and wood ash. Ash is used in landfill structures, road building, other earthworks, and as a fertiliser. Fertilisers can be made from ash originating from clean wood, peat, and energy crops, as long as it satisfies the requirements of Finnish fertiliser legislation (www.finlex.fi).

The quality of ash can vary considerably between power plants. The physical and chemical properties of ash depend, above all, on the composition and quality of the fuel, but also on the type of boiler, the combustion technology and parameters used, and the ash recovery system. Table 6.11 illustrates the melting behaviour of peat ash in an oxidising atmosphere. Table 6.12 lists typical metal contents of ash generated by the combustion of peat, sludge, and wood. The use of peat ash as a fertiliser is usually limited by low nutrient content and arsenic concentrations in excess of the maximum laid down in the Fertiliser Product

Decree. The most suitable ashes for forest fertilisation are wood-peat ashes resulting from the combustion of fuel blends with more than 50% wood. Peat ash contains less potassium than wood ash.

Table 6.11. Melting behaviour of peat ash in an oxidising atmosphere (Taipale 1996, Vapo Oy 2015).

Fuel type	Milled peat			Sod peat		
	Average	Minimum	Maximum	Average	Minimum	Maximum
Ash melting temperature (VTT), ºC						
ST, sphere temperature	1,130	1,100	1,190	1,136	1,040	1,335
HT, hemisphere temperature	1,253	1,200	1,375	1,273	1,145	1,415
FT, flow temperature	1,290	1,205	1,430	1,308	1,175	1,490
Ash melting temperature (Vapo), ºC						
DT, deformation temperature	1,181	1,080	1,360	1,222	1,080	1,420
ST, sphere temperature	1,202	1,100	1,390	1,252	1,130	1,430
HT, hemisphere temperature	1,236	1,130	1,450	1,271	1,150	1,500
FT, flow temperature	1,282	1,160	1,510	1,297	1,160	1,530

Table 6.12. Metal contents of fly ash from the fluidised bed combustion of peat, wood, and wood bark sludge, mg/kg, dry basis (Korpijärvi et al. 2009).

Property	**Mixed peat and wood ash**	**Wood ash**	**Wood bark sludge fly ash***
Arsenic, As	30–120	1–60	11–12
Barium, B	150–2,200	200–300	
Cadmium, Cd	0.5–5.0	6–40	3.7–14.0
Cobalt, Co	10–50	3–200	
Chromium, Cr	43–130	40–250	50–230
Copper, Cu	60–200	50–300	52–85
Mercury, Hg	0.3–2.0	0.02–1.00	0.004–1.1
Molybdenum, Mo	10–50	15	
Nickel, Ni	30–700	20–100	38–89
Lead, Pb	85–1,000	3–1,100	34–72
Selenium, Se	< 10–26		
Vanadium, V	20–500	20–30	
Zinc, Zn	50–2,200	200–2,000	790–3,700

* Sludge refers to biosludge, which may contain debarking and fibre sludge.

Table 6.13 lists heavy metal contents of wood ash and peat ash and Table 6.14 the nutrient contents of different types of ash. The pH of the ashes studied was extremely high (Table 6.14). With wood-based ashes, in particular, the pH was almost 12 in all ash categories. Potassium and calcium, which have a direct impact on alkalinity, stand out in wood ashes, while their concentrations in peat-based ashes are lower (Kirjavainen 2015).

The term ‘mixed ash’ in Tables 6.13–6.14 refers to a mixture of fly ash and bottom ash, which is produced especially by grate boilers when these fractions mix on the wet ash conveyor (Kirjavainen 2015). Tables 6.15–6.19 provide a summary of the fuel handling properties of peat.

Table 6.13a. Total concentrations (mg/kg, dry basis) of As, Ba, Cd, Cr, Cu, and Hg found in wood ash and peat ash by ash category and type of fuel (Kirjavainen 2015).

Ash category		As	Ba	Cd	Cr	Cu	Hg
Mixed ash							
Wood ≥ 50% 23 samples	Median	1.9	2,400	3.4	64.0	98.0	0.1
	Range	1.0–1.9	230–3,900	0.3–17.0	9.2–780.0	63–220	0.0–0.8
Peat ≥ 50% 23 samples	Median	22.0	810	0.5	68.0	103.0	0.1
	Range	1.8–140	410–2,200	0.1–4.9	25–310	43–260	0.0–0.4
Fly ash							
Wood ≥ 50% 13 samples	Median	27	1,300	5.5	57	100	0.4
	Range	4–110	550–4,400	0.8–37	29–94	34–250	0.1–0.8
Peat ≥ 50% 25 samples	Median	40	630	2	78	110	0.3
	Range	4–150	1.5–1,700	0.2–12	41.6–250	52–3,100	0–0.6
Bottom ash / fluidised bed ash							
Wood ≥ 50% 5 samples	Median	4	300	0.2	23	49.5	0.1
	Range	0.5–5.8	130–470	0.1–0.4	14–97	12–100	0–0.4
Peat ≥ 50% 8 samples	Median	5.9	372	0.3	21.5	53	0.1
	Range	1–17	59–860	0–1.3	13–73	12–83	0–0.1

Table 6.13b. Total concentrations (mg/kg, dry basis) of Mo, Ni, Pb, Sb, Se, V, and Zn found in wood ash and peat ash by ash category and type of fuel (Kirjavainen 2015).

Ash category		Mo	Ni	Pb	Sb	Se	V	Zn
Mixed ash								
Wood ≥ 50% 23 samples	Median	2.0	32.0	9.7	0.5	1.0	14.0	490.0
	Range	1.4–17.0	13.0–230.0	1.0–110.0	0.1–1.5	0.1–18.0	8.2–92.0	75.0–1,300
Peat ≥ 50% 23 samples	Median	12.0	57.0	16.0	0.5	2.6	100.5	42.0
	Range	1.4–47	28–120	1–100	0.1–1.0	0.1–12	27–240	1–620
Fly ash								
Wood ≥ 50% 13 samples	Median	6.9	40	59	2.1	4.9	67	930
	Range	2.2–23	14–67	9–200	0.5–11	1–22	9.5–160	120–19,600
Peat ≥ 50% 25 samples	Median	10	56	36	1.4	6.4	130	215
	Range	2.4–21	23–140	15–2,400	0.1–16	0.5–30	40–270	41–1,980
Bottom ash / fluidised bed ash								
Wood ≥ 50% 5 samples	Median	2	14	8.2	0.5	1	19.5	180
	Range	2–2	9–30	1.2–9.7	0.5–0.5	1–1	19–20	120–230
Peat ≥ 50% 8 samples	Median	2.0	23.5	21.0	1.0	1.0	22.0	155
	Range	0.7–6.2	8.5–51	1.1–50	0.5–2.6	1–2	17–79	4.5–590

Table 6.14. Total nutrient contents of different ash categories on a dry basis (mg/kg) and pH (Kirjavainen 2015).

Ash category		Potassium, K	Calcium, Ca	Phosphorus, P	pH
		mg/kg			
Mixed ash					
Wood ≥ 50% 23 samples	Median	44,000	170,000	13,000	12.4
	Range	10,000–96,000	88,000–410,000	4,500–36,000	10.5–13.1
Peat ≥ 50% 23 samples	Median	2,350	78,500	11,000	9.2
	Range	1,100–10,000	30,000–150,000	4,100–19,000	7.3–12.0
Fly ash					
Wood ≥ 50% 13 samples	Median	27,500	100,000	12,000	11.7
	Range	4,200–99,100	45,000–290,000	2,720–22,600	9.0–13.1
Peat ≥ 50% 25 samples	Median	7,600	45,000	8,370	9.4
	Range	2,250–41,000	13,500–160,000	3,000–37,000	7.9–12.7
Bottom ash / fluidised bed ash					
Wood ≥ 50% 5 samples	Median	39,250	135,100	6,400	10.5
	Range	5,900–65,000	12,000–206,000	990–12,000	10.4–10.5
Peat ≥ 50% 8 samples	Median	12,000	28,000	5,840	9.1
	Range	1,600–18,300	4,000–41,000	1,000–110,000	7.9–11.5

Table 6.15. Angle of slide and friction coefficient of (unscreened) milled peat (Rautalin et al. 1986).

Surface	**Angle of slide, °**	**Deviation, °**	**Friction coefficient**	**Deviation**
Steel plate, Fe 37, unpainted	34.90	1.60	0.70	0.03
Painted plate, “Miranol”	38.10	1.26	0.78	0.02
Water-resistant plywood	33.20	0.59	0.65	0.01
Painted plate, “Inerta 51 HB”	34.20	1.16	0.68	0.02
Painted plate, “Inerta 160”	35.74	1.69	0.72	0.03
Glass plate	35.36	0.94	0.71	0.02
Acrylic plate	35.60	0.67	0.72	0.01

Table 6.16. Effect of the moisture content of milled peat on pourability (Rautalin et al. 1986, Thun & Rautalin 1980).

Consolidation pressure, kPa	Moisture, %	Compressive strength on unobstructed surface, kPa	Maximum tension, kPa	Cohesion, kPa	Internal angle of repose, °	Effective angle of repose, °	Value of pourability function with one consolidation
7.59	0	8.90	24.36	1.90	41.8	51.0	2.74
	10	10.35	27.77	22.0	44.3	53.5	2.68
	25	11.19	25.77	2.46	44.1	55.7	3.20
	50	11.23	20.98	2.68	40.3	51.4	1.87
10.35	0	9.44	27.75	1.70	44.8	51.0	2.93
	10	8.25	34.23	1.64	46.6	52.1	4.15
	25	12.38	31.52	2.50	45.6	43.4	2.55
	50	15.44	33.07	3.12	43.1	37.5	2.14
13.11	0	12.23	35.57	2.74	41.6	49.8	2.91
	10	14.56	44.80	2.97	45.6	52.9	3.07
	25	15.86	40.63	3.24	45.6	54.0	2.56
	50	15.44	33.07	3.43	42.1	53.8	2.14
15.87	0	13.84	44.90	3.06	42.3	49.2	3.24
	10	17.98	52.99	3.65	45.8	53.4	2.95
	25	18.25	46.73	3.75	45.4	54.2	2.56
	50	18.42	41.27	4.04	42.7	53.4	2.29
18.63	0	15.12	51.43	3.3	42.8	49.4	3.40
	10	19.64	59.81	4.2	43.6	51.0	3.04
	25	20.98	55.39	4.4	44.2	52.8	2.64
	50	19.57	46.32	4.4	41.6	52.1	2.37

Table 6.17. Angle of drain and angle of flow of milled peat (Rautalin et al. 1986).

Fraction, mm	**Angle of drain, °**	**Asymmetry, °**	**Angle of flow, °**
Unscreened	47.8	0.8	-5.9
	48.8	2.4	-5.9
< 0.5 (bottom)	41.8	0.6	85.6
	45.5	1.6	85.6
0.5–1.0	41.8	1.3	58.9
	40.8	1.7	58.7
1.0–3.15	35.4	1.9	76.7
	35.9	1.6	73.7
0.18–1.89	47.0	1.7	63.7
	49.0	2.7	63.9

Table 6.18. Friction coefficient between different surface materials and milled peat (Rautalin et al. 1986).

Fraction, **mm**	**Moisture, w-%**	**Friction coefficient**				
		Film covered plywood	**Steel plate**	**Masonite**	**Acrylic plate**	**Glass fibre**
Unscreened	21	0.37	0.45	0.43	0.43	0.37
	30	0.58	0.74	0.66	0.64	0.61
	40	0.57	0.74	0.66	0.56	0.74
	55	0.65	0.76	0.72	0.50	0.55
	67	0.49	0.61	0.68	0.48	0.51
0.1–0.5	30		0.67			0.57
0.5–1.0	30		0.77			0.64
1.0–3.15	30		0.80			0.67
3.15–10	30		0.77			0.54

Table 6.19. Angle of drain of sod peat products (Rautalin et al. 1986).

Material	**Particle size, mm**	**Angle of drain, °**	**Asymmetry, °**
SOD PEAT 1	Ø 60 Length: 30–170	23.9	4.2
		26.2	7.1
		26.1	6.7
		26.0	1.4
		Average 25.5	
		Standard deviation 1.0	
SOD PEAT 2 (small)	Ø 30 Length: 20–175 With coarse particles accounting for ~13.3 w-% ~17.5 vol-%	42.5	7.4
		37.2	4.8
		39.5	13.5
		37.7	6.1
		Average 39.2	
		Standard deviation 2.1	
SOD PEAT 3 (small)	Ø 30 Length: 20–175 With coarse particles removed by screening	38.5	14.2
		37.7	8.8
		32.2	5.3
		32.9	3.5
		Average 35.3	
		Standard deviation 2.8	

7. Energy crops and animal residues and by-products

7.1 Bioenergy potential of energy crops

The cultivation of energy crops is one of the ways in which fields released from food production and bogs released from peat production can in the next few years be used for so-called non-food production in Finland. Herbaceous crops provide a versatile source of energy raw material (Figure 7.1). Vegetable oil based fuels, which are an alternative to diesel, can be made from e.g. sunflower seeds, rapeseed, turnip rape, hemp, and soya bean seeds, fats, and palm oil. Alcohol-based fuels can be produced from sugar-producing plants and starchy crops, such as sugarcane, sugar beet, potato, corn, and cereals, and used on their own or as a component in petrol. Modern technology also enables the production of liquid transport fuels from energy crops with high levels of lignocellulose. For example, straw, grains, hay, and bioenergy production residues, such as rapeseed cake, can be burnt in their solid form (Sankari 1994 & 1995).

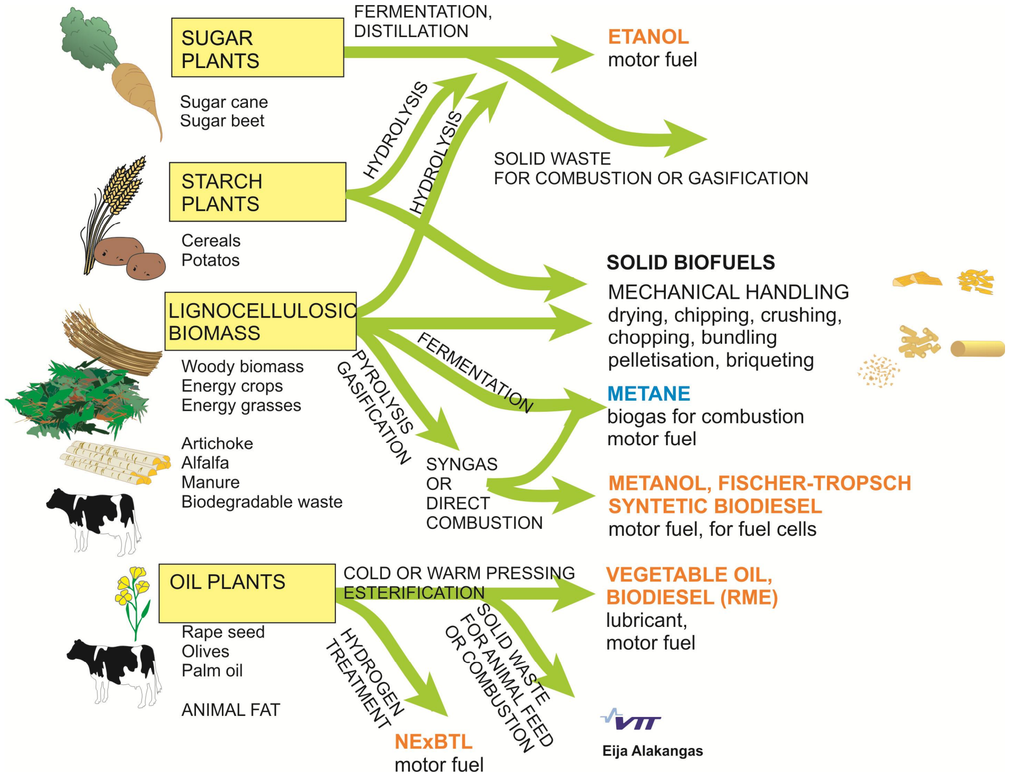


Figure 7.1. Biomass-based raw materials that can be used to produce energy, alternative processing methods, and energy consumption alternatives (Alakangas 2000). Figure: VTT.

The bioenergy potential of energy crops in Finland is 12–22 TWh (43.2–79.2 PJ) (Mikkola 2012), if 0.1–0.5 million hectares of land is dedicated to growing energy crops. Pahkala & Lötjönen (2015) have estimated the technical and techno-economical potential of field crop by-products until 2050 (Table 7.1). Field crop by-products include cereal straw, stems of oleiferous plants and legumes, and root vegetable tops. Alternative ways of using by-products include using cereal straw as livestock bedding or feed, or as a protective layer in agriculture or horticulture. It has been estimated that approximately 10–20% of Finland's annual straw harvest is used as livestock bedding or feed. Agricultural land in Finland measures 2.3 million hectares, of which 0.7 million hectares is grass and 0.2 million hectares is fallow. Some of the grassy and fallow fields could be assigned to bioenergy production, while also at the same time reducing the risk of nutrient leaching. Reed canary grass was grown across 16,700 hectares in 2010 and across just 4,200 hectares in 2015 (Lötjönen & Paappanen 2013).

Table 7.1. Technical and techno-economical potential of field crop by-products in Finland: current status, 2030, and 2050 (Pahkala & Lötjönen 2015).

Plant	**Current technical potential**		**Techno-economical, TWh (PJ)**		
	1,000 tonnes, dry basis	**TWh (PJ)**	**Current status**	**2030**	**2050**
Cereals	2,119	10.6 (38.2)	3.8 (13.7)		
Oleiferous plants	114	0.6 (2.2)	0.2 (0.7)		
Potato	85	0.4 (1.4)	0.2 (0.7)		
Legumes	5	0.0 (0.0)	0.0 (0.0)		
Sugar beet	54	0.3 (1.1)	0.1 (1.1)		
Total		11.9 (42.8)	4.3 (15.5)	5.1 (18.4)	6.2 (22.3)

Mikkola (2012) estimated the annual potential of straw as 8 TWh (28.8 PJ). Korpinen et al. 2014 calculated the techno-economical annual potential of straw as 3 TWh (10.8 PJ) and Natural Resources Institute Finland as 3.8 TWh (13.7 PJ) (Table 7.1). Farms used 0.2 TWh (0.7 PJ) of straw to produce energy and 0.4 million dry tonnes as livestock bedding in 2013 (Korpinen et al. 2014).

7.2 Cereals and straw

The straw and grains of cereals (barley, wheat, rye, and oat) can be used as solid fuels. Grains and straw have different combustion properties, which is why they need to be used separately. In addition to farms, potential applications for straw include heating stations in rural areas and small houses. A special boiler is required for burning straw. As the ash melting temperatures of straw from different species of cereals vary considerably, the straw boiler grate should work with both melted and unmelted ash, and the ash removal equipment must be able to handle both ash that has resolidified after melting and unmelted ash (Ahokas et al. 1983, Sankari 1994).

The biggest problem in using straw is its density (loose straw has a density of 30–40 kg/m^3, and baled straw has a density of 100–150 kg/m^3), which makes storage difficult and transport expensive. Another significant problem is the late harvesting time in the autumn, which, in some years, can make it difficult to get straw into storage sufficiently dry. Straw can be used as fuel in the form of soft and hard bales, chopped, ground, or briquetted. Figure 7.2 illustrates straw harvesting in the form of soft, square bales.

Straw and wood are similar kinds of fuel in terms of a few of their properties. Their elementary composition (elementary analysis) and net calorific value are very close to each other. Both contain a high volume of volatile matter and, therefore, burn with tall flames and require a large space to burn. The low energy density, high ash content, and low ash melting temperature of straw nevertheless make it a more challenging fuel than wood and other solid fuels (Ahokas et al. 1983, Sankari 1994).

Straw is threshed at a moisture content of 30–60% and usually burnt at a moisture content of less than 20%. Straw dries by between two and six percentage points in storage, which means that the moisture content of straw collected for burning must not exceed 25% at the time of harvesting. If straw needs to be harvested at a moisture content of more than 30%, it must be dried mechanically to enable combustion (Ahokas et al. 1983, Tuunanen 1993).

The net calorific value of straw is approximately 13.5 MJ/kg at a moisture content of 20%. The net calorific value of straw on a dry basis is 16.7–17.8 MJ/kg, and its average calorific value on a dry basis is 17.4 MJ/kg (Table 7.2).

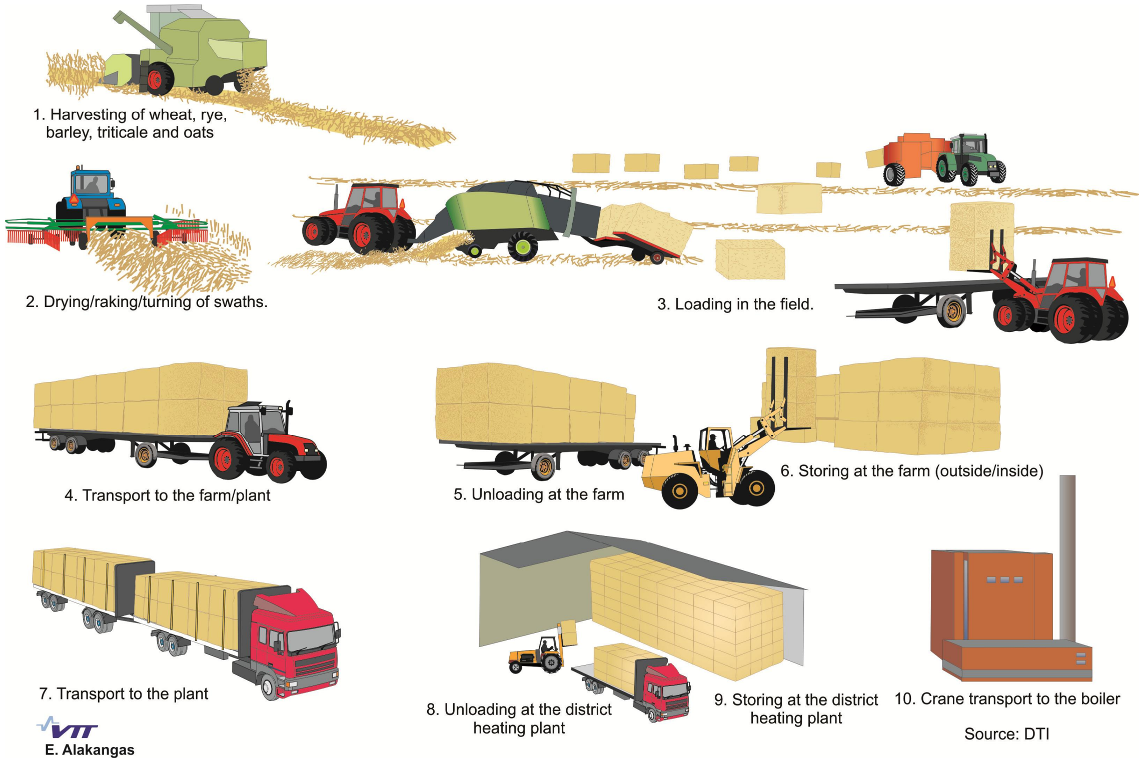


Figure 7.2. Straw harvesting as square bales. Source: Alakangas & Virkkunen 2012.

Table 7.2 compares the composition of straw, reed canary grass, and hemp (*Cannabis sativa*), and Table 7.3 compares the ash content and calorific value of straw from different cereal species. Hemp stem consists of phloem fibre (35%) and a woody core (65%) (Laine 2015).

Table 7.2. Chemical composition of reed canary grass and straw on a dry basis, w-% (Paavilainen 1997, Laine 2015, VTT analysis (hemp 2/2016)).

Component	Reed canary grass	Straw (wheat)	Hemp
Cellulose	34	37	55
Hemicellulose	22	23–30	16
Lignin	14	20	4
Ash	7	5–9	2.2–2.4
Silicate	2	1.5–2.0	

Table 7.3. Ash content and calorific value of straw from different cereal species (Puuronen et al. 1984, Tuunanen 1994, Taipale 1996).

Property	Rye	Wheat	Barley	Oat	Cereal straw in general
Ash content on a dry basis, w-%	4.5	6.5	4.5–5.9	4.9	5.0
Net calorific value on a dry basis, MJ/kg	17.0	17.8	17.4	16.7	17.4
Net calorific value at 20% operational moisture, MJ/kg	13.6	13.8	13.4	12.9	13.5

The properties of straw ash vary considerably depending on the cereal species, growth site, and fertilisation. Oat straw has the lowest calorific value and poor ash melting properties (sintering). Moreover, oat straw is tough. Cereal straw contains 4.5–6.5% of ash on a dry basis. Wheat straw has the highest ash content. Volatile matter accounts for 60–70% (Ståhlberg et al. 1985, Puuronen et al. 1994, Ahokas 1983, Sankari 1994 and 1995). Properties of cereal straw are listed in Tables 7.4–7.5.

Table 7.4. Composition of cereal straw ash on a dry basis, w-% (Taipale 1996).

Compound, w-%	Straw in general	Straw in general	Wheat**	Rye	Barley	Oat
	Ashing at 815 °C	Ashing at 550 °C				
	Range / average					
SiO_2	18–61 / 43	21–79 / 52	78.2/68.4	61.7	44.7	37.3
K_2O	6.8–38 / 25.8	11.0–24 / 18	6.6/13.2	19.2	37.1	40.3
CaO	4.4–13 / 7.7	4.7–14.4 / 8.6	5.0/4.3	7.4	9.3	12.3
P_2O_5	2.0–7.5 / 3.8	1.5–3.5 / 2.5	3.3/2.0	3.7	3.8	4.1
MgO	1.5–4.7 / 3.0	1.3–3.8 / 2.7	3.6/2.0	2.8	2.5	3.0
Al_2O_3	0.32–3.8 / 1.5	0.13–3.5 / 0.7	2.0/0.85	2.1	0.4	0.8
Fe_2O_3	1.4–6.8 / 3.3	< 0.1–1.9 / 0.5	1.5/0.45	1.5	0.5	0.5
SO_3	1.8–5.4 / 3.7	/ 3.0*	1.4/0.90	1.3	1.4	1.4
Na_2O	0.31–9.9 / 3	0.2–10.4 / 2.1	0.3/0.25	0.3	0.3	0.3
TiO_2			/ 0.04			

* Computational value ** Figures from two different sources

Chemical composition is affected not just by the plant species but also by the age of the plant and cultivation conditions (weather conditions, soil, and fertilisation). The chemical composition of different parts of plant can also vary. The time of harvesting also affects the composition of biomass. Carbon, hydrogen, and nitrogen contents remain relatively constant. The chlorine and alkali contents of straw decrease, if it is left to be rained on in a field. The chlorine content of straw harvested early (yellow straw) is almost four times that of straw harvested late (grey straw) (Sankari 1994, Huusela-Veistola et al. 1991, Tuunanen 1994).

The calcium, magnesium, and potassium contents of straw ash are high. Burning straw with e.g. peat causes the sulphur produced by combustion to be bound to the ash specifically thanks to the high calcium, magnesium, and potassium contents of straw (Puuronen et al. 1994). Table 7.6 lists the metal contents of cereal straw.

Straw ash melting occurs across a wide temperature range (Table 7.7). Straw ash from different species varies in terms of its SiO_2, K_2O, and CaO contents. SiO_2 increases the melting temperature and K_2O and CaO lower the melting temperature. The melting point of straw harvested late is 150 °C higher than that of straw harvested early. The melting point can be raised by burning straw and coal as a blend. The melting point can also be raised by using additives, such as kaolin. Adding 2% kaolin to straw pellets raises the deformation temperature from 770 °C to 1,100 °C (Puuronen et al. 1994, Taipale 1996).

Table 7.5. Elemental and metal content of straw from different cereal species (Taipale 1996).

Element	Cereal straw			Barley straw	Wheat straw
	In general / average	Harvested early	Harvested late		
CHEMICAL COMPOSITION ON A DRY BASIS, w-%					
Carbon, C	45–47 / 46	49	51	45.8 ± 0.7	46.2 ± 0.7
Hydrogen, H	5.8–6.0 / 5.9	5.9	6.1	5.7 ± 0.4	5.8 ± 0.3
Nitrogen, N	0.4–0.6 / 0.5	0.41	0.48	0.52 ± 0.19	0.59 ± 0.20
Oxygen, O	39–41 / 40	44	45	41.9 ± 1.8	41.3 ± 2.1
Sulphur, S	0.01–0.13 / 0.08	0.19	0.15	0.12 ± 0.04	0.08 ± 0.03
Chlorine, Cl	0.14–0.97 / 0.31	0.88	0.24	0.4 ± 0.4	0.15 ± 0.10
ASH-FORMING ELEMENTS ON A DRY BASIS, w-%					
Silicon, Si	0.6–4.0 / 1.8	0.6	0.6	1.2 ± 0.4	1.8 ± 0.9
Aluminium, Al		0.035	0.04	0.037 ± 0.033	0.023 ± 0.022
Iron, Fe		0.12	0.08	0.026 ± 0.023	0.026 ± 0.027
Magnesium, Mg	0.06–0.14 / 0.11	0.06	0.05	0.10 ± 0.03	0.11 ± 0.02
Calcium, Ca	0.26–0.66 / 0.4	0.3	0.15	0.40 ± 0.09	0.40 ± 0.12
Potassium, K	0.69–1.3 / 0.99	0.6	0.4	1.1 ± 0.5	0.94 ± 0.25
Sodium, Na	0.01–0.6 / 0.11	0.07	0.05	0.20 ± 0.17	0.042 ± 0.052
Phosphorus, P	0.04–0.10 / 0.07	0.06	0.05	0.092 ± 0.032	0.075 ± 0.020
HEAVY METAL CONTENT ON A DRY BASIS, mg/kg					
Cadmium, Cd	0.036–0.083	0.01			
Chromium, Cr	0.044–0.086	0.02			
Copper, Cu	2.6–9.2	10	5		
Mercury, Hg	0.028–0.036	1			
Lead, Pb	0.72–0.83	100			
Zinc, Zn	43–46	0.01	20		

Table 7.6. Metal content of straw ash (Taipale 1996).

Element	**Content, mg/kg**	**Element**	**Content, mg/kg**
Antimony, Sb	< 20	Copper, Cu	85
Arsenic, As	32	Nickel, Ni	45
Barium, Ba	90	Mercury, Hg	< 5
Lead, Pb	45	Selenium, Se	< 30
Cadmium, Cd	3	Vanadium, V	28
Chromium, Cr	58	Zinc, Zn	125
Cobalt, Co	< 20		

Table 7.7. Ash melting behaviour of straw from different cereal species (Ahokas et al. 1983).

Cereal species	In an oxidising atmosphere		
	Sphere temperature, ST, °C	Hemisphere temperature, HT, °C	Flow temperature, FT, °C
Wheat	1,050	1,350	1,400
Rye	840	1,150	1,330
Barley	765	1,035	1,190
Oat	735	1,045	1,175

If straw is stored chopped in a stockpile over winter, the moisture content must be 20–24%. The stockpiles need to be compressed and covered with plastic. In VTT's studies, no mould growth or self-heating was observed in stockpiles (Lindh et al. 1998).

Briquetting and pelletisation increase the density of the fuel and make it easier to handle. Straw briquettes are produced using roll, piston, or screw presses. The shape of briquettes varies from pillow-like to discs and bars. Their diameter is 12–100 mm, and their moisture content is 8–15%. The particle density of straw briquettes is 450–1,100 kg/m^3, and their storage density is 300–550 kg/m^3 (Peltola 1981, Ahokas et al. 1983).

Straw pellets are produced using ring or flat dies. The raw material is pressed through a perforated disc or cylinder with the help of rollers. The pellets have a diameter of 6–15 mm, a gross density of 800–1,400 kg/m^3, a bulk density of 450–750 kg/m^3, and a moisture content of 8–15% (Peltola 1981, Ahokas et al. 1983).

Chopping does not increase the density of biomass unless the length of the chopped pieces is small enough. The grinding of biomass, on the other hand, increases the density of e.g. straw by approximately 220–240 kg/m^3 (cf. Table 7.18 on reed canary grass).

Cereal grains have almost the same calorific value per one kilogram of dry matter as fuelwood or straw. Oat grains in particular burn similarly to straw, as they contain a high volume of husk. Grains can be burnt as is or ground down. The net calorific value of barley grains at their operational moisture content is 4.5 MWh/tonne (16.2 MJ/kg) or 2.41 MWh/m^3 (8.4 GJ/m^3). Their density is 536 kg/m^3 (Tuunanen 1993). The chlorine content of grains varies between 0.028 w-% and 0.048 w-%, and their ash content on a dry basis is 2.5 w-% (Silvennoinen & Hedman 2011). The net calorific value of oat chaff on a dry basis is 17.4–17.8 MJ/kg.

Properties of oat, oat brans, and residues of certain oleiferous plants are listed in Table 7.8 and properties of oats, turnip rape, and pressed turnip rape in Table 7.9. Analyses of cereals and cereal dust are listed in Table 7.10.

Table 7.8. Properties of oats, oat brans, and residues of certain oleiferous plants (Natural Resources Institute Finland).

Fuel	Moisture, w-%	Ash, w-%, dry basis	Gross calorific value, MJ/kg, dry basis	Net calorific value, MJ/kg	
				Dry basis	As received
Powdered oat husk	9.0	4.7	18.89	17.56	15.77
Oat bran	8.3	4.9	18.26	16.93	15.33
Pressed Camelina, briquette	9.1	5.7	22.68	21.35	19.20
Pressed Camelina, disc	10.0	5.7	22.41	21.08	18.73
Feed oats	12.2	3.4	19.24	17.91	15.42
Cereal fraction briquette	8.9	7.4	18.91	17.59	15.80

Table 7.9. Comparison of oats, turnip rape, and pressed turnip rape against wood and peat pellets (Kouki et al. 2008).

Property	**Oat**	**Wood pellets**	**Peat pellets**	**Turnip rape**	**Pressed turnip rape**	**Oats (80%) and peat (20%) blend**
Moisture, w-%	11.4	5.3	10.4	5.5	6.8	11.2
Net calorific value as received, MJ/kg	15.91	17.62	16.75	23.99	20.94	16.08
Bulk density, kg/loose m^3	570	630				
CONTENT ON A DRY BASIS						
Ash, w-%	2.4	0.3	2.5	4.4	6.1	2.4
Gross calorific value, MJ/kg	19.59	20.15	20.21	27.08	24.2	19.71
Net calorific value, MJ/kg	18.26	18.74	18.97	25.54	22.65	18.40
CONTENTS ON A DRY BASIS, mg/kg						
Aluminium, Al	24.4	9.9	782.7	[1]	9.4	176.1
Boron, B	1.5	2.6	1.5	13.3	15.3	1.5
Calcium, Ca	640	940	1,620	5,410	5,980	836
Cadmium, Cd	[1]	0.11	0.15	0.17	0.16	0.03
Copper, Cu	4.4	1.9	2.5	3.5	4.8	4.1
Iron, Fe	80	10	1,790	60	90	422
Potassium, K	5,290	670	190	7,910	10,170	4,270
Magnesium, Mg	1,330	200	630	3,380	5,410	1,190
Manganese, Mn	40	70	40	20	50	40
Molybdenum, Mo	[1]	[1]	[1]	[1]	[1]	[1]
Sodium, Na	42.9	10.4	77.0	24.8	36.3	49.7
Nickel, Ni	1.8	0.2	1.6	0.7	1.9	1.7
Phosphorus, P	4,010	40	310	8,880	12,640	3,278
Lead, Pb	[1]	[1]	7.25	[1]	[1]	[1]
Sulphur, S	1,540	70	1,160	4,350	4,910	1,544
Zinc, Zn	28.0	7.2	13.3	34.4	57.5	25.1
Chlorine, Cl	383	67	278	117	92	362

[1] Below the limit of determination

Table 7.10. Properties of cereals and cereal dust (VTT, Eurofins Viljavuuspalvelu Ltd).

Property	Cereal residue 1	Cereal residue 2	Cereal residue 3	Cereal residue 4	Cereal residue 5	Cereal residue 6	Cereal residue 7
oisture, w-%	6.7	6.4	7.10	7.3	11.3	12.4	11.0
Ash, w-%, dry basis	6.7	8.6	6.4	6.1	5.4	4.7	6.4
Bulk density, kg/m^3					194	137	235
Gross calorific value, MJ/kg, dry basis	18.86	18.53	19.11	19.09	19.3	18.49	18.94
Net calorific value, MJ/kg, dry basis	17.46	17.10	17.71	17.65	17.97	17.24	17.63
Net calorific value as received, MJ/kg	16.12	15.87	16.29	16.18	15.67	14.80	15.42
CONTENT ON A DRY BASIS, w-%							
Volatile matter						76.0	76.3
Fixed carbon (calculated)						19.3	17.3
Carbon, C	47.0	45.8	47.0	47.1		46.4	46.0
Hydrogen, H	6.2	6.3	6.2	6.4		5.7	6.0
Sulphur, S	1.1	1.0	1.3	1.5		0.04	0.14
Nitrogen, N						0.3	1.4
Chlorine, Cl						0.24	0.16
CONTENT ON A DRY BASIS, mg/kg							
Arsenic, As					0.5		
Cadmium, Cd					0.073		
Chromium, Cr					8.0		
Copper, Cu					10		
Nickel, Ni					28		
Lead, Pb					2.0		
Zinc, Zn					75		
Mercury, Hg					0.07		
Sodium, Na						37	51
Potassium, K						4,000	7,400
ASH MELTING TEMPERATURES (oxidising/reducing atmosphere), °C							
Deformation, DT						910/890	1,110/1,040
Sphere, ST						1,000/990	1,170/1,110
Hemisphere, HT						1,110/1,140	1,260/1,220
Flow, FT						1,250/1,320	1,400/1,290
SCREEN ANALYSES, w-%							
10 mm (samples 1–4)	0.0	0.0	0.0	1.4		-	
> 5 mm (samples 6–7)	-	-	-	-		0.5	0.5
3.15–5 mm (samples 6–7)	-	-	-	-		1.0	0.8
3 mm (samples 1–4)	1.1	1.7	1.8	1.3		-	-
2–3.15 mm (samples 6–7)	-	-	-	-		57.6	38.3
1–2 mm (samples 6–7)	-	-	-	-		33.5	23.4
1 mm (samples 1–4)	3.9	70.1	77.4	73.6		-	-
0.71–1 mm (samples 6–7)	-	-	-	-		4.2	6.4
0.5 mm (samples 1–4)	8.7	11.6	12.8	15.5		-	-
0.5–0.71 mm (samples 6–7)	-	-	-	-		1.3	6.1
< 0.5 mm (bottom)	86.3	16.6	8.0	8.2		1.9	24.3

7.3 Oleiferous plants and fibre crops

Studies indicate that the oleiferous turnip rape and oil seed rape and the oleiferous fibre crop flax can also be used as solid fuels. Properties of these plants are listed in Table 7.11.

Turnip rape (*Brassica rapa oleifera*) and oil seed rape (*Brassica napus oleifera*) are thin-rooted plants belonging to the cabbage family. Turnip rape seeds have an oil content of 30–40% and oil seed rape an oil content of 35–45% (Taipale 1996).

Flax (*Linum usitatissimum*) is an old fibre crop in Finland. Flax comes in two varieties: fibre flax and oilseed flax. Oilseed flax is shorter and more branched than fibre flax. Woody shives separated from the fibrous stem core of flax can e.g. be pressed into briquettes and used as solid fuel. The tough stems left behind in fields in connection with oilseed flax threshing could also potentially be turned into fuel, although it is likely that their toughness would cause similar problems in boilers as straw (Sankari 1994 and 1995).

Straw harvests from turnip rape and oil seed rape are 1,945 kg/ha on average. The energy content of straw at a moisture content of 25% is approximately 7 MWh/ha (25.2 GJ/ha). Seeds as well as pellets produced from the meal generated by vegetable oil pressing can also be burnt as is. Turnip rape seeds have an energy content of 10–13 MWh/ha (36–46.8 GJ/ha), i.e. 7.3 MWh/tonne (26.3 GJ/t) or 4.43 MWh/m^3 (15.9 GJ/m^3) (with a net calorific value on a dry basis of 23.9 MJ/kg). Turnip rape seed density is 665 kg/m^3 (Tuomi & Kouki 1993, Tuunanen 1994, Taipale 1996).

Table 7.11. Fuel properties and elemental analysis of turnip rape, oil seed rape, and flax (Taipale 1996).

Fuel property	Turnip rape straw	Turnip rape seed	Oil seed rape straw	Flax straw, whole	Flax shives
Gross calorific value, MJ/kg, dry basis	19.33		18.2 ± 0.5	20.04	20.19
Net calorific value, MJ/kg, dry basis	18.04–18.9	26.4		18.71	18.86–21.1
CONTENT ON A DRY BASIS, w-%					
Volatile matter	79.2		74.4	78.8	63–78.6
Ash	2.4–2.86	4.6	9.6 (6.7–14)	2.93	1.81–2.1
Fixed carbon (calculated)	17.94			18.27	19.59
Carbon, C	46–48.1	58.6	46.2 ± 0.9	49.1	50.3
Hydrogen, H	5.7–5.9	8.5	5.7 ± 0.2	6.10	6.10
Nitrogen, N	0.8	3.7	0.76 ± 0.12	1.30	0.60
Oxygen, O	39–42.13		38.8 ± 0.7	40.45	41.12
Sulphur, S	0.17–0.21		0.17 ± 0.04	0.12	0.07
Chlorine, Cl	0.22–0.10	0.5	0.22 ± 0.06	0.06	0.04
ASH-FORMING ELEMENTS ON A DRY BASIS, w-%					
Sodium, Na	0.017		0.14 ± 0.06	0.013	0.009
Potassium, K	0.58		1.0 ± 0.3	0.51	0.34
Magnesium, Mg			0.10 ± 0.03		
Silicon, Si			2.1 ± 2.2		
Phosphorus, P			0.085 ± 0.017		
Calcium, Ca			1.3 ± 0.2		
Iron, Fe			0.16 ± 0.16		
Aluminium, Al			0.22 ± 0.20		

7.4 Reed canary grass and common reed

Reed canary grass *(Phalaris arundinacea L.)* is a perennial grass indigenous to Finland, which has a high biomass yield. Reed canary grass can also be used as a raw material for paper manufacturing. Moreover, it can be used to filter and evaporate run-off water and as animal feed. Reed canary grass occurs naturally by the sea and lakes, in ditches, and on road verges. In natural habitats, it grows in tussocks of approximately one square metre or more and spreads easily. Harvests from the most promising new cultivated varieties have amounted to more than 10 tonnes/ha on a dry basis. Reed canary grass has been trialled as a blended fuel primarily with peat, or it has been turned into reed canary grass pellets (Taipale 1996, Lindh 1995). Figure 7.3 shows the stem of reed canary grass and drawings of different parts of reed canary grass.

Figure 7.3. Reed canary grass. Photo: Vapo Oy.

The fuel properties of reed canary grass are affected by the cultivar, the growth site and soil, fertilisation, and the time of harvesting (Tables 7.12 and 7.13). The tables also compare the properties of reed canary grass harvested at different times of year against other fuels (Lindh 1995). The ash content of reed canary grass grown in clay soils in particular is higher than that of plants grown in humic soils or peatlands.

Table 7.12. Typical fuel properties of reed canary grass compared to other solid biofuels (Lindh 1995).

Property	**Reed canary grass (spring-harvested)**	**Reed canary grass (autumn-harvested)**	**Wheat straw**	**Wood fuel**	**Sod peat**
Moisture, w-%	14	15	15	50	40
Net calorific value on a dry basis, MJ/kg	17.6	17.9	17.4	19.2	21.5
Net calorific value as received, MJ/kg	14.6	14.8	14.4	8.5	12
Ash flow temperature, °C	1,404	1,075	930	1,150	1,100
CONTENT ON A DRY BASIS, w-%					
Volatile matter	74	72	73	80	70
Ash	5.5	6.5	7.0	1.5	4.0
Carbon, C	46	46	46	50	55
Hydrogen, H	5.5	5.7	5.5	6.0	5.6
Nitrogen, N	0.9	1.3	0.5	0.3	1.5
Sulphur, S	0.1	0.17	0.15	0.05	0.25
Chlorine, Cl	0.09	0.5	0.5	0.02	0.05
Potassium, K	0.2	0.8	0.8	0.2	0.05
Calcium, Ca	0.2	0.4	0.4	0.3	0.5
Magnesium, Mg	0.05	0.2	0.1	0.05	0.05
Sodium, Na	0.01	0.01	0.1	0.01	0.01
Silicon, Si	1.8	1.2	1.8	0.4	0.8
CONTENT ON A DRY BASIS, mg/kg					
Arsenic, As	0.2	0.1		0.1	2
Mercury, Hg	0.03	0.03	0.03	0.02	0.09
Cadmium, Cd	0.06	0.04	0.05	0.1	0.1
Lead, Pb	2	1	1	4	5

Reed canary grass and common reed have been trialled as a blended fuel among peat. The time of harvesting affects important combustion properties, such as ash melting behaviour and the chlorine content of the fuel. The properties of autumn-harvested reed canary grass are poorer in these respects than those of spring-harvested reed canary grass (Flyktman 1998). Autumn-harvested reed canary grass contains more potassium than spring-harvested reed canary grass. Potassium affects ash melting behaviour by lowering the sphere temperature of ash (Table 7.14, Lindh 1995).

Table 7.13. Analysis results on reed canary grass and Timothy-grass (Lindh 1995).

Property	Reed canary grass, autumn 1994					Reed canary grass, spring 1994		Timothy-grass, July 1994	Reed canary grass, autumn 1994	
	1	2	3	4	5	1	1	1	1	2
Soil type	Clay	Clay	Clay	Clay	Half-bog	Clay	Clay	Clay	Mineral soil	Peat bog
N fertilisation, kg/ha	0	50	100	150	110	100	200	60	80	110
CALORIFIC VALUES ON A DRY BASIS, MJ/kg										
Gross calorific value	17.95	18.11	18.34	18.44	18.95	18.38	18.74	18.48	18.64	18.86
Net calorific value	16.74	16.89	17.10	17.21	17.66	13.17	17.47	17.20	17.36	17.55
CONTENT ON A DRY BASIS, w-%										
Volatile matter	71.5	72.1	72.5	72.8	75.2	76.4	76.4	74	76.1	77.9
Ash	8.7	7.8	7.1	6.6	5.2	7.5	6.2	4.7	4.3	2.4
Carbon, C	44.6	44.9	45.5	45.7	46.7	45.5	46.1	45.5	46.2	46.7
Hydrogen, H	5.55	5.62	5.69	5.64	5.9	5.73	5.82	5.84	5.89	5.99
Nitrogen, N	0.81	0.82	1.09	1.2	1.43	0.65	1.04	1.2	0.74	0.7
Oxygen, O (difference)	40.11	40.6	40.41	40.57	40.61	40.52	40.67	42.69	42.75	44.11
Sulphur, S	0.22	0.22	0.21	0.25	0.21	0.08	0.13	0.09	0.12	0.06
Chlorine, Cl			0.4			0.09				
Sodium, Na	0.004	0.0007	0.0023	0.002	0.001	0.004	0.008	0.03	0.002	0.004
HEAVY METALS ON A DRY BASIS, mg/kg										
Mercury, Hg	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Arsenic, As	< 0.5	< 0.5	< 0.5	< 0.5	0.6	0.5	< 0.5	< 0.5	< 0.5	< 0.5
Cadmium, Cd	< 0.03	< 0.03	0.25	0.035	0.03	0.03	0.04	0.03	< 0.03	0.4
Lead, Pb	0.65	< 0.5	0.5	0.5	0.8	1.6	1.25	0.6	0.5	0.6

Table 7.14. Ash melting behaviour of ash from a blend of peat and reed canary grass (Flyktman 1998).

Sample	Ashing temperature, °C	Peat / reed canary grass, blend, w-%	Reed canary grass	Sphere temperature, ST, °C	Hemisphere temperature, HT, °C	Flow temperature, FT, °C
1	815	90/10	Spring	1,080	1,205	1,300
2	815	70/30	Spring	1,080	1,350	1,415
3	550	50/50	Spring	1,080	1,510	1,550
4	815	90/10	Autumn	940	1,240	1,285
5	815	70/30	Autumn	915	1,290	1,380
6	550	0/100	Autumn	820	1,190	1,400
7	815	100/0	-	1,060	1,155	1,270
8	550	0/100	Spring	1,125	1,555	1,590

Table 7.15 lists properties of reed canary grass on the basis of experiments carried out by VTT at CHP plants in Jyväskylä (Rauhalahti) and Kokkola. Reed canary grass accounted for 1–2% of total energy consumption. The ash content of the reed canary grass used in the experiments was low (cf. Table 7.13). In terms of flammable substances (C, H, N, S), the composition of reed canary grass is similar to that of bark.

Table 7.15. Properties of reed canary grass on a dry basis at two CHP plants (Paappanen et al. 2008).

Property	**Reed canary grass 1 – Rauhalahti, Jyväskylä**	**Reed canary grass 2 – Kokkola**
Net calorific value, MJ/kg	18.2	17.9
CONTENT ON A DRY BASIS, w-%		
Ash (550 °C)	1.0	3.4
Ash (815 °C)	1.1	3.3
Carbon, C	49	48
Hydrogen, H	6.1	5.9
Nitrogen, N	0.44	0.71
Chlorine, Cl	0.02	0.04
Sulphur, S	0.06	0.08
Potassium, K	0.08	0.20
Sodium, Na	0.002	0.003
Calcium, Ca	0.10	0.12
Silicon, Si	0.23	1.16
Phosphorus, P	0.04	0.09
Manganese, Mn	0.02	0.01
Magnesium, Mg	0.05	0.06
Aluminium, Al	0.002	0.006
Iron, Fe	0.006	0.01
ASH MELTING TEMPERATURES, °C (reducing atmosphere)		
Deformation temperature, DT	1,110	> 1,450
Sphere temperature, ST	1,170	> 1,450
Hemisphere temperature, HT	1,200	> 1,450
Flow temperature, FT	1,260	> 1,450

Burvall (1997) proposes a correlation between the Si/(Ca + K + Mg) ratio and the deformation temperature of ash in the context of reed canary grass. When the ratio is approximately 1, the deformation temperature is 1,000–1,100°C. The ratio for the reed canary grass sample from Rauhalahti (Table 7.15) is 1, and the deformation temperature of 1,110 °C is therefore fully in line with Burvall's study (1997). The ratio for the reed canary grass sample from Kokkola was 3, which, according to Burvall, results in a deformation temperature of more than 1,400 °C, and that value is therefore also in line with Burvall's study. The analyses for Burvall's study were carried out in an oxidising atmosphere.

Table 7.16 lists results of reed canary grass ash analyses and Table 7.17 results of heavy metal analyses on samples of blended peat and reed canary grass ash.

Table 7.16. Composition of reed canary grass ash (Moilanen et al. 1996, Taipale 1996).

Compound	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**K_2O**	**Na_2O**	**TiO_2**	**SO_3**	**P_2O_5**
w-%	89.8	1.4	1.2	3.5	1.5	3.2	0.15	0.1	1.1	4.1

Table 7.17. Heavy metal analyses on samples of blended peat and chopped reed canary grass ash (Flyktman 1998).

Test	**Blend of chopped reed canary grass and peat (1:5), reed canary grass accounting for 12% of energy**	**Blend of chopped reed canary grass and peat (1:8), reed canary grass accounting for 7% of energy**	**Standard Sawing residue and bark**
HEAVY METALS ON A DRY BASIS, mg/kg			
Arsenic, As	1.0	2.7	0.47
Cadmium, Cd	9.3	9.7	11.7
Chromium, Cr	2.2	3.2	0.38
Lead, Pb	61.0	63.0	58.4
Copper, Cu	80.0	77.0	93.4
Nickel, Ni	55.0	36.0	31.3
Zinc, Zn	1,140	1,510	2,060
Chlorine, Cl	121	284	462
Combustible components, %	13.3	18.1	19.8

Some of the chopped reed canary grass particles were under 4 cm and some over 4 cm.

Reed canary grass is lighter than peat and wood-based fuels. In Lötjönen and Paappanen's study (2013), the density of spring-harvested bales varied between 108 and 171 kg_{dry}/loose m^3. This may lower the power output of boilers when burning blended fuels, as the handling equipment is not designed for transporting light fuels. Based on tests, the homogeneity of the blend affects plant usability. Another important factor is the length of shredded reed canary grass particles (shorter particles of less than 4 cm perform better, Table 7.18). Spring-harvested reed canary grass can be used in blends as long as the boiler does not need to be on full power and the percentage of reed canary grass in the blend is not significant. In practice, the energy contribution of reed canary grass cannot exceed 10% without modifications to the plant's handling equipment (Flyktman 1998). The maximum percentage achieved in the tests carried out at the Rauhalahti plant was 15% in the winter, when reed canary grass was delivered mixed in with peat (Paappanen et al. 2008).

Studies have been conducted into the storing of chopped reed canary grass in stockpiles, and wet (24–33% moisture), autumn-harvested reed canary grass was found to keep poorly and the stockpiles were found to heat and "burn" on their own. The net calorific value on a dry basis dropped (14.3 MJ/kg), while reed canary grass usually has a net calorific value of more than 17 MJ/kg. Spring-harvested, dry chopped reed canary grass (less than 10% moisture) kept better, and although the moisture content increased to approximately 24%, the temperature of the stockpiles did not increase (Lindh et al. 1998).

Reed canary grass is light like straw (Table 7.18), and its bulk density can be increased by means of compression. Studies conducted by VTT gave a maximum bulk density of 218 kg/ loose m^3 (164 kg_{dry}/ loose m^3), when it was 91.5 kg/loose m^3 (69 kg_{dry}/loose m^3) before the test.

Properties of reed canary grass pellets are listed in Table 7.19.

Table 7.18. Lengths and bulk densities of chopped reed canary grass produced by different kinds of shredders (Lindh et al. 1998).

Shredder	Precision chopper Nokka 2000	Precision chopper JF-850*	Double chopper Elho Super Louko		Self-mowing chopper Hietaranta	Precision chopper JF-900*	Corn harvester Kemper
Location	Jokioinen	Alavus	Alavus		Alavus	Liminka	Liminka
Chopped particle length	Chopped mass, w-%						
More than 4 cm	49.2	10.6	44.4	53.6	61.7	6.3	16.2
Less than 4 cm	50.8	89.4	55.6	46.5	38.3	93.7	83.8
BULK DENSITY ON A DRY BASIS							
kg/m^3	59–61	59–61	50	50	50	93.7	83.8

* Setting 15 mm

Table 7.19. Properties of reed canary grass pellets (Vapo Oy).

Property	**Pellet 1**	**Pellet 2**	**Pellet 3**
Moisture, w-%	8.9	10.8	11.7
Gross calorific value, MJ/kg, dry basis	18.45	19.06	19.57
Net calorific value, MJ/kg, dry basis	17.28	17.86	18.24
Net calorific value, MJ/kg, as received	15.52	15.67	15.82
CONTENT ON A DRY BASIS, w-%			
Ash (815 °C)	7.3	5.4	
Ash (550 °C)			3.5
Carbon, C	46.5		49.5
Hydrogen, H	5.8		6.1
Nitrogen, N	0.56	1.14	0.52
Chlorine, Cl		0.050	0.016
Sulphur, S	0.07	0.13	0.05
CONTENT ON A DRY BASIS, mg/kg			
Sodium, Na		< 21	170
Potassium, K		2,200	1,100
PROPERTIES AS RECEIVED			
Mechanical durability (Lignotester), w-%	91.2		97.1
Mechanical durability (EN standard), w-%			94.3
Bulk density, kg/m^3			659
Length, L, mm			15.1
Fines, F, w-%			0.15
Deformation temperature, DT, °C	1,160	> 1,420	1,180
Sphere temperature, ST, °C	1,190	> 1,420	1,200
Hemisphere temperature, HT, °C	1,240	> 1,420	1,300
Flow temperature, FT, °C	1,340	> 1,420	1,380

Common reed (*Phragmites australis*) is the largest natural plant in Finland. It can easily grow to three metres, but half of its length is under water. The plant has long, thick, branched and perennial roots. The leaves can be as wide as 2 cm. Common reed primarily spreads through its root system. Common reed prefers water bodies with a high nutrient content, but it is also found in bogs and coastal areas that were previously under water. The annual yield of common reed amounts to 5–12 tonnes/ha. The moisture content of winter-harvested common reed is less than 20%, which makes it suitable for storing. The net calorific value of common reed is 17.5 MJ/kg on average (Puuronen et al. 1994, Taipale 1996). Table 7.20 illustrates an analysis of ash from spring-harvested common reed.

Table 7.20. Ash analysis of spring-harvested common reed (Puuronen et al. 1994).

Element	**g/kg**	**Element**	**mg/kg**
Aluminium, Al	2.4	Cadmium, Cd	0.8
Arsenic, As	< 1	Lead, Pb	4.1
Potassium, K	30	Chromium, Cr	165
Calcium, Ca	26	Nickel, Ni	115
Iron, Fe	5.3	**Element**	**w-%**
Sodium, Na	14	Sulphur, S	7.4
Phosphorus, P	21	Carbon, C	< 0.5
Magnesium, Mg	24	Hydrogen, H	< 0.5
Vanadium, V	< 0.1	Nitrogen, N	< 0.5

7.5 Animal residues and by-products

Relatively little research has been conducted on animal residues and by-products in Finland. VTT has studied the fluidised bed combustion of a blend of meat and bone meal and coal (Aho & Ferrer 2005) and the use of horse and chicken manure as fuel. Table 7.21 lists properties of the meat and bone meal and chicken manure used in VTT's studies.

Table 7.21. Properties of meat and bone meal and chicken manure (Aho & Ferrer 2005).

Property	Meat and bone meal (< 5 mm)	Chicken manure
Moisture, w-%	5.6	
Gross calorific value, MJ/kg	19.38	
Net calorific value, MJ/kg	18.16	15.7
CONTENT ON A DRY BASIS, w-%		
Volatile matter	71.9	
Ash (550 °C)	18.3	
Ash (815 °C)	17.8	16.0
Carbon, C	44.9	
Hydrogen, H	6.4	
Nitrogen, N	11.2	0.45
Sulphur, S	0.97	
Chlorine, Cl	0.35	0.54
Oxygen, O (difference)	18.77	
Silicon, Si		0.36
Phosphorus, P		1.60
Potassium, K		3.10
Calcium, Ca		1.95
Magnesium, Mg		0.61
Aluminium, Al		0.04
Sodium, Na		0.50

Table 7.22 lists horse manure analyses. Other properties of manure are discussed in Section 12.4. A horse produces approximately 17 m^3 of manure per year, which also includes bedding. Bedding comprises peat or sawdust.

Table 7.22. Properties of horse manure (Vapo Oy 2016, Tyni et al. 2009, Lundgren & Pettersson 2009).

Property	**Horse manure 1**	**Horse manure 2**	**Horse manure 3**
Moisture, w-%	69.9	80.3	77.6
Net calorific value as received, MJ/kg	3.39	1.49	
Gross calorific value, MJ/kg, dry basis	18.04	18.74	
Net calorific value, MJ/kg, dry basis	16.90	17.55	
CONTENT ON A DRY BASIS, w-%			
Ash (550 °C)	13.3	11.0	
Ash (815 °C)	12.4	10.7	7.5
Carbon, C	45.8	46.4	45.0
Hydrogen, H	5.2	5.5	6.0
Nitrogen, N	1.49	1.11	1.5
Volatile matter	63.6		
Sulphur, S	0.19	0.13	< 2
Oxygen, O		36.16	38
Chlorine, Cl	0.62	0.13	
Fluorine, F	0.003		
Silicon, Si			1.71
Phosphorus, P			0.47
Potassium, K	1.45		0.94
Calcium, Ca	0.62		0.32
Magnesium, Mg	0.26		0.29
Aluminium, Al			0.10
Sodium, Na	0.4		0.23
Iron, Fe			0.04
Titanium, Ti			0.002
Manganese, Mn			0.02
Zinc, Zn			157
CONTENT ON A DRY BASIS, mg/kg			
Arsenic, As	1.4		
Cadmium, Cd	0.07		
Mercury, Hg	< 0.05		
ASH MELTING BEHAVIOUR (ashing at 550 °C)			
Deformation temperature, DT, °C	1,140		
Sphere temperature, ST, °C	1,170		
Hemisphere temperature, HT, °C	1,200		
Flow temperature, FT, °C	1,230		

8. Solid recovered fuels (SRF)

8.1 Origin of waste

The aim of the National Waste Plan is to stabilise the volume of municipal solid waste (MSW) at the level established in the 2000s (2.3–2.5 million tonnes/year) and for the volume of waste to begin decreasing by 2016. The target is to prevent the generation of waste by making more efficient use of materials and by increasing the conversion of waste to energy in order to reduce landfill. The volume of waste generated each year is approximately 97 million tonnes. Statistically, the total volume of waste includes all primary-sector waste materials, with the exception of timber harvesting residues left in forests. The largest contributors to waste (approximately 90%) are the industrial sector and agriculture, as well as the construction industry. EU law and Finnish legislation stipulate that any waste generated must primarily be reused or recycled and only where this is not possible can waste be finally deposited in landfill sites, for example. Priority is given to the reuse of waste as materials, but if this is not possible for economic or environmental reasons, waste can be recycled as energy (Häkkinen et al. 2014).

Solid recovered fuels (SRF) comprise dry, combustible industrial, commercial, and municipal solid waste sorted at source, as well as fuels made from the same, which are used to replace solid fuels in existing heat and power plants and other thermal processes. Figure 8.1 illustrates the fractions that can be used for energy production either as solid fuels or by turning them into pellets or organic waste into biogas (Section 11.4).

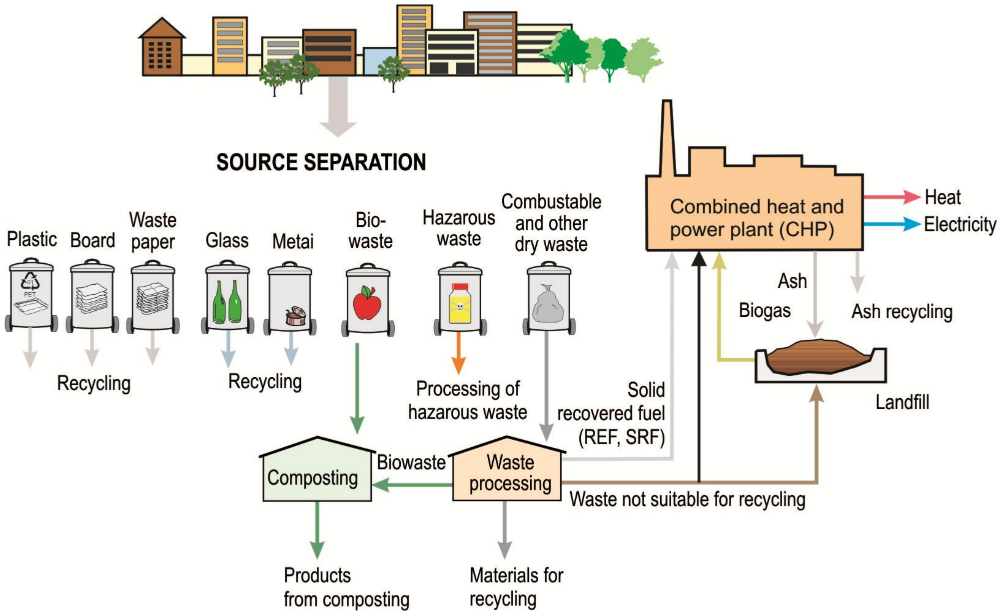


Figure 8.1. Alternatives of reusing and recycling waste as energy. Figure: VTT.

Almost 50% of the MSW accumulated in Finland in 2014 was burnt (Figure 8.2). The percentage of waste incineration has grown extremely rapidly, as only 12% of waste was burnt 10 years previously. The landfilling of waste, on the other hand, has decreased at approximately the same rate, which means that, in practice, all the incinerated MSW is waste away from landfills. The amount of waste deposited in landfill sites accounted for less than one fifth of the total volume (Waste Statistics 2014).

A total of 2.6 million tonnes of MSW was generated in 2014. Per capita per year, the volume of MSW has remained at approximately 500 kg/capita/year throughout the 21st century. MSW is generated by households and the service sector, and the majority consists of paper and cardboard, biodegradable food waste, as well as packaging and scrap metal. Households are estimated to contribute just below 60% to the total volume of MSW. However, the volume of unsorted, combustible mixed waste is the largest of all and growing as waste incineration increases (Waste Statistics 2014, Salmenperä et al. 2015).

The volume of MSW used for energy production amounted to 1.3 million tonnes, and the volume taken to landfill sites was 460,000 tonnes in 2014. The rest, i.e. 856,000 tonnes, was reused as material, most of which comprised paper, biodegradable kitchen waste, as well as scrap metal and waste electrical and electronic equipment. The volume of recycling has remained more or less constant for a long time, but the trend appears to be slightly upward (Figure 8.2).

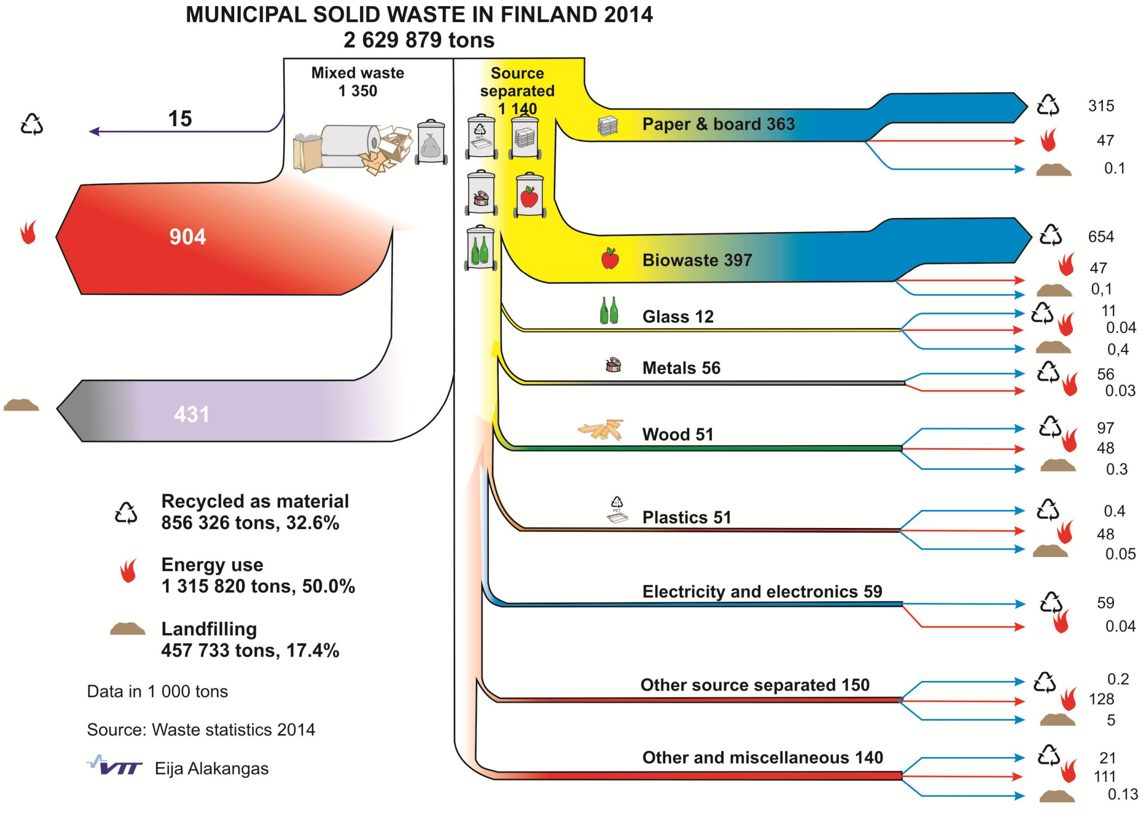


Figure 8.2. Combustion, reuse and recycling of municipal solid waste in 2014. Source: Waste Statistics 2014. Figure: VTT.

There are waste incineration plants in six towns, and three new towns are due to get a plant in the next few years. Waste incineration has increased rapidly, and the majority of the capacity was completed after the year 2012. Seven industrial and communal CHP plants use significant volumes of SRF in co-incineration. There are also 19 plants that are able to blend crushed SRF with other fuels to make up 5–30% of their fuel consumption (Pöyry 2015).

Industrial and commercial packaging, paper and plastic waste, as well as construction waste are the best suited for energy production. The dry fraction of MSW remaining after the separation of metal and glass waste is the most suitable for thermal energy production. Wet biowaste is usually composted or used to produce biogas.

Energy producers are interested in all fuels the burning of which has been officially sanctioned and proven technologically feasible and controllable, the risks associated with which can be managed, and that are economically viable. The economic downfalls of using SRF include the potential need to invest in fuel reception and handling and technical risks resulting from inconsistencies in the quality of these fuels. It is, therefore, important to know the properties of the SRF used in order to ensure an efficient and clean combustion process without jeopardising the environmental, technological, and/or economic operating conditions of the plant (Juvonen 1998).

The SRF production chain consists of sorting the energy fraction at source, collection, transport, fuel production, storage, and delivery to consumers. Each link in the production chain must have a coordinator who ensures the technological and qualitative properties of its own operations. The product labels of SRF show the quality class, limit values for element contents and properties, the origins of energy fractions sorted at source, and the percentages of different materials. The safe use of SRF requires a low level of impurities, a high standard of sorting at source, and appropriate production processes.

Raw materials for SRF originate from multiple different sources (Table 8.1), which is why the quality of the fuels varies (Table 8.2). The most important quality criteria for SRF are

- particle size,
- moisture content,
- impurities (such as metal, glass) and ash content, and
- chemical composition (e.g. chlorine content, metallic aluminium, and heavy metals).

Table 8.1. Average composition of energy waste (Salmenperä et al. 2015).

Waste fraction	Percentage, w-%
Plastic	33
Paper/cardboard	46
Wood	4
Other combustible	2
Impurities	15

Particle size has proved crucial for homogeneity, feedability, and the success of combustion at all plants that burn crushed waste (fluff). For SRF, a nominal particle size of 63 mm and a maximum particle size of 300 mm are suitable for fuel feeding equipment. Based on practical experience, the shredding/crushing of certain fractions, such as plastic, textiles, and rubber, to the target particle size is more of a problem (Hiltunen 1998, Juvonen 1998).

The quality of SRF depends on the origin of the fuels and the materials they contain. Most SRFs are made up of several different waste fractions (plastic, wood, paper or packaging, aluminium foil, etc.). Fuels that contain high volumes of plastic have low moisture content and a higher calorific value due to their higher hydrogen and carbon contents. Fuels that contain wood have higher moisture content and a lower calorific value. Fuels that contain PVC have higher chlorine content. At high steam superheating temperatures in connection with electricity production, attention must be given to the potential risk of high-temperature corrosion resulting from the chlorine content of the fuel (when the superheating temperature is above 480 ºC). SRF can also have a higher sodium, potassium, and aluminium content than other fuels, in which case the risk of boiler fouling must be taken into account. Heavy metals can cause emissions to the environment and hamper the use of ash. In addition, SRF can alter the ash melting behaviour of fuel blends (Juvonen 1998, Hiltunen 1998). Table 8.2 lists VTT's measurements of SRF properties.

The percentage of aluminium increases with the presence of household foil products and aluminium contained in construction waste. From the perspective of combustion, the biggest problem is metallic aluminium. Aluminium has a low melting point (660 ºC) but is nevertheless not easily oxidised. Any aluminium contained in the fuel melts and forms droplets covered by a thin oxide layer which are quick to attach themselves to the first colder surface, which is usually either the grate or the superheater. Aluminium in fuel has even led to blockages in boilers in some circumstances. Aluminium also has other harmful effects. Moreover, SRF can contain lead the compounds of which are highly fouling and corrosive. The concentrations of certain heavy metals in filter ash (Cr, Cu, Pb, and Zn) usually increase slightly compared to solid biofuels (Hiltunen 1998).

There may be health risks involved in the production, storage, and handling of SRF, which are measured by occupational hygiene. The most important quality criteria for occupational hygiene are the number and nature of microbes, which are determined by different environmental factors: moisture content (moisture content of the material and relative humidity of the ambient air), temperature, nutrients, pH, storage period, and time of year (Juvonen 1998).

Table 8.2. Variations in the properties of solid recovered fuels (Alakangas 2000).

Property	**Combined range**	**SRF I Average of different analyses**	**SRF III Average of different analyses**
Moisture, %	5–30	9.1 bulk 3.2 pellets	28.5 bulk 3.2 pellets
Bulk density as received, kg/m^3		180 bulk 300 pellets	210 bulk 300 pellets
Ash, %, dry basis	1–16	5.9	9.5
Volatile matter, %, dry basis	70–86		
Calorific values, MJ/kg			
Gross	20–40	24.7	22.9
Net on a dry basis	17–37	23.1	21.5
Net as received		20.8	14.6
Elemental analysis, w-%, dry basis			
Carbon, C	48–75	56.0	52.9
Hydrogen, H	5–9	7.4	7.3
Nitrogen, N	0.2–0.9	0.63	0.71
Sulphur, S	0.05–0.20	0.16	0.13
Chlorine, Cl	0.03–0.7	0.19	0.71
Ash melting behaviour	Oxidising/reducing atmosphere		
Deformation temperature, DT	1,150–1,220/1,100–1,200 ºC		
Hemisphere temperature, HT	1,200–1,260/1,200–1,250 ºC		
Flow temperature, FT	1,210–1,265/1,220–1,270 ºC		

SRF I = Blend containing packaging and wood waste sorted at source
SRF III = Municipal solid waste sorted at source

Lassila & Tikanoja has studied the quality and properties of SRF, producing approximately 400 analysis results from the years 2006–2014 (Hannula 2014). Based on the results, the average net calorific value of SRF batches as received was 17.9 MJ/kg. The samples had an average moisture content of 20.2%. Sulphur content (average of 0.24% in the samples) is raised especially by gypsum contained in construction waste, and chlorine content (average of 0.5%) is raised by hard plastics, rubber, and textiles. Other average properties on a dry basis included a bromine content of 0.013% and a Na + K content of 0.34%. The following properties were given as medians according to the EN 15358:2011 SRF standard: mercury 0.12 mg/kg, cadmium 0.4 mg/kg, copper 85 mg/kg, lead 35 mg/kg, and zinc 250 mg/kg. The material composition and quality properties of SRF change as recycling and reuse increase. As technology develops, it can be that cardboard, paper, and plastics end up being recycled instead. This would make the composition and calorific value of SRF very different. Material recycling side streams and processing rejects will provide a good source of raw material for SRF in the future (Hannula 2014).

8.2 Packaging and waste paper

Fibre-based packaging materials include both products made exclusively from fibrous raw material and various kinds of composite materials. Fibrous packaging includes e.g. different kinds of cardboard packaging, corrugated board, paper sacks, kraft paper, etc. Tables 8.3–8.6 list properties of various paper products.

Table 8.3. Combustion properties of fibrous materials (Viinikainen & Aittola 1990, Vesterinen 1997).

Material	Moisture, w-%	Net calorific value, MJ/kg		w-%, dry basis		
		As received	Dry basis	Volatile matter	Carbon, C	Ash
Newspaper	6.0	18.5	19.7	86.3	12.2	1.5
Wrapping paper	5.8	16.9	17.9	89.1	9.8	1.1
Magazine paper	4.1	12.2	12.7	69.2	7.3	23.4
Corrugated board boxes	5.2	16.4	17.3	81.7	12.9	5.3
Plastic-coated paper	4.7	17.1	17.9	88.4	8.9	2.8
Waxed cardboard	3.5	26.3	27.2	94.2	4.6	1.2
Food packaging cardboard	6.1	16.9	19.0	80.5	12.6	6.9
Liquid packaging cardboard	15.7	15.6	21.3	89.6	49.3	1.73
Liquid packaging cardboard (incl. aluminium)	6.13	21.8	23.4	82.8	51.9	9.0

Table 8.4. Waste paper properties (Thun & Korhonen 1999).

PROPERTY		**CONTENT ON A DRY BASIS, w-%**	
Moisture, %	3.9	Ash	28.2
CALORIFIC VALUE, MJ/kg		Volatile matter	64.5
Gross on a dry basis	12.5	Carbon, C	34.1
Net on a dry basis	11.6	Hydrogen, H	4.4
Net as received	11.0	Nitrogen, N	0.1
Chlorine Cl, mg/kg, dry basis	65	Sulphur, S	0.04

Table 8.5. Properties of different kinds of packaging, plastics, and fuels made from dry waste (Manninen et al. 1994, Vesterinen 1997).

Property	Ref. 1	PDF LPB 1	PDF LPB 2	PDF MP	PDF PE	PDF PE	PDF PET	PDF Ekor	RDF ASJ	RDF ASJ	RDF ASJ
Thermal percentage, %		13			19		19	26	12	26	
Moisture, w-%	43.5*	40.3*			39.0*		36.7*	37.2*	41.9*	38.9*	
CONTENT ON A DRY BASIS, w-%											
Volatile matter	6.7	61.1			64.2		68.4	61.4	59.6	61.6	
Ash	5.8	6.1	2.8	18	5.8	0.6	4.7	8.5	7.8	9.1	14.5
Carbon, C	60.1	59.3			57.7		55.1	53.4	58.9	53.7	
Hydrogen, H	5.5	5.6			6.7		6.1	6.0	5.5	6.0	
Nitrogen, N	1.0	1.1	0.17	0.80	1.6	0.25	1.6	1.6	1.2	1.6	1.13
Sulphur, S	0.37	0.36	0.02	0.08	0.35	0.01	0.27	0.36	0.37	0.37	0.14
Oxygen, O (difference)	27.2	27.5			27.7		32.1	29.9	26.1	29.0	
Chlorine, Cl	0.06	0.07	0.06	0.00013	0.10	0.54	0.11	0.33	0.18	0.29	0.86
Cadmium, Cd			< 0.0001	0.0026		0.0006					1
Chromium, Cr			0.001	0.013		0.001					100
Copper, Cu			< 0.001	0.0020		< 0.001					140
Mercury, Hg			< 0.000005	< 0.0001		0.00009					0.12
Lead, Pb			0.003	0.0019		0.002					300
Tin, Sn			< 0.001	0.003		< 0.001					< 10
Zinc, Zn			0.0020	0.023		0.015					500
CALORIFIC VALUE, MJ/kg											
Gross, dry basis	23.0	22.7			24.0		22.0	21.6	22.5	21.9	
Net * dry basis * as received	21.8	21.5	19.6 16.6	31.8 19.4	22.6	26.5 25.7	20.7	20.3	21.3	20.6	18.6 11.4

* Moisture content analysed from wet weight
Ref. 1 = peat / coal / wood chip blend
PDF = packaging-derived fuel
LPB = liquid packaging board,1 production waste and 2 collected from consumers
MP = mixed plastics collected from consumers
RDF = refuse-derived fuel
ASJ = fuel supplied by Ab Avfallsservice Stormossen Jätehuolto Oy
Ekor = combustible waste sorted by households (supplied by Ekorosk)
PE = polyethylene collected from consumers
PET = polyethylene terephthalate, drinks bottles collected from consumers

Table 8.6. Properties of different kinds of packaging-derived fuels and dry waste collected from the Helsinki Region (Vesterinen 1997, Manninen et al. 1984, Manninen 1996).

Property	Ref.	LPB	LPB-Al	Stormossen-REF	YTV 1	YTV 2	YTV 3	YTV 4
Moisture, w-%	32.0	15.7	6.13	38.8	39.7	11.5	41.5*	
CONTENT ON A DRY BASIS, w-%								
Volatile matter	68.6	89.6	82.7	75.7	73.7	75.7	57.7	
Ash	3.83	1.73	9.22	13.3	12.6	14.3	8.2	15.8
Carbon, C	55.8	49.3	51.3	49.6	45.6	48.7	59.5	
Hydrogen, H	5.62	6.84	7.61	6.92	6.17	6.90	5.4	
Nitrogen, N	5.72	0.04	0.25	0.95	0.99	0.88	1.3	1.19
Sulphur, S	0.16	0.07	0.08	0.15	0.20	0.2	0.40	0.17
Oxygen, O (difference)	0.05	0.05	0.02	0.46	0.32	0.52	0.20	1
Chlorine, Cl								0.0002
Cadmium, Cd								0.013
Chromium, Cr								0.007
Copper, Cu								0.00019
Mercury, Hg								0.026
Lead, Pb								< 0.001
Tin, Sn								0.067
Zinc, Zn	0.05	0.05	0.02	0.46	0.32	0.52	0.20	1
CALORIFIC VALUE, MJ/kg								
Gross, dry basis	22.6	20.3	25.1	20.9	18.6	21.7	22.8	
Net * dry basis * as received	21.3	18.9	23.4	19.3	17.4	20.4	21.6	18.6 11.6

Ref. = peat
LPB = liquid packaging board
LPB-Al = liquid packaging board containing aluminium
Stormossen-REF = Recovered fuel supplied by Stormossen

YTV 1 = SRF produced by Neste Oy from waste supplied by Helsinki Metropolitan Area Council (YTV)
YTV 2 = SRF produced by Maa- ja Vesi Oy from waste supplied by Helsinki Metropolitan Area Council (YTV)
YTV 3 = Crushed, manually sorted packaging waste supplied by Helsinki Metropolitan Area Council (YTV)
YTV 4 = Crushed, manually sorted dry municipal solid waste supplied by Helsinki Metropolitan Area Council (YTV)

Plastics account for approximately 5% of the total weight of separately collected MSW in Finland. Almost 717,000 tonnes of packaging was used in 2013, of which 58% was recycled. Paper, cardboard, containerboard, and plastics made up 53% of commercial packaging in 2013 (Pirkanmaa Centre for Economic Development, Transport and the Environment, www.environment.fi). After use, packaging material can be reused as raw material for new products or recycled as energy. Discarded plastics break down slowly in the environment and are a problem aesthetically. Plastics are made from oil, and the raw material consists of one or more hydrocarbon polymers, potentially strengthening agents, as well as various kinds of fillers and alloying elements. Plastic has an extremely high calorific value (20–46.5 MJ/kg) (Table 8.7).

The most commonly used packaging plastic is polyethylene (PE). Large volumes of polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) and moderate volumes of polyamide (PA) and polyvinyl chloride (PVC) are also used. PVC is a problematic plastic in power plant boilers, as it contains 57% of chlorine (Alakangas 1992).

Identifying plastics is difficult, and one method is combustion testing. Combustion testing allows plastics to be identified on the basis of e.g. the colour and odour of the smoke. Polyethylene melts before it ignites, and it produces a light-coloured smoke with an odour that resembles that of a candle. Polystyrene and polyethylene terephthalate produce dark smoke when burnt. PVC has a pungent odour, and the smoke is dark in colour. Many plastic packaging materials carry labels that make them easier to identify (Table 8.7). They are difficult to identify when mixed with waste.

Table 8.7. Identifying characteristics and combustion properties of different plastics (KWH Plast).

Plastic	Volume and colour of smoke	Flammability compared to wood	Burning droplets	Calorific value on a dry basis, MJ/kg	Flash point, ºC	Autoignition temperature, ºC
Polyethylene, PE 04 PE-LD 02 PE-HD	Low, light	High	Yes	46.0	320	350
Polypropylene, PP 05 PP	Low, light	High	Yes	46.5	340	350
Hard polyvinyl chloride, PVC 03 PVC	Moderate, grey	Low	No	20.0	400	450
Soft PVC	High, grey	Low	No	20–30	330–400	420–430
Polystyrene, PS 06 PS	High, dark	High	Yes	42.0	350	490
Polyesters 06 PS	Moderate, dark	Resin: high	No	6.0–18.0	32 (resin)	490 (resin)

Polyesters: unsaturated polyester resins

Resin: liquid, unhardened polyester resin

Fuel made from the combustible fractions of MSW (SRF, RDF) has a calorific value of 10–15 MJ/kg as received. The net calorific value of industrial waste mostly consisting of packaging is higher on an as-received basis than that of dry municipal solid waste (14–18 MJ/kg). If different plastics are collected, the calorific value of the mixture is 31.8 MJ/kg, while that of waste consisting exclusively of polyethylene is 39.8 MJ/kg. Due to impurities, the calorific value of polyethylene waste collected from consumers is slightly lower than that of clean polyethylene (46 MJ/kg). Plastic waste has low ash content (0.6–3.2%).

8.3 Refuse-derived pellets

Pelletisation is recommended for eliminating the disadvantages of fluff. Pellets guarantee a homogeneous fuel with handling properties comparable to those of wood chips and sod peat. The refuse-derived pellet plant of Ewapower Oy in Pietarsaari produces fuel pellets from combustible waste separated from kitchen residue as well as from combustible industrial waste (Table 8.8).

Table 8.8. Properties of REF pellets (Ajanko et al. 2005, Vesterinen 1995 and 1997).

Fuel	**REF pellets** Ajanko	**REF pellets** Vesterinen
Moisture, %		2.5–4.5
CALORIFIC VALUES, MJ/kg		
Gross on a dry basis Net on a dry basis Net as received		23–26 22–25 21–24
CONTENT ON A DRY BASIS, w-%		
Ash		4–10
Carbon, C		52–58
Hydrogen, H		6.5–8.5
Nitrogen, N	0.45	0.5–1.5
Sulphur, S	0.11	0.10–0.20
Chlorine, Cl	0.65	0.3–0.9
METALS ON A DRY BASIS, mg/kg		
Arsenic, As	8.7	1.7–2.7
Cadmium, Cd	1.3	0.1–4.0
Chromium, Cr	37	0.75–44
Copper, Cu	82	45–51
Lead, Pb	47	50–100
Zinc, Zn	270	140–290
Mercury, Hg	0.07	
METALS ON A DRY BASIS, g/kg		
Aluminium (total), Al		4.5–10
Magnesium, Mg		0.6–1.5
Potassium, K		1.2–2.5
Calcium, Ca		8–21
Sodium, Na		2–3.5
Potassium + Sodium, K + Na	0.24	
Nickel, Ni	4.2	
Cobalt, Co	5.6	
Vanadium, V	4.2	
Antimony, Sb	12	
Thallium, Tl	< 1	
Manganese, Mn	110	

8.4 Industrial and construction waste

VTT has studied the properties of many different kinds of industrial and municipal refuse-derived fuels. The following tables list results of the analyses (Tables 8.9–8.12).

Table 8.9. Results of VTT's SRF analyses on different kinds of combustible fractions collected primarily from the industrial sector (Alakangas 2000).

Fuel	Industrial waste (packaging)	Dry household waste	Fraction 1	Fraction 2	Fraction 3	Fraction 4	Average of the fractions
Moisture, %	19.5	29.3	6.73	13.3	22.7	18.5	18.3
CALORIFIC VALUES, MJ/kg							
Gross on a dry basis	24.9	23.3	18.3	21.3	21.0	21.1	21.7
Net							
* dry basis	23.2	21.7	17.0	19.8	19.6	19.6	20.2
* as received	18.2	14.6	15.7	16.9	14.6	15.5	15.9
CONTENT ON A DRY BASIS, w-%							
Carbon, C	54.7	53.	45.2	49.6	50.0	49.6	50.4
Hydrogen, H	7.76	7.41	5.90	6.74	6.76	6.74	6.89
Nitrogen, N	0.42	0.80	0.26	0.27	0.37	0.21	0.39
Sulphur, S	0.07	0.17	0.16	0.14	0.28	0.14	0.16
Chlorine, Cl	0.24	0.78	0.06	0.12	0.34	0.12	0.28
Ash	5.53	13.8	6.22	5.36	9.06	5.89	7.64
METALS ON A DRY BASIS, mg/kg							
Arsenic, As	4.38	14.2	0.70	0.54	0.49	2.76	3.85
Cadmium, Cd	< 0.2	< 0.2	< 0.2	< 0.2	< 3	< 3	-
Chromium, Cr	7.66	62.4	8.57	5.74	< 20	< 20	21.1
Copper, Cu	14.5	522	21.8	24.2	24	21	104.6
Lead, Pb	12.1	136	11.9	9.5	< 20	< 20	42.4
Zinc, Zn	56.2	537	59.1	75.8	51	59	139.7
Mercury, Hg	0.010	0.16	0.063	0.012	0.008	0.030	0.047
METALS ON A DRY BASIS, g/kg							
Aluminium, Al	2.95	11.0	7.04	4.70	7.06	2.58	5.89
Magnesium, Mg	0.98	1.74	1.60	1.11	1.09	0.78	1.22
Potassium, K	1.49	3.77	0.31	0.52	1.16	0.74	1.33
Calcium, Ca	14.5	14.7	6.32	6.69	14.9	5.12	10.4
Sodium, Na	4.50	4.95	0.93	1.18	4.19	1.56	2.89

Table 8.10. Properties of solid recovered fuel produced from separately collected industrial and commercial waste (Vesanto et al. 2007).

PROPERTY	**Average**	**Median**	**Number of analysis results**
Moisture, w-%	18.2 (5.9)	17.7	159
Net calorific value as received, MJ/kg	16.7 (2.3)	16.0	159
CONTENT ON A DRY BASIS, w-%			
Ash	6.4 (2.2)	6.0	163
Chlorine, Cl	0.28	0.20	163
Sulphur, S	0.13	0.10	163
Nitrogen, N	0.71	0.66	163
Sodium + Potassium, Na + K	0.24	0.20	163
CONTENT ON A DRY BASIS, mg/kg			
Mercury, Hg	0.06	0.02	152
Cadmium, Cd	0.63	0.24	152
Zinc, Zn	360	310	37
Lead, Pb	59	37	40
Arsenic, As	5.3	3.3	21
Cobalt, Co	6.6	4.9	21
Chromium, Cr	110	68	21
Copper, Cu	870	180	21
Nickel, Ni	41	29	21
Vanadium, V	5.2	5.1	21
Antimony, Sb	140	110	21
Thallium, Tl	0.8	0.5	21
Manganese, Mn	105	99	21

The figures in brackets denote deviation.

Table 8.11. Properties of solid recovered fuel produced from industrial production waste (Vesanto et al. 2007).

PROPERTY	**Average**	**Median**	**Number of analysis results**
Moisture, w-%	8.4 (4.0)	7.6	55
Net calorific value as received, MJ/kg	22.3 (3.5)	22.1	55
CONTENT ON A DRY BASIS, w-%			
Ash	5.0 (1.9)	4.7	20
Chlorine, Cl	0.06	0.04	55
Sulphur, S	0.10	0.08	26
Nitrogen, N	0.88	0.83	22
Sodium + Potassium, Na + K	0.15	0.15	22
Mercury, Hg, mg/kg	0.008	0.006	21
Cadmium, Cd, mg/kg	0.03	0.02	22

The figures in brackets denote deviation.

Table 8.12. Results of VTT's analyses on different kinds of construction waste (Vesterinen 1995 and 1997).

Fuel	Construction waste	Railway sleepers[1]	Impregnated wood[2]	Laminate[3]	Layered board[3]
Moisture, %	15–35	45.6	23.4	1.93	2.20
CALORIFIC VALUES, MJ/kg					
Gross on a dry basis	20–21	21.1	20.2	17.4	20.4
Net					
* dry basis	18.6–19.5	19.8	18.9	16.7	19.3
* as received	11.2–15.6	9.6	13.9	16.3	18.8
CONTENT ON A DRY BASIS, w-%					
Volatile matter		81.7	82.7	55.9	69.4
Ash	1.7–2.6	4.0	1.4	42.7	21.3
Carbon, C	49–51	52.3	50.4	39.2	51.7
Hydrogen, H	6–6.5			3.4	5.0
Nitrogen, N	0.1–0.8	0.19	0.13	0.01	0.5
Sulphur, S	0.01–0.2	0.07	0.02	0.0	0.0
Chlorine, Cl	0.01–0.1	0.008	0.009	0.03	0.01
CONTENT ON A DRY BASIS, mg/kg					
Arsenic, As	0.8–70	5.5	3,214		
Mercury, Hg		0.13	0.15		
Cadmium, Cd		< 0.1	0.31		
Cobalt, Co		1.97	< 0.2		
Chromium, Cr		21.8	5,272		
Copper, Cu		6.1	1,911		
Lead, Pb		2.37	1.80		
Manganese, Mn		115	81		
Nickel, Ni		7.79	3.55		
Zinc, Zn		19	12.1		
CONTENT ON A DRY BASIS, g/kg					
Potassium, K	0.5–1.0	0.84	0.20		
Sodium, Na	0.5–1.0	0.72	0.068		

[1] impregnated with creosote [2] primarily electric poles impregnated with copper, chromium, and arsenic

[3] contains glass fibre

Nasrullah (2015) has studied the material and energy balances of SRF production based on municipal solid waste, commercial and industrial waste, and construction and demolition waste. Properties of these waste fractions and SRF produced from the same are listed in Tables 8.13 and 8.14.

Table 8.13. Properties of different waste fractions and solid recovered fuels produced from the same (Nasrullah 2015).

Property	MSW → SRF		C&IW → SRF		C&DW → SRF	
	Municipal solid waste	Product	Commercial and industrial waste	Product	Construction and demolition waste	Product
Moisture, w-%	13.5	15.0	26.5	25.0	14.0	16.5
CONTENT ON A DRY BASIS, w-%						
Ash (550 ºC)	22.4	9.8	16.6	12.5	46.8	9.0
Carbon, C	47.0	53.0	48.0	57.4	30.0	50.0
Hydrogen, H	6.2	7.4	7.0	8.0	4.0	6.4
Nitrogen, N	0.5	0.6	0.6	0.5	0.5	1.0
Sulphur, S	0.2	0.2	0.2	0.3	0.7	0.3
Oxygen, O (difference)	19.6	28.0	18.0	17.8	17.0	31.6
NET CALORIFIC VALUE, MJ/kg						
As received	16.7	20.2	13.0	18.0	9.8	18.0
Dry basis	19.6	22.4	18.5	25.0	11.0	20.0

MSW = municipal solid waste
C&IW = commercial and industrial waste
C&DW = construction and demolition waste
SRF = solid recovered fuel

Table 8.14. Elementary analysis of different waste fractions and solid recovered fuels produced from the same on a dry basis (Nasrullah 2015).

	MSW → SRF		C&IW → SRF		C&DW → SRF	
	Municipal solid waste	Product	Commercial and industrial waste	Product	Construction and demolition waste	Product
CONTENTS, w-%						
Chlorine, Cl	1.5	0.6	0.6	0.6	0.6	0.4
Fluorine, F	0.01	0.01	0.007	0.01	0.01	0.004
Bromine, Br	0.002	0.004	0.005	0.003	0.005	0.003
Sulphur, S	0.2	0.2	0.2	0.3	0.7	0.3
CONTENTS, mg/kg						
Sodium, Na	7,920	1,590	2,990	3,460	8,370	1,470
Potassium, K	3,530	920	2,150	2,175	6,120	1,080
Calcium, Ca	30,625	28,925	18,530	36,260	58,050	17,150
Magnesium, Mg	2,960	1,390	1,590	1,480	5,940	1,270
Phosphorus, P	380	340	870	960	315	520
Aluminium, Al	12,400	6,260	7,300	8,200	18,090	4,800
Silicon, Si	41,500	9,240	22,180	18,870	51,660	12,150
Iron, Fe	6,680	1,390	4,400	4,840	7,560	1,275
Titanium, Ti	2,480	1,990	3,090	3,160	1,530	1,275
Chromium, Cr	150	370	290	50	135	35
Copper, Cu	1,240	270	5,800	375	660	350
Manganese, Mn	105	55	110	80	270	70
Nickel, Ni	50	11	20	20	38	8.0
Zinc, Zn	560	230	4,120	335	400	175
Antimony, Sb	70	540	7.2	50	42	84
Arsenic, As	3.4	0.7	5.0	1.8	15	6.6
Barium, Ba	468	280	290	290	260	138
Cadmium, Cd	1.0	0.7	1.2	0.6	1.5	4.4
Cobalt, Co	3.6	3.4	2.4	3.6	6.0	2.8
Lead, Pb	280	30	90	120	135	42
Molybdenum, Mo	12.4	3.2	3.0	3.6	4.8	1.5
Selenium, Se	1.2	0.5	0.5	0.5	1.8	2.7
Thallium, Tl	0.5	0.5	< 0.5	< 0.5	0.5	0.5
Tin, Sn	26	12	8.8	18.8	13.5	14.7
Vanadium, V	20	8.0	6.0	5.3	23.4	4.0
Mercury, Hg	0.15	0.1	0.1	0.1	0.2	0.2

MSW = municipal solid waste
C&IW = commercial and industrial waste
C&DW = construction and demolition waste
SRF = solid recovered fuel

8.5 Automotive shredder residue and scrap tyres

VTT has also studied the properties of automotive shredder residue and its suitability for gasification (Nieminen et al. 2006). Approximately 75% of the material content of cars is metal, which can be recycled to provide raw material for new products. After metals, the largest groups of materials in cars are plastics, which account for 9.1% on average, and rubber, which accounts for approximately 6%. Other materials include glues, paints, glass, textiles, liquids, and other substances. The terms *shredder residue* (SR) and *automotive shredder residue* (ASR) are used depending on the origin of the waste.

Table 8.15 lists average compositions of automotive shredder residue. The materials originated from Finnish and a foreign supplier. Although the number of samples was too small to draw clear conclusions from the analyses, they nevertheless illustrate how the properties of ASR vary depending on the origin of the waste and how it has been processed. Figure 8.3 shows the average metal content of ASR on a dry basis, w-%.

Table 8.15. Average compositions of automotive shredder residue (Nieminen et al. 2006)

Origin of the waste	**Finnish SR**	**Foreign ASR**[1]	**Normal foreign SR**[3]	**Foreign SR-2005**[5]
Moisture, w-%	3.9	3.1	8.3	12.9
Dry basis, w-%				
Volatile matter	32.6	54.7	33.8	60.1
Fixed carbon	< 0.1	2.2	0.0	6.6
Ash	69.6	43.1	69.4[4]	33.4
Dry basis, w-%				
Carbon, C	19.1	42.2	20.6	50.2
Hydrogen, H	2.2	5.3	2.6	5.9
Nitrogen, N	0.6	1.4	0.7	1.3
Sulphur, S	0.26	0.37	0.28	0.24
Oxygen, O (as difference)	8.2	7.7	6.6	9.1
Dry basis, mg/kg				
Chlorine, Cl	Not analysed	17,000	9,000	25,000
Bromine, Br	Not analysed	< 50[2]	260	2,100
Fluorine, F	Not analysed	270[2]	340	350
Mercury, Hg	2.0	0.8[2]	1.3	1.6
Net calorific value on a dry basis, MJ/kg	8.5	14.9[2]	9.4	21.3

[1] Raw material: 100% ELV (end-of-life vehicles)

[2] Only one analysed sample

[3] Raw material: 20% ELV + 80% scrap metal

[4] The high ash content is due to the oxidation of metals.

[5] Raw material: 20% ELV + 80% scrap metal (*advanced* processing)

SR = shredder residue

ASR = automotive shredder residue

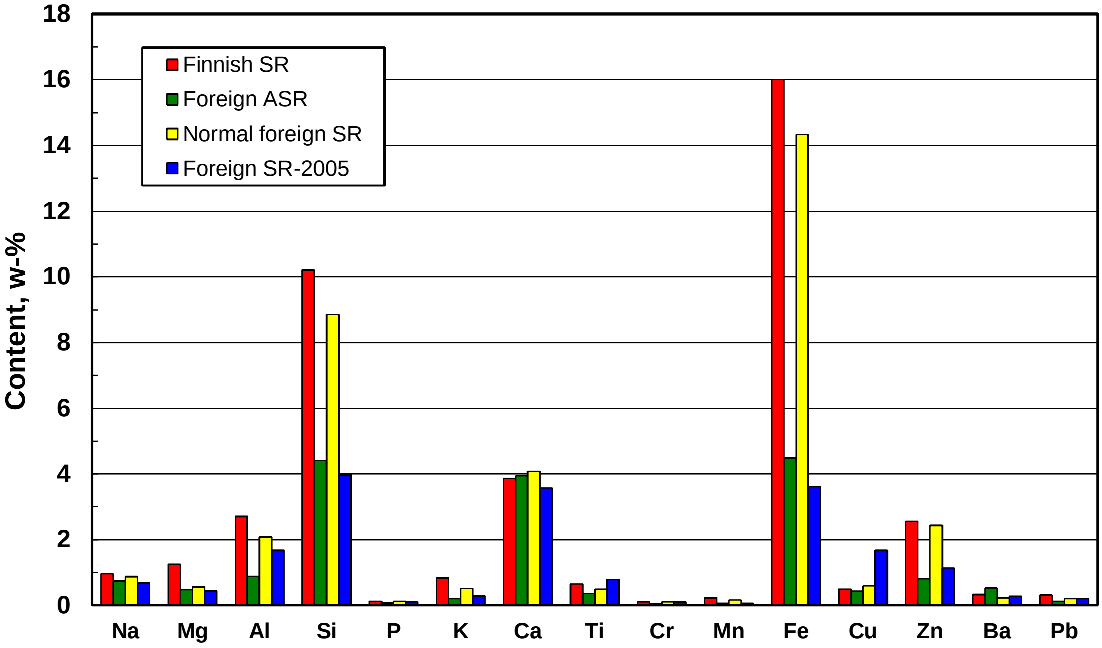


Figure 8.3. Average metal content of automotive shredder residue on a dry basis, w-%. Figure: VTT.

Using scrap tyres – whole or shredded – to fuel cement kilns is relatively common. In a cement kiln, the inorganic material in tyres is mixed into the clinker. Shredded tyres can be used in fuel blends. Shredding tyres requires a high amount of energy, and steel wires in large tyres are especially problematic. They cause problems in feeding equipment and during ash removal. Other inorganic material in tyres (ZnO) is usually mixed into ash from the main fuel and can cause problems in that way. The calorific value of scrap rubber is 30 MJ/kg and that of shredder waste is 10–20 MJ/kg (Ranta 1999). Properties of scrap tyres are listed in Table 8.16.

Table 8.16. Fuel properties of scrap tyres (Ranta 1999).

Property	Coarse rubber	Shredded tyres	Automotive shredder residue
Moisture, %	0.5	1	6 (range 1–25)
Density, kg/m^3	390	400	300–400
Net calorific value, MJ/kg, dry basis	39	32	10–40 as received
CONTENT ON A DRY BASIS, w-%			
Ash	4.3	12	
Carbon, C			30
Hydrogen, H			3.7
Oxygen, O			7
Sulphur, S	1.9	1.2	0.3–0.8
Chlorine, Cl	0.03		1–2
Iron, Fe			13
Silicon, Si			9.5

Excluding steel, the composition of ash from scrap tyres in an oxidising atmosphere is as follows (approximate values): Al_2O_3 5.8%, Fe_2O_3 0.3%, TiO_2 0.8%, ZnO 48%, CaO 1.8%, K_2O 1.4%, SiO_2 30%, and SO_3 6.6% (Energy Potential of Industrial By-products 1988).

8.6 Properties of landfill waste

VTT has also studied the properties of waste taken to a 10-year-old 30-metre landfill site (Kaartinen et al. 2013). The waste samples, which were between five and 10 years old, were taken by drilling to three different depths. The sample sizes varied between 3.4 and 11.0 tonnes. The samples were screened and sorted both manually and mechanically. Table 8.17 lists properties of samples of more than 20 mm and more than 70 mm. The fractions of more than 20 mm had the highest percentage of plastics, approximately 24% of the mass. Older samples contained less plastic. Based on manual sorting, 40–45 w-% of the material was potentially combustible. Metals accounted for 3–4 w-% according to manual screening. Mechanical screening successfully separated approximately 1 w-% of magnetic metals. Mechanical sorting gave the combustible fraction as approximately 30 w-%.

Table 8.17. Properties of landfill waste (Kaartinen et al. 2013). The figures in brackets denote deviation.

Property	**Samples (particle size > 20 mm)**		**Samples (particle size > 70 mm)**	
	Middle layer	**Lowest layer**	**Middle layer**	**Lowest layer**
Solids content, w-%	80 (3.5)	74 (3.5)	85	98
CALORIFIC VALUE ON A DRY BASIS, MJ/kg				
Gross	24 (1.1)	24 (0.64)	26	21
Net	22 (1.0)	22 (0.62)	25	20
CONTENT ON A DRY BASIS, w-%				
Aluminium, Al	1.5 (1.1)	2.2 (0.359)	1.2	1.5
Barium, Ba	0.03 (0.01)	0.02 (0.01)	0.06	0.005
Bromine, Br	< 0.01	0.02 (0.01)	0.01	< 0.01
Calcium, Ca	3.0 (0.71)	3.8 (0.14)	3.8	3.9
Chlorine, Cl	1.6 (1.2)	1.2 (0.0)	0.59	2.1
Chromium, Cr	0.01 (0.0)	0.01 (0.0)	0.01	0.02
Copper, Cu	0.04 (0.04)	0.04 (0.03)	0.01	0.04
Fluorine, F	< 0.01	0.06 (0.06)	< 0.01	< 0.01
Iron, Fe	1.1 (0.80)	2.0 (0.28)	1.9	2.0
Potassium, K	0.52 (0.32)	0.48 (0.13)	0.52	0.52
Magnesium, Mg	0.40 (0.14)	0.41 (0.01)	0.35	0.34
Manganese, Mn	0.03 (0.01)	0.04 (0.01)	0.04	0.04
Sodium, Na	0.71 (0.29)	0.60 (0.16)	0.52	0.45
Nickel, Ni	< 0.01	< 0.01	0.01	< 0.01
Phosphorus, P	0.10 (0.04)	0.01 (0.02)	0.08	0.1
Lead, Pb	0.03 (0.02)	0.03 (0.02)	< 0.01	0.03
Sulphur, S	0.57 (0.01)	0.65 (0.04)	0.9	0.71
Antimony, Sb	0.03 (0.02)	0.04 (0.04)	< 0.01	0.3
Selenium, Se	< 0.01	< 0.01	0.02	< 0.01
Silicon, Si	5.0 (3.9)	4.1 (1.8)	3.6	3.8
Strontium, Sr	0.02 (0.01)	0.01 (0.0)	0.01	0.02
Titanium, Ti	0.44 (0.03)	0.36 (0.04)	0.55	0.45
Zinc, Zn	0.10 (0.06)	0.06 (0.01)	0.09	0.07
Zirconium, Zr	< 0.01	0.01 (0.0)	< 0.01	0.01
Potassium + Sodium, K + Na	1.2	1.1	1.0	0.97

9. Sludges

Sludges originate from agriculture, industry, and municipal wastewater treatment plants. Animal husbandry is the biggest source of sludges (= manure). Sludges originating from the wood processing industry include e.g. primary sludge, biosludge, deinking sludge, and chemical sludge. The majority of common sludge originates from wastewater treatment plants. The volumes of cesspool and septic tank sludges are also considerable. The volume of wastewater treatment sludge generated per capita amounts to just over 100 g on a dry basis per day (see also Section 11.4). Common sludges and forest industry sludges amount to 600,000–700,000 tonnes per year on a dry basis (Lohiniva et al. 2001). In 2010, sludge generated at Finnish municipal wastewater treatment plants amounted to 142,700 tonnes on a dry basis (approximately 1 million tonnes on a wet basis). Common sludge is used as a soil conditioner (Häkkinen et al. 2014). Forest industry sludges amounted to 537,000 tonnes in 2014, and 332,000 tonnes of this was used to produce energy.

The aim is to deposit in each kind of sludge in as harmless a way as possible. Priority is given to making sludges usable. Sludges can be used either as material or by utilising their energy content. Forest industry sludges can be burnt or turned into fertilisers. Wastewater treatment sludges and agricultural sludges can be turned into biogas (see Section 12.4 Biogas) to produce electricity and heat.

Primary sludge (fibre sludge, primary clarification sludge) refers to sludge produced by settling during primary clarification. Primary sludges from the forest industry contain bark, fibres, bulking agents, additives, and pigments. Their quality depends on several factors, e.g. the production process. The ash content of sludge is dependent on the production process: Fine paper plant sludges contain 50–60% of ash, and pulp industry sludges have an ash content of 5–20 w-%. Moisture content varies between 60 and 65 w-% and net calorific value at the operational moisture level between 4 and 6 MJ/kg (Isännäinen & Huotari 1994).

Biosludge, i.e. activated sludge, is sludge produced by the biological treatment of wastewater. Forest industry biosludge is comparable to municipal sewage sludge (see Tables 9.1 and 9.2). In addition to microbial mass, it contains wood extractives, lignin compounds, and adsorbed chloro-organic compounds. Biomass accounts for 65–75 w-% of biosludge when using the activated sludge method, and the ash content is 5–50 w-%. Nutrient contents are lower than in municipal sewage sludge. Problems stem from the impurities found in biosludges, which may become concentrated in the liquor cycle (Isännäinen 1993, Vakkilainen 1993).

Debarking plants produce many different kinds of sludges, e.g. bark sludge, sand sludge from the sand separator, and sludge from the clarifier. Bark is processed using bark presses and sludge from the clarifier using water separators. The blend is burnt in a bark boiler or sometimes taken to a landfill site. The proportion of debarking sludge varies 0.5–8 kg/tree-m^3. The proportion depends on the type of debarking plant, the feeding method, the wood species, and storage conditions (Isännäinen & Huotari 1994).

Deinking sludge is generated by the deinking of recycled paper, which involves removing printing ink, fillers, and coatings from waste paper, leaving recycled fibre. The volume of deinking sludge produced is 50–205 kg/product tonne, and it mostly consists of ash and fibres. The volume of sludge depends on the quality of the recycled paper. The average solids content of deinking sludges is more than 40%, and their ash content varies between 30% and 60% depending on the quality of the paper and the deinking technology used. The maximum net calorific value on a dry basis is just 15 MJ/kg. Deinking sludge contains 0.1–0.3 w-% sodium, 0.2–0.5 w-% potassium, and 0.2–0.6% chlorine on a dry basis (Table 9.1).

Table 9.1. Properties of different kinds of sludges (Isännäinen 1993, Niittymäki 1993).

Property	Pulp mill mixed sludge	Primary sludge	Paper mill mixed sludge	Biosludge	Deinking sludge	Debarking plant sludge
Moisture, w-%	75–80	70		85	60	70
CONTENT ON A DRY BASIS, w-%						
Ash	16–21	0.4	12–20	16	30–60	2.5
Carbon, C	40–42	44	44–46	47	25–45	50
Hydrogen, H	4.5–5.0	6	5.5–6.0	5.2	4–5.5	6
Sulphur, S	0.4–0.9	0.1	0.05–0.1	1.2	0.1–0.3	0.02
Nitrogen, N	1.3–1.6	0.4	0.5–0.7	1.6	0.1–0.3	0.8
Oxygen, O	25–29	25		30	22	34
Chlorine, Cl	0.1–0.6		0.0-0.1		0.2–0.6	
Net calorific value on a dry basis, MJ/kg	14–16	13.5		17.4	8–13	3.0
Net calorific value as received, MJ/kg	9.3	2.3		0.5	2.9	

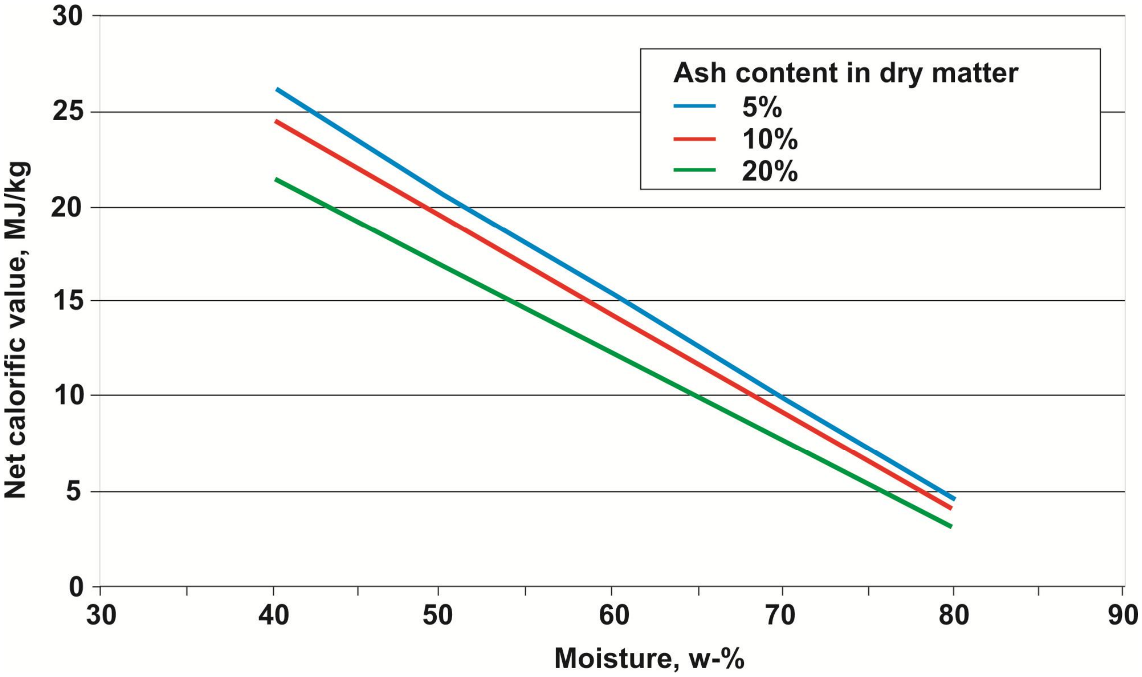


Figure 9.1. Calorific value of sludge at the operational moisture level (MJ/kg) as a function of sludge moisture and ash content (Lohiniva et al. 2001). Figure: VTT.

Sludges can be combusted in rotary kilns, fluidised bed boilers, recovery boilers, mass burn plants, and grate boilers, gasified on their own or mixed with a primary fuel. Forest industry sludges are commonly burnt in fluidised bed boilers mixed in with other fuels (usually less than 10 w-% of thermal input). Biosludge can also be combusted in recovery boilers. Mechanically dried biosludge is mixed with weak black liquor and concentrated as normal in an evaporation plant (Lohiniva et al. 2001).

Combustibility depends on e.g. the ash content and moisture of sludge (Figure 9.1). In Finland, 60% of forest industry sludges are burnt. Burning makes sludges easier to process and takes up less space. No energy can usually be recovered from the combustion of sludge. Moisture and the composition of sludge affect the combustion process. In order to be able to maintain combustion, the net calorific value of a fuel must be at least 5 MJ/kg, which means that, in practice, sludge almost always requires a base fuel. Bark is a typical base fuel for sludge. If the solids content of sludge can be raised high enough, sludge can also be burnt without a base fuel. Depending on the combustion technique, a solids content of 30–50% is required.

Solids content can be raised by means of mechanical water separation. A filter belt press achieves a solids content of 10–50%, spin dryers a solids content of 10–30%, and screw presses a solids content of 20–40%. Filter belt presses are capable of raising the solids content of forest industry primary sludges to 20–50% and that of biosludges to 10–20%. A suction filter can be used to dry primary and mixed sludges to a solids content of 15–25% (Isännäinen 1993, Lohiniva et al. 2001). Factors affecting the combustibility and calorific value of sludge are listed in Table 9.2

Table 9.2. Properties of forest industry sludges (Kyllönen et al. 2010).

Property	WAS 1	WAS 2	WAS 3	WAS from wastewater treatment plants	Tertiary sludge from the forest industry
Solids content, w-%	3.7	1.4	0.8	0.4	1.2
pH	7.0	7.9	8.0	7.2	6.5
Average particle size, D50, mm	0.053	0.069	0.063	0.066	0.034
CONTENT ON A DRY BASIS, w-%					
Ash	25.0	20.0	40.0	30.0	37.0
Carbon, C	40	43	31	27	36
Hydrogen, H	5.2	5.6	3.8	4.6	4.9
Nitrogen, N	3.8	5.1	3.8	5.2	4.9
Sulphur, S	1.2	1.7	3.6	1.7	3.7
Sodium, Na	0.7	1.3	9.6	1.9	3.8
Phosphorus, P	0.5	0.5	0.5	1.8	0.6
Aluminium, Al	2.8	0.9	0.3	1.4	3.1
Chlorine, Cl	0.1	0.1	8.0	1.2	1.2
Iron, Fe	0.4	0.2	0.4	14.0	2.0

WAS = waste activated sludge (biosludge)

Forest industry sludges typically contain relatively low levels of heavy metals compared to municipal sewage sludge, and there are usually no pathogenic microbes (Tables 9.3–9.4). However, they contain various chlorine compounds produced in the bleaching process the exact quantity and quality of which are not known. Non-chlorine bleaching lowers the volume of chlorine compounds in sludge and reduces the potential harmful effects, which today are considerably fewer than before. The volume of absorbable organic halogens (AOX) contained in forest industry wastewater amounted to an average of 0.12 kg per one tonne of bleached pulp in 2014, while it was 1.12 kg in 1999. AOX is the total concentration of chlorine bound to organic compounds in waste water. The volume of chlorine compounds found in sludges has decreased at a corresponding rate (Isännäinen 1993, Lohiniva et al. 2001, http://www.forestindustries.fi).

The ash content of sludges and the levels of ash-forming minerals vary considerably depending on the process used (Table 9.5) in industry. For example, the high levels of ash-forming minerals found in deinking sludge are often the result of the deinking process (fillers in paper). (Lohiniva et al. 2001)

Table 9.3. Average heavy metal contents of different kinds of sludges on a dry basis, mg/kg (Isännäinen 1993, Lohiniva et al. 2001).

Property	Primary sludge	Biosludge	Pulp plant mixed sludge	Deinking sludge	Manure	Sewage sludge
Cadmium, Cd	0.0–2.5	0.6-0.9		0.03–0.1	0.3	2.9–4.3
Chromium, Cr		16–22	38.4	17–116	5.3	102–150
Copper, Cu	3.4–31	15–43	22.9	38–253	40	300–319
Mercury, Hg	0.0–0.2	0.6	0.09	< 1.0	0.1	1.4–2.2
Nickel, Ni	7.0–26.7	6–11		10–231	7.5	55–80
Lead, Pb	0.0–15.5	0.3–4.3	13.5	1.2–5.5	6.5	

Table 9.4. Heavy metal contents of ash from forest industry bark boilers, green liquor dregs, and biosludge, mg/kg (Thun & Korhonen 1999).

Material	Arsenic, As	Cadmium, Cd	Copper, Cu	Chromium, Cr	Nickel, Ni	Lead, Pb	Zinc, Zn
Wood ash	5–33	90–320	90–320	70–560	45–390	5–140	900–3,000
Green liquor dregs	< 5	3.5–22	110–250	170–520	100–330	5-30	1,400–2,200
Biosludge	< 5	0.5–4	9.3–60	17–65	7–40	5–13	90–510

Table 9.5. Properties of ash from different kinds of sludges (Lohiniva et al. 2001).

Sludge	Common sludge	Deinking sludge	Deinking sludge, biosludge, and fibre sludge	Biosludge / fibre sludge	Bark
CONTENT IN ASH, w-%					
P_2O_5	13.1	0.37	0.6		1.3
SiO_2	19.4	32.7	38.1		50.9
Fe_2O_3	18.0	5.8	1.3		2.3
Al_2O_3	6.3	16.3	22.1	2.6	7.7
CaO	20.6	33.4	28.1	2.0	22.1
MgO	1.5	4.0	4.6	7.4	2.6
Na_2O	0.5	0.7	0.3	7.1	1.3
K_2O	0.7	1.0	0.8	2.9	5.0
TiO_2	-	-	0.6		0.5
Sulphur, S	1.3		0.3	1.1	0.5
Chlorine, Cl	0.07		0.10	0.60	0.0
Sphere temperature, ST, °C			1,150	1,170	1,190
Hemisphere temperature, HT, °C			1,230	1,210	1,265
Flow temperature, FT, °C			1,290	1,220	1,340

10. Fast pyrolysis oil

Liquid fuel produced by means of fast pyrolysis is estimated to be the most techno-economically profitable biofuel for replacing fossil heating oils. Fast pyrolysis involves heating biomass, e.g. wood, to a high temperature (approximately 500 °C) in the absence of oxygen extremely quickly (in less than two seconds), which causes the majority of the wood material to convert into gases and aerosols which are liquefied in a gas condenser. Fast pyrolysis converts approximately 76% of dry wood into oil. Other products, uncondensed gases and carbon residue, are usually used as energy in the process (Oasmaa et al. 1997). Figure 10.1 shows the bio-oil production process in a combined heat and power (CHP) plant by means of integrated pyrolysis.

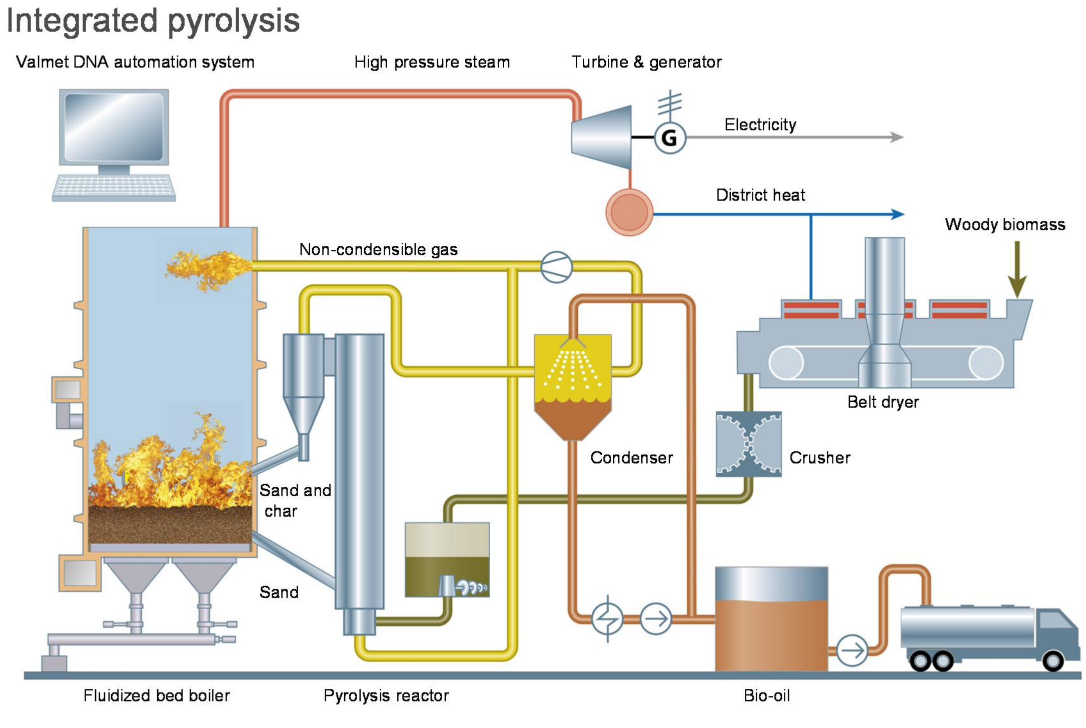


Figure 10.1. Bio-oil production in a CHP plant by means of integrated pyrolysis. Figure: Valmet Corporation.

Fast pyrolysis oil has completely different properties compared to fossil fuels, other bio-oils, or tar produced by slow pyrolysis. Fast pyrolysis oil is a brown, acidic liquid, which smells of tar and dissolves in polar solvents, such as alcohols, but not in hydrocarbons like mineral oils. The calorific value of fast pyrolysis oil is twice as high as that of wood. The resulting liquid typically contains approximately 25 w-% of chemically dissolved water and approximately 45–50 w-% of oxygen. Fast pyrolysis oil has a high density and a low calorific value, and its viscosity is between that of heavy and light fuel oil.

Fast pyrolysis oil contains hundreds of chemical compounds. The oil contains hardly any hydrocarbons, and the main compounds are, in addition to water, organic acids (acetic acid and formic acid), aldehydes, ketones, phenol derivatives, sugar-like compounds, and other various products of carbohydrate breakdown. The oil also contains a substantial volume (typically 25 w-%) of heavy (mostly lignin-based) molecules.

Pyrolysis oil is not as stable as mineral oils, which is evidenced, for example, by its increasing viscosity over time and especially under heating (Oasmaa et al. 2015a).

Table 10.1 compares the properties of typical fast pyrolysis oil to those of Finnish mineral oils (Lehto et al. 2013, Oasmaa et al. 2015b). More detailed information about the composition of fast pyrolysis oils produced from different raw materials can be found e.g. in Oasmaa & Peacocke 2010, Oasmaa et al. 2010, and Table 10.2.

Biofuels must comply with the EU's sustainability criteria and greenhouse gas emission reduction targets in order to count them towards meeting biofuel requirements and to receive excise tax benefits on the basis of low emissions. Compliance with the requirements is strictly monitored. Suppliers who introduce fuels to the market report to their respective Member States, which in turn report to the European Commission. The basic rule is that biofuel cannot be produced from raw materials originating from areas of high biodiversity (conservation areas, old-growth forests, etc.) or from high-carbon soils (bogs, wetlands, certain kinds of forests). Moreover, the use of biofuels must achieve lower greenhouse gas emissions compared to fossil fuels. Pursuant to the Renewable Energy Directive, the drop in emissions must be at least 35%. This criterion will be made even stricter in the next few years, when the so-called ILUC (Indirect Land Use Change). Directive (2012/0288(COD)) on biofuels enters into force definitively and the resulting changes are incorporated into both the Fuel Quality Directive (FQD, Directive 98/70/EC) and the Renewable Energy Directive (RES, Directive 2009/28/EC).

Table 10.1. Composition of typical fast pyrolysis oils (bio-oils) and comparison to mineral oils (Lehto et al. 2013, Oasmaa et al. 2015b).

Property	Standard (see Appendix D)	Typical bio-oils	Heavy fuel oil 180/420	Light fuel oil
Solids, %	ASTM D 7579	< 0.5		
pH	ASTM E 70	2–3		
Water content, w-%	ASTM E 203	20–30	~ 0	~ 0
Viscosity (40 ºC), mm^2/s (cSt)	EN ISO 3104, ASTM D 445	15–35[1]	max 180/420 50 ºC	2.0–4.5
Density (15 ºC), kg/dm^3	EN ISO 12185, ASTM D 4052	1.10–1.30[1]	max 0.99/0.995	max 0.845
Total acid number (TAN), mg KOH/g	ASTM D 664	70–100		
Net calorific value as received, MJ/kg	DIN 51900, ASTM D 240	13–18[1]	min 40.6	42.6
Ash, w-%	EN ISO 6245	0.01–0.1[2]	max 0.08	max 0.01
Carbon residue (MCR, CCR), w-%	ASTM D 4530, ASTM D 189	17–23		
C, w-%, dry	ASTM D 5291	50–60		
H, w-%, dry	ASTM D 5291	7–8		
N, w-%, dry	ASTM D 5291	< 0.4	0.4	0.02
S, w-%, dry	EN ISO 20846, ASTM D 5453	< 0.05	max 1.0	max 0.001
O, w-%, dry	calculation	35–40		
Na+K+Ca+Mg, w-%, dry	EN ISO 16476	< 0.06		
Cl, ppm	ISO 8754, ASTM D 4294	< 75		
Flash point, ºC	EN ISO 2719, EN ISO 9038, ASTM D 93B	40–110[3]	min 65	min 60
Pour point, ºC	EN ISO 3016, ASTM D 97	−36…−9	max 15	min −5

[1] Depends on the water content.

[2] Metals are oxidised on heating, which can lead to excessively high ash content (i.e. an ash content greater than the volume of solids).

[3] The flash point determination method is not suitable for pyrolysis oil. More information: Oasmaa et al. 2012.

Table 10.2. Properties of fast pyrolysis oils produced from different raw materials (Oasmaa et al. 2010).

Property	Pine		Forest residue, brown, stored		Forest residue, green, fresh		Barley straw		Timothy-grass		Reed canary grass	
	Raw material	Oil	Raw material	Oil	Raw material	Oil	Raw material	Oil	Raw material	Oil	Raw material	Oil
Moisture, w-%	9.5	23.9	4.9	26.7	8.1	25.5	8.8	51.1	3.9	39.3	10.9	27.4
PROPERTIES AS RECEIVED, w-%, RAW MATERIALS ON A DRY BASIS												
Solids	-	0.01		0.17		0.09		0.43		0.01		0.15
Ash*	0.1	0.03	3.8	0.3	2.1	0.1	5.8		3.2	0.004	1.1	
Volatile matter	84.0		73.2		76.7		73.9		76.7		81.3	
Carbon, C	50.5	40.6	51.1	41.4	51.4	41.2	48.8	26.5	47.6	32.1	45.7	39.3
Hydrogen, H	6.4	7.6**	5.9	7.4**	6.0	8.0**	5.9	9.0**	6.1	8.5**	5.6	7.7**
Nitrogen, N	< 0.1	< 0.1	0.5	0.3	0.5	0.3	0.8	0.9	0.7	0.6	0.9	0.6
Oxygen, O (difference)	43	52	43	51	42	51	45	63	46	59	48	52
Sulphur, S		0.01		0.03		0.02						
Chlorine, Cl		0.006		0.002		0.004						
PROPERTIES ON A DRY BASIS, ppm												
Sodium, Na		< 5				8						
Potassium, K		34		110		89						
PROPERTIES ON A DRY BASIS (dry) or AS RECEIVED (ar), MJ/kg												
Gross calorific value, dry	20.4	22.2	20.5	23.1	20.8	22.4	18.5	22.7	19.1	21.9	19.7	22.0
Gross calorific value, ar		16.9		16.9		16.7		11.1		13.3		16.0
Net calorific value, dry	19.0	20.8	19.3	20.9	19.5	20.4	17.2	18.6	17.8	18.4	18.5	19.7
Net calorific value, ar	17.0	15.3	18.2	15.3	17.7	15.2	15.5	9.1	17.0	11.5	16.2	14.3
Viscosity (40 ºC), mm^2/s (cSt)		17		17		24				5		
Density (15 ºC), kg/dm^3		1.206		1.194		1.210				1.150		
Flash point, °C		53		42		65						
Pour point, °C		−36		−12		−27						
pH		2.7		3.2				3.7		3.4		3.6

*Oil ash at 775 °C. ** Total hydrogen includes also hydrogen from fuel moisture.

Bio-oil properties are usually reported as received (on a wet basis).

11. Gaseous fuels

11.1 Refinery, coking, and blast furnace gas

In Finland, pig iron is manufactured in blast furnaces in which iron oxides are reduced to pig iron with the help of carbon monoxide and hydrogen gases. They are formed when coke produced from coal and extra heavy base oil, which is a by-product of oil refining, burn in a blast furnace. A blast furnace is a continuously operating shaft furnace used for producing iron. The blast furnace gas generated by the process is used to pre-heat the air blown into the furnace, in other processes in the plant, and to produce electricity. Coke is produced from coal in coking plants.

The gas is composed mostly of hydrogen, different kinds of hydrocarbons, nitrogen, carbon monoxide, and carbon dioxide. Approximately 8 g/m^3 of ammonia is also generated. Impurities, such as tar, ammonia, and naphthalene, must be removed from the gas before it can be burnt. Blast furnace gases are recovered and used in other stages of the process either directly as fuel or in the power plant. Today, all pig iron is turned into steel. This is done in an oxygen converter, in which molten pig iron is decarburised using oxygen gas. Gases with significant energy content can also be recovered from this process (Energy in Finland 2004).

Combustible gases, i.e. so-called refinery gases, are produced at different stages of oil refining, which have varying properties. The gases mostly contain hydrogen, carbon monoxide, ethane, and methane. Table 11.1 lists the most important properties of different kinds of process gases.

Table 11.1. Properties of refinery gas, coking gas, and blast furnace gas (Arasto et al. 2013).

Property	**Refinery gas**	**Coking gas**	**Blast furnace gas**
Net calorific value, MJ/kg	6.4	38.4	2.6
Composition, vol-%			
Methane, CH_4	0.0	23.1	0.0
Ethane, C_2H_6	0.0	0.7	0.0
Ethylene, C_2H_4	0.0	2.0	0.0
Hydrogen, H_2	0.0	57.9	5.3
Nitrogen, N_2	15.0	6.9	45.1
Carbon dioxide CO_2	2.2	1.8	13.0
Carbon monoxide, CO	69	5.1	23.1
Oxygen, O_2	0.0	0.0	0.2

11.2 Biogas

Biogas is formed when different kinds of microbes break down organic matter in the absence of oxygen. Biogas is a product of the anaerobic digestion of organic matter, which primary consists of methane (55–70%) and carbon dioxide (30–45%). Hydrogen is produced as an intermediate product, which micro-organisms usually use to produce methane. The process conditions can also be regulated so that some of the organic matter can be broken down into hydrogen. The production of hydrogen and methane can be made into a two-stage process so that the end products are both hydrogen and methane. The production of hydrogen is still being researched mostly in laboratories and on a pilot scale, and there are no full-scale applications so far. (Tähti & Rintala 2010)

Both methane and carbon dioxide are colourless, odourless gases. Depending on the source, the gas contains smaller concentrations of hydrogen sulphide (0–2%), nitrogen (0–25%), and chlorine and fluorine compounds. Biogas has a calorific value of 4–6 kWh/m^3_n (14.4–21.6 MJ/m^3_n). The production of biogas that can be used as a fuel in engines involves both energy production and environmental conservation in the form of lower greenhouse gas emissions and odours.

Biogas can be made from a variety of organic mass. As methane bacteria work best in an aqueous environment, the method is especially well suited for treating waste in the form of sludge. Such sludges are generated on farms (manure sludge), at municipal wastewater treatment plants, by the food processing industry, etc. The feeding of organic matter can be made more efficient by adding materials such as solid plant mass into sludges to bring their solids content close to or even slightly above 10%. The theoretical methane yield is the highest from fats (1,014 l/kg VS), followed by protein (496 l/kg VS) and carbohydrates (415 l/kg VS). VS stands for volatile solids. Tables 11.2 and 11.3 list methane yield potentials and volatile matter contents of different feedstocks. Table 11.4 lists solids contents (TS) of biodegradable waste and plants and percentages of organic matter (VS) of total solids (VS/TS) (Tähti & Rintala 2010).

Table 11.2. Examples of the methane production potential of different feedstocks (Lehtomäki & Rintala 2006).

Feedstock	**m^3 CH_4/t of organic matter**	**m^3 CH_4/t wet weight**
Slaughterhouse waste	570	150
Biowaste	500–600	100–150
Energy crops	300–500	30–150
Wastewater sludge	310–640	8–16
Manure	100–400	7–20

Table 11.3. Organic matter content and methane production potential of feedstocks (Paavola 2007, Lehtomäki 2006).

Feedstock	Total solids, TS, %	Volatile solids, VS, %	VS/TS ratio	VS of total weight, kg/t	CH_4 yield, l/kg VS	CH_4 yield, m^3/t
Wastewater treatment sludge	5	3	60	30	150	5
Cow manure	6.5	5.3	82	53	175	9
Biowaste	40	28	70	210	550	116
Grass	30	27.9	93	279	400	112
Sugar beet	20	17.9	89	179	229	41

Table 11.4. Solids content (TS) of biodegradable waste and plants and percentage of organic matter (VS) of total solids (VS/TS). Both an average and the range (in brackets) are given (Tähti & Rintala 2010).

Waste	**Total solids, TS, %**	**Percentage of organic matter, VS/TS %**
Slaughterhouse waste	26.4 (20.0–31.0)	90
Plant waste	11.3 (7.12–19.0)	92
Municipal biowaste	34.5 (33.5–35.0)	74
Municipal wastewater treatment sludges*	18.5 (3.0–50.0)	70
Food processing industry wastewater treatment sludges	10.0 (2.0–30.0)	70
Forestry and paper industry wastewater treatment sludges	2.5 (2.0–3.0)	70
Straw	89.8 (89.6–90.0)	92
Grass	24.0 (17.4–43.7)	92
Root vegetable tops	11.6 (-)	85

* The solids content of sludges varies considerably, as the Finnish VAHTI system, from which the figures were pulled, gives the solids content of some sludges on the basis of raw sludge and the solids content of other sludges on the basis of dried sludge.

Anaerobic techniques refer to the controlled microbiological or biochemical breakdown of wet organic matter in the absence of oxygen. The reaction is one of the oldest in the world. It is based on the functioning of extremely primitive bacteria and known as digestion, biogasification, or biomethanation. Biogas is produced in reactors in a controlled manner or in landfill sites in an uncontrolled manner.

There were farm-specific biogas plants in 13 locations. Municipal solid waste was treated in 14 biogas plants. In 2014, reactor plants produced 61.5 million m^3 of biogas, and a total of 309.6 GWh (1,115 TJ) of it was used as heat and electricity. A total of 94.0 million m^3 of biogas was recovered from 40 landfill sites. Of pumped biogas, 74.7 million m^3 was used to produce electricity and heat, and a total of 303.7 GWh (2,920 TJ) of energy was produced. The total amount of biogas produced was 155.5 million m^3 (Huttunen & Kuittinen 2015). In Finland, 0.5 million tonnes of municipal solid waste is taken to landfill sites every year. The amount of biogas generated at landfill sites has been estimated at approximately 200 million m^3 per year. The Government Decree on Landfill Sites (331/2013) prohibits the deposition of organic waste in landfill sites as of 2016 (Huttunen & Kuittinen 2015, Häkkinen et al. 2014). Figure 11.1 shows a diagram of a biogas plant.

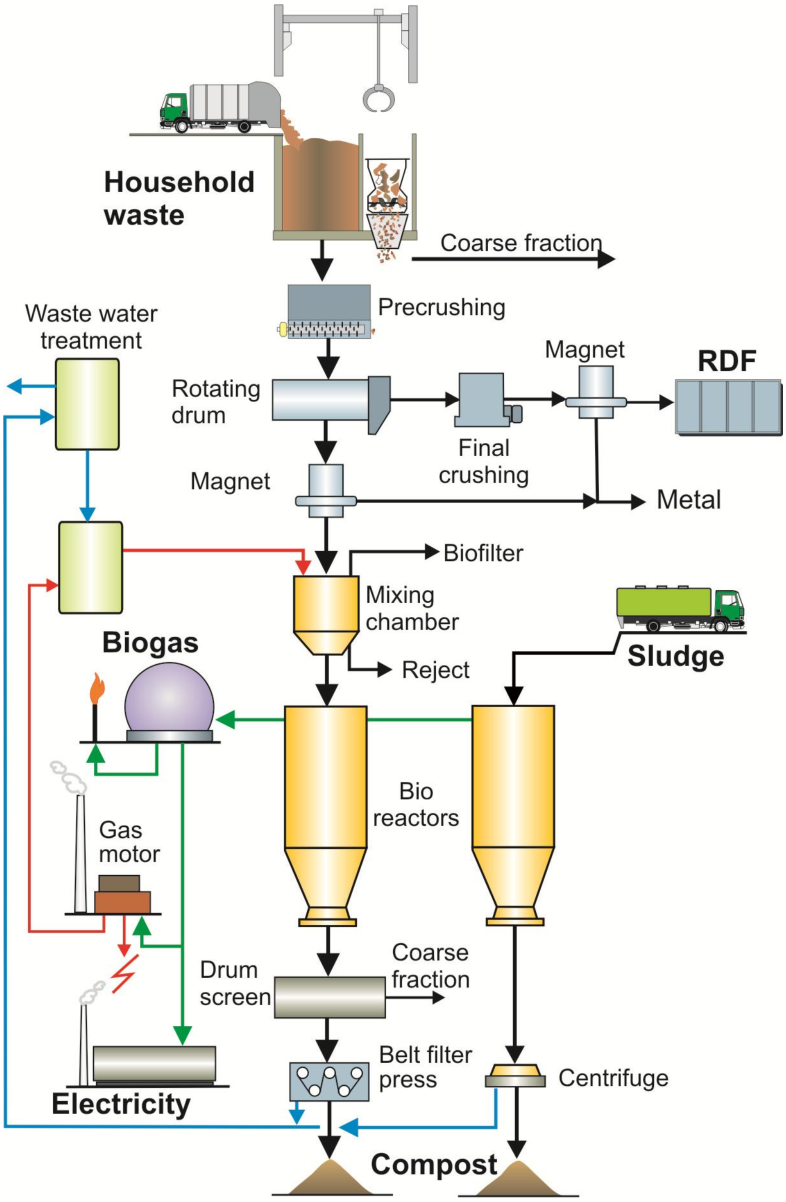


Figure 11.1. Diagram of a biogas plant. Figure: VTT.

Biogasification of manure sludge from livestock – such as cows or pigs – boosts the profitability of agriculture considerably (Figure 11.2). Finland produces more than 17 million m^3 of manure sludge from livestock, i.e. 2.25 million tonnes on a dry basis. The techno-economical potential of manure is 1.4 TWh/a (5 PJ/a) (0.9–1.8 TWh/a, 3.2–6.5 PJ/a). It has been estimated that 60% of the manure collected from cows, pigs, and poultry and 10% of sheep manure can be put to use (Tähti & Rintala 2010). Energy potential can be calculated by converting wet weight into total solids (TS) and volatile solids (VS) using the values given in Table 11.5. A material's energy potential is its mass (t) x methane production (m^3/tTS) x the calorific value of methane (10 kWh/m^3, 36 GJ/ m^3) (Table 11.5).

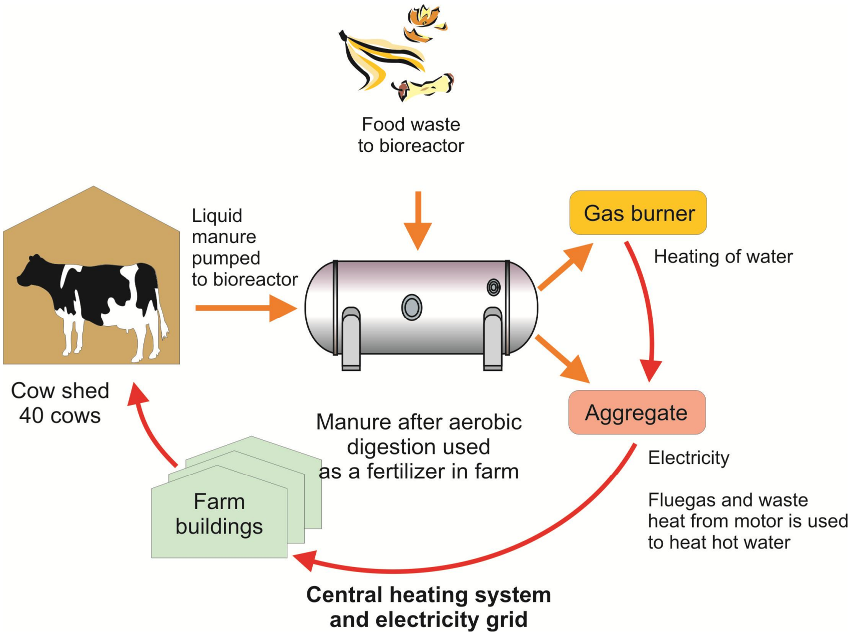


Figure 11.2. Biogas production on a farm. Figure: VTT.

Table 11.5. Volume (m^3) of manure produced by animals annually on a dry basis, including bedding (and water used to clean manure sludge, the figures for which are given in brackets), density of manure (t/m^3), solids content (TS), and the percentage of organic matter in total solids (VS/TS). (Tähti & Rintala 2010)

Animal	**Average, m^3/animal/a**	**Density, t/m^3**	**Total solids (TS), %**	**Percentage of organic matter (VS/TS), %**
Dairy cow	24 (24)	0.78 (0.99)	21.5 (5.5)	80
Suckler cows	15 (15)	0.78 (0.99)	21.5 (5.5)	80
Heifers and bulls	15 (15)	0.78 (0.99)	21.5 (5.5)	80
Calves, under 1 year	4 (4)	0.78 (0.99)	21.5 (5.5)	80
Boars, sows, and fattening pigs more than 50 kg	2.4 (2.4)	0.64 (1.00)	29.3 (3.5)	75
Other pigs of 20–50 kg and piglets less than 20 kg	1.2 (1)	0.64 (1.00)	29.3 (3.5)	75
Ewes of over 1 year, lambed and pregnant ewes of less than 1 year, other sheep, and goats	1.5	0.59	34	
Horses	12	0.53	31	88
Mink and polecat	0.25	0.74	47	
Fox and raccoon dog	0.5	0.53	31	88
Laying hens of at least 20 weeks, cockerels, and broiler hens	0.05	0.62	48	75
Chicks of less than 20 weeks, broilers	0.015	0.62	48	75
Turkey	0.03	0.62	48	75

One cubic metre of manure sludge produces approximately 20 m^3 of gas, which equates to approximately 6.5 kWh (23.4 MJ) of energy. One cubic metre of livestock sludge contains 5–7% of organic solids (Tables 11.6 and 11.7).

Tended, uncultivated fields and green fallows generate a considerable volume of biomass that could also be used to produce biogas. Considering variations in harvests (1.33–10.3 tonnes of solids per hectare), the annual potential would be approximately 4.7 TWh (16.9 PJ) (Pahkala & Lötjönen 2015).

Table 11.6. Biogas yield from agricultural waste (Finnish Biogas Association, Sankari 1994, Alakangas 2000).

Base material	**Yield, m^3/kg, dry basis**
Grass (heavily fertilised)	0.6–0.7
Potato leaves and stems	0.45–0.55
Sugar beet leaves / sugar beet	0.56/0.88*
Straw	0.25–0.35
Tree leaves	0.35–0.66
Lucerne	0.77*
Common reed	0.44*
Energy willow	0.49*
Manure	0.4–0.7

* biogas m^3/kg of organic matter (without ash and water)

Table 11.7. Volumes of organic waste produced by animals (Finnish Biogas Association, Alakangas 2000).

Animal	**Volume of manure, kg_{dry}/a**	**Biogas, m^3/a**	**Electricity, kWh**
Cow	1,600	640–1,120	3,392–5,936
Pig	104	42–73	223–387
Sow	336	136–235	721–1246
Fox	18	7–13	37–69
Raccoon dog	20	8–14	42–74
Mink	7.5	3–5	16–27
Chicken	6.2	2–4	13–23

One average-size landfill site in a Finnish town produces approximately 200–400 m^3/h of methane gas. The breakdown of one tonne of municipal solid waste produces 100–200 m^3 of biogas. Anaerobic digestion – the reaction that produces biogas – begins between two and four years after landfilling and continues for several decades. It has been illegal to take biodegradable waste to landfill sites in Finland as of the beginning of 2016, which means that the production of landfill gas will decrease.

It is not just landfill sites but also wastewater treatment plants and industrial digestion plants that produce considerable amounts of gas. Producing 1 kWh of electricity and 1.23 kWh (4.4 MJ) of heat requires e.g. 5–7 kg of biowaste, 5–15 kg of household waste, 8–12 kg of manure or organic waste, or 4–7 m^3 of wastewater. Landfill gas primarily consists of methane CH_4 (25–64%) and carbon dioxide CO_2 (35–45%). The gas also contains low concentrations of several hydrochlorocarbons and hydrofluorocarbons as well as sulphur compounds, which are the cause of the unpleasant odour typical of landfill gas.

When released to outdoor air, landfill gas is highly flammable, odorous, and polluting. In addition, methane gas (CH_4) accelerates the greenhouse effect considerably more than carbon dioxide. When released to the atmosphere, methane is 20 times more potent a greenhouse gas than carbon dioxide. When it burns, methane is an excellent energy gas, which only produces carbon dioxide and water. Methane also causes fires in landfill sites.

Landfill gas is collected with the help of screen wells, which can be installed either vertically (suction wells) or horizontally (French drains) in the waste mass (Figure 12.3). Combined structures and tunnels can also be used. In Finnish conditions, vertical wells have proved effective in tall landfills, while French drains are better suited for areas where the landfill height is less than six metres. Both systems can also be used to collect gas in active landfill sites.

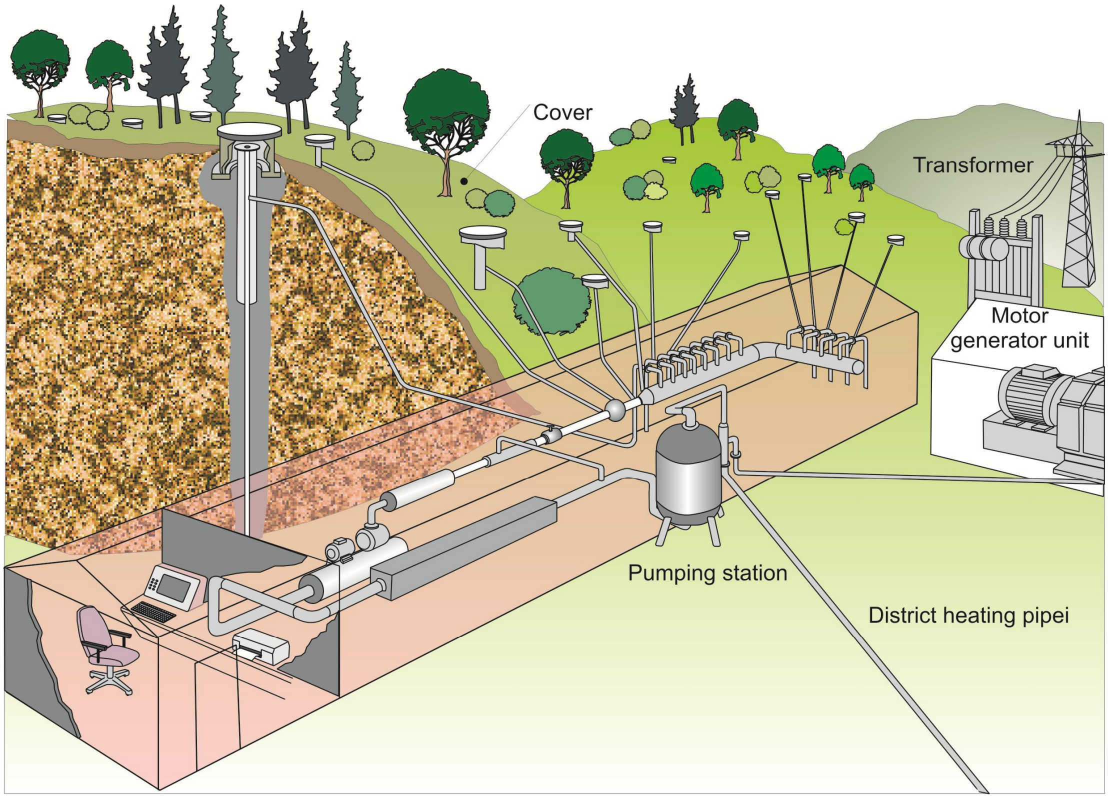


Figure 11.3. Collection and use of landfill gas as engine fuel. Figure: VTT.

At the end of 2014, there were 16 biogas reactor plants in operation at municipal wastewater treatment plants in Finland. Three plants carried out anaerobic treatment of industrial wastewater. Table 11.8 lists compositions of wastewater treatment plant biogas.

As sewage plants became more common in towns and densely populated areas, increasing the efficiency of wastewater treatment also became essential. In addition to aerobic bacteria, anaerobic bacteria were introduced for breaking down organic matter. Closed-circuit biogas reactors were built, and the biogas generated was collected and put to use. The digestion of wastewater treatment sludge produces humus and biogas. The volume of humus generated is 30–40% of the original weight of the sludge, and the biogas yield is 60–80 m^3 per tonne of treated sludge. The methane content of the biogas produced is 60–70%, and its calorific value is 6–6.5 kWh/m^3. Depending on the size of the wastewater treatment plant and local conditions, the biogas generated can be used to produce heat only or both heat and electricity, and it can be further refined into transport fuels or to be fed into the natural gas network by raising its methane content.

The Stormossen plant in Mustasaari, Vaasa is the oldest plant in Finland that co-digests the compost fraction of municipal solid waste (biowaste) and mechanically dried common sludge. The waste arriving at the plant is processed both mechanically and biologically. The plant produces just over 2 million m^3 of biogas, of which 1.8 million m^3 is used. Finland has 14 co-digestion plants, which produced more than 30 million m^3 of biogas in 2014. The methane content of biogas is 58–70%.

Table 11.8. Typical components of wastewater treatment plant biogas and ranges (Latvala & Pasanen 2005).

Component	**Range, %**	**Component**	**Range, mg/m^3**
Methane, CH_4	55–70	Ammonium, NH_4	< 0.2
Carbon dioxide, CO_2	30–45	Organic silicon compounds	0.2–32
Oxygen, O_2	< 0.5	Particles	< 5
Nitrogen, N_2	< 1	Fluorine, F	< 0.2
Moisture, H_2O	2–4	Chlorine, Cl	< 2
Component	**Range, ppm**		
Hydrogen sulphide, H_2S	10–40		
Methanethiol, CH_3SH	< 0.005		
Dimethyl sulphide, CH_3SCH_3	< 0.005		
Methyl sulphide, CH_3SSCH_3	< 0.01		

Biogas is difficult to store (storing the raw material is easier). The most common method of storing biogas is in a gas holder or a membrane tank. Only approximately one day’s biogas production can be stored economically, which is why efficient use requires that the energy contained in the gas can be used continuously in a profitable manner.

Biogas can be turned into heat and electricity after cleaning, or into transport fuels after refining. Biogas can be refined into a fuel similar to natural gas by raising its methane content. The problems of storing biogas, among other issues, can be avoided if the gas is refined and fed into a natural gas network. This also increases the number of potential applications for biogas considerably. The biogas available via natural gas distribution networks and from vehicle fuelling stations is refined gas (95% methane). Refined biogas has a net calorific value of 10 kWh/m^3 (36 MJ/m^3), which is similar to that of natural gas. Biogas the methane content of which has not been raised is used in the vicinity of the biogas production plant and mostly distributed to business customers. The properties of unrefined biogas vary from one production plant to the next. Approximately 50 GWh (180 TJ) of biogas is produced for the natural gas network per year (Gasum Oy).

LABIO Oy’s biogas plant in Kujala processes separately collected biowaste, garden waste, and wastewater treatment sludges by means of digestion. The waste is turned into raw biogas, which Gasum refines into biogas that corresponds to natural gas by its properties. The gas is fed into Gasum’s natural gas network, and it can be used, for example, as a transport fuel. The Helsinki Region Environmental Services Authority’s wastewater treatment plant in Espoo also produces biogas for the natural gas network.

The nutrient-rich organic matter remaining after biogasification is collected and used as a fertiliser, either as sludge or dried. Biogasification removes the unpleasant odour and pathogens from the raw materials and therefore reduces the risk of surface water and groundwater contamination resulting from the waste.

12. Properties of fuels and energy production

12.1 Links between fuel properties and combustion behaviour

The net calorific value of fuel on a dry basis is a measure of the amount of energy released in the combustion of a completely dry fuel, assuming that the latent heat contained in the water vapour formed from the hydrogen in the fuel cannot be recovered. The latent heat of water vapour can be recovered with the help of a flue gas condenser. The net calorific value as received factors in the reduction in the calorific value resulting from the moisture contained in the fuel. In addition to lowering the calorific value, moisture also increases flue gas and reduces the thermal efficiency of the boiler. Wet fuels are also more prone to freezing in the winter and can cause problems in the fuel feeding equipment.

Energy density is a measure of energy content per unit of volume. Energy density affects e.g. the required capacities of fuel storage, handling, and feeding equipment, as well as transport costs. Figure 12.1 shows a comparison of the energy densities of different fuels from the perspective of the amount of space required.

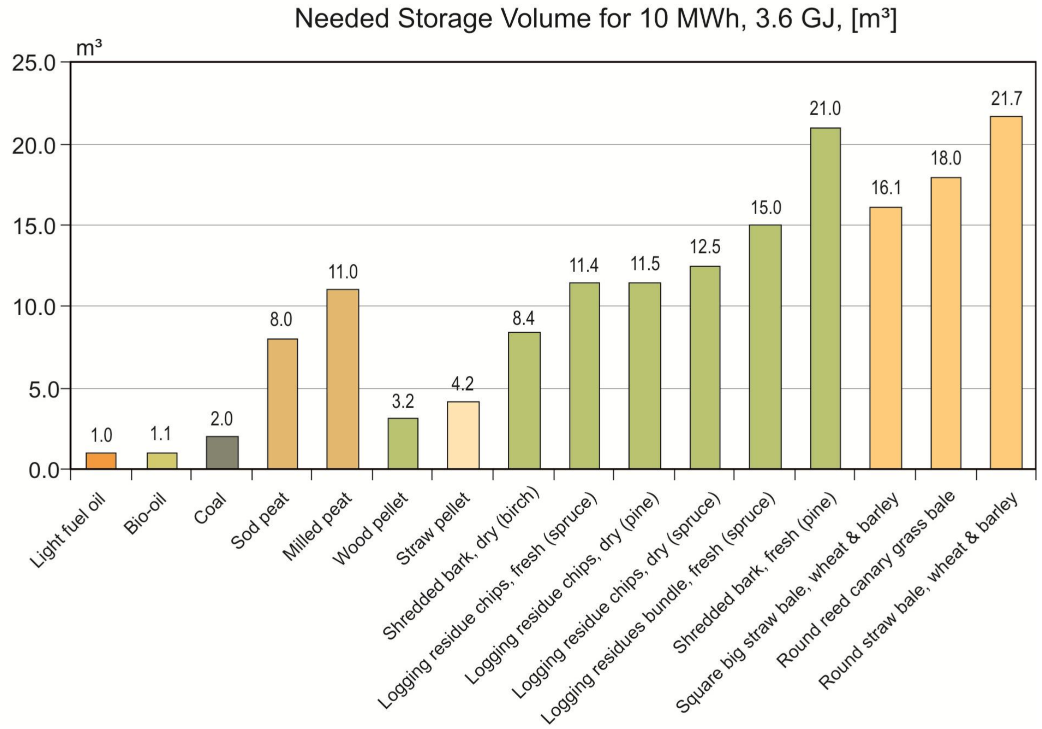


Figure 12.1. Space required by different fuels when the amount of energy is 10 MWh (3.6 GJ). Figure: VTT.

The particle size (distribution) required of fuels varies depending on the combustion technique and substance. Particle size distribution affects not just the combustion process itself, but also the operation of transport and handling equipment, such as bridging behaviour. Wood chips have a more homogeneous particle size than hog fuel, and wood chips have better handling properties than hog fuel, which contains longer particles.

Among other effects, ash content lowers the calorific value of fuel and affects the capacity required of ash handling equipment. Impurities, such as soil, glass, stones, and metals increase the ash content of solid biofuels and waste-derived fuels.

Figure 12.2 illustrates the interdependence of physical and mechanical properties.

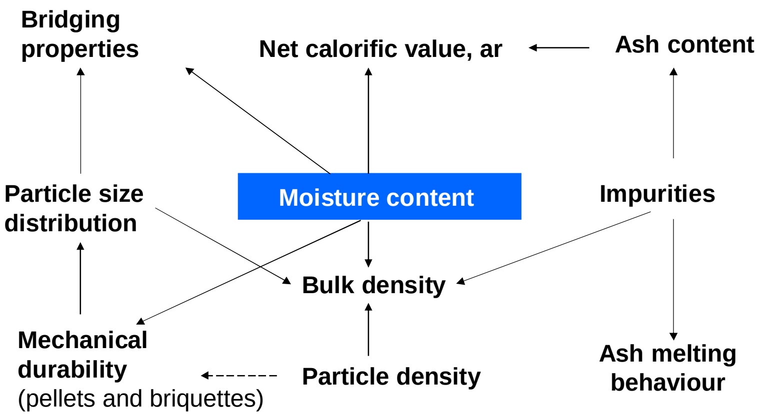


Figure 12.2. Interdependence of fuel properties. Source: Hartmann 2007.

The percentage of volatile matter affects e.g. the burning profile, reactivity, and emissions. In pulverised fuel combustion the increase in volatile matter content facilitates ignition and helps to stabilise the flame. Volatile matter accounts for a high percentage of solids in solid biofuels and for a low percentage in coal.

From the perspective of the amount of energy released by combustion, the most notable elements are carbon and hydrogen. Figure 12.3 shows typical carbon and hydrogen contents, volatile matter percentages, and calorific values for different types of fuel (Kurki-Suonio 1981).

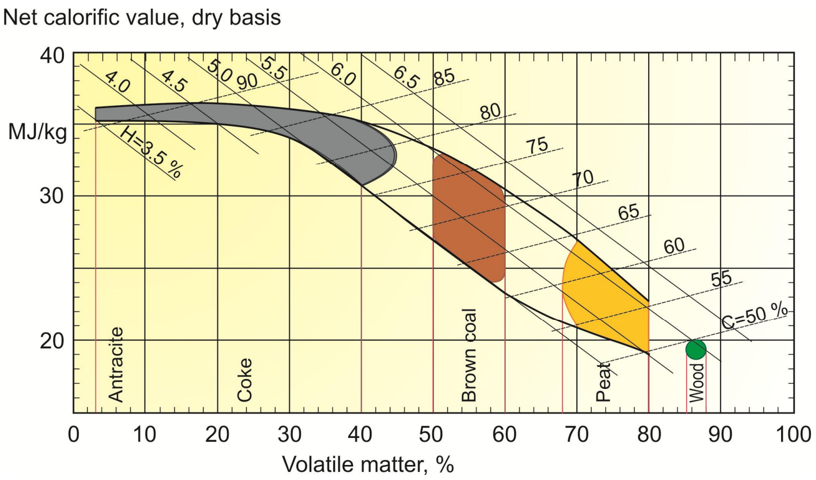


Figure 12.3. Carbon and hydrogen contents, volatile matter percentages, and calorific values of different types of fuel on a dry basis. Figure: VTT.

The majority of the nitrogen contained in fuel is converted into elementary nitrogen, but a significant portion still forms harmful nitrogen oxide emissions, of which nitrogen monoxide (NO) is the most abundant. Nitrogen monoxide oxidises rapidly into nitrogen dioxide in the atmosphere, which, when reacting with water, forms nitric acid and nitrous acid, which both cause rainwater to become acidic.

Sulphur content is significant both in terms of emissions (SO_2) and from the perspective of ash chemistry, in preventing high-temperature corrosion. Some of the sulphur can, nevertheless, also form sulphuric acid, which can lead to dew point corrosion at the “cold end” of the flue gas duct, if the temperatures of the heat transfer surfaces are too low. Dew point corrosion resulting from sulphuric acid is also a major problem in ducts and equipment such as electrostatic precipitators, when the structural temperature is below the dew point of sulphuric acid (especially cold bridges). Chlorine is the most notable cause of high-temperature corrosion in superheaters when burning solid biofuels and waste-derived fuels, and it also has significance in terms of emissions (HCl, PCDD/F).

The composition of ash determines the so-called ash chemistry of the combustion process (fouling, slagging, corrosion, and sand agglomeration mechanisms). For example, alkali metals (K, Na) contribute to boiler fouling, ash melting, corrosion (together with chlorine), and fluidised bed sand agglomeration, a phenomenon where small bed sand particles adhere to each other due to glue-like components forming large agglomerates. Heavy metals have an effect on emissions to the air, the usability of ash, and corrosion mechanisms (especially lead (Pb) and zinc (Zn)). These effects are discussed in more detail in the sections that follow.

Figure 12.4 illustrates the effect of the chemical properties of fuel on challenges in combustion according to Valmet Corporation.

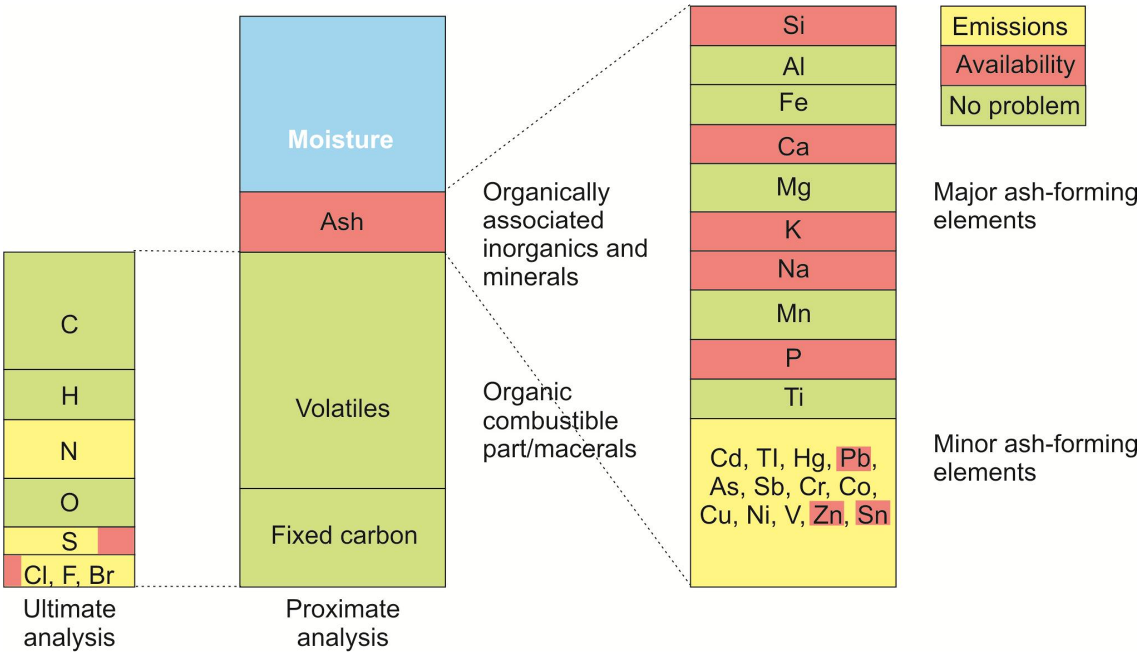


Figure 12.4. Links between fuel analysis results and combustion behaviour. Source: Valmet Corporation.

12.2 Fuels and associated challenges in combustion processes

The properties of different fuels differ considerably from each other, which is why they pose varying degrees of requirements and challenges for plants (Tables 12.1 and 12.2). Figure 12.5 shows a fuel quality classification drawn up by Amec Foster Wheeler based on calorific values and problems in combustion. The best fuels, i.e. those with a high calorific value and that do not pose challenges during combustion, are shown in the top right corner of the graph. The worst, i.e. those that pose multiple challenges and have a low calorific value, are shown in the bottom left corner. Combustion-related challenges can relate to, for example, phenomena harmful to boilers, such as fouling, slagging, corrosion, and ash melting. Challenges can also relate to the feedability of the fuel, hygiene, or emissions.

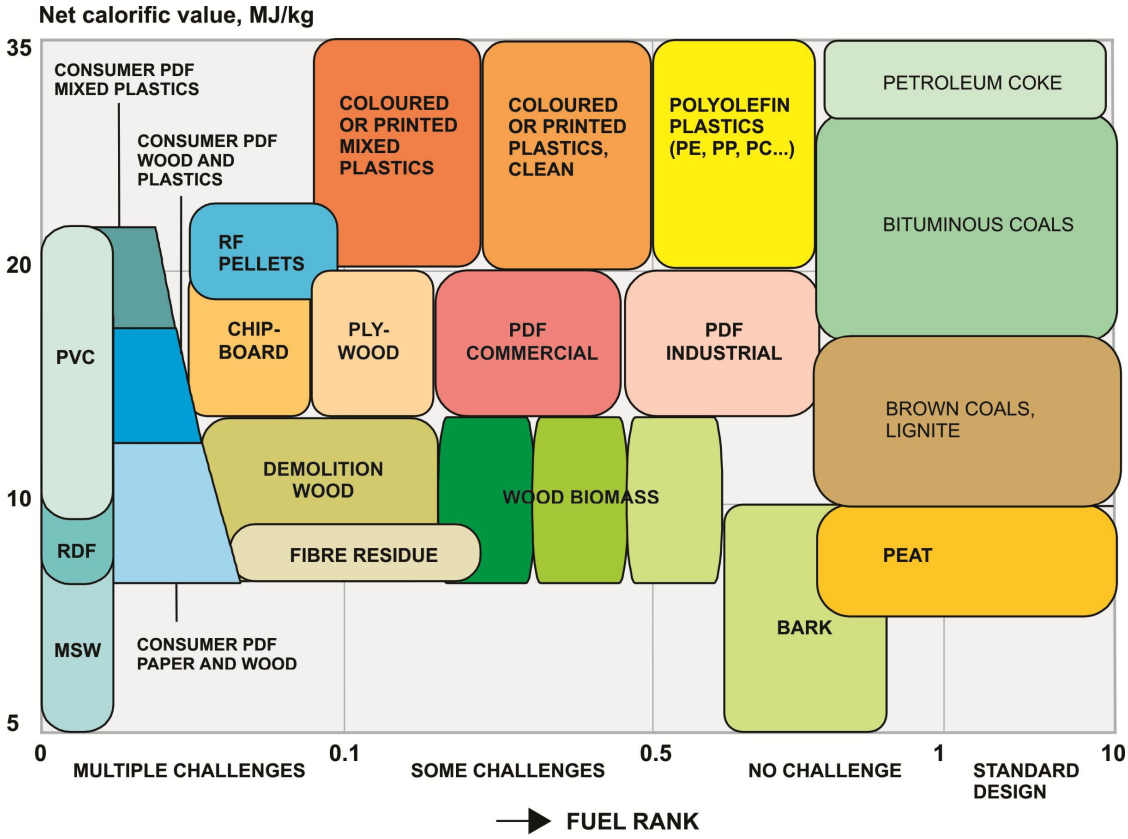


Figure 12.5. Challenges presented by different fuels from the perspective of boiler design. Adapted from a picture supplied by Amec Foster Wheeler. The challenge scale is relative and adjusted according to space.

Different kinds of waste-derived materials are among the more challenging fuels. The problems mostly originate from high chlorine and alkali content, but also from heavy metals. The alkali chlorides formed during combustion increase the risk of high-temperature corrosion in superheater tubess especially when the steam superheating temperature is above 450–480 ºC. The zinc and lead compounds formed from waste-derived fuels can cause corrosion also at lower temperatures (approximately 350–400 °C), which makes also the steam boiler tubes (panelled walls of the furnace) also vulnerable to corrosion. This is why the pressure (and, therefore, also the metal temperature of the boiling surfaces) in boilers that are primarily fuelled by waste must be kept lower than when using traditional fuels. Waste-derived fuels can also contain bromine, which has been found to be as harmful – or potentially even more harmful – as chlorine (Vainikka 2011), but the levels of bromine are usually almost negligible compared to chlorine levels. Waste-derived fuels also sometimes contain metallic aluminium, which can cause fouling and, in extreme cases, blockages. Heavy metals can cause problems in terms of emissions and the use of ash. The handling and feeding of waste-derived materials are also often challenging, and there are always health, odour, and hygiene risks involved.

The use of untreated municipal solid waste (MSW) is hampered by particle size and the high volume of non-combustible foreign objects (glass, ceramics, metals, etc.), which is why untreated MSW can only be burnt in grate boilers. Waste that has not been sorted at source can also be turned into refuse-derived fuel (RDF) with a particle size that is suitable for fluidised bed boilers and containing fewer foreign objects. However, with fluidised bed boilers, it is still important to ensure that over-sized particles are removed effectively from the bed. In other respects, the challenges to the boiler are similar to those associated with MSW.

Various kinds of consumer packaging waste (PDF) also make for challenging fuels, as do fuels derived from waste sorted at source (REF or SRF). The problems stem from the same reasons as with RDF but are less severe thanks to pre-sorting. A general rule for waste-derived fuels is that waste originating from consumers is the most problematic, followed by commercial waste, making industrial waste the least problematic. Industrial and commercial waste is often much more homogeneous and contains fewer foreign objects and harmful substances, such as chlorine.

Demolition wood, particle board, and plywood residue can be challenging in some circumstances. Plywood edges contain high levels of sodium originating from glues, and they have been found to cause serious bed agglomeration in fluidised bed boilers if burnt without a protective fuel or special bed sand that prevents agglomeration (e.g. Silvennoinen 2002 & 2003). Demolition wood can contain concrete, nails, and toxic substances originating from e.g. paints, lacquers, and preservatives. Impregnated wood contains high levels of arsenic, chromium, and copper. This is why a separate quality classification system has been developed for used wood (see Section 4.9, Alakangas 2014, Alakangas et al. 2016)).

Burning forest chips can also be challenging, if boilers are only used to burn wood fuels or if their percentage is very high. This is the case especially if the boiler is not designed for high levels of forest chips. In these circumstances, there is a risk of superheater fouling and high-temperature corrosion. The problems are caused by the chlorine and alkalis (in practice, potassium) contained in the wood. Although potassium levels and especially chlorine levels are relatively low in forest chips, they cause problems, as wood lacks the kinds of compounds found in e.g. peat and coal that protect boilers. If coal or peat is mixed in with wood, the problems can often be eradicated altogether. Co-combustion is discussed in more detail in Section 12.3. From the perspective of combustion, it is beneficial for coniferous trees to drop their needles before combustion, as this lowers chlorine and potassium levels in particular considerably compared to woody biomass containing the green fraction. This is based on the fact that alkali and chlorine levels are higher in the needles.

Straw is in some respects a similar fuel to wood: Its elementary composition (C, H, N) and net calorific value on a dry basis are close to those of wood, and both contain high levels of volatile compounds. The lower energy density of straw and especially its higher ash content and properties nevertheless make it a considerably more challenging fuel than wood fuels. Straw contains high levels of alkalis that cause fouling and chlorine, which contributes to corrosion, in addition to which it has a low ash melting temperature. In fluidised bed combustion, bed agglomeration is especially prominent when using straw, and it cannot therefore be burnt alone in fluidised bed boilers. The chemical composition and, therefore, also combustion properties of different species of plant, are naturally different. Growth conditions (fertilisation, soil, weather conditions) also affect the composition of herbaceous agrobiomasses. The harvesting time has a considerable impact on the levels of harmful substances in straw. For example, due to the effect of rain, the chlorine content of straw harvested late (grey straw) can be many times lower than that of straw harvested early (yellow straw) (see Chapter 7).

Plastics would be good fuels in principle due to their high calorific value, but the risks associated with PVC are a problem (see Section 8.2). Clean PVC contains as much as 57 w-% chlorine. As long as plastics are clean and contain no PVC, there are usually no notable problems in combustion.

There are usually no problems in burning coal or Finnish peat.

12.3 Co-combustion of solid biofuels and peat/coal

The challenges posed by solid biofuels to boilers are primarily due to chlorine and alkalis. During combustion, these form corrosive and fouling alkali chlorides, in addition to which alkalis react with the bed material in fluidised bed boilers, causing the bed particles to agglomerate. Co-combustion with so-called protective fuels is a cost-effective way to prevent the problems discussed above.

Co-combustion refers to the simultaneous combustion of multiple fuels in a boiler. The boiler type has a major impact on co-combustion possibilities. Bubbling fluidised bed (BFB) boilers and especially circulating fluidised bed (CFB) boilers can be flexibly run on different kinds of fuels, while grate boilers and especially pulverised combustion plants set considerably stricter requirements for co-combustion (Hurskainen & Vainikka 2016).

As their name suggests, protective fuels contain compounds that protect boilers against damage and faults. The most important protective substances are sulphur and aluminium silicates, which are capable of rendering alkali chlorides harmless and of binding alkalis. Coal and peat are examples of the most common protective fuels. Some sludges, such as common sludge and fibre sludge, have also been found to have a similar protective effect. Almost all Finnish power plant scale fluidised bed boilers are used for co-combustion – most commonly of peat and different kinds of wood fuels.

Figure 12.6 illustrates the effect of co-combustion on the fouling and corrosion of superheater tubes. When using a solid biofuel alone, the gas-phase alkali chlorides generated by combustion condense on the surface of superheater tubes that are cooler than the flue gases, forming a corrosive layer that accelerates fouling. When peat (or coal) is added, the protective substances turn alkali chlorides into alkali sulphates and alkali aluminium silicates, causing chlorine to be released as hydrogen chloride (HCl, hydrochloric acid) and extracted with flue gases without causing superheater corrosion.

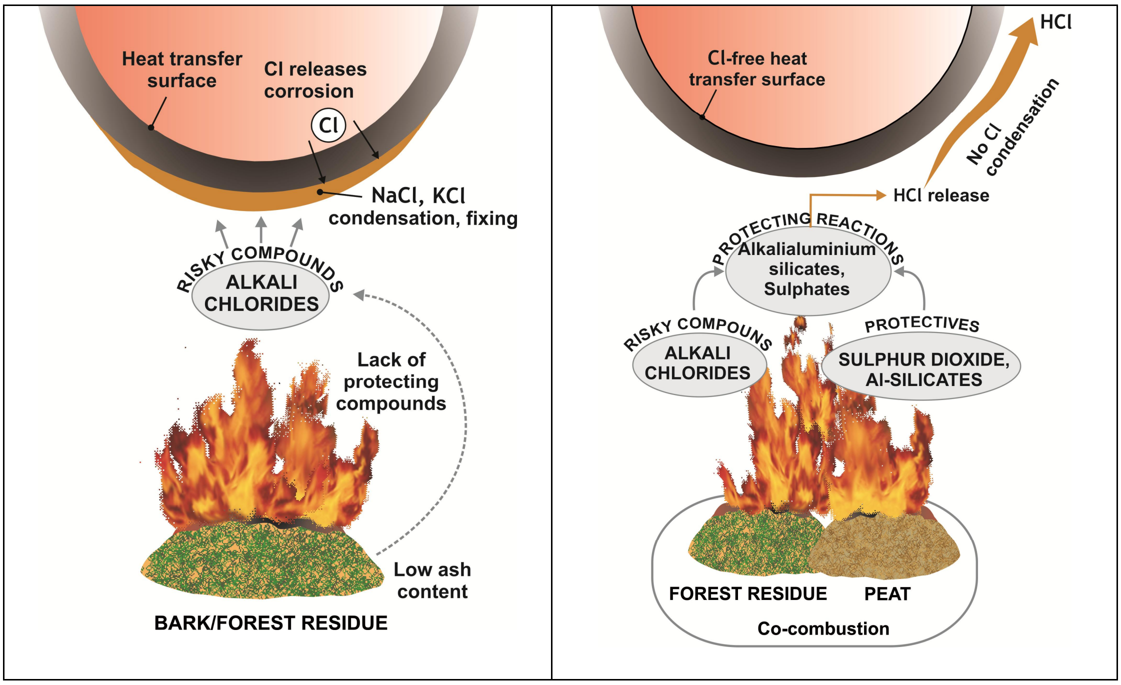


Figure 12.6. Simplified description of phenomena in a furnace if a fuel blend does not contain enough protective substances to prevent chlorine deposition (left) and if one of the fuels in co-combustion releases these protective substances that prevent chlorine deposition (right). Source: Aho et al. 2004. Figure: VTT.

The chemical reaction equations 12.1 and 12.2 illustrate safety mechanisms, namely the effect of sulphur and the effect of a specific aluminium silicate respectively. In order for sulphur to react with alkali chlorides sufficiently quickly, it first needs to form sulphur trioxide (SO_3). During combustion, the majority of sulphur forms sulphur dioxide (SO_2), and only a small portion is oxidised further into sulphur trioxide, which can then react with alkali chlorides. In the case of peat, the protective effect is primarily based on reaction 12.1. With coal, both reactions typically have a considerable effect. In general, the protective effect of coal is greater than that of peat, which allows a higher percentage of the challenging fuel to be used than with peat. However, coal is usually not well suited for bubbling fluidised bed boilers. BFB boilers are best suited for wet fuels that contain high levels of volatile matter (wood, peat, sludges). Circulating fluidised bed boilers that run on, for example, wood, peat, and coal can be designed to operate at whatever blend ratio, including 100% coal. Results of analyses on the protective effects of different fuels can be found in e.g. Aho 2001, Aho & Silvennoinen 2004, Aho & Ferrer 2005, Aho et al. 2015, and Yrjas et al. 2005.

In addition to co-combustion, sulphur-based protective substances can be introduced to boilers in the form of elementary sulphur (Hedman et al. 2012) or different kinds of sulphate solutions (Aho et al. 2008, Roppo 2012, Henderson et al. 2006). Aluminium silicates have been trialled in the form of kaolin, which is also used as a filler in paper making (Öhman & Nordin 2000). However, the aforementioned chemicals have been relatively little used in power plants so far. One example of the commercial use of kaolin is a CFB plant in Polaniec, Poland, which runs on 100% biomass, of which 20% is straw, sunflower residues, and other agrobiomasses.

$$2\ MCl(g) + SO_2(g) + \tfrac{1}{2}\ O_2(g) + H_2O(g) \rightarrow M_2SO_4(s) + 2\ HCl(g) \tag{12.1}$$

$$Al_2O_3 \times 2SiO_2(s) + 2\ MCl(g) + H_2O(g) \rightarrow M_2O \times Al_2O_3 \times 2SiO_2(s) + 2\ HCl(g) \tag{12.2}$$

in which M = potassium (K) or sodium (Na).

There are also other benefits to the co-combustion of solid biofuels and peat (or coal). Although the example addressed only superheater area, protective substances also simultaneously reduce the agglomeration of bed particles as well as particulate emissions by binding alkalis. Biomass fuel ash, which contains alkalis and alkaline earth metals (primarily K and Ca) also helps to reduce the high SO_2 emissions typical of peat and coal combustion. In other words, co-combustion takes advantage of synergies between different types of fuel. The most notable weakness of co-combustion relates to the potential uses of ash.

The high-temperature corrosion risks posed by fuels and fuel blends to superheaters can be estimated roughly with the help of fuel analyses. The most important elements to analyse are alkalis (sodium and potassium), calcium, sulphur, and chlorine. The volume of aluminium silicates can be analysed using X-ray powder diffraction (XRD), or their concentrations can be estimated roughly on the basis of ash composition by factoring in the volume of any inactive aluminium silicates. Chemical fractionation of fuels can be used to analyse the agglomeration of ash-forming elements and thereby e.g. their volatility and reactivity, which provides a clearer picture of the properties of the fuel (Zevenhoven et al. 2010 & 2012, Aho et al. 2005, Alakangas et al. 2012). A chemical fractionation analysis involves dividing the compounds found in a fuel into several different fractions by dissolving the fuels using different solvents, starting with the weakest.

The superheater tube corrosion risk in the co-combustion of peat and wood can be evaluated on the basis of the molar S/Cl ratio of the fuel blend. It is impossible to give an exact figure for the required ratio, but it can be estimated at between four and five, which equates to approximately 15–35% of peat depending on the types of fuel used (Aho et al. 2015). It must, nevertheless, be noted that this is a simplification, and high levels of calcium, for example, can weaken the protective effect of sulphur and therefore increase the required S/Cl ratio.

Figure 12.7 shows an example of the effect of the molar ratio of kaolinite (the most common aluminium silicate in coal) and chlorine on the risk of high-temperature corrosion in the co-combustion of coal and RDF (Ferrer et al. 2005). The results are based on experiments performed on pilot-scale (100 kW_{fuel} and 4 MW_{fuel}) circulating fluidised bed equipment. Two different types of coal were used in the experiments. Corrosion risk is indicated by the chlorine content of deposits collected on the probes that simulated superheater tubes. When the kaolinite/chlorine molar ratio was above three, no chlorine deposition was observed in, which also eliminated the risk of high-temperature corrosion.

Biomass boiler manufacturers usually state the highest acceptable combined concentration of reactive, i.e. soluble, potassium and sodium (ΣK+Na) in a fuel on a dry basis. Sums in excess of 0.3 w-% (3,000 mg/kg) usually cause problems, unless this has been taken into consideration in the boiler design (Alakangas et al. 2011).

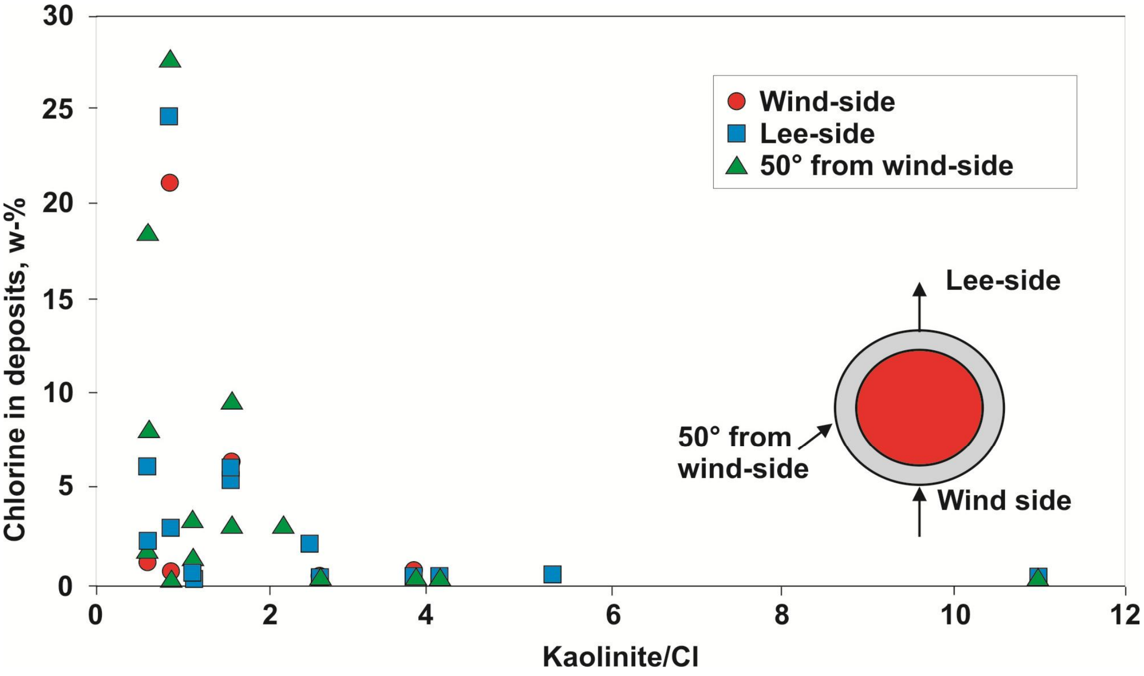


Figure 13.7. Dependence of the amount of chlorine deposited on probes that simulate superheater tubes on the kaolinite/chlorine molar ratio in pilot-scale co-combustion experiments with coal and RDF. Kaolinite binds alkalis and prevents chlorine from being carried to the test probe (Ferrer et al. 2005, adapted).

12.4 Quality requirements of solid fuels for different user groups

Table 12.1 lists quality requirements of solid fuels for different user groups and different technologies. The table only covers technologies that are in use in Finland. The significance of fuel properties is discussed in Chapter 12 and in more detail in the sections dedicated to each fuel. Tables 12.2 and 12.3 compare the most important properties of different fuels.

Table 12.1. Most important quality requirements of solid fuels for different user groups and for different technologies.

User group	Fuel	Technology	Most important fuel quality requirements
Households (< 50 kW)	Wood pellets	Pellet boilers and fireplaces	Good mechanical durability (97.5 w-%) and low ash content (< 0.7 w-%)
	Firewood, wood briquettes	Fireplaces Log boilers	Low ash content (< 0.7 w-%) for briquettes and low moisture content (15–20 w-%) for firewood
	Delimbed stem wood chips	Stoker-fired boilers	Low moisture content (< 35 w-%) and homogeneous particle size (30–45 mm)
Farms, large properties (< 1 MW)	Whole-tree or stem wood chips, sod peat	Stoker-fired boilers Grate combustion	Low moisture content (< 35 w-%) and homogeneous particle size (30–45 mm)
	Straw bales	Grate combustion, including whole bales	Homogeneous bales, low moisture content (< 18 w-%)
	Wood pellets	Pellet boilers and stoker-fired boilers	Good mechanical durability (97.5 w-%) and low ash content (< 0.7 w-%)
District heating plants (< 5 MW_{th}) or small CHP plants	Forest residue or whole-tree chips, sod peat	Grate combustion Fluidised bed combustion	Moisture content < 40 w-% for grate combustion and fluidised bed combustion
	Extremely good, clean fuels	Downdraft gasification (< 2 MW)	Moisture content < 25 w-%, particle size 10–100 mm, ash content < 1 w-%, high ash melting temperature, high bulk density (> 200 kg/m^3)
Heat and CHP plants (5–10 MW)	Forest residue, whole-tree or stem wood chips	Grate combustion (Fluidised bed combustion)	Moisture content < 50 w-%, (alkalis and chlorine)
	Relatively wide fuel base	Updraft gasification (< 10 MW)	Particle size 10–100 mm, moisture content < 50%
	Wood and straw pellets	Stoker-fired combustion, pulverised combustion	Boiler-specific quality requirements
	Straw bales or e.g. agrobiomass bales	Grate combustion (Fluidised bed combustion)	Large bales, moisture content < 20 w-%, ash melting properties and high alkali and chlorine contents to be taken into account in boiler design.
Heat and CHP plants (10–50 MW)	Forest residue chips, stump hog fuel, sawdust, bark, milled peat, and energy crops	Fluidised bed combustion	Moisture content 40–60 w-%. Elementary analysis, especially alkalis and chlorine, to be checked. In co-combustion, what matters are the properties of the fuel blend, not of individual fuels.
	Recovered wood (C grade)	Fluidised bed combustion	Boiler-specific quality requirements
	Fuel-flexible: also difficult biomasses and waste-derived fuels	Bubbling/circulating fluidised bed gasification (20–100 MW)	Particle size 30–50 mm, moisture content < 50 w-%. Need for gas cleaning depends on impurities in the fuel and the type of boiler.
Power and CHP plants (> 50 MW)	Forest residue and stem wood chips, stump hog fuel, sawdust, bark, solid recovered fuels, milled peat, sludges	Fluidised bed combustion	Moisture content < 50 w-%. Elementary analysis, especially chlorine, alkalis, heavy metals (waste-derived fuels), and ash. In co-combustion, what matters are the properties of the fuel blend, not of individual fuels
	Municipal solid waste (MSW)	Grate combustion	Boiler-specific quality requirements
	Coal, wood pellets, sawdust	Pulverised combustion	Boiler-specific quality requirements
	Recovered wood	Fluidised bed combustion	Boiler-specific quality requirements
	Fuel-flexible: also difficult biomasses and waste-derived fuels	Bubbling/circulating fluidised bed gasification (20–100 MW)	Particle size 30–50 mm, moisture content < 50 w-%. Need for gas cleaning depends on impurities in the fuel and the type of boiler.
Industrial process kilns (e.g. lime kiln)	Forest residue and stem wood chips, stump hog fuel, sawdust, bark	Circulating fluidised bed gasification (20–100 MW)	Particle size 30–50 mm, moisture content < 15 w-%. Elementary analysis of ash must be known (kiln loading is the limiting factor).

Table 12.2. Comparison of the net calorific value, moisture content, bulk density, and ash content of fuels.

Fuel	Net calorific value, dry basis, $q_{p,\text{net, d}}$, MJ/kg	Moisture, M_{ar}, w-%	Net calorific value, as received, $q_{p,\text{net,ar}}$, MJ/kg	Bulk density, BD, kg/loose m^3	Energy density, E_{ar} MWh/loose m^3	Ash content, dry basis, A_{d}, w-%
Coal	27.0–28.8	8–14	24.3–25.1	-	-	4.4–17.0
Heavy fuel oil	40.5–41.5	< 0.1	40.5–41.5	985–1,020	-	0.02–0.05
Light fuel oil	35.2–35.9 MJ/litre	0.01–0.02	35.2–35.9 MJ/litre	820–840	-	< 0.001
Pyrolysis oil	18.4–20.1	20–30	13.0–18.0	1,100–1,300		0.01–0.1
Milled peat (average)	20.6	47	9.8	330	0.91	6.3
Sod peat (average)	21.3	35	11.9	385	1.30	3.5
Peat pellets	19.7–21.0	14–18	15.1–18.7	680–750	3.0–3.7	2.0–6.0
Sawdust	19.0–19.2	45–60	2.2–10.0	250–350	0.45–0.70	0.4–0.5
Birch bark	21.0–23.0	45–55	8.0–11.0	300–400	0.60–0.90	1.0–3.0
Softwood bark	18.5–20.0	50–65	5.0–9.0	250–350	0.50–0.70	1.0–3.0
Plywood hog fuel	19.0–19.2	5–15	16.0–18.0	200–300	0.9–1.1	0.4–0.8
Wood pellets	18.9–19.5	6–9	7.0–18.2	600–650	2.8–3.3	0.1–0.5
Torrefied wood pellets	18.5–20.6	1–7	18.0–20.0	550–700	3.4–3.6	0.5–1.4
Stem wood chips	18.5–20.0	40–55	7.0–11.0	250–350	0.7–0.9	0.5–2.0
Firewood	18.5–19.0	20–25	13.4–14.5	240–320	1.35–1.70 MWh/stacked m^3	0.5–1.2
Logging residue chips	18.5–20.0	50–60	6.0–9.0	250–400	0.7–0.9	1.0–3.0
Whole-tree chips	18.5–20.0	45–55	7.0–10.0	250–350	0.7–0.9	1.0–2.0
Stump hog fuel	17.2–20.9	12–45	6.8–15.5	250–300	0.7–1.2	0.5–20.0 (average 4.0)
Willow chips	18.6	51–53	8.1–8.5	300–440	0.3–0.4	0.4–1.1
Reed canary grass (spring-harvested)	17.3–18.7	10–25	12.6–16.6	60–80	0.3	1.0–8.0
Energy grains	17.3	11	15.5	600	2.6	2.0
Straw, chopped	17.4	17–25	12.4–14.0	80	0.3–0.4	5.0
Solid recovered fuel, SRF	17.0–37.0	15–35	13.0–35.0	150–250	0.7–1.0	3.0–7.0
Household dry waste	18.5–23.4	25–36	11.7–16.9	150–200	0.7–1.0	5.3–16.1

Table 12.3. Comparison of chemical properties of fuels (w-%, dry basis).

Fuel	Carbon, C	Hydrogen, H	Sulphur, S	Nitrogen, N	Chlorine, Cl	Sodium, Na	Potassium, K
Coal	66–74	3.5–5.0	< 0.7	1.2–2.1	< 0.005	< 0.010	< 0.003
Heavy fuel oil	88.4	10.1	0.8–0.95	0.3–0.4	-	< 0.0004	-
Light fuel oil	86.2	13.7	0.1	0.01–0.03	-	-	-
Pyrolysis oil	50–60	7.0–8.0	< 0.05	< 0.4	0.07	< 0.008	< 0.001
Fuel peat	52–56	5.0–6.5	0.05–0.3	1.0–3.0	0.02–0.06	0.007	0.02
Sawdust	48–52	6.2–6.4	< 0.05	0.3–0.4	0.01–0.03	0.001–0.005	0.02–0.15
Bark	48–52	6.2–6.8	< 0.05	0.3–0.5	0.01–0.05	0.007–0.020	0.1–0.5
Plywood hog fuel	48–52	6.2–6.4	< 0.05	0.1–0.5	< 0.05	0.25–0.50	0.7
Wood pellets	49–50	6.0–6.1	< 0.007	< 0.16	0.01–0.03	0.001–0.002	0.02–0.15
Torrefied pellets	51–57	5.2–6.4	not available	0.09–0.59	not available	not available	not available
Firewood	48–52	6.0–6.5	< 0.05	0.3–0.5	0.01–0.03	0.001–0.002	0.02–0.15
Stem wood chips	48–52	5.4–6.0	< 0.06	0.3–0.5	0.01–0.03	0.001–0.002	0.02–0.15
Logging residue chips	48–52	6.0–6.2	< 0.05	0.3–0.5	0.01–0.04	0.075–0.0300	0.1–0.4
Whole-tree chips	48–52	5.0–6.0	< 0.05	0.3–0.5	0.01–0.03	0.001–0.002	0.02–0.15
Stump hog fuel	47–54	5.6–6.5	< 0.05*	0.1–1.1*	not available	not available	not available
Willow chips	47–48	6.1	< 0.025	0.2	< 0.04	< 0.005	0.2
Reed canary grass (spring-harvested)	45–50	5.4–6.2	0.04–0.17	0.3–2.0	0.01–0.09	< 0.002–0.04	< 0.08–0.6
Energy grains	45	6.5	0.14	2.0	0.04	0.002–0.005	0.4–1.0
Straw, chopped	45–47	5.8–6.0	0.01–0.13	0.4–0.6	0.14–0.97	0.01–0.6	0.69–1.30
Solid recovered fuel (SRF)	45–56	5–9	0.05–0.20	0.2–0.9	0.1–0.9	0.001–0.005	0.001–0.002
Household dry waste	47.1–53.5	6.1–7.2	0.08–0.22	0.67–1.07	0.2–1.5	0.001–0.005	0.001–0.004

* soil increases the figures.

12.5 Effect of fuel reactivity on gasification

VTT has studied the gasification reactivity of many different biomasses (Moilanen 2006, Kurkela et al. 2006, Nasrullah 2009, Nasrullah & Moilanen 2009, Moilanen et al. 2009, Moilanen & Nasrullah 2011, Kurkela et al. 2014, Kurkela 2015), and the results vary considerably. Knowing the elementary analyses and the ash composition or ash melting behaviour of a biomass is not enough for assessing how the biomass can be gasified. The effect of different gasification conditions – temperature, pressure, and the gas atmosphere – on the biomass reactivity and on ash sintering has been studied systematically using spruce bark, which is a common biomass in Finland. The results of these analyses are shown in Figures 12.8–12.11 (Nasrullah 2009). The sintering degree is given as asterisks (VTT's method, Moilanen 2006) on the basis of the method described in Section 2.8.

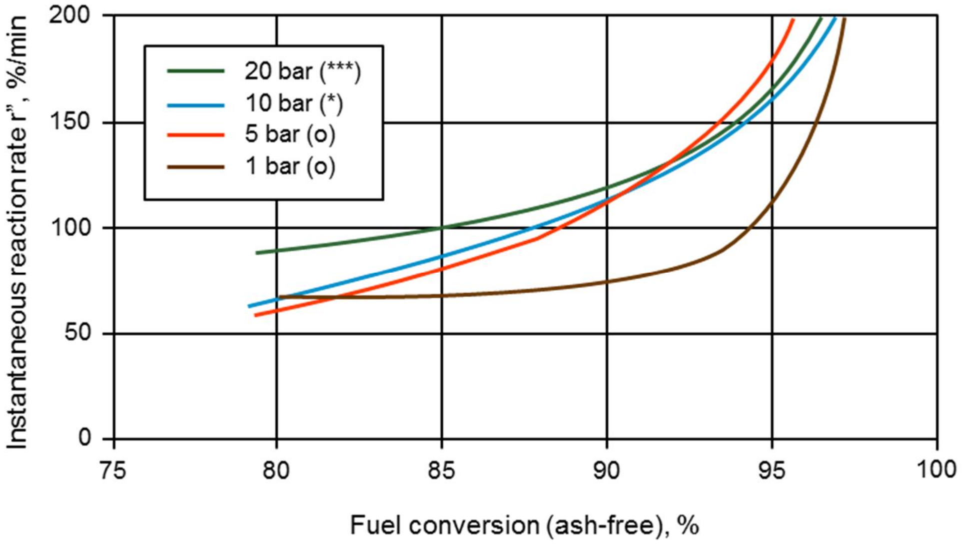


Figure 12.8. Effect of temperature on the reactivity of spruce bark in 100% steam gasification (1 bar). Figure: VTT.

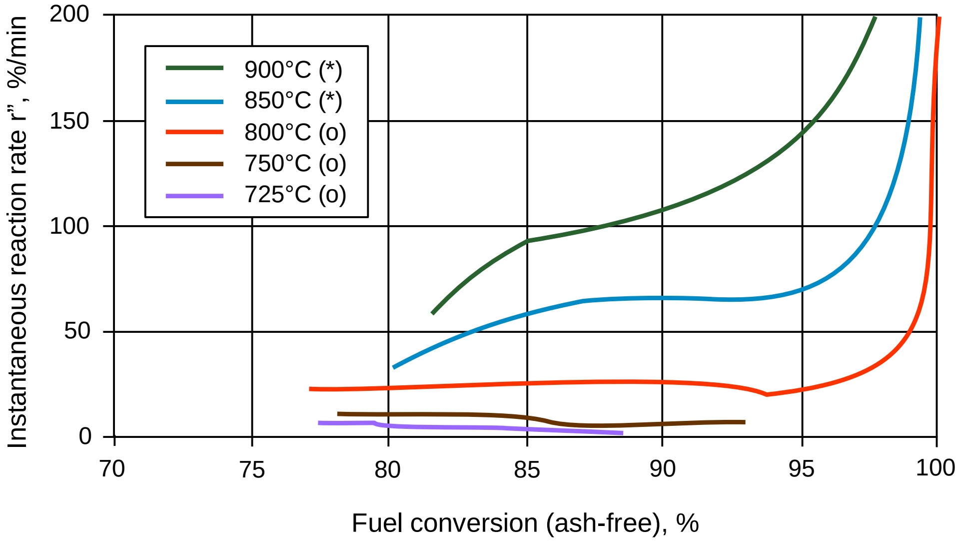


Figure 12.9. Effect of temperature on the reactivity of spruce bark in 100% CO_2 gasification (1 bar). Figure: VTT.

The reactivity of biomass increases with the gasification temperature. Char conversion is better at higher temperatures than in lower ones. Ash sintering is possible at higher temperatures, but, with spruce bark, it only began to occur at 950 °C in steam gasification and at 850–900 °C in CO_2 gasification.

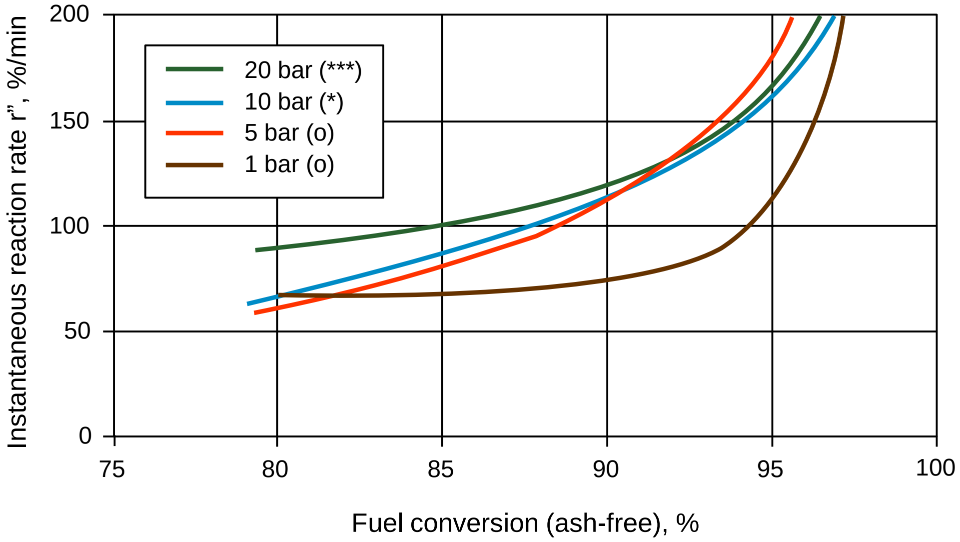


Figure 12.10. Effect of pressure on the reactivity of spruce bark in 100% steam gasification (850 °C). Figure: VTT.

Figure 12.10 shows the effect of pressure on the reactivity of spruce bark in steam gasification. The effect of pressure is not as clear as that of temperature. With spruce bark, raising the pressure from atmospheric pressure to 5 bar increases reactivity, but reactivity no longer increases and may in fact decrease with further increases in pressure. In biomass gasification, the alkali metals in ash act as catalysts for gasification, and pressure and the gas atmosphere also have a major impact on ash behaviour. In steam gasification, ash sintering is more pronounced at a higher pressure.

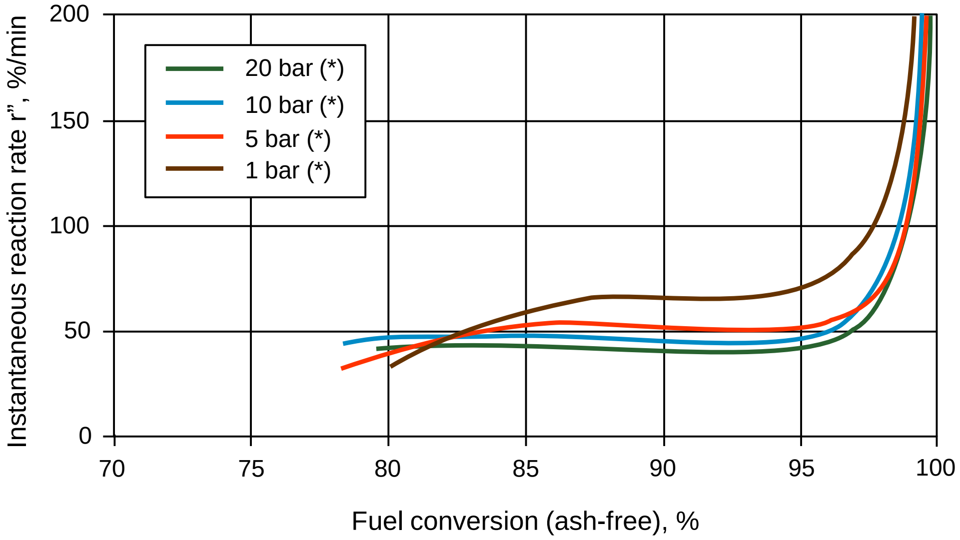


Figure 12.11. Effect of pressure on the reactivity of spruce bark in 100% CO_2 gasification (850 °C). Figure: VTT.

Figure 12.11 shows the corresponding results for spruce bark in CO_2 gasification, in which raising the process pressure lowers reactivity. Partial sintering of ash could be observed at all pressure levels, and raising the pressure had not as much of an impact on it than in steam gasification. This is due to the decrease in reactivity as process pressure increases.

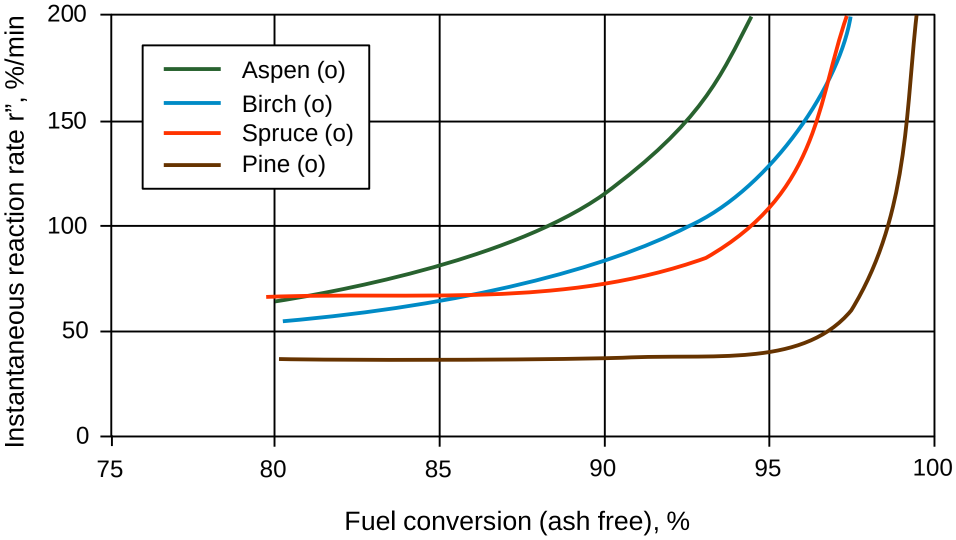


Figure 12.12. Reactivity of different kinds of bark in reference conditions: 1 bar, 850 °C, and 100% steam gasification. Figure: VTT.

An example of the effect of the feedstock type (biomass) on reactivity is shown in Figure 12.12, which presents results for aspen, birch, spruce, and pine bark in the so-called standard conditions (1 bar, 850 °C, and 100% steam). Aspen bark has the highest reactivity of these, followed by birch bark, spruce bark, and then pine bark. No signs of ash sintering were observed in these kinds of bark.

In addition to the aforementioned factors, fuel reactivity also varies between different parts of biomass (e.g. bark and needles) and depending on their growth site and storage conditions. More detailed research results on these can be found in Kurkela 2015, Moilanen et al. 2009, and Moilanen & Nasrullah 2011.

Figure 12.13 shows a diagram of Vaskiluodon Voima's 140 MW biomass gasification plant in Vaasa. The gasifier is connected to the plant's current pulverised combustion boiler (PC boiler).

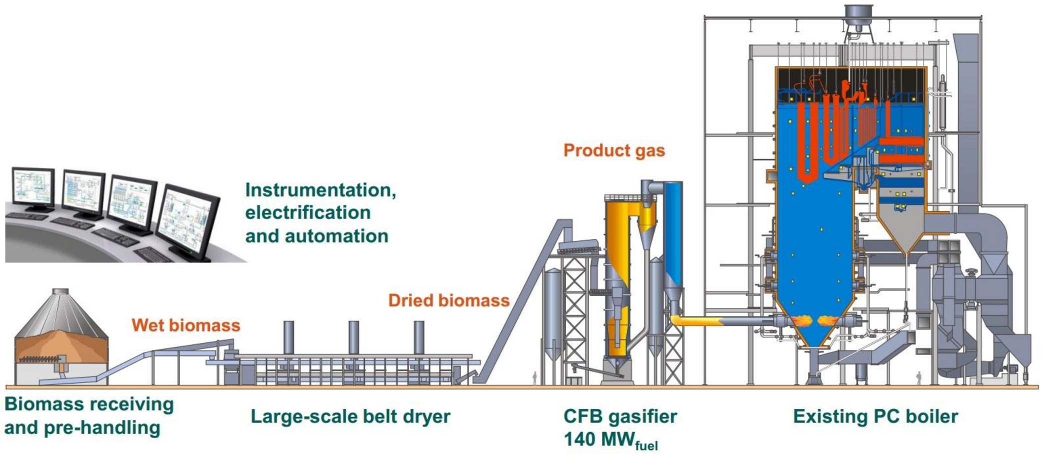


Figure 12.13. 140 MW biomass gasification plant in Vaasa. Figure: Valmet Corporation.

The reactivity determination has also been done for several foreign biomasses with high alkali and chlorine contents. Tables 12.4–12.8 list summaries of analyses on these biomasses and their reactivity. The analyses show that Northern woody biomasses are clean fuels, and the greatest differences relate to inorganic matter content (impurities).

Table 12.4. Analyses of European biomasses (Moilanen 2006, Kurkela et al. 2006).

Biomass	Dry basis, w-%								Dry basis, mg/kg		
	Volatile matter	Fixed carbon	Ash	C	H	N	S	O*	Na**	K**	Cl**
Pine dust	83.1	16.8	0.1	51.0	6.0	0.1	-	42.8			
Pine bark	73.0	25.3	1.7	52.5	5.7	0.4	0.03	39.7	30	2,100	85
Spruce bark	75.2	22.5	2.3	49.9	5.9	0.4	0.03	41.5	90	3,000	280
Forest residues (pine)	79.3	19.4	1.3	51.3	5.8	0.4	0.02	40.9			
Willow	79.9	18.9	1.2	49.4	6.1	0.4	0.03	42.9	40	4,060	40
Barley straw	76.1	18.0	5.9	46.2	5.7	0.6	0.08	41.5			
Reed canary grass	73.5	17.6	8.9	45.0	5.7	1.4	0.14	38.9			
Forest residues (Sweden)	77.0	21.7	1.3	51.4	5.8	0.4	0.02	41.1	160	1,600	< 300
Bark pellets (Sweden)	74.5	22.3	3.2	53.2	6.0	0.5	0.04	37.1	290	2,400	< 300
Willow pellets (Sweden)	80.1	18.6	1.4	50.0	6.1	0.5	0.03	42.0	70	2,500	< 200
Wheat straw (Sweden)	72.7	16.0	11.3	43.8	5.5	0.8	0.10	38.5	620	7,400	1,100
Wheat straw 1995 (Denmark)	76.1	19.1	4.8	47.5	5.9	0.7	0.16	40.9	140	16,700	6,100
Wheat straw 1997 (Denmark)	74.0	18.0	8.0	46.1	5.7	1.7	0.2	38.3	860	19,400	4,360
Miscanthus	78.5	18.2	3.3	47.9	6.0	0.6	0.6	41.6			
Sweet sorghum	77.2	18.1	4.7	47.3	5.8	0.4	0.1	41.7			
Olive mill waste, Alpeorujo (Spain)	75.3	17.2	7.5	52.0	6.3	1.3	0.16	32.7	250	22,500	2,600
Olive tree (Italy)	78.1	18.9	3.0	49.8	6.0	0.7	0.06	40.4	290	8,710	350
Wine tree (Italy)	76.6	20.7	2.7	49.0	5.7	0.7	0.05	41.9	190	9,430	260
Robinia (Italy)	80.6	17.3	2.1	48.2	6.0	1.2	0.05	42.5	140	3,140	300

* Difference

** Na, K, and Cl contents were determined using the INAA (Instrumental Neutron Activation Analysis) method.

Table 12.5. Analyses of biomasses growing outside Europe (Moilanen 2006, Kurkela et al. 2006).

Biomass	Dry basis, w-%								Dry basis, mg/kg		
	Volatile matter	Fixed carbon	Ash	C	H	N	S	O*	Na**	K**	Cl**
Kenaf	79.4	17.0	3.6	46.6	5.8	1.0	0.1	42.8			
Alfalfa (USA)	75.8	19.2	5.0	45.8	5.4	2.2	0.1	41.5	960	15,900	3,920
Oil palm dry sticks (India)	77.3	19.3	3.4	47.5	5.6	0.3	0.04	43.2	280	7,900	7,500
Oil palm fibre (India)	70.4	20.3	9.3	51.3	5.4	0.3	0.11	33.6	90	2,000	350
Dry oil palm fruit (India)	69.6	19.1	11.3	48.4	5.4	2.2	0.03	32.7	430	8,200	400
Coconut fibre (India)	70.4	26.6	3.0	51.3	5.4	0.3	0.03	40.0	1,200	1,100	5,200
Coconut twigs (India)	75.5	19.2	5.3	46.0	5.5	0.1	0.03	43.1	4,800	7,600	16,000
Jute waste (India)	59.7	11.1	29.2	44.0	5.1	1.0	0.25	20.5	1,400	7,200	< 300

* Difference

** Na, K, and Cl contents were determined using the INAA (Instrumental Neutron Activation Analysis) method.

Table 12.6. Ash content and ash composition of European biomasses (ashing at 550 ºC) (Moilanen 2006, Kurkela et al. 2006).

Biomass	Ash, w-%	Chemical composition of ash, w-%									
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	SO_3	P_2O_5
Pine dust	0.1	8.3	2.0	1.8	41.8	11.8	12.3	0.3	0.12	1.9	5.2
Pine bark	1.7	1.3	5.3	0.3	40.6	4.5	7.6	0.5	0.12	2.1	4.8
Spruce bark	2.3	1.5	1.1	0.1	39.2	5.1	7.6	0.4	0	1.0	4.1
Forest residues (pine)	1.3	38.5	4.7	3.7	15.4	4.0	8.3	0.4	0.5	1.6	3.2
Willow	1.2	0.4	0.7	0.2	30.8	5.1	26.5	0.8	0.02	3.0	11.5
Barley straw	5.9	62.0	0.2	0.2	4.5	2.2	19.3	0.5	0.02	1.4	2.5
Reed canary grass	8.9	89.8	1.4	1.1	3.5	1.5	3.1	0.1	0.05	1.1	4.1
Forest residues (Sweden)	1.3	3.4	1.2	0.7	33.6	5.1	7.5	0.6	0.06	1.4	3.2
Bark pellets (Sweden)	3.2	21.4	3.2	1.7	29.4	3.5	6.1	0.9	0.14	0.7	2.5
Willow pellets (Sweden)	1.4	3.0	0.5	1.7	33.6	4.0	14.5	0.3	0.04	1.8	10.1
Wheat straw (Sweden)	11.3	70.6	4.5	2.3	5.3	1.6	8.1	0.7	0.28	1.0	3.0
Wheat straw 1995 (Denmark)	4.8	34.2	0.3	0.2	8.4	2.2	30.1	0.5	0.02	3.2	3.9
Wheat straw 1997 (Denmark)	8.0	29.9	0.8	1.3	10.6	5.6	27.7	1.5	0.07	5.5	10.8
Miscanthus	3.3	42.8	0.5	0.4	7.6	4.8	25.3	0.7	0.03	2.1	5.3
Sweet sorghum	4.7	57.8	0.7	0.5	9.0	2.7	8.2	1.5	0.05	3.0	3.0
Olive mill waste, Alpeorujo (Spain)	7.5	20.3	5.9	2.3	9.9	4.2	30.1	0.2	0.23	1.6	3.4
Olive tree (Italy)	3.0	6.0	1.9	1.4	45	6	27	1.3	0.1	3	7
Grape wine (Italy)	2.7	2.0	0.6	0.5	38	10	36	1.0	0	4	7
Robinia (Italy)	2.1	1.2	0.4	0.4	59	6	18	1.0	0	6	7

Table 12.7. Ash content and ash composition of biomasses growing outside Europe (ashing at 550 ºC) (Moilanen 2006, Kurkela et al. 2006).

Biomass	Ash, w-%	Chemical composition of ash, w-%									
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	SO_3	P_2O_5
Kenaf	3.6	6.6	1.8	1.2	30.8	6.0	13.3	1.3	0.08	5.7	2.7
Alfalfa (USA)	5.0	3.0	0.3	0.7	22.4	9.0	27.7	1.9	0.02	3.0	8.0
Oil palm dry sticks (India)	3.4	23.5	0.3	0.6	23.8	3.3	21.7	0.7	0.04	2.7	1.9
Oil palm fibre (India)	9.3	68.4	2.8	4.0	9.5	2.8	2.4	0.3	0.4	1.1	3.7
Dry oil palm fruit (India)	11.3	42.8	3.4	2.7	13.6	6.5	11.4	0.5	0.3	1.4	4.4
Coconut fibre (India)	3.0	20.7	1.3	1.4	7.8	5.3	38.5	4.0	0.1	3.7	1.9
Coconut twigs (India)	5.3	7.1	0.8	0.6	25.2	10.0	14.5	11.5	0.06	1.9	4.4
Jute waste (India)	29.2	49.2	10.2	6.3	9.4	1.4	2.2	0.5	1.1	0.9	0.7

Table 12.8. Reactivity of different kinds of biomasses (when conversion X = 95%) and ash sintering degree in standard conditions (1 bar, 850 ºC, 100% steam) (Moilanen 2006, Kurkela et al. 2006).

Biomass	Reactivity r”, %/min	Ash sintering degree
Pine dust	25	
Pine bark	15	o
Spruce bark	135	o
Forest residues (pine)	30	
Willow	100	o
Barley straw	25	
Reed canary grass	20	
Forest residues (Sweden)	140	o
Bark pellets (Sweden)	100	o
Willow pellets (Sweden)	160	o
Wheat straw (Sweden)	20	
Wheat straw 1995 (Denmark)	100	***
Wheat straw 1997 (Denmark)	60	***
Miscanthus	45	
Sweet sorghum	60	
Kenaf	85	
Olive mill waste, Alpeorujo (Spain)	220	*
Olive tree (Italy)	400	*
Grape wine (Italy)	400	*
Robinia (Italy)	320	*
Alfalfa (USA)	370	**
Oil palm dry sticks (India)	120	o (*)
Oil palm fibre (India)	35	o (*)
Dry oil palm fruit (India)	55	*
Coconut fibre (India)	80	*
Coconut twigs (India)	200	o
Jute waste (India)	200	o

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Appendix A. Solid biofuels standards

List of the most important standards related to the determination of solid biofuel properties[2]

Property	Standard
Total moisture as received (M_{ar})	Solid biofuels. Determination of moisture content. Oven dry method. Part 1: Total moisture. Reference method (EN ISO 18134-1) Part 2: Total moisture. Simplified method (EN ISO 18134-2) Part 3: Moisture in general analysis sample (EN ISO 18134-3)
Ash content (A_d)	Solid biofuels. Determination of ash content. (EN ISO 18122)
Net calorific value ($q_{p,net,d}$)	Solid biofuels. Method for the determination of calorific value (EN 14918 / EN ISO 18125)
Particle size distribution (P)	Solid biofuels. Determination of particle size distribution for uncompressed fuels. Part 1: Oscillating screen method using sieves with apertures of 1 mm and above. (EN 15149-1 / EN ISO 17827-1) Part 2: Vibrating screen method using sieves with apertures of 3.15 mm and below. (EN 15149-2 / EN ISO 17827-2)
Pellet length (L) and diameter (D)	Solid biofuels. Determination of length and diameter of pellets (EN ISO 17829)
Particle size distribution of disintegrated pellets	Solid biofuels. Particle size distribution of disintegrated pellets (ISO 17830:2016)
Fines content of pellets (F)	Solid biofuels. Determination of fines content in quantities of pellets (EN ISO 18846)
Bulk density (BD)	Solid biofuels. Determination of bulk density (EN ISO 17828)
Particle density of pellets and briquettes	Solid biofuels. Determination of particle density of pellets and briquettes (EN ISO 18847)
Heavy extraneous materials	Determination of content of heavy extraneous materials large than 3.15 mm (EN ISO 19743)
Mechanical durability (DU)	Solid biofuels. Determination of the mechanical durability of pellets and briquettes. Part 1: Pellets (EN ISO 17831-1) Part 2: Briquettes (EN ISO 17831-2)
Carbon (C), hydrogen (H), and nitrogen (N) content	Solid biofuels. Determination of total content of carbon, hydrogen and nitrogen - Instrumental methods (EN ISO 16948)
Sulphur (S) and chlorine (Cl) content	Solid biofuels. Determination of total content of sulphur and chlorine (EN ISO 16994)
Determination of water soluble chloride (Cl), sodium (Na), and potassium (K) content	Solid biofuels. Determination of the water soluble chloride, sodium and potassium content (EN ISO 16995)
Major elements (Al, Si, K, Na, Ca, Mg, Fe, P, and Ti)	Solid biofuels. Determination of major elements (EN ISO 16967)
Trace elements (As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Se, Te, V, and Zn)	Solid biofuels. Determination of minor elements (EN ISO 16968)
Volatile matter (VM)	Solid biofuels. Determination of the content of volatile matter (EN ISO 18123)
Conversion of analytical results from one basis to another	Solid biofuels. Conversion of analytical results from one basis to another (EN ISO 16993)
Ash melting behaviour	Solid biofuels. Method for the determination of ash melting behaviour – Part 1: Characteristic temperatures method (CEN/TS 15370-1 / EN ISO 21404)
Elemental composition	Solid biofuels. Determination of elemental composition by X-ray fluorescence (ISO/TS 16996)

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[2] The latest published versions of the standards are always used. EN standards will be replaced by EN ISO standards during 2016–2017, the numbers of which are also included in the table.

The following standards are also needed in quality classification and in the application of quality assurance, sampling, and sample preparation related to solid biofuels*:*

- EN 15234-1:2011, Solid biofuels. Fuel quality assurance. Part 1: General requirements
- EN 15234-4:2012, Solid biofuels. Fuel quality assurance. Part 4: Wood chips for non-industrial use
- EN 14778:2011 / EN ISO 18135, Solid biofuels. Sampling
- EN 14780:2011 / EN ISO 14780, Solid biofuels. Sample preparation
- EN ISO 17225-1:2014, Solid biofuels. Fuel specifications and classes. Part 1: General requirements
- EN ISO 17225-2:2014, Solid biofuels. Fuel specifications and classes. Part 2: Graded wood pellets
- EN ISO 17225-3:2014, Solid biofuels. Fuel specifications and classes. Part 3: Graded wood briquettes
- EN ISO 17225-3:2014, Solid biofuels. Fuel specifications and classes. Part 4: Graded wood chips
- EN ISO 17225-5:2014, Solid biofuels. Fuel specifications and classes. Part 5: Graded firewood
- EN ISO 17225-6:2014, Solid biofuels. Fuel specifications and classes. Part 6: Graded non-woody pellets
- EN ISO 17225-7:2014, Solid biofuels. Fuel specifications and classes. Part 7: Graded non-woody briquettes
- ISO/TS 17225-8:2016, Solid biofuels. Fuel specifications and classes. Part 8: Graded thermally treated and densified biomass fuels

Appendix B. Recovered solid fuel standards

Property	Standard
Moisture content	EN 15414-3:2011, Solid recovered fuels. Determination of moisture content using the oven dry method. Part 3: Moisture in general analysis sample CEN/TS 15414-2:2010, Solid recovered fuels. Determination of moisture content using the oven dry method. Part 2: Determination of total moisture content by a simplified method
Ash content	EN 15403:2011, Solid recovered fuels. Determination of ash content
Net calorific value	EN 15400:2011, Solid recovered fuels. Determination of calorific value
Particle size	EN 15415-1:2011, Solid recovered fuels. Determination of particle size distribution. Part 1: Screen method for small dimension particles EN 15415-2:2012, Solid recovered fuels. Determination of particle size distribution. Part 2: Maximum projected length method (manual) for large dimension particles EN 15415-3:2012, Solid recovered fuels. Determination of particle size distribution. Part 3: Method by Figure analysis for large dimension particles
Bulk density	CEN/TS 15401:2010, Solid recovered fuels. Determination of bulk density
Carbon (C), hydrogen (H), and nitrogen (N) content	EN 15407:2011, Solid recovered fuels. Methods for the determination of carbon (C), hydrogen (H) and nitrogen (N) content
Sulphur (S), chlorine (Cl), fluorine (F), and bromine (Br) content	EN 15408:2011 Solid recovered fuels. Methods for the determination of sulphur (S), chlorine (Cl), fluorine (F) and bromine (Br) content
Volatile matter	EN 15402:2011, Solid recovered fuels. Determination of the content of volatile matter
Major elements (Al, Ca, Fe, K, Mg, Na, P, Si, Ti)	EN 15410:2011, Solid recovered fuels. Methods for the determination of the content of major elements
Trace elements (As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Se, Te, V, and Zn)	EN 15411:2011, Solid recovered fuels. Methods for the determination of the content of trace elements (As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Sb, Se, Tl, V and Zn)
Determination of metallic aluminium	CEN/TS 15412:2010, Solid recovered fuels. Methods for the determination of metallic aluminium

Other solid recovered fuel standards:

- EN 15358:2011, Solid recovered fuels. Quality management systems. Particular requirements for their application to the production of solid recovered fuels
- EN 15359:2011, Solid recovered fuels. Specifications and classes
- EN 15413:2011, Solid recovered fuels. Methods for the preparation of the test sample from the laboratory sample
- EN 15440:2011, Solid recovered fuels. Methods for the determination of biomass content
- EN 15442:2011, Solid recovered fuels. Methods for sampling
- EN 15443:2011, Solid recovered fuels. Methods for the preparation of the laboratory sample
- EN 15590:2011, Solid recovered fuels. Determination of the current rate of aerobic microbial activity using the real dynamic respiration index
- CEN/TR 15404:2010, Solid recovered fuels. Methods for the determination of ash melting behaviour by using characteristic temperatures
- CEN/TS 15405:2010, Solid recovered fuels. Determination of density of pellets and briquettes
- CEN/TS 15639:2010, Solid recovered fuels. Determination of mechanical durability of pellets

Appendix C. Peat standards

Property	Standard
Moisture content as received (M_{ar})	Solid biofuels – standards, Appendix A
Ash content (A)	Solid biofuels – standards, Appendix A
Net calorific value ($q_{p,net,d}$)	Solid biofuels – standards, Appendix A or ISO 1929:2009: Solid mineral fuels. Determination of gross calorific value by the bomb calorimetric method and calculation of net calorific value
Particle size distribution (P) and fines (F)	Solid biofuels – standards, Appendix A
Bulk density (BD)	Solid biofuels – standards, Appendix A and Determination in vehicles: ISO 1013:1995: Coke - Determination of bulk density in a large container or SS 187178 Standard meta description. Biofuels and peat – Determination of raw bulk density and calculation of dry raw bulk density in a large container
Particle density (DE), pellets and briquettes	Solid biofuels – standards, Appendix A
Mechanical durability (DU) of pellets and briquettes	Solid biofuels – standards, Appendix A
Carbon (C), hydrogen (H), and nitrogen (N) content	Solid biofuels – standards, Appendix A or ISO 29541:2010. Solid mineral fuels – Determination of total carbon, hydrogen and nitrogen content – Instrumental method
Sulphur (S) and chlorine (Cl) content	Solid biofuels – standards, Appendix A
Ash melting behaviour	ISO 540:2008, Solid Mineral fuels – Determination of fusibility of ash – High temperature tube method or DIN 51730:2007-9 Determination of fusibility of fuel ash
Major elements (Al, Si, K, Na, Ca, Mg, Fe, P, and Ti)	Solid biofuels – standards, Appendix A
Trace elements (As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Se, Te, V, and Zn)	Solid biofuels – standards, Appendix A
Volatile matter (VM)	Solid biofuels – standards, Appendix A
Conversion of analytical results from one basis to another	Solid biofuels – standards, Appendix A

Appendix D. Standards relating to the determination of pyrolysis oils

Property	Standard
Water content as received (M_{ar})	ASTM E 203: 1996. Standard test method to water using volumetric Karl Fischer Titration. Easton, MD: American Society for Testing and Materials.
Ash content (A)	EN ISO 6245:2011, Petroleum products – Determination of ash
Net calorific value ($q_{p,net,d}$)	DIN 51900-3. 2003. Testing of solid and liquid fuels; determination of gross calorific value by the bomb calorimeter and calculation of net calorific value; method with the adiabatic jacket. Berlin: DIN Deutsches Institut für Normung e.V. ASTM D240-14. Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter
Carbon (C), hydrogen (H), and nitrogen (N) content	ASTM D 5291-92. Standard test methods for instrumental determination of carbon, hydrogen, and nitrogen in petroleum products and lubricants. Easton, MD: American Society for Testing and Materials.
Sulphur (S) and chlorine (Cl) content	Adapted EN ISO 16994, see Appendix A, ISO 10304-1:2007, Water quality – Determination of dissolved anions by liquid chromatography of ions – Part 1: Determination of bromide, chloride, fluoride, nitrate, nitrite, phosphate and sulphate *Sulphur*: ISO 20846-2011, Petroleum products. Determination of sulphur content of automotive fuels. Ultraviolet fluorescence method or ASTM D 5453-12. Standard Test Method for Determination of Total Sulphur in Light Hydrocarbons, Spark Ignition Engine Fuel, Diesel Engine Fuel, and Engine Oil by Ultraviolet Fluorescence
Na, K, Ca, P, Cu, Zn	EN 16476:2014, Liquid petroleum products. Determination of Sodium, Potassium, Calcium, Phosphorus, Copper and Zinc contents in diesel fuel. Method via Inductively Coupled Plasma Optical Emission Spectrometry (ICP OES)
Solids	ASTM D 7579:2013. Standard test method for pyrolysis solids content in pyrolysis liquids by filtration of solids in methanol. Easton, MD: American Society for Testing and Materials.
Carbon residue, MCR	ASTM D 4530-15. Standard test method for determination of carbon residue (Micro Method). Easton, MD: American Society for Testing and Materials, *or* ASTM D 189-(06):2014. Standard Test Method for Conradson Carbon Residue of Petroleum Products, or ISO 10370:2014, Petroleum products – Determination of carbon residue – Micro method
Acid number	ASTM D 664. Standard test method for acid number of petroleum products by potentiometric titration. Easton, MD: American Society for Testing and Materials.
Viscosity	EN ISO 3104:1994/Cor. 1:1997, Petroleum products – Transparent and opaque liquids – Determination of kinematic viscosity and calculation of dynamic viscosity ASTM D 445-15a. Standard test method for kinematic viscosity of transparent and opaque liquids (and the calculation of dynamic viscosity). Easton, MD: American Society for Testing and Materials.
Flash point	ISO 2719:2002, Determination of flash point – Pensky-Martens closed cup method, or ISO 9038:2013, Determination of sustained combustibility of liquids or ASTM D 93-15a. Standard test method for flash point by Pensky-Martens closed tester. Easton, MD: American Society for Testing and Materials.
Pour point	ISO 3016:1994, Petroleum products – Determination of pour point, or ASTM D 97-16. Standard test method for pour point of petroleum oils. Easton, MD: American Society for Testing and Materials
Density	EN ISO 12185:1996, Crude petroleum and petroleum products. Determination of density. Oscillating U-tube method, or ASTM D 4052-15. Standard test method for density and relative density of liquids by digital density meter. Easton, MD: American Society for Testing and Materials

Property	Standard
Pyrolysis oil quality classification	ASTM D 7544-11. Standard specification for pyrolysis liquid biofuel. Easton, MD: American Society for Testing and Materials.
	EN 16900 (in preparation), Fast pyrolysis bio-oils for industrial boilers – Requirements and test methods
	Technical report (in preparation): Fast pyrolysis bio-oils for stationary internal combustion engines – Quality designation

Many standardised methods are not directly suitable for pyrolysis oil, which is why certain changes have been proposed. Some standards cannot be applied, such as those concerning flash point, filterability, distillability, and cloud point. For more information, see Oasmaa & Peacocke 2010 and Lehto et al. 2014.

Appendix E. Properties of recovered wood

Table E.1. Properties of recovered wood.

Property	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Net calorific value, MJ/kg, dry basis	18.7	18.7	18.9	18.7		18.6	18.6
CONTENT ON A DRY BASIS, w-%							
Ash	1.7	1.5	0.7		1.9	3	
Carbon, C	50.1	49.9				49.1	50
Hydrogen, H	6.4	6.1				6	6.2
Nitrogen, N	0.5	0.5	0.25		0.68	1	0.1
Sulphur, S	0.02	0.04	< 0.02		0.08	0.05	0.01
Chlorine, Cl	0.035	0.03	0.034	0.018	0.12	0.08	
Fluorine, F	< 0.002					< 0.01	
CONTENT ON A DRY BASIS, mg/kg							
Aluminium, Al	600	130		459			< 0.01
Iron, Fe	490						
Potassium, K	Σ Na + K: 1,100	910	630		Σ Na + K: 2,200	728	1,200
Manganese, Mn	72	76.7	84.6	80		94	74
Sodium, Na	Σ Na + K: 1,100	630	200		Σ Na + K: 2,200	625	120
Phosphorus, P	49						
Arsenic, As	34	2.9	2.4	8	18	19	2
Cadmium, Cd	0.29	0.235	0.16		0.5	0.27	0.09
Chromium, Cr	39	9.3	5.2	27.3	60	39	6
Copper, Cu	31	5.5	7	9.2	80	40	3
Mercury, Hg	< 0.1	0.053	< 0.01		0.05	< 0.04	< 0.06
Nickel, Ni	< 4	3.2	3.3	8.9	10	9.7	2.1
Lead, Pb	26	14	5.4	65	76	62	3.9
Vanadium, V	< 5	0.96	< 0.50	2.2	2	0.94	< 0.10
Zinc, Zn	160	210	79	142	300	275	21

Table E.2. Properties of recovered wood.

Property	Sample 8	Sample 9	Sample 10	Sample 11	Sample 12	Sample 13	Sample 14	Sample 15
Moisture, w-%	12.3	14.6	17.7	19.7	13.5	6.6	29.2	28.2
Gross calorific value, MJ/kg, dry basis	20.18	20.28	19.95	20.11	20.00	19.56	20.01	20.05
Net calorific value, MJ/kg, dry basis	18.93	19.02	18.6	18.76	18.75	18.34	18.7	18.88
Net calorific value, MJ/kg, as received	16.31	15.90	14.87	14.58	15.89	16.96	12.53	12.87
CONTENT ON A DRY BASIS, w-%								
Volatile matter	80.8	81.3			81.2	80		79.9
Ash	1.9	1.2			1.3	1.0	1.7	3.1
Carbon, C			50.0	49.8			49.9	
Hydrogen, H			6.2	6.2			6.0	
Nitrogen, N			0.1	0.6			0.19	
Sulphur, S			0.01	0.03				0.03
Chlorine, Cl	0.055	0.038	0.009	0.036			0.011	0.022
CONTENT ON A DRY BASIS, mg/kg								
Arsenic, As	< 6	< 6	2	52	6.5	5.7	< 0.2	5
Copper, Cu	11	4	3	40	5.3	7.4	2.4	12
Chromium, Cr	12	9.4	6	32	1.9	9.1	19	17
Aluminium, Al			< 100	< 100	< 100	< 100	< 100	< 100
Potassium, K			1,200	1,500	600	900	1,500	1,600
Manganese, Mn			74	73	76	82	78	85
Sodium, Na			100	1,100	700	500	410	600
Cadmium, Cd	< 0.4	< 0.4		0.15	0.32	< 0.10	0.08	0.21
Mercury, Hg	< 0.02	< 0.02	< 0.06	< 0.06	< 0.10	< 0.10	0.05	< 0.05
Nickel, Ni			2.1	1.7	1.2	1.9	6.7	5.9
Lead, Pb	11	< 4	3.9	5.1	34	4.1	0.69	14
Vanadium, V	< 2	< 2	< 0.1	0.33	1	0.53	1.3	< 0.1
Zinc, Zn	60	40	21	58	150	170		240
Tin, Sn			0.15	0.39	0.25	1.2	< 0.5	< 0.10
Thallium, Tl			< 0.10	< 0.10	< 0.10	< 0.10	< 0.2	< 0.10
Cobalt, Co			0.1	0.26	0.71	0.32	0.25	0.89
Antimony, Sb			< 0.10	0.45	0.37	0.16	< 0.2	0.21

Table E.3. Properties of recovered wood.

Property	Sample 16	Sample 17	Sample 18	Sample 19	Sample 20	Sample 21	Sample 22
Moisture, w-%	24.0	21.2	24.0	12.2	27.0	22.3	19.1
Gross calorific value, MJ/kg, dry basis	19.94	20.02			20.28	19.60	20.07
Net calorific value, MJ/kg, dry basis	18.68	18.79			19	18.37	18.81
Net calorific value, MJ/kg, as received	13.61	14.39	14.60		13.21	13.73	14.75
CONTENT ON A DRY BASIS, w-%							
Volatile matter	81.3	79.7			84.3	81.8	83.3
Ash	1.0	1.6	1.5				
Hydrogen, H	6.1						
Nitrogen, N	0.30	0.82		0.27			
Sulphur, S	0.05	0.04		0.07			
Chlorine, Cl	0.017	0.03	0.03	0.02	0.012	0.02	0.023
CONTENT ON A DRY BASIS, mg/kg							
Arsenic, As	0.65	0.31	2.9		< 0.10	8.8	15
Copper, Cu	3.5	2.3	5.5		2.6	12	13
Chromium, Cr	5	3.9	9.3		35	20	27
Aluminium, Al	< 100	< 100	100	47	77	< 100	< 100
Potassium, K	400	400	Σ Na + K: 150	377			
Manganese, Mn	70	69	76.7		66	95	79
Sodium, Na	200	140	Σ Na + K: 150	384			
Cadmium, Cd	0.51	0.19	0.24	< 0.2			
Mercury, Hg	< 0.03	< 0.03	0.05	0.06			
Nickel, Ni	2.2	1.5	3.2		19	4.4	3.2
Lead, Pb	18	12	13.5		1.7	97	96
Vanadium, V	< 0.10	2.7	1		0.52	4.2	2
Zinc, Zn	610	87	210		27	230	170
Tin, Sn	0.26	0.24	0.4				
Thallium, Tl	< 0.10	< 0.10	0.12		< 0.10	< 0.01	< 0.01
Cobalt, Co	0.86	0.43	0.6		39	0.85	0.44
Antimony, Sb	0.32	0.23	0.2		0.71	0.7	0.3

Table E.4. Properties of recovered wood.

Property	Sample 23	Sample 24	Sample 25	Sample 26	Sample 27	Sample 28	Sample 29	Sample 30
Moisture, w-%	23.9	27.0	27.7	34.6	3.6	25.5	23.3	26.1
Gross calorific value, MJ/kg, dry basis	21.34	19.80		19.71		20.53	19.90	20.30
Net calorific value, MJ/kg, dry basis	19.93	18.48		18.4		19.2	18.64	19.01
Net calorific value, MJ/kg, as received	15.63	12.83		11.19		13.71	13.73	13.41
CONTENT ON A DRY BASIS, w-%								
Ash	4.8	3.2		3.9		1.4	2.1	1
Carbon, C	50.9	48.1		49.0	49.6	50.6	49.5	50.0
Hydrogen, H	6.5	6.1		6.01	6.2	5.97	5.8	5.9
Nitrogen, N	1.00	2.87	0.04	1.16		0.23	1.51	0.27
Sulphur, S	0.22	< 0.03	0.021	0.07	0.038	0.036	0.054	
Chlorine, Cl	0.16	0.014	0.036	0.014	0.018	0.103	0.061	0.019
Fluorine, F		< 0.005		< 0.005		< 30		
CONTENT ON A DRY BASIS, mg/kg								
Arsenic, As	23	1.6	25	< 0.8	54.18	< 0.8	4.3	1.6
Copper, Cu	41	8	21	6	59	14	7	8
Chromium, Cr	40	5	30	3	65	3	7	6.7
Aluminium, Al	200	200		200		100		
Calcium, Ca	9,100	2,830		4,660		2,230		
Potassium, K	500	1,100	500	2,400	600	500	790	530
Iron, Fe	1,070	810		780		350		
Magnesium, Mg	720	640		770		470		
Manganese, Mn	100	110		240	57	66		98
Sodium, Na	600	600	600	1,000	1,000	300	620	330
Phosphorus, P	100			340		26		
Cadmium, Cd	0.9	< 0.2	0.4	0.2	< 0.2	< 0.2	0.7	0.16
Mercury, Hg	< 0.07	< 0.07	0.1	< 0.07	< 0.1	0.07	< 0.07	< 0.01
Nickel, Ni	4	3		2	< 2	2	1	1.8
Lead, Pb	37	2	13	2	5.7	3	36	4.1
Vanadium, V	3	13		12	< 1	< 0.1		< 0.5
Zinc, Zn	180	40	91	72	91	35	190	31
Tin, Sn	6	< 3		< 3	< 1	< 3		
Thallium, Tl	< 0.2	< 0.2		< 0.2	< 1	< 0.2		
Cobalt, Co	1	< 1		< 1	< 1	10		0.96
Antimony, Sb	8	< 1		< 1	0.9	< 1		0.52
Barium, Ba	120	< 0.005			39	24		
Bromine, Br	< 5	< 0.005		< 0.005		< 50		
Selenium, Se					< 1			
Molybdenum, Mo					< 2			

Appendix F. Average properties of milled peat and sod peat

Table F.1. Milled peat properties in 1985–1992 and 1994–2005 (Electrowatt-Ekono Oy, 2005).

Property	1985	1986	1987	1988	1989	1990	1991	1992	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	Average
Volume, GWh	7,650	8,820	8,593	8,364	8,061	10,165	11,702	11,312	13,986	15,645	19,538	19,276	15,831	13,887	10,619	16,492	18,914	22,210	15,186	11,986	254,400
Net calorific value on a dry basis, MJ/kg	21.0	20.9	20.9	20.9	20.9	20.8	21.0	20.9	20.9	20.8	20.8	20.7	21.0	20.7	20.6	20.7	20.7	20.7	20.9	21.0	20.8
Average moisture, w-%	49.8	49.5	50.2	51.2	48.4	47.1	48.1	49.3	47.1	46.3	46.0	46.3	46.5	46.9	46.1	46.5	44.9	45.0	47.0	48.5	47.1
Net calorific value as received, MJ/kg	9.4	9.3	9.2	8.9	9.6	9.8	9.7	9.4	9.9	10.1	10.1	10.0	10.1	10.0	10.0	9.9	10.3	10.3	9.9	9.6	9.90
Density on a dry basis, kg/m^3	173	170	171	169	176	173	176	171	176	178	178	179	178	175	175	173	177	177	170	165	175
Bulk density as received, kg/m^3	345	337	344	346	342	328	340	337	332	331	330	333	333	330	325	323	321	321	321	320	330
Energy density, MWh/m^3	0.9	0.87	0.88	0.86	0.91	0.89	0.92	0.88	0.91	0.92	0.93	0.93	0.93	0.90	0.90	0.89	0.92	0.92	0.89	0.86	0.91
Ash content on a dry basis (815 °C), w-%	4.7	5.1	5.1	5.3	5.5	5.6	5.5	5.5	5.6	5.5	5.7	5.5	5.8	6.4	5.9	6.8	6.3	5.8	5.9	5.7	5.8
Sulphur content on a dry basis, w-%	-	-	-	-	-	-	-	-	0.21	0.20	0.22	0.21	0.21	0.22	0.31	0.22	0.21	0.22	0.21	0.21	0.22

* No peat statistics exist for the year 1993, and the volumes in May–December 2005 are based on estimates and the other property data on the data collected in January–April.

Table F.2. Average sod peat properties in 1985–1992 and 1994–2005 (Electrowatt-Ekono Oy, 2005).

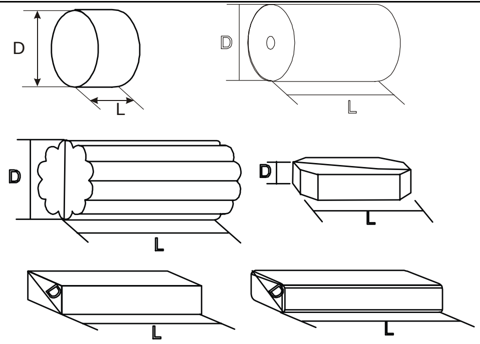
Property	1985	1986	1987	1988	1989	1990	1991	1992	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	Average
Volume, GWh	994	1,011	961	611	645	863	718	838	2,175	2,217	1,505	1,570	360	489	192	191	139	389	95	27	15,730
Net calorific value on a dry basis, MJ/kg	21.7	21.2	20.7	21.0	20.3	21.2	21.2	21.8	21.3	20.7	21.2	21.1	21.4	21.9	21.9	21.5	21.3	22.1	20.7	20.7	21.2
Average moisture, w-%	39.9	40.9	42.4	41.1	37.5	37.8	39.4	40.6	40.5	38.1	38.4	37.7	39.4	41.8	39.0	37.0	35.3	34.5	35.4	35.2	39.5
Net calorific value as received, MJ/kg	12.0	11.5	10.9	11.4	11.7	12.3	11.9	11.9	11.7	11.9	12.1	12.3	12.0	11.7	12.4	12.6	12.9	13.6	12.5	13.6	11.9
Density on a dry basis, kg/m^3	238	230	227	230	242	237	231	233	231	239	239	242	234	218	223	226	225	228	226	233	233
Bulk density as received, kg/m^3	397	390	394	391	387	382	381	392	389	386	387	389	387	374	366	358	348	348	350	360	385
Energy density, MWh/m^3	1.33	1.25	1.19	1.23	1.26	1.30	1.26	1.30	1.26	1.27	1.30	1.32	1.29	1.21	1.26	1.26	1.25	1.31	1.22	1.36	1.27
Ash content on a dry basis, w-%	5.6	5.3	5.1	5.2	5.0	4.9	4.5	4.6	4.9	4.9	4.5	5.1	3.7	4.2	3.6	3.4	2.9	2.8	2.9	2.7	4.8
Sulphur content on a dry basis, w-%	-	-	-	-	-	-	-	-	0.20	0.20	0.20	0.20	0.21	0.20	0.21	0.21	0.20	0.20	0.23	0.23	0.20

* No peat statistics exist for the year 1993, and the volumes in May–December 2005 are based on estimates and the other property data on the data collected in January–April.

1 GWh = 3.6 TJ

Appendix G. Peat fuel quality classification

Table G.1. Quality classes for briquettes (NT ENVIR 009:2005).

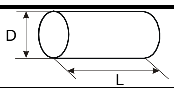
	Master table		
	Origin		Fuel peat alone or blend of the following: Woody biomass or herbaceous biomass specified according to Table 1 in EN ISO 17225-1:2014. Proportion of each fraction shall be stated.
	Traded form		Briquette
Normative	Dimensions (mm), Diameter (D) or equivalent (diagonal or cross cut)		
	D40	$25 \leq D \leq 40$	 Examples of briquettes
	D50	$40 < D \leq 50$	
	D60	$50 < D \leq 60$	
	D80	$60 < D \leq 80$	
	D100	$80 < D \leq 100$	
	D125	$100 \leq D \leq 125$	
	D125+	≥ 125, actual value to be stated	
		Length (L)	
	L50	≤ 50	
	L100	≤ 100	
	L200	≤ 200	
	L300	≤ 300	
	Moisture (w-% as received)		
	M10	≤ 10%	
	M15	≤ 15%	
	M20	≤ 20%	
	Ash (w-% of dry basis)		
	A2.0	≤ 2.0%	
	A4.0	≤ 4.0%	
	A6.0	≤ 6.0%	
	A8.0	≤ 8.0%	
	A10.0	≤ 10%	
	A10.0+	> 10.0%, actual value to be stated	
	Sulphur (w-% of dry basis)		
	S0.15	≤ 0.15%	
	S0.20	≤ 0.20%	
	S0.25	≤ 0.25%	
	S0.30	≤ 0.30%	
	S0.35	≤ 0.35%	
	S0.40	≤ 0.40%	
	S0.45	≤ 0.45%	
	S0.50	≤ 0.50%	
	S0.50+	> 0.50%, actual value to be stated	
	Net calorific value as received (MJ/kg (= MWh/t))[a]		
	Q18.0	≥ 18.0 (≥ 5.0 MWh/t)	complies with moisture content of M10
	Q16.2	≥ 16.2 (≥ 4.5 MWh/t)	complies with moisture content of M15
	Q14.4	≥ 14.4 (≥ 4.0 MWh/t)	complies with moisture content of M20
	Additives (w-% of pressing mass)		
	Type and content of pressing aids, slagging inhibitors, or any other additives, e.g. dust prevention agent, have to be stated.		

Informative	Nitrogen, N (w-% of dry basis)	
	N1.0	≤ 1.0%
	N1.5	≤ 1.5%
	N2.0	≤ 2.0%
	N2.5	≤ 2.5%
	N3.0	≤ 3.0%
	N3.0+	> 3.0%, actual value to be stated
	Particle density (kg/dm^3)	
	DE0.8	0.80–0.99 kg/dm^3
	DE1.0	1.00-1.09 kg/dm^3
	DE1.1	1.10-1.19 kg/dm^3
	DE1.2	≥ 1.20 kg/dm^3
	Bulk density as received (kg/bcm)	Recommended to be stated if traded by volume basis.
	Ash melting behaviour (oxidising atmosphere), deformation temperature (DT), °C	It is recommended to state DT if temperature is < 1,100 °C. NOTE: It is recommended to report all characteristic temperatures together with the test method used (ISO or EN).
	Chlorine, Cl (w-% of dry basis)	It is recommended to state chlorine content as one of the following categories: Cl 0.03, Cl 0.05, Cl 0.07, Cl 0.10 and Cl 0.10+ (if Cl > 0.10%, actual value to be stated).

[a] Minimum requirement for net calorific value on a dry basis ≥ 18 MJ/kg.

If peat is milled before pressing, it has to be specified.

Table G.2. Quality classes for peat pellets (NT ENVIR 009:2005).

	Master table		
	Origin		Fuel peat alone or blend of the following: Woody biomass or herbaceous biomass specified according to Table 1 in EN ISO 17225-1:2014. Proportion of each fraction shall be stated.
	Traded form		Pellets
Normative	Dimensions (mm)		
	Diameter (D) and Length (L)[a]		
	D06	6 mm ± 0.5 mm, and L ≤ 5 x Diameter	
	D08	8 mm ± 0.5 mm, and L ≤ 5 x Diameter	
	D10	10 mm ± 0.5 mm, and L ≤ 5 x Diameter	
	D12	12 mm ± 1.0 mm, and L ≤ 5 x Diameter	
	D14	14 mm ± 1.0 mm, and L ≤ 5 x Diameter	
	D25	25 mm ± 1.0 mm, and L ≤ 4 x Diameter	
	Moisture (w-% as received)		
	M10	≤ 10%	
	M15	≤ 15%	
	M20	≤ 20%	
	Ash (w-% of dry basis)		
	A2.0	≤ 2.0%	
	A4.0	≤ 4.0%	
	A6.0	≤ 6.0%	
	A8.0	≤ 8.0%	
	A10.0	≤ 10%	
	A10.0+	> 10.0%, actual value to be stated	
	Sulphur (w-% of dry basis)		
	S0.15	≤ 0.15%	
	S0.20	≤ 0.20%	
	S0.25	≤ 0.25%	
	S0.30	≤ 0.30%	
	S0.35	≤ 0.35%	
	S0.40	≤ 0.40%	
	S0.45	≤ 0.45%	
	S0.50	≤ 0.50%	
	S0.50+	> 0.50%, actual value to be stated	
	Net calorific value as received (MJ/kg (= MWh/t))[b]		
	Q18.0	≥ 18.0 (≥ 5.0 MWh/t)	complies with moisture content of M10
	Q16.2	≥ 16.2 (≥ 4.5 MWh/t)	complies with moisture content of M15
	Q14.4	≥ 14.4 (≥ 4.0 MWh/t)	complies with moisture content of M20
	Mechanical durability (w-% of pellets after testing)		
	DU95.0	≥ 95.0%	
	DU90.0	≥ 90.0%	
	DU90.0–	≤ 90.0%, actual value to be stated	
	Amount of fines (w-%, < 3.15 mm) after production at factory gate[b]		
	F2.0	≤ 2.0%	[b] At the last point where it is practical to take samples
	F4.0	≤ 4.0%	
	F4.0+	> 4.0%, actual value to be stated	
	Additives (w-% of pressing mass)		
	Type and content of pressing aids, slagging inhibitors, or any other additives, e.g. dust prevention agent, have to be stated.		

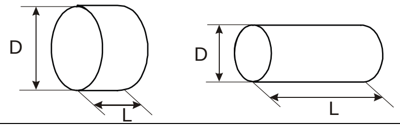
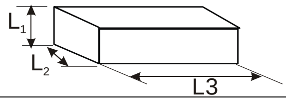
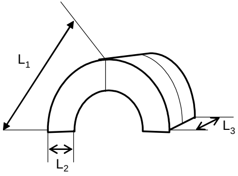
Informative	Nitrogen, N (w-% of dry basis)	
	N1.0	≤ 1.0%
	N1.5	≤ 1.5%
	N2.0	≤ 2.0%
	N2.5	≤ 2.5%
	N3.0	≤ 3.0%
	N3.0+	> 3.0%, actual value to be stated
	Ash melting behaviour (oxidising atmosphere), deformation temperature (DT), °C	It is recommended to state DT if temperature is < 1,100 °C. NOTE: It is recommended to report all characteristic temperatures together with the test method used (ISO or EN).
	Chlorine, Cl (w-% of dry basis)	It is recommended to state chlorine content as one of the following categories: Cl 0.03, Cl 0.05 or Cl 0.07, Cl 0.10 and Cl 0.10+ (if Cl > 0.10%, actual value to be stated).
	Bulk density as received (kg/loose m^3)	Recommended to be stated if traded by volume basis. BD 500, BD 600, BD 700

[a] Maximum 20 w-% of pellets may have a length of 7.5 x Diameter.

[b] Minimum requirement for net calorific value on a dry basis ≥ 18 MJ/kg.

If peat is milled before pressing it has to be specified.

Table G.3. Quality classes for sod peat (NT ENVIR 009:2005).

	Master table		
	Origin	Peat	
	Traded form	Sod peat (Table 6.1)	
Normative	Dimensions (mm)[a]		
	Shape	Diameter (D) / Length (L)	
	cylindrical 	P40	≤ 40 mm, and L ≤ 5 x Diameter
		P60	≤ 60 mm, and L ≤ 5 x Diameter
		P80	≤ 80 mm, and L ≤ 5 x Diameter
	cubic 	P30	$L_1 \leq$ 30 mm, $L_2 \leq$ 40 mm, $L_3 \leq$ 200 mm
	arched (wave-like sod peat) 	P70	$L_1 \leq$ 250 mm, $L_2 \leq$ 70 mm, $L_3 \leq$ 250 mm
	Over-sized particles (% of weight), maximum weight of over-sized particles of a single load		
	OP0.5	≤ 0.5%	
	OP1.0	≤ 1.0%	
	Over-sized particles, maximum dimension of a single particle and sum of maximum dimensions (mm)		
	MD300	300 mm, and sum of the maximum dimensions 450 mm	
	MD500	500 mm, and sum of the maximum dimensions 700 mm	
	MD700	700 mm, and sum of the maximum dimensions 900 mm	
	Moisture (w-% as received)		
	M30	20 ≤ M ≤ 30%	
	M38	25 ≤ M ≤ 38%	
	M47	30 ≤ M ≤ 47%	
	M55	40 ≤ M ≤ 55%	
	Ash (w-% of dry basis)		
	A2.0	≤ 2.0%	
	A4.0	≤ 4.0%	
	A6.0	≤ 6.0%	
	A8.0	≤ 8.0%	
	A10.0	≤ 10%	
	A10.0+	> 10.0%, actual value to be stated	
	Net calorific value as received (MJ/kg (= MWh/t))[b, c]		
	Q14.0	≥ 14.0 (≥ 3.9 MWh/t)	complies with moisture content of M30
	Q12.0	≥ 12.0 (≥ 3.3 MWh/t)	complies with moisture content of M38
	Q10.0	≥ 10.0 (≥ 2.8 MWh/t)	complies with moisture content of M47
	Q8.0	≥ 8.0 (≥ 2.2 MWh/t)	complies with moisture content of M55
	or Energy density as received (E) (MWh/loose m^3)		
	E1.30	≥ 1.30 MWh/ loose m^3	complies with moisture content of M30
	E1.15	≥ 1.15 MWh/ loose m^3	complies with moisture content of M38
	E1.00	≥ 1.00 MWh/ loose m^3	complies with moisture content of M47
	E0.80	≥ 0.80 MWh/ loose m^3	complies with moisture content of M55

Normative	Amount of fines (w-%, < 20 mm for P40–P80 and < 5 mm for P30) after production at receiving station		
	F5.0	≤ 5.0%	
	F10.0	≤ 10.0%	
	F15.0	≤ 15.0%	
	F15.0+	> 15.0%, actual value to be stated	
	Sulphur (w-% of dry basis)		
	S0.15	≤ 0.15%	
	S0.20	≤ 0.20%	
	S0.25	≤ 0.25%	
	S0.30	≤ 0.30%	
	S0.35	≤ 0.35%	
	S0.40	≤ 0.40%	
	S0.45	≤ 0.45%	
	S0.50	≤ 0.50%	
	S0.50+	> 0.50%, actual value to be stated	
Informative	Nitrogen, N (w-% of dry basis)		
	N1.0	≤ 1.0%	
	N1.5	≤ 1.5%	
	N2.0	≤ 2.0%	
	N2.5	≤ 2.5%	
	N3.0	≤ 3.0%	
	N3.0+	> 3.0%, actual value to be stated	
	Bulk density as received (kg/loose m^3)		Recommended to be stated if traded by volume basis as one of the following categories: (BD280, BD300), maximum BD550.
	Chlorine, Cl (w-% of dry basis)		It is recommended to state chlorine content as one of the following categories: Cl 0.03, Cl 0.05 or Cl 0.07, Cl 0.10 and Cl 0.10+ (if Cl > 0.10%, actual value to be stated).
	Ash melting behaviour (oxidising atmosphere), deformation temperature (DT), °C		It is recommended to state DT if temperature is < 1,100 °C. NOTE: It is recommended to report all characteristic temperatures together with the test method used (ISO or CEN).

[a] The wave-like sod peat drawing describes sod peat in production phase. In delivery, arched sod is broken into 2–4 pieces.

[b] Select either net calorific value as received or energy density.

[c] Minimum requirement for net calorific value on a dry basis ≥ 18 MJ/kg.

Table G.4. Quality classes for milled peat (NT ENVIR 009:2005).

	Master table		
	Origin		Peat
	Traded form		Milled peat
Normative	Over-sized particles [a]		
	Over-sized particles (OP), weight (w-%) of over-sized particles of a single load		
	OP0.5	≤ 0.5%	
	OP1.0	≤ 1.0%	
	Over-sized particles, maximum dimension of a single particle and sum of maximum dimensions (mm)		
	MD400	400 mm, and sum of the maximum dimensions 600 mm	
	MD750	750 mm, and sum of the maximum dimensions 1,000 mm	
	MD1000	1,000 mm, and sum of the maximum dimensions 1,500 mm	
	Moisture (w-% as received)		
	M45	40 ≤ M ≤ 45%	single load maximum 50%, minimum 38%
	M50	40 ≤ M ≤ 50%	single load maximum 55%, minimum 38%
	M55	45 ≤ M ≤ 55%	single load maximum 60%, minimum 38%
	M60	50 ≤ M ≤ 60%	single load maximum 65%, minimum 38%
	Ash (w-% of dry basis)		
	A2.0	≤ 2.0%	
	A4.0	≤ 4.0%	
	A6.0	≤ 6.0%	
	A8.0	≤ 8.0%	
	A10.0	≤ 10.0%	
	A10.0+	> 10.0%, actual value to be stated	
	Net calorific value as received (MJ/kg[b] = MWh/t)		
	Q10.0	≥ 10 MJ/kg (≥ 2.8 MWh/t)	complies with moisture content of M45
	Q8.0	≥ 8 MJ/kg (≥ 2.2 MWh/t)	complies with moisture content of M50
	Q6.0	≥ 6 MJ/kg (≥ 1.7 MWh/t)	complies with moisture content of M55
	Q5.0	≥ 5 MJ/kg (≥ 1.4 MWh/t)	complies with moisture content of M60
	Q5.0–	< 5.0 MJ/kg (< 1.4 MWh/t)	moisture content ≥ 60 w-%
	or Energy density (E) (MWh/ loose m^3)[c]		
	E0.8	≥ 0.8 MWh/ loose m^3	complies with moisture content of M45
	E0.7	≥ 0.7 MWh/ loose m^3	complies with moisture content of M50
	E0.5	≥ 0.5 MWh/ loose m^3	complies with moisture content of M55
	E0.4	≥ 0.4 MWh/ loose m^3	complies with moisture content of M60
	Sulphur (w-% of dry basis)		
	S0.15	≤ 0.15%	
	S0.20	≤ 0.20%	
	S0.25	≤ 0.25%	
	S0.30	≤ 0.30%	
	S0.35	≤ 0.35%	
	S0.40	≤ 0.40%	
	S0.45	≤ 0.45%	
	S0.50	≤ 0.50%	
	S0.50+	> 0.50%, actual value to be stated	
	Ash melting behaviour (oxidising atmosphere), deformation temperature (DT), °C		
	It is recommended to state DT if temperature is < 1,100 °C. NOTE: It is recommended to report all characteristic temperatures together with the test method used (ISO or EN).		

Appendix H. Fuel classification by Statistics Finland

Code	Heading	Fuel-specific unit	CO_2 default emission factor, t/TJ	Default oxidation factor	Default net calorific value (as fired), GJ/unit
1	FOSSIL FUELS				
111	PETROLEUM GASES				
1111	Refinery gas	t	54.0	1.0	50.0
1112	LPG (liquefied petroleum gas)	t	64.9	1.0	46.3
1119	Other gas	t	65.0	1.0	8–55
112	LIGHT DISTILLATES				
1121	Naphtha	t	72.7	1.0	44.3
1122	Motor gasoline	t	69.4	1.0	41.9
1123	Aviation gasoline	t	71.3	1.0	43.7
113	MEDIUM DISTILLATES				
1131	Kerosene (jet fuel)	t	73.2	1.0	43.3
1132	Other kerosenes	t	71.5	1.0	43.1
1133	Diesel oil	t	65.5	1.0	43.2
1134	Gasoil, low sulphur (heating fuel oil)	t	73.5	1.0	43.0
1135	Gasoil, sulphur-free (for non-road use and heating)	t	73.5	1.0	43.0
1139	Other medium distillates	t	74.1	1.0	42.7
114	HEAVY DISTILLATES				
1141	Heavy fuel oil, sulphur content < 1%	t	79.2	1.0	40.4
1142	Heavy fuel oil, sulphur content ≥ 1%	t	78.4	1.0	40.2
1143	Other heavy distillates	t	79.2	1.0	40.2
1144	Heavy fuel oil, sulphur content ≤ 0.1%	t	76.1	1.0	42.1
1145	Heavy fuel oil, sulphur content ≤ 0.5%	t	77.0	1,0	41.5
1148	Asphaltene	t	83.7	1.0	37.8
115	PETROLEUM COKE	t	97.0	1.0	33.5
116	RECYCLED AND WASTE OILS	t	78.8	1.0	41.0
119	OTHER PETROLEUM PRODUCTS	t	78.8	1.0	30.0
12	COAL				
121	Hard coal and anthracite				

Code	Heading	Fuel-specific unit	CO_2 default emission factor, t/TJ	Default oxidation factor	Default net calorific value (as fired), GJ/unit
1211	Anthracite	t	98.3	0.99	33.5
1212	Hard coal	t	93.3	0.99	25.0
122	Other coal				
1221	Semi-bituminous coal, brown coal	t	108.0	0.99	20.0
1222	Coal briquettes	t	94.6	0.99	30.0
1228	Coal tar	t	90.6	0.99	37.0
1229	Other non-specified coal	t	108.0	0.99	10.0
123	Coke	t	107.0	0.99	29.3
124	Coke oven gas	1,000 m^3	41.5	0.99	16.7
125	Blast furnace gas	1,000 m^3	263.7	0.99	3.8
126	CO gas	1,000 m^3	155.0	0.99	11.5
13	Natural gas				
131	Natural gas				
1311	Natural gas	1,000 m^3	55.30	1.0	36.5
1312	Liquefied natural gas (LNG)	t	55.8	1.0	49.3
2	PEAT				
21	Peat				
211	Milled peat	t	107	0.99	10.1
212	Sod peat	t	103.0	0.99	12.3
213	Peat pellets and briquettes	t	97.0	0.99	18.0
3	RENEWABLES AND MIXED FUELS				
31	BIOMASS				
311	Forest fuelwood				
3111	Firewood (stems and split firewood)	t	109.6*	0.99	14.0
3112	Chips from roundwood	t	109.6*	0.99	9.5
3112a	Chips from roundwood, small-sized trees	t	109.6*	0.99	9.5
3112b	Chips from roundwood, large-sized trees	t	109.6*	0.99	9.5
3113	Forest residue chips	t	109.6*	0.99	10.0
3114	Hog fuel from stumps (previously stump wood chips)	t	109.6*	0.99	11.5
3115	Energy willow (and other short rotation coppice)	t	109.6*	0.99	10.0

Code	Heading	Fuel-specific unit	CO_2 default emission factor, t/TJ	Default oxidation factor	Default net calorific value (as fired), GJ/unit
312	Industrial wood residue				
3121	Bark	t	109.6*	0.99	7.5
3122	Sawdust	t	109.6*	0.99	7.0
3123	Wood residue chips	t	109.6*	0.99	10.5
3124	Cutter shavings, grinding powder, etc.	t	109.6*	0.99	17.0
3128	Unspecified industrial wood residue	t	109.6*	0.99	7.5
3129	Other industrial wood residue	t	109.6*	0.99	8.8
313	Black liquor and other concentrated liquors	t_d		0.99	11.5
314	By-products from wood processing industry				
3141	Pine oil and pitch	t	77.0*	0.99	37.0
3142	Methanol and turpentine	t	70.0*	0.99	19-45
3149	Other by-products from the wood processing industry	TJ	109.6*	0.99	
315	Recovered wood	t	109.6*	0.99	12.0
316	Wood pellets and briquettes	t	109.6*	0.99	16.0
317	Vegetable-based fuels				
3171	Reed canary grass	t	110.0*	0.99	13.0
3172	Cereal crops and straw parts	t	100.0*	0.99	13.5
3174	Vegetable oils and fats	t	72.0*	0.99	37.0
3179	Other vegetable-based fuels	t	100.0*	0.99	15.0
318	Animal-based fuels				
3181	Animal fats	t	75.0*	0.99	37.0
3189	Other animal-based fuels	t	100.0*	0.99	15.0
32	OTHER BIOFUELS AND MIXED FUELS				
321	Biogas				
3211	Landfill gas	1,000 m^3	56.1*	1.0	17.0
3212	Biogas from wastewater treatment plants	1,000 m^3	56.1*	1.0	23.0
3213	Industrial biogas	1,000 m^3	56.1*	1.0	28.0
3214	Biomethane	1,000 m^3	56.1*	1.0	36.0
3215	Synthetic biogas	1,000 m^3	56.1*	1.0	36.0
3219	Other biogases	1,000 m^3	56.1*	1.0	20.0

Code	Heading	Fuel-specific unit	CO_2 default emission factor, t/TJ	Default oxidation factor	Default net calorific value (as fired), GJ/unit
322	Bioliquids				
3221	Biofuel oil	t	75.0*		38.5
3222	Biopyrolysis oil	t	79.6*		17.0
3223	Bio-LPG/Biopropane	t	65.0*		46.2
3229	Other liquid biofuels	t	79.6*		15–40
323	Mixed fuels (fossil and non-fossil)				
3231	Recovered fuels	t	31.8 bio share 60%	0.99	20.0
3232	Demolition wood	t	11.4 bio share 90%	0.99	15.0
3233	Impregnated wood (chemically treated)	t	11.4 bio share 90%	0.99	12.0
3234	Deinking sludge	t	60.0*	0.99	4.0
3235	Waste pellets	t	45.0 bio share 45%	0.99	15.0
3236	Rubber waste	t	68.0 bio share 25%	0.99	28.0
3238	Municipal waste / mixed waste	t	40.0 bio share 50%	0.99	10.0
3239	Other mixed fuels	t	100.0 bio share 10%	0.99	10.0
324	Gasified waste (Product gas)	1,000 m^3	..	0.99	..
325	Biosludge	t	132*	0.99	2.5
326	Biocoal	t	112*	0.99	18–33
491	OTHER BY-PRODUCTS AND WASTES USED AS FUELS				
4911	Plastics waste	t	74.1	0.99	25.0
4913	Hazardous waste	t	117.0	0.99	10.0
4919	Other waste	t	75.0	0.99	15.0

* solid and liquid biofuel whose carbon dioxide emissions are not counted in the total emission amount of Finland’s greenhouse gases.

CO_2 factor of mixed fuels is an estimate taking into account only the share of fossil carbon. The energy content of deinking sludge is given for a bio share of 100%, and the CO_2 emissions are caused by the decomposition of carbonates.

Always check the latest classification online (www.tilastokeskus.fi/polttoaineluokitus).

Series title and number

VTT Technology 272

Title	**Properties of indigenous fuels in Finland**
Author(s)	Eija Alakangas, Markus Hurskainen, Jaana Laatikainen-Luntama & Jaana Korhonen
Abstract	The properties of indigenous fuels used in Finland have been studied in this publication based both on literature and on the research carried out at VTT and other research institutes and universities. Data have also been collected from the fuel producers and energy utilities. Transport fuels are not included. The main properties of the fuels discussed in this publication are calorific value, chemical composition, moisture content, density, grindability and other fuel handling properties, ash content, ash melting behaviour and ash composition, and concentrations of harmful substances, such as alkali and heavy metals. The properties of different kinds of fuels, such as wood fuels, peat, energy crops, sludges, fast pyrolysis oil, and gaseous fuels are presented in the form of tables. Both commercial fuels and fuels under development are covered. The definitions for the fuels and the properties, the analysis methods for different properties, and the formulae for calculation of the values are presented in the beginning of the publication. A brief presentation is also given of the production methods of indigenous fuels, as well as estimates of the production and utilisation potentials in Finland. At the end of the publication there are analyses of how the properties affect combustion and gasification. Appendices include lists of standards, fuel specifications of milled and sod peat, and peat pellets. Additional data on peat, used wood and solid recovered fuels are also given.
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