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Franz Josef Straße 18 8700 Leoben

Masterarbeit

Efficient use of energy in the European paper industry

Vorgelegt von:
Martin Hartmann
m0335034

Betreuer
Univ. Prof. Dipl.-Ing. Dr. techn. Harald Raupenstrauch
O. Univ. Prof. Dipl.- Ing. Dr. techn. Karl Lorber

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I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

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DANKSAGUNG

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Danke Jos !

Kurzfassung

Effiziente Energienutzung in der europäischen Papierindustrie

Wirtschaftliche und ökologische Motive sowie gesetzliche Vorschreibungen zwingen die Papierindustrie ihre Produktionsprozesse und Herstellungsverfahren energieeffizient und nachhaltig zu gestalten. Diese Masterarbeit beschreibt die gängigsten Papier- und Kartonherstellungsverfahren, die in der europäischen Papierindustrie Anwendung finden und zeigt auf, durch welche Maßnahmen diese Verfahren energieeffizient und ressourcenschonend betrieben werden. Beginnend mit dem Entrinden der Holzstämme bis zum fertigen Produkt, das die Papiermaschine verlässt, gibt diese Masterarbeit einen Überblick über Abfallverwertungs- und Energierückgewinnungsverfahren, die zu einem nachhaltigen Produktionsprozess beitragen.

Abstract

Efficient use of energy in the paper industry

Due to economical, ecological and legislative reasons, the paper industry is forced to operate its facilities in an energy efficient- and natural resources saving way. In this context, this master thesis describes measures that are taken in European pulp- and paper mills to reduce the demand of energy and raw materials and to minimize energy losses along the production process of paper. Beginning with the pre-treatment of the wood logs (e.g.: debarking) to the final product that leaves the paper machine, the subsequent pages explain different technologies, such as waste combustion and heat recovery processes, that contribute to an energy efficient production process.

Contents

1 Introduction

Who could imagine a world without paper? It is one of the most versatile and commonly used materials in our everyday life. Even in times of electronic communication and knowledge storage paper is still irreplaceable, not only in the field of education and information transfer but also for numerous every day activities.

The idea of papermaking had its origin about 2000 years ago in China and became popular in Europe in the middle of the 13th century [6]. In these times, fibres from mulberry bark, papyrus, straw or cotton were used as raw materials for paper manufacturing. In the mid of the 19th century the industrialization of paper production began and people started to extract the fibres of wood to use them as raw materials [1]. Energy has always played a major role for the production of paper. Early manufacturing always took place beneath big rivers to ensure the water supply and the use of hydropower for manufacturing processes. The power of the sun and the wind helped to dry and to bleach the paper. With beginning industrialization, the use of fossil fuels had its origin too.

The production of paper and pulp contributes to severe impacts on our environment, as the process intensively uses wood, chemicals, water and has a very high demand of energy. In this context, this Master Thesis describes paper manufacturing methods and gives an outlook on energy efficiency- and energy saving methods in the modern pulp and paper industry.

1.1 Purpose of the study

This Master Thesis is the result of the research work carried out for the IUSES (Intelligent Use of Energy at School) project of the European Union. This project, funded by the Intelligent Energy Europe Programme, aims to promote a more efficient way of using energy in every day live among secondary school students and teachers. For better understanding of the principles of energy efficiency, three handbooks (on transport, buildings and industry) on this topic were written. The industry handbook demonstrates important energy efficiency aspects in the industry, with an emphasis on paper industry. The results of the research work done for this handbook are summarized in this Master Thesis.

1.2 Goals of the study

This Master Thesis aims to explain the most important technologies to achieve energy efficient operation of pulp- and paper mills.

2 Energy and Energy Efficiency in the Industry

2.1 Definition of Energy

Energy can be defined as the action or work achieved by a specific force. The industry generally uses six different forms of energy:

- Chemical energy is the energy that bonds atoms and ions together and is stored for example in carbon based fuels. Through the chemical oxidation reaction of combustion, this energy can be released and transformed into more useable forms such as mechanical energy or thermal energy.
- Mechanical energy, including wave and tidal energy is responsible for motions and can therefore be used to drive machines, for example power generators to produce electrical energy.
- Thermal energy due to the internal motion of particles of matter can be generated by combustion, mechanical dissipation, nuclear reactions or resistance to electricity. Heat (Q) can be defined as the action of thermal energy transfer from one mass with higher temperature to another mass with lower temperature by:
    - conduction: due to interaction of highly energetic particles with low energetic particles in solids, fluids and gases;
    - convection: energy is transferred from a solid surface at a specific temperature to a moving gas or liquid;
    - thermal radiation: due to changes of the electronic configurations of atoms and molecules, energy is transported by electromagnetic waves;
- Electrical energy due to forces of electric charges doing work by rearrangement of positions of charges, is closely related to magnetic energy, which is the energy represented by an electric- or magnetic field.
- Gravitational energy can be defined as the work done by gravity.
- Nuclear energy which is the energy stored in nuclei of atoms, released by fusion or fission of the nuclei [27].

Primary energy is the energy that is stored in raw fuels (for example: natural gas) prior to any processing, including combustible wastes, received by a system as an input. Different transformation processes transform primary energy into other, more applicable forms, such as electricity or steam. Final energy is the energy that reaches the consumer and can be both primary (e.g.: natural gas) or secondary energy (e.g.: electricity) [27].

2.2 Energy in the European Industry

In 2004, the industry of the EU – 25 consumed about 319 Mtoe (million tonnes oil equivalent = 11 004 PJ) which accounted for 30% of the primary energy demand or 28% of the final energy use of the member states. The iron and steel industry, the petrochemical industry and the oil products industry are the three main primary energy consuming industries in Europe. The paper and printing sector demands for approximately 1.8% of primary energy consumed in the European union and is the fifth – biggest energy consuming industry.[27] Figure 1 shows the share of primary energy use in the European industry.

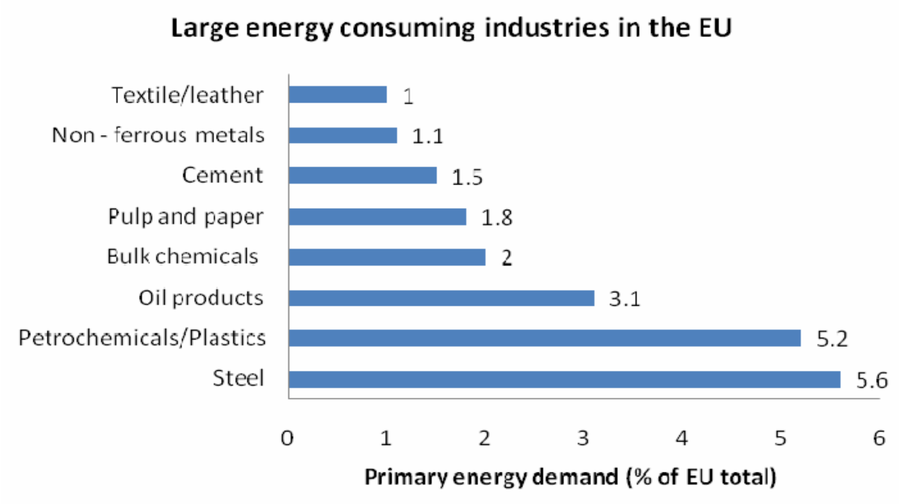

Figure 1: Percentage of EU primary energy demand used by industry sectors [27].

European paper industry facts[1]

- The Industry provides direct and indirect employment for more than 2 Million people and comprises 1200 pulp[2] and paper mills and 800 other companies in Europe. The European pulp and paper industry has an annual turnover of 79 billion Euros, i.e. 1.4% of the total European manufacturing industry`s turnover.

- Paper consumption in Europe increases on average by 2.6% per annum. The annual production capacity of European Countries is somewhat higher than 110 Million tonnes [25]. In 2007, 48.8% of all paper products were graphic papers, 40.2% were packaging papers and board, 11.4% were sanitary- household and other products.

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[1] Facts for CEPI (Confederation of European Paper Industry) countries. Members in 2007: Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, The Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Spain, Sweden, Switzerland, United Kingdom [25].

[2] Paper mainly consists of fibres from wood or recovered paper. The fibres are chemically or mechanically separated from the wood or any other raw material and are called “pulp”.

- Most of the fibrous raw material for the European paper production comes from Finland and Sweden, they are Europe`s most important pulp manufacturing countries (see Figure 2a).

- Regarding paper production, Germany is the most important country, followed by Finland, Sweden, Italy and France. The share is demonstrated in Figure 2b.

- Today about 48% of the primary energy used in the European paper and pulp Industry is generated from fossil fuels. More than half of the industry’s heat and electric power is generated by the combustion of biomass - based fuels [17]. Table 1 demonstrates the share of primary energy sources for the European pulp and paper industry.

- The wood consumption of the CEPI Countries in 2007 was slightly higher than 119 million tonnes. Table 2 shows the share of wood consumption in 2007.

Table 1: Thermal energy and electricity consumption in CEPI Countries 2004 – 2006 [25]

	2004	**2005**	**2006**	**Share of total % in 2006**
Gas (TJ)	503 742	494 868	487 144	36.8
Fuel oil (TJ)	77 789	70 313	67 700	5.1
Coal (TJ)	58 991	48 314	47 613	3.6
Other fossil fuels (TJ)	20 202	19 714	24 210	1.8
Biomass (TJ)	644 943	636 682	687 881	52
Other (TJ)	5 360	8 702	8 342	0.6
Total primary energy consumption	**1 312 886**	**1 278 568**	**1 322 872**	**100**
Fraction of biomass in total primary energy consumption	49.10%	49.80%	52.00%	
Total electricity production at site (GWh)	51 938	49 591	50 205	41.9
Purchased electricity (GWh)	73 507	74 436	77 380	64.9
Sold electricity (GWh)	-7 090	-8 568	-8 141	-6.8
Total electricity consumption (GWh)	**119 046**	**115 655**	**119 773**	**100**

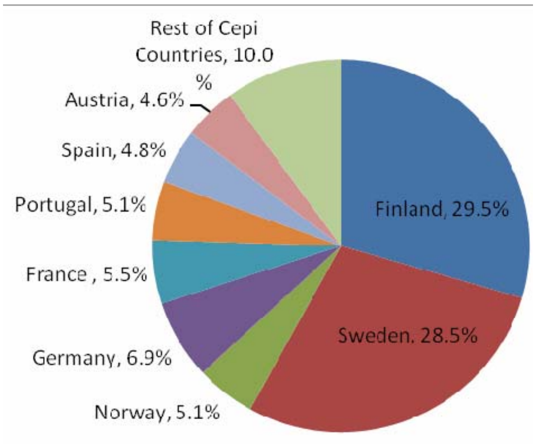

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Figure 2a: Pulp production share of CEPI countries [25].

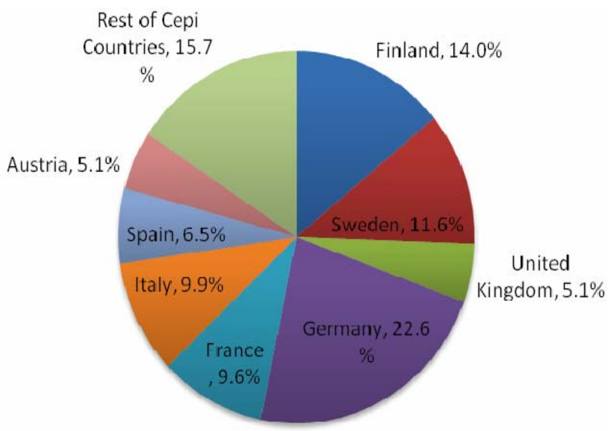

Figure 2b: Paper production share of CEPI countries [25].

Table 2: Share of wood consumption for the European Paper production in 2007 [25].

Wood type	**%**	**Wood type**	**%**
Hardwood	36.6	Softwood	63.4
Aspen	2.3	Spruce	31.7
Beech	3.9	Pine	31.1
Birch	15.7	Other	1.2
Eucalyptus	11.1		
Other	3.6		

2.3 Definition of Energy Efficiency

Energy efficiency is a widely used term, aimed to address different objectives such as the reduction of climate – changing emissions, the enhancement of security of energy supply and the reduction of energy costs for the industry. Energy efficiency can be expressed by the specific energy consumption (SEC), which is the amount of energy that one unit of product or output of a system consumes as it is produced. The SEC can be expressed as different ratios, for example GJ of energy consumed for the production of one ton of a product, energy consumed per m² of a building or energy consumed per employee of a company.

The SEC can be declared e.g. for a product, a production unit or a total plant by analyzing all energy flows into- and out of a system as shown in Figure 2 [27].

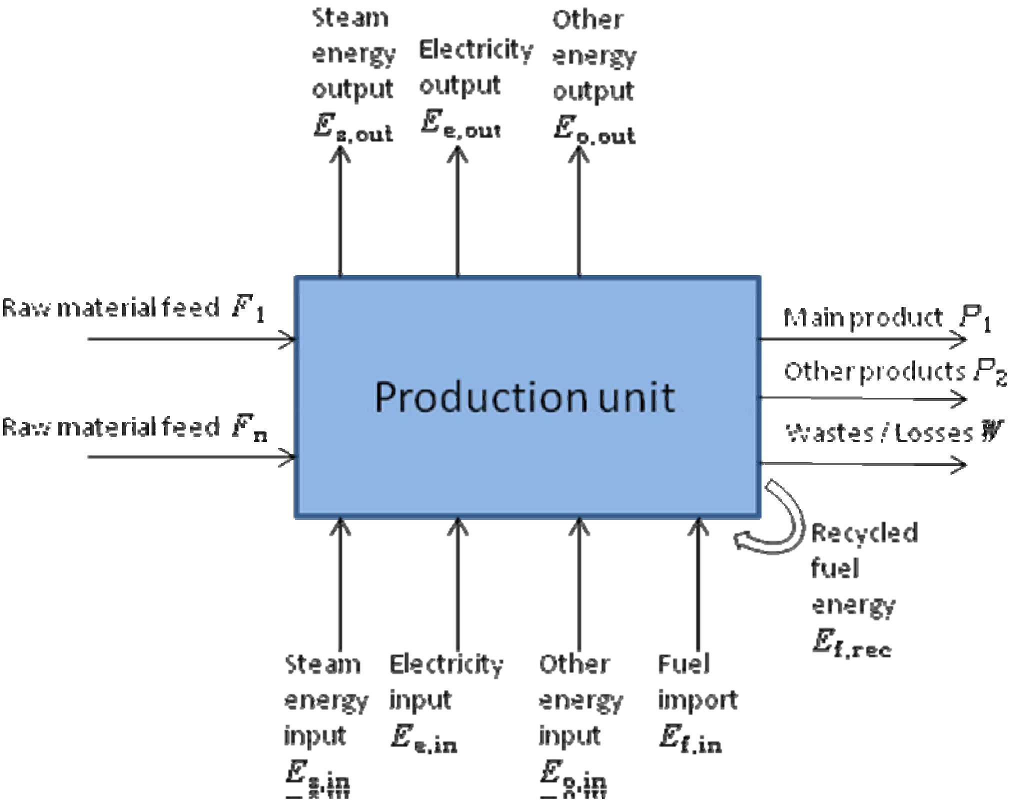

Figure 2: Input- and output material- and energy flows of a production unit [27].

The SEC in this case can be determined by summing up all the energy entering and leaving the system and dividing this sum by the mass of main product P_1, as expressed in formula one [27].

$$SEC = \frac{(E_{s,in} + E_{e,in} + E_{f,in} + E_{f,rec} + E_{o,in}) - (E_{s,out} + E_{e,out} + E_{o,out})}{P_1}$$

2.4 The legal framework for energy efficiency in the industry: the IPPC Directive

The directive 2008/1/EC of the European parliament and the European council concerning the integrated pollution prevention and control (IPPC directive) makes up the legal background for the efficient use of energy in the paper- and other industries in order to achieve a high level of protection of the environment taken as a whole [28]. The directive targets a prevention, or where not possible, a reduction of emissions to the air, to water and land coming from the activities of:

- energy industries,
- production and processing of metals,
- mineral industry,
- chemical industry,
- waste management,
- other industrial activities such as the production of pulp from timber and other fibrous material and the production of paper and cardboard with a capacity higher than 20 tonnes per day.

The IPPC directive obligates the competent authorities of the member states and operators of the above listed industrial plants to ensure, that installations are operated in such a way, that:

- appropriate preventive measures (installation of best available techniques) are taken against pollution, whereas “pollution” is defined as: “*direct or indirect introduction, as result of human activity, of substances, vibrations, heat or noise into the air, water or land which may be harmful to human health or the quality of the environment, result in damage to material property, or impair or interfere amenities and other legitimate uses of the environment”;*
- no significant pollution is caused;
- waste production is avoided as far as possible, produced waste has to be recovered, or, if not technically or economically possible, disposed of avoiding or reducing impacts to the environment;
- energy is used efficiently;
- measures are taken to prevent accidents and to limit their consequences [28].

3 Raw materials for the production of paper

The main inputs of the papermaking process are fibres (chemical- or mechanical pulp; recycled fibres), chemicals (pigments, fillers), water and energy. These raw materials are mixed and form the “stock” that is applied to the paper machine [3]. Figure 3 shows the mass ratio of raw materials for the paper production within the CEPI countries.

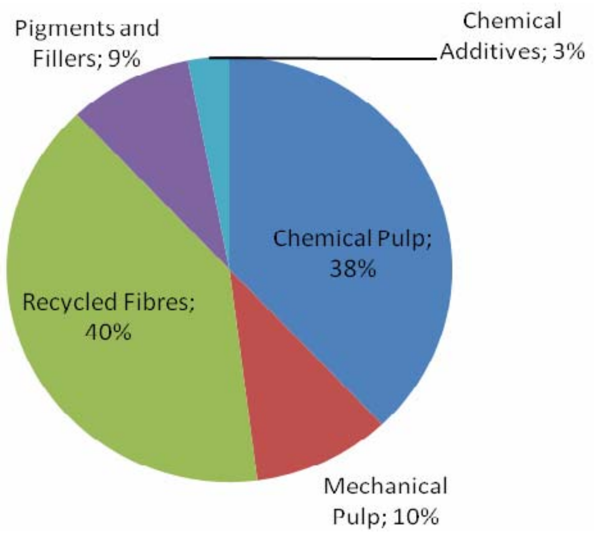

Figure 3: Share (mass ratio) of raw materials for paper production [17].

3.1 Fibres

Different fibrous materials such as wood, non-wood plants or industrial sawmill wastes (primary or virgin fibres) and recovered paper[1] (secondary fibres) can be considered as raw materials for the production of paper. In the first manufacturing step, the fibres are extracted from the raw material and the so called “pulp” is produced. This pulp can be extracted chemically (chemical pulp) or mechanically (mechanical pulp) from the wood and is mixed with water and chemicals before it is applied to the paper machine, where the formation of the paper sheet takes place [3].

3.1.1 Wood

Wood is an organic material that consists of approximately 49% carbon, 44% oxygen, 6% hydrogen, less than 1% nitrogen and inorganic elements such as sodium (Na), potassium (K), calcium (Ca), magnesium (Mg) and silicon (Si).

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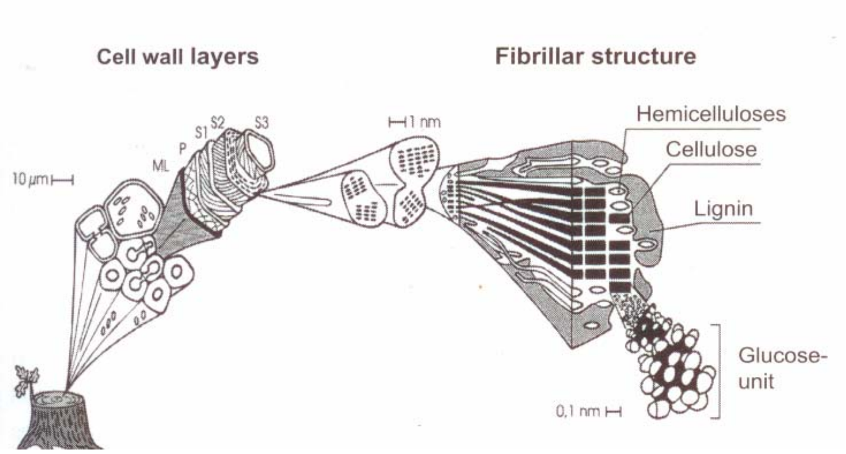
[1] “Waste paper” is an outdated terminology in technical contexts, the industry favors the terminology “recovered paper” [30].

These elements form macromolecules and thereby create the basic constitutes of wood cell walls: cellulose, hemicelluloses and lignin. The flexible cellulose fibres are bonded together and made rigid by the lignin [7]. Figure 4 shows the simplified principle of the cellular composition of a wood cell.



ML: middle lamella; P: primary wall; S: secondary wall (S1, S2, S3)

Figure 4: Simplified principle of cellular composition of wood [7].

Cellulose is the framework substance of the cell wall, hemicelluloses and lignin form the matrix. Lignin is incrusted in the micro capillary regions of the cell walls. For manufacturing paper, single wood fibres have to be separated mechanically or chemically from the other wood components [7]. Table 3 shows the ratio of softwood and hardwood cell wall components.

Table 3: Macromolecular composition of soft- and hardwood [7]

Component	**Content in softwood [%]**	**Content in hardwood [%]**
Cellulose	40 - 44	43 - 47
Hemicelluloses	25 - 29	25 - 35
Lignin	25 - 31	16 - 24
Extractives [1]	1 - 5	2 - 8

Fibres from softwood trees, such as spruce, fir and pine are longer and coarser than hardwood fibres. Softwood fibres make the paper resistant to stretching and tearing, whereas hardwood (beech, birch, maple) fibres lead to a smoother surface of the paper sheet [1].

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[1] Extractives: Volatile oils (turpentine, terpentines), wood resins, fats and waxes [7].

However, since softwood generally contains more lignin than hardwood, more chemicals and energy are necessary to separate the desired fibres from the other wood components [15].

3.1.2 Non-wood plants

Non-wood plants such as grass, flax, and hemp as well as agricultural residues, for example straw and sugar cane are important raw materials for the virgin fibre production in countries like China and India. They are only of minor importance for the European paper industry [13,14].

3.1.3 Recovered paper

In 2007, 56% of the paper and board consumed in Europe was produced out of recovered paper. The collection rate[1] of paper was 66.1% and the utilization rate[2] 48.4%. Newsprint and cardboard are the main products that are manufactured out of recovered paper. Figure 5 shows the development of the recycling rate within CEPI countries from 1991 to 2007 [17].

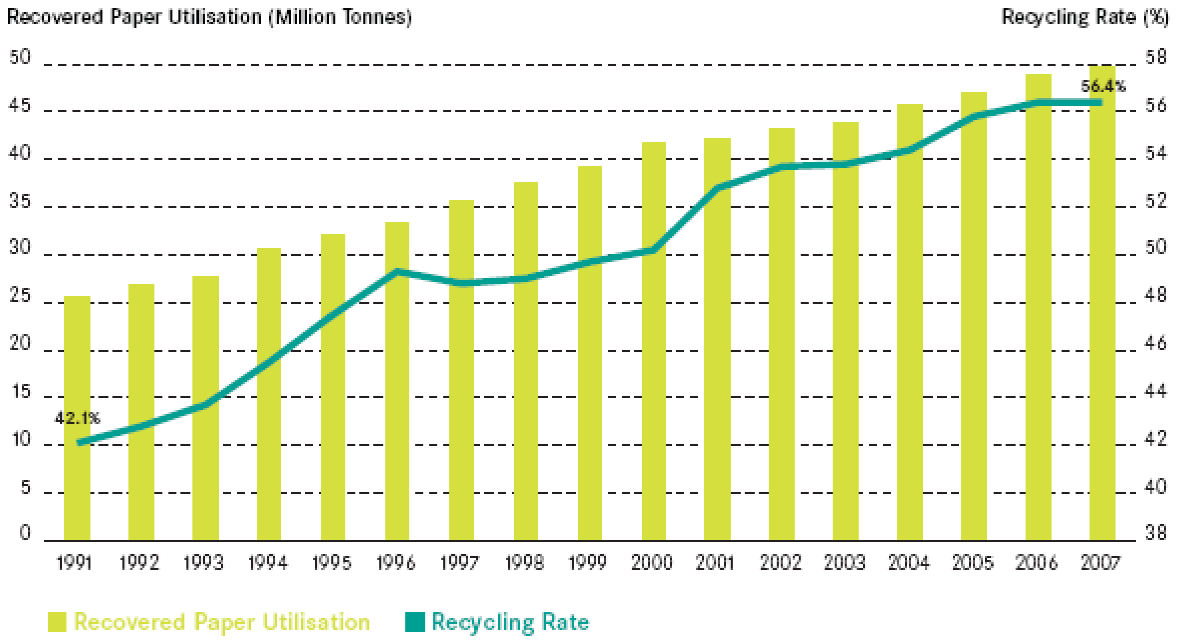

Figure 5: Recovered paper utilization and recycling rate[3] of the CEPI countries [17].

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[1] Percentage of apparent paper collection compared to the total paper consumption [25].

[2] Percentage of recovered paper utilization rate compared to total paper production [25].

[3] Percentage of recovered paper utilization compared to total paper consumption [25].

3.2 Fillers, Coatings

For some paper grades, mineral substances such as fillers and coatings account for up to 38% of the total stock. The addition of fillers improves certain paper qualities such as:

- brightness and opacity;
- smoothness of the sheet surface;
- sheet formation by filling the gaps between the fibre matrix;
- ink receptivity of the paper sheet;
- dimensional stability of the paper sheet, since most fillers remain inert when they get wet;
- and permanence of the paper [3].

Typical fillers are hydrous kaolin $Al_4(OH)_8(Si_4O_{10})$, calcium carbonate $CaCO_3$, gypsum $CaSO_4$ titanium dioxide TiO_2, and talc $Mg_3(OH_2)(Si_4O_{10})$ [3].

3.3 Chemical Additives

The pulp production process (e.g. Kraft – process) requires certain auxiliary chemicals such as sodium hydroxide (NaOH) and sodium sulfide (Na_2S) for the extraction of the cellulose fibres out of the wood and substances for bleaching and cleaning (e.g.: hydrogen peroxide (H_2O_2)) [3].

3.4 Water

The most important raw material component is water. It is necessary for substance transport, cleaning, cooling, steam generation and works as binding “agent” to form hydrogen bonds between the fibres within the paper sheet. Depending on the paper grade, production processes require for example 8 – 10 m^3/t of fresh water for printing papers and 3 – 5m^3/t for packaging papers. Modern paper mills use water loops and circulation systems to minimize the fresh water demand [3]. Figure 6 shows a typical water circulation system of a paper mill.

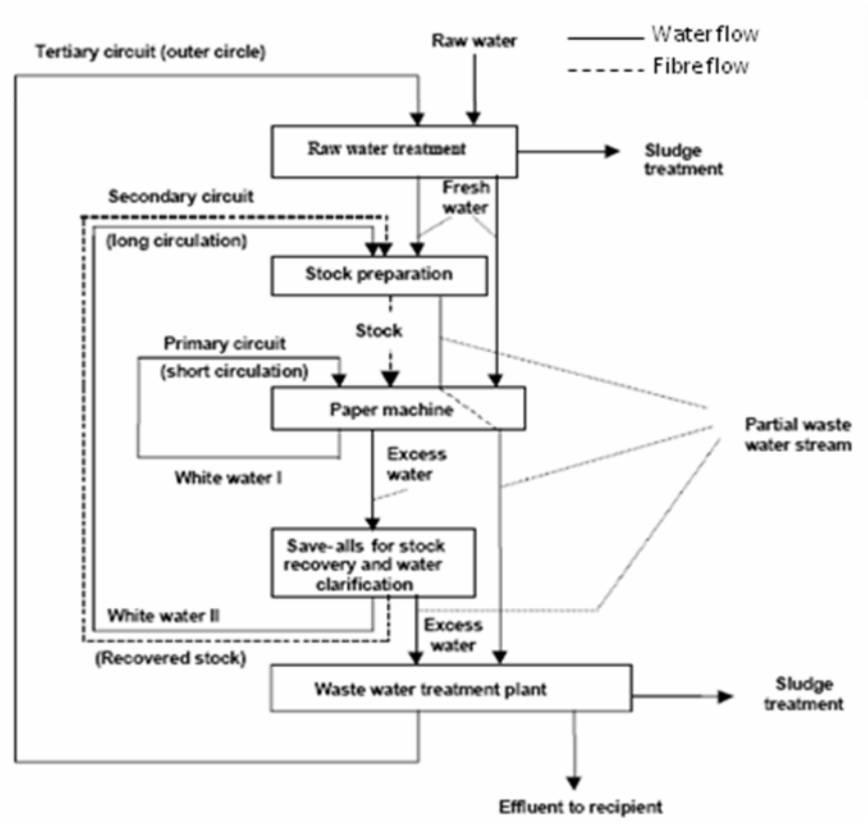

Figure 6: Water circuits in a paper mill [2].

Fresh water can contain humic substances and inorganic elements such as oxidised or bound to organic matter like iron and manganese. Filtration of fresh water to reduce organic components is commonly followed by:

- oxidation of iron (II) and manganese (II) to iron (III) and manganese (III) by chlorine or permanganate;
- hydrolysis of the trivalent cations to produce hydroxides;
- coagulation of the hydroxides;
- removal of the coagulate [3].

3.5 Energy

Most paper mills have their own plants for the generation of electricity and the production of steam. Today self generation of energy accounts for almost 60% of the total energy use in the European pulp and paper industry. Hydropower, natural gas, fossil fuels, electricity from the grid, wastes and biomass fuels as well as energy that is recovered within the production process supply energy to the production process [14].

Electricity from the “grid” can be produced from many different sources. Figure 7 shows the ratio of fuels for electricity generation within the European Union.

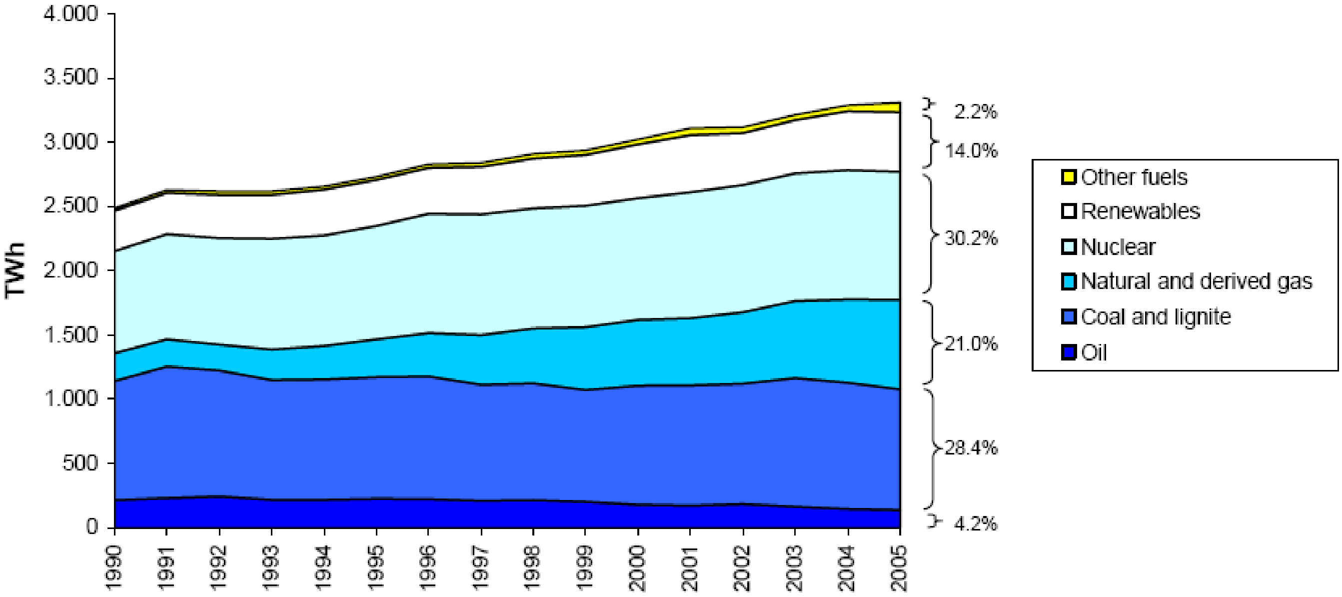

Figure 7: Annual electricity production and fuel share in the EU – 27 [20].

“Renewables” in Figure 7 include electricity produced from hydropower, biomass- and biogas combustion, municipal waste combustion, wind energy, geothermal energy and solar photovoltaic power [20]. Paper mills use energy in form of steam for heating and drying purposes (for example in the paper machine) and electricity to run the different pumps and machines. Energy costs are in a range of 15 – 25% of the total production costs. Pulp and paper manufacturing is the world’s fourth biggest primary energy using Industry [13]. The energy demand for the production of one ton of paper is in a range of 3-5 MWh, this is the average amount of energy that is consumed by an European household within 3 months[1]. Due to these economical reasons it has always been a key task for the paper industry to reduce the primary energy demand and to enforce the efficient use of the generated steam and electricity. Especially the incineration of wastes from the production process and biomass fuels such as bark, wood residues and other residues from forestry operations contribute to a reduced use of fossil fuels and to a sustainable input of resources. Above that, energy regeneration- and heat recovery installations throughout the manufacturing process reduce the total demand for energy generation and in this way also the amount of CO_2- and other emissions [15].

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[1] Sources: www.aee.or.at; The average energy consumption of a typical European household per year (including all electrical consumers and the heating system) is approximately 20.000 kWh.

4 Production process of paper

Papermaking begins in the pulp mill, where wood and other raw materials are transformed into a mass of single fibres which is mixed with water and chemicals in the paper mill and is applied to the paper machine. Figure 8 shows the simplified mass flow sheet of paper production [3].

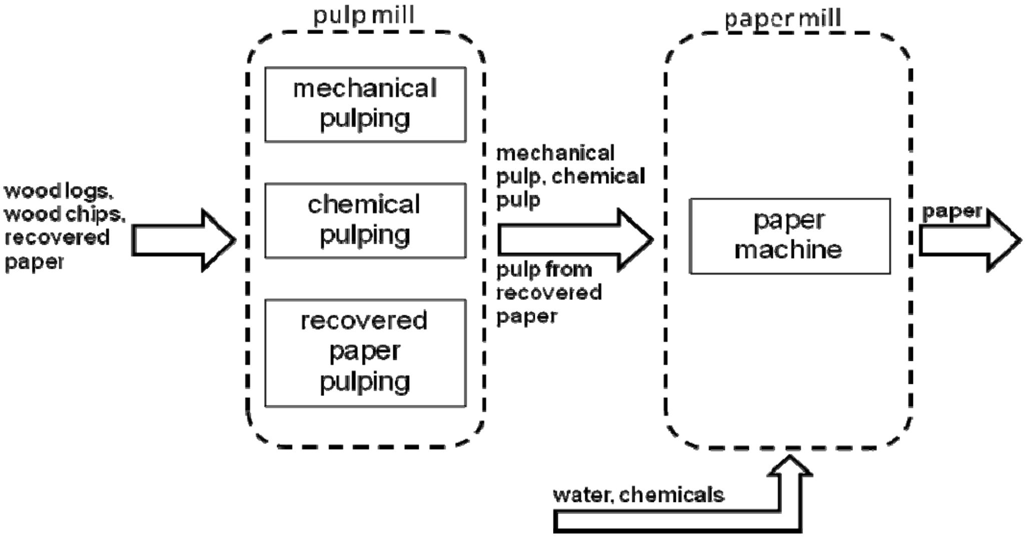


Figure 8: Simplified flow sheet of paper production [3].

4.1 Pulp production

In a pulp mill, the cellulose fibres of the wood are separated from other wood components and a mass of individual fibres is assembled. This happens mechanically or chemically [7]. In case of an integrated pulp- and paper mill, pulp production and paper manufacturing happens at the same plant, otherwise the pulp is dried and pressed to bales for the use in any paper mill. [15].

Wood logs are transported to the pulp mill and piled up. Due to microbiological deterioration, dry wood substance losses of 1 - 2 % during one year of open air storage can occur, resulting in quality losses such as decreasing strength and discoloration of the fibres. When wood logs are stored, sufficient water drainage and air circulation must be ensured. Efficient measures must be taken to collect the water from the log yards and prevent pollution of the ground water by soluble wood- and bark substances. Off cuts or slabs from the wood industry and already finished wood chips can be considered as raw material sources too [7]. Figure 9 shows the flow sheet of the wood handling system in a pulp mill.

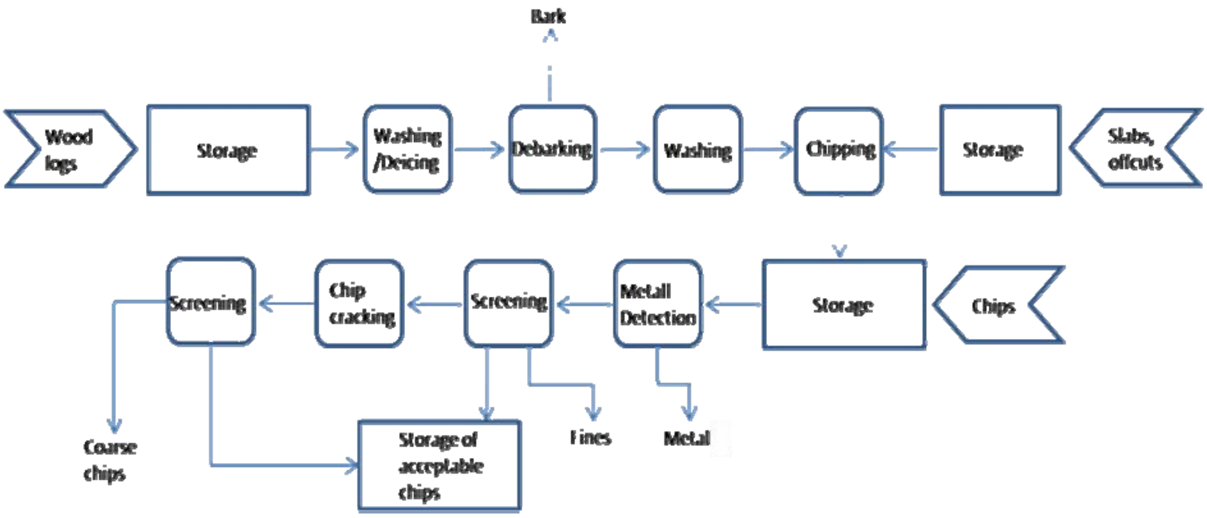


Figure 9: Flow sheet of wood handling for paper production [7].

Wood log debarking commonly happens in a rotating drum debarker where the bark is separated from the wood by friction between the logs and steel lifters fitted at the inside of the rotating drum. Bark and loose wood pieces fall out of the drum through elongated slots [7]. At many pulp mills, bark is combusted for energy generation purposes in order to reduce the demand of fossil fuels and the amount of waste from the process. The industry uses both wet and dry debarking processes. Since wet debarking causes additional costs and efforts, for example for effluent treatment, modern pulp mills often operate a dry debarking process, also due to the fact that the overall energy efficiency of the plant is increased when the dry bark is combusted [2]. Subsequently, the debarked wood logs are washed and chipped to pieces with a length of approximately 15 – 25 mm, a width of 20 mm and a thickness of 3 – 5 mm [7]. Figure 11 a shows the functional principle of a drum chipper. A uniform chip – size distribution increases the efficiency of the process and the quality of the pulp. Therefore the subsequent screening (see Figure 11 b) removes oversized chips to be crushed to a suitable size and sawdust that can be combusted together with bark and other residues [2].

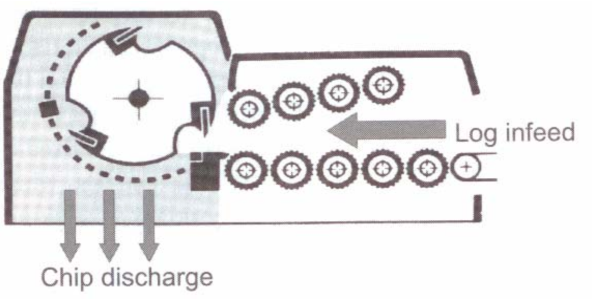


Figure 11 a: Drum chipper [7].

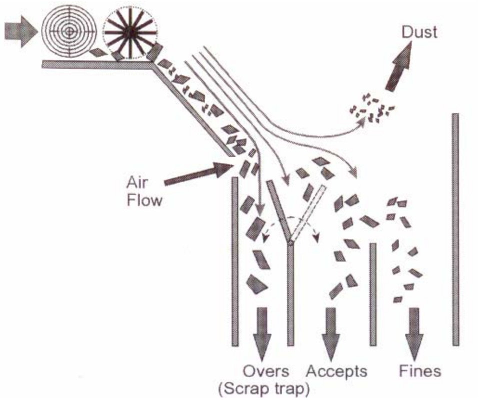


Figure 11 b: Wind screening of wood chips [7].

4.1.1 Chemical pulp

Chemical pulping processes reduce wood to a fibrous mass (pulp) by dissolving wood components with different chemical cooking liquids. The sulphate- or Kraft process, and the acid sulphite process are the most important technologies for the chemical production of pulp. [7]

4.1.1.1 Sulphate (Kraft) process

90% of all the worldwide produced chemical pulp is manufactured by the sulphate process [3]. This process is operated with a cooking liquor, (which is called “white liquor”) containing sodium hydroxide (NaOH) and sodium sulphide (Na_2S) as active chemicals to dissolve the lignin and parts of the hemicelluloses out of the wood. The wood chips are preheated by direct contact with steam to remove air and subsequently get impregnated with white liquor in a batch or continuous digester [2]. Since each single cooking system is custom – designed under consideration of desired pulp qualities, input wood species and many other aspects, pulping applications have to be adapted from case to case. Due to this fact, there is no general optimum system in Kraft pulping and both batch- and continuous cooking systems may feature the same advantages or disadvantages [7].

Continuous cooking

Modern continuous digesters are several thousand cubic meters in size and transfer more than 62% of the input fibre material into pulp. Figure 10 shows the material and energy flow sheet of a continuous digester [7].

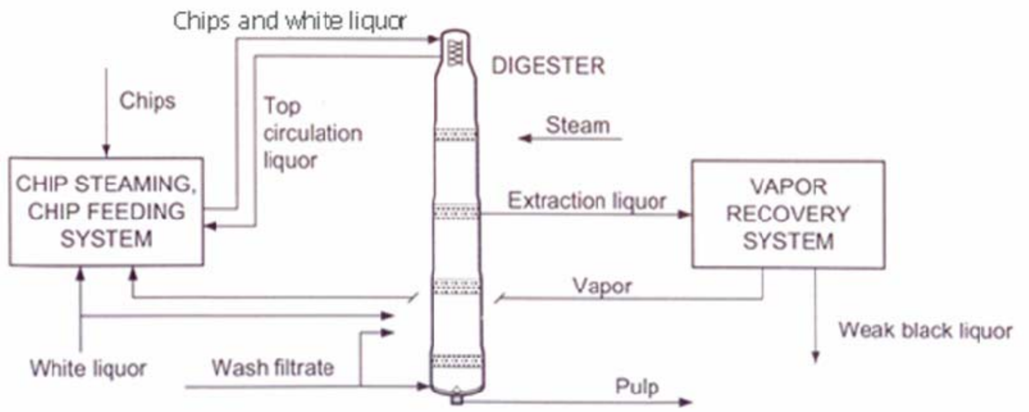


Figure 10: Flow sheet of a continuous cooking system [7]

Chips, mixed with white liquor are applied to the top of the steam heated, cylindrical shaped vessel and move to the bottom by gravity. The influence of the cooking chemicals and process temperatures from 155 to 175 °C, liberate the cellulose fibres and parts of hemicelluloses from the lignin. Pulp is counter currently treated with washing liquor to remove cooking chemicals and is withdrawn at the bottom of the digester [7].

Spent cooking liquor (“black liquor”) is extracted from the vessel and undergoes a vapour recovery step. Recovered vapour is used to impregnate and heat the fresh wood chips (see page 42). After that, the black liquor is lead to the recovery system for regeneration of cooking chemicals and recovery of energy.

Batch cooking

There are many different ways how to operate batch cooking, this Master Thesis will only describe the principle of displacement batch cooking. Batch digesters are typically about 300 to 400 cubic meters in size, therefore a number of them is necessary to fulfill the production capacity of a pulp mill. The idea of displacement cooking is to store the cooking liquors from one finished cooking period and to reuse their chemicals and energy content in the next period. This principle requires a number of batch digesters, a tank farm for the storage of the cooking liquors and a discharge tank where the pulp is lead to at the end of the cooking cycle. White- and wash liquor are applied to the tank farm, as well as steam, which can also be directly consumed in the digesters. Weak black liquor undergoes a fibre recovery step, before it is forwarded to the chemical- and energy recovery plant [7]. Figure 11 shows the simplified mass flow sheet of a displacement batch cooking system.

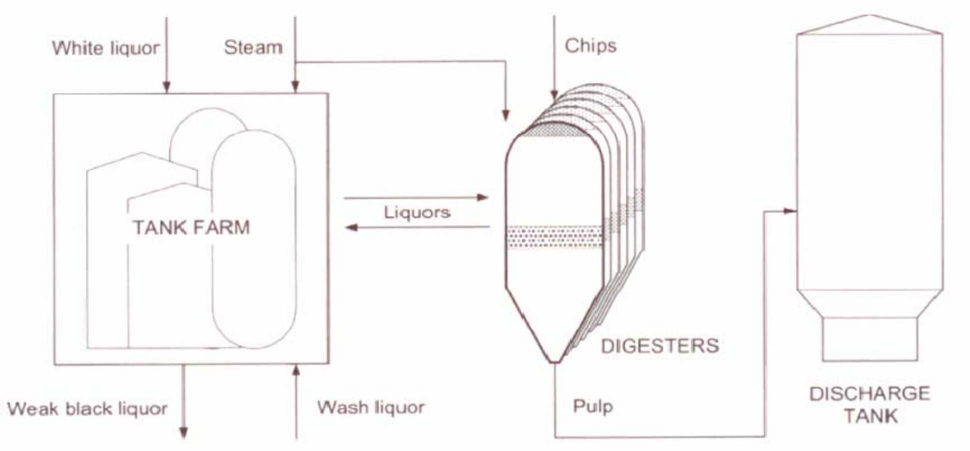


Figure 11: Principal flow sheet of a displacement batch cooking system [7].

The chips, fed to the digester, are pre – impregnated and preheated with “warm black liquor” to soften the wood and to remove oxygen from within the chips by its own increasing volume and the rising partial pressure of the wood moisture. After chip preheating, the digester vessel is filled with “hot black liquor” from a previous cooking cycle which passes on its heat energy directly to the wood chips and brings the digester close to its cooking temperature. After that, “hot white liquor” displaces the impregnation liquor (this operation is called “hot displacement”) and the cooking is carried out. Further indirect heating via steam heated heat exchangers may be necessary.

As soon as the cooking is finished, the polluted cooking liquor (“black liquor”) is led to the tank farm and the digester is filled with wash liquor, to remove coarse impurities from the pulp and to forward it to the discharge tank This step is called “cold displacement” [7].

Excess hot black liquor in the tank farm, that is not reused for heating up the digester, transfers its heat via heat exchangers to fresh white liquor coming from the recovery system to the tank farm. Further heating of the cooking liquid by steam may be necessary [7]. After white liquor heating, the black liquor passes the black liquor cooler to heat incoming water from 45°C to approximately 75°C and is stored in the warm liquor tank for the reuse as pre-heating and pre–impregnating agent. Wash liquor entering the system at 90°C is cooled down to 80°C producing hot water with 75°C. Gases vented from the digester plant contain malodorous compounds (e.g. mercaptanes) and moisture, they pass a gas cooler and are collected for the reason of emission control [10]. Figure 12 shows a more detailed flow sheet of batch cooking.

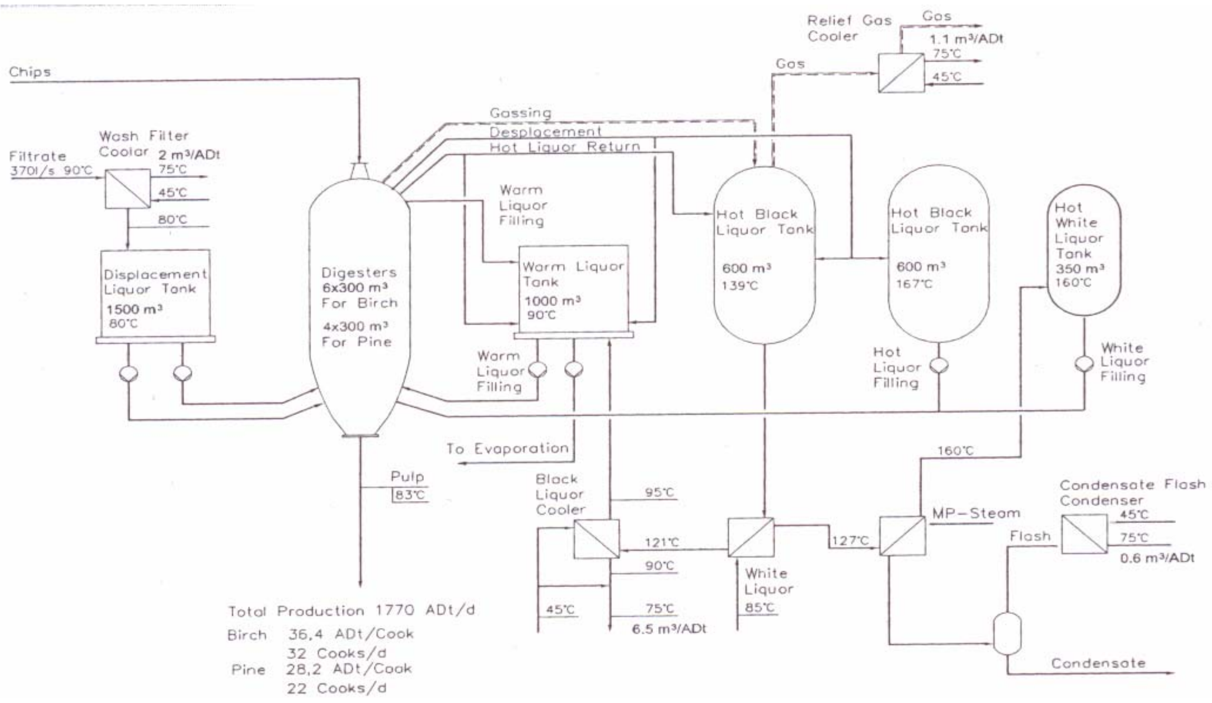


Figure 12: Detailed flow sheet of a batch digester system [10].

Pulp handling

Further processing for pulp coming from a continuous or batch digester comprises screening and centrifugal cleaning in order to remove “knots”, fibre bundles and other particles with a different specific weight from the pulp stream. After screening, oxygen delignification is operated with oxidized white liquor and pure oxygen to rise the brightness of the fibres by removing organic pollutions of the pulp (hemicelluloses, lignin). The dissolved organic substances are lead to the recovery system in order to minimize the effort for waste water treatment [2].

The pulp passes a second washing step before it is applied to the bleaching plant to remove the rest of the lignin and other impurities. Commonly used bleaching chemicals are chlorine dioxide and ozone (have to be produced on site), as well as oxygen, and peroxide, which are delivered to the plant [2]. After bleaching, the pulp is lead to a final screening step. In an integrated pulp and paper mill, the pulp is applied to the paper machine in a wet state with approximately 4% consistency. Otherwise the pulp has to be dewatered and finally dried before it is pressed to bales and transported to any other paper mill [2]. Figure 13 shows the main energy and material flows of the kraft process.

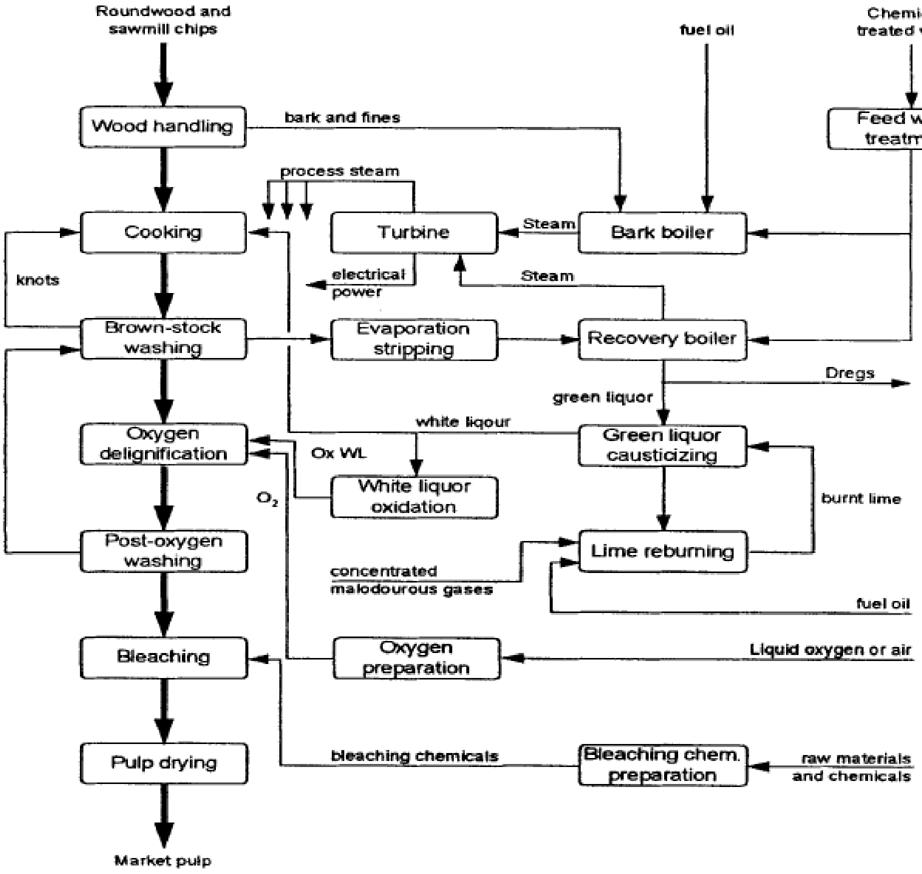


Figure 13: Energy and material flows for the Kraft pulping process [2].

The chemical- and energy recovery system

A recovery system, recovering more than 70% of the energy input to the cooking process and up to 99% of the chemicals [2], comprises:

- the evaporation plant to produce thick liquor,
- the recovery boiler to combust the thick liquor,
- the causticizing plant for the treatment of the residues from the recovery boiler,
- the calcination of the lime [7].

Evaporation plant

In the evaporation plant, the water content of the black liquor is decreased from initially 82 – 87% to finally 20 – 35% in order to enable an efficient combustion in the recovery boiler. The most economic way to heat the evaporator is to take steam as a heat source. Falling film type evaporators made of stainless steel with plates or tubes as heating elements are commonly used in pulp mills. A circulation liquor pump feeds thin liquor to the liquor distributor on top of the boiler, from there it flows down on the hot surface of the steam heated heating elements by gravity. Water is evaporated and the concentrated liquor is finally collected at the bottom of the evaporator. The generated vapor escapes from the evaporator, passing a droplet separator to retain entrained droplets. The steam driving the evaporator can be fresh low pressure steam or for example vapor from another evaporator (see multi effect evaporator: Figure 15) and condenses inside the heating elements. Steam from another evaporator often contains gases, that are not condensable at the given conditions, such as methanol and reduced sulfur compounds. These odorous and inflammable, non condensable gases (NCG) are forwarded to the incineration in the recovery boiler by continuous venting of the evaporator. Figure 14 shows the schematic diagram of a falling film type evaporator [5].

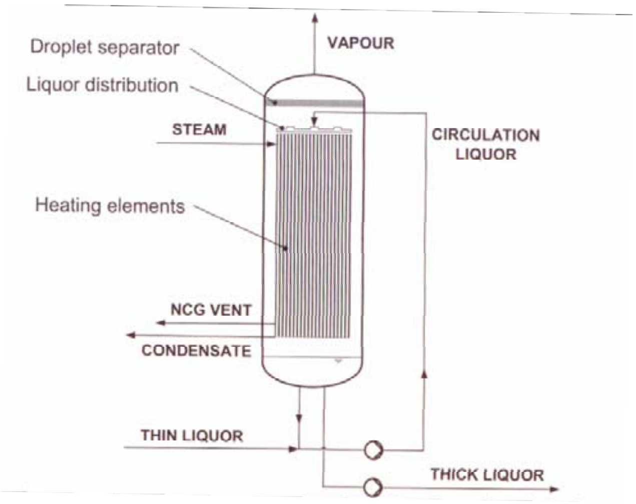


Figure 14: Schematic diagram of a falling film type evaporator [5].

A commonly used method is to carry out the evaporation of thin black liquor in a multi effect evaporator system, shown in Figure 15 [5].

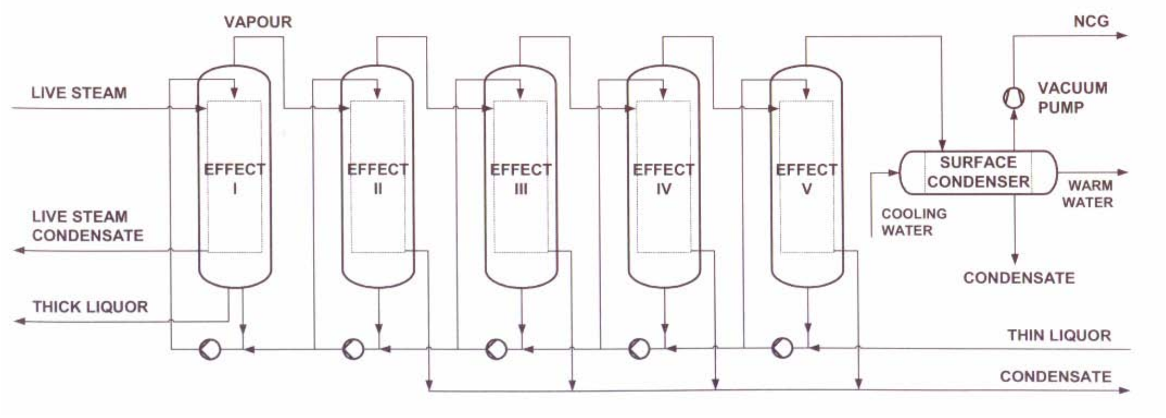


Figure 15: Multi effect evaporator system for the Kaft pulping recovery system [5].

The most important advantage of a multi effect evaporator is, that the vapor produced in one column can be used as heat energy source for the subsequent columns, thus reducing the demand for fresh steam. In a multi effect evaporator system, a number of evaporators is connected in series with countercurrent flow of vapor and liquor. Fresh steam (live steam) is applied at the first effect of the plant and evaporates water from the liquor.

The vapor released at the first effect is lead to the second effect and so on, until the vapor from the last step is condensed in a surface condenser at a temperature in the range of 55 – 65 °C, generating warm water for any use in the pulp mill. Non condensable gases are removed by a vacuum pump and lead to the recovery boiler. The condensates can be used elsewhere in the mill to replace fresh water for example for pulp washing or in the causticizing plant. Only the condensate from the surface condenser has to be treated to remove remaining dissolved gases such as organic sulfur compounds before it can be used. The fresh steam condensate from the first effect is collected for the reuse as boiler feed water [5].

Recovery boiler

In the recovery boiler, the organic wood components (lignin and carbohydrate degradation products) in the black liquor are combusted at temperatures around 1000°C to produce steam. Typical net heating values (NHV) for thick black liquor (with a dry solids concentration of 75%) are in a range of 10.9 – 13.2 kJ/kg [5]. Figure 16 shows the principal design of a recovery boiler.

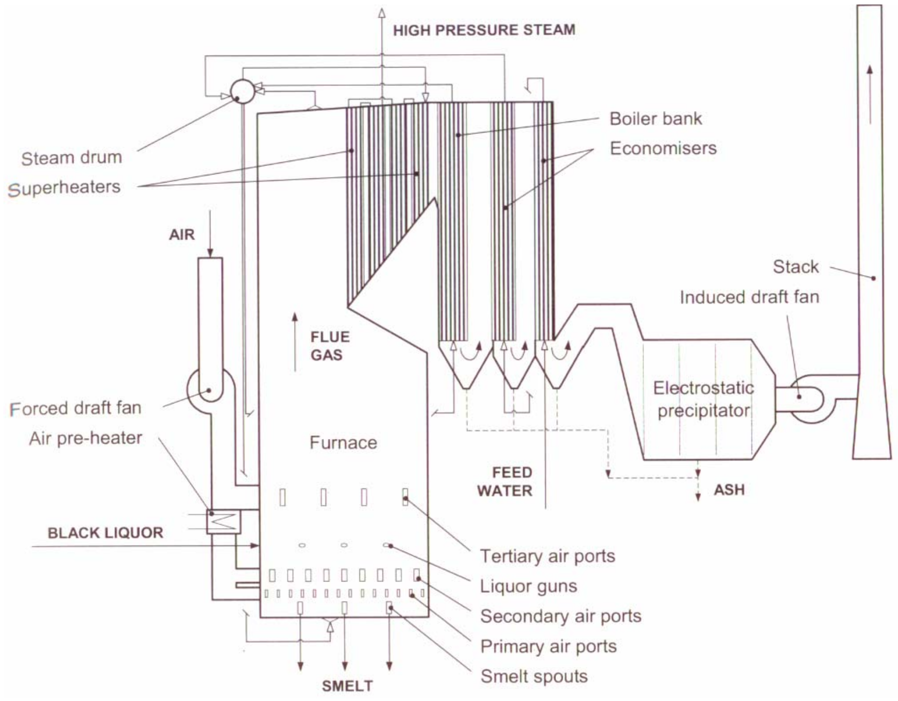


Figure 16: Recovery Boiler [5].

In a recovery boiler, there is an oxidising and a reducing zone (see

Figure 17). Thick liquor is sprayed into the reducing zone of the boiler by a series of nozzles, the liquor guns. Primary, secondary and tertiary combustion air is introduced at three different levels. The droplets with a diameter of 2 – 3 mm dry and burn to char particles that sink to the bottom of the boiler where the inorganic sulphur components (e.g.: Na_2SO_4) are reduced to sulphides by carbon, forming carbon monoxide and carbon dioxide. Small amounts of hydrogen sulphide are created too. The char finally forms a smelt at the bottom of the furnace that consist mainly of sodium sulphide (Na_2S) and sodium carbonate (Na_2CO_3) [2].

In the oxidising zone of the recovery boiler, sulphur (for example bonded in H_2S) is oxidised to sulphur dioxide which reacts with sodium to form sodium sulphite. Hydrogen, carbon and oxygen are oxidised to water, carbon dioxide and carbon monoxide [2]. The hot flue gases leave the boiler and pass the superheater and the economizer to generate steam [5].

For the recovery of cooking chemicals, the char is extracted from the boiler and dissolved in water or fresh white liquor. Green liquor is formed, clarified and filtrated to remove ash residues and other impurities before it is lead to the causticizing plant [5].

Figure 17 shows the chemical reactions within a recovery boiler.

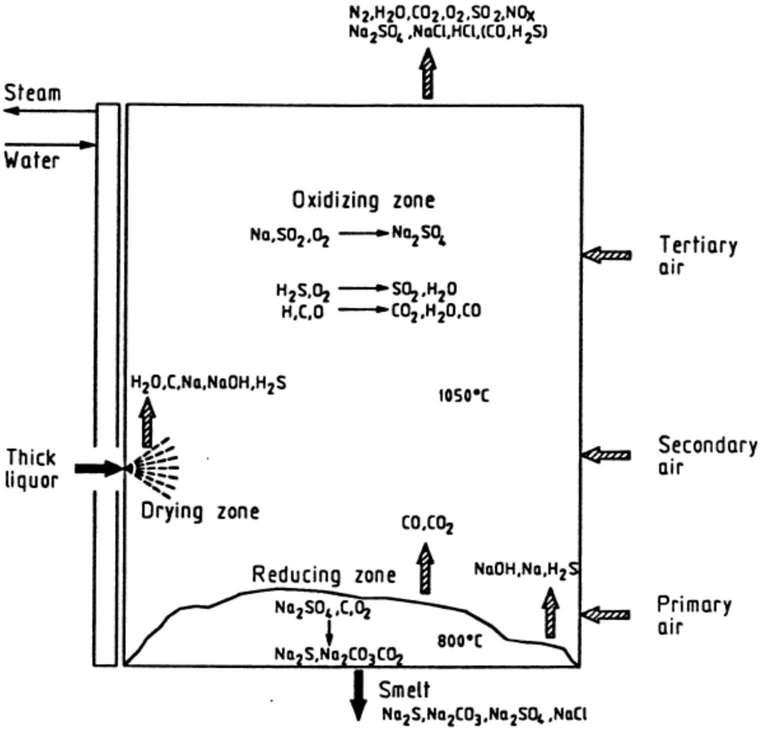


Figure 17: Chemical reactions within a recovery boiler [2].

Table 4 shows a rough energy balance of a recovery boiler combusting 1,333 kg black liquor with a solids concentration of 75%, which means 1,000 kg of solids. All the enthalpies of the input and output streams are listed, whereas output streams have negative enthalpies. For the reaction enthalpies, the higher heating value (HHV) of black liquor solids is estimated at 14,000 kJ/kg, the reduction energies are subtracted from the HHV. Summing up all enthalpies, the heat to steam amounts to approximately 9.9 GJ/t of black liquor dry solids, which is the same as 7.4 GJ/t of black liquor. It is assumed, that boiler feed water with a temperature of 120°C at a pressure of 95 bar is transformed into steam with 480°C and 80 bar. The gross amount of steam generated in the superheaters is about 3.5 tons per ton of dry solids which is equivalent to 2.6 tons per ton of black liquor. Some of the steam is consumed by the boiler itself, furthermore, steam for air pre-heating and feed water preparation have to be subtracted to obtain the net steam quantity that is available for other process steps in the pulp mill [5].

Table 4: Energy balance of a recovery boiler [5].

system input / output	mass [kg/ton dry solids]	specific enthalpy [kJ/kg]	enthalpy [MJ/ton dry solids]
enthalpy of input/output streams			
black liquor	1,333	364	485
dry pre-heated air	4,909	120	589
humidity of pre-heated air	70	2,725	190
sootblowing steam	100	2,820	282
dry flue gas	5,137	173	-888
humidity of flue gas	827	2,840	-2,349
smelt	448	1,500	-672
reaction enthalpy			
HHV of black liquor solids	1,000	14,000	14,000
reduction to Na_2S	89	13,090	-1,170
other reduction	25	9,625	-244
losses			
heat losses through boiler wall etc.			-300
heat to steam			**9,923**
feedwater/steam			
feedwater	3,494	510	1,782
Total steam generation	**3,494**	**3,350**	**11,705**

The thermal efficiency of the recovery boiler can now easily be calculated, as the efficiency η is the ratio of the useful thermal power output (Q) of the system to the total energy input (H_i). The useful heat to steam output of the recovery boiler is 9,923 MJ/t of black liquor dry solids, the total energy input can be calculated by summing up all positive enthalpies and has a value of 15,546 MJ per tonne of dry solids.

$\eta = Q/H_i$ = 9,923 MJ/15,546 MJ = 0,638 ~ 64%

Basic reactions of the causticizing plant and the calcination of lime

In the first step of the causticizing plant, burned lime (CaO) coming from the lime kiln is mixed with water and thereby converted into slaked lime (calcium hydroxide $Ca(OH)_2$) [5].

$CaO + H_2O \rightarrow Ca(OH)_2$ dH = -65 kJ/mol

Slaked lime and green liquor are mixed by an impeller. The next step is the reaction of calcium hydroxide with the sodium carbonate from the green liquor to form sodium hydroxide that is needed for cooking and calcium carbonate which is applied to the lime kiln [5].

$Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3 \qquad dH = 0\ kJ/mol$

Calcium carbonate is finally separated from the liquor in form of lime mud by a pressure disk filter and forwarded to the lime kiln to be burned to CaO which is again applied to the first step [5].

The lime mud is applied to the rotary kiln and passes the drying-, heating- and calcinations zone in counter current to the gas flow. After 2-4 hours the burned lime exits the rotary kiln and is cooled in a satellite cooler against heating up the combustion air [5]. Figure 18 shows the schematic of a lime kiln and the temperature profiles of solids and gas.

$CaCO_3 \rightarrow CaO + CO_2 \qquad dH = +178\ kJ/mol$

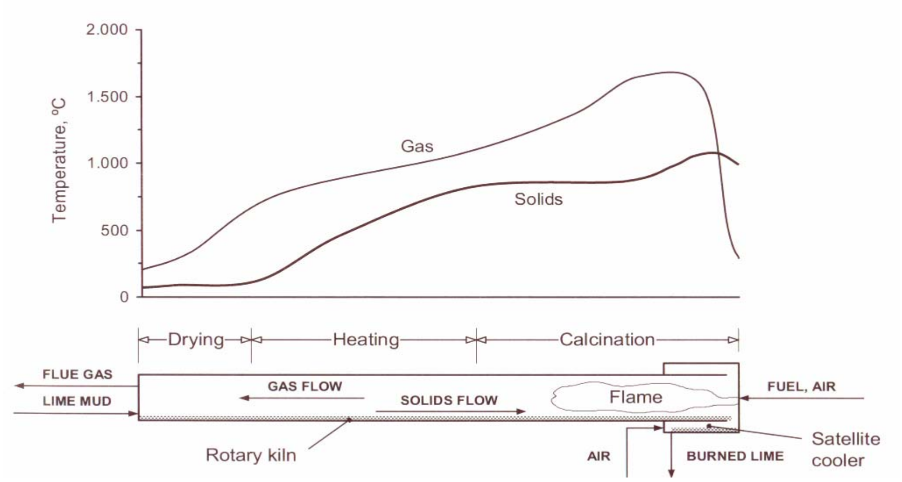


Figure 18: Material flows and temperature profile of a lime kiln [5].

The energy input for the calcination of one ton of burned lime is supplied by the combustion of approximately 150 kg of fuel oil or 200 Nm³ of natural gas. About one half of the chemical fuel energy is consumed by the calcination reaction, one quarter is needed for water evaporation from the incoming lime mud and the rest is lost with the flue gas and via the kiln shell.

The recovered white liquor from the causticizing plant is finally recycled to the cooking plant [5]. Figure 19 shows the overall flow sheet of the chemical- and energy recovery system of a Kraft pulping mill.

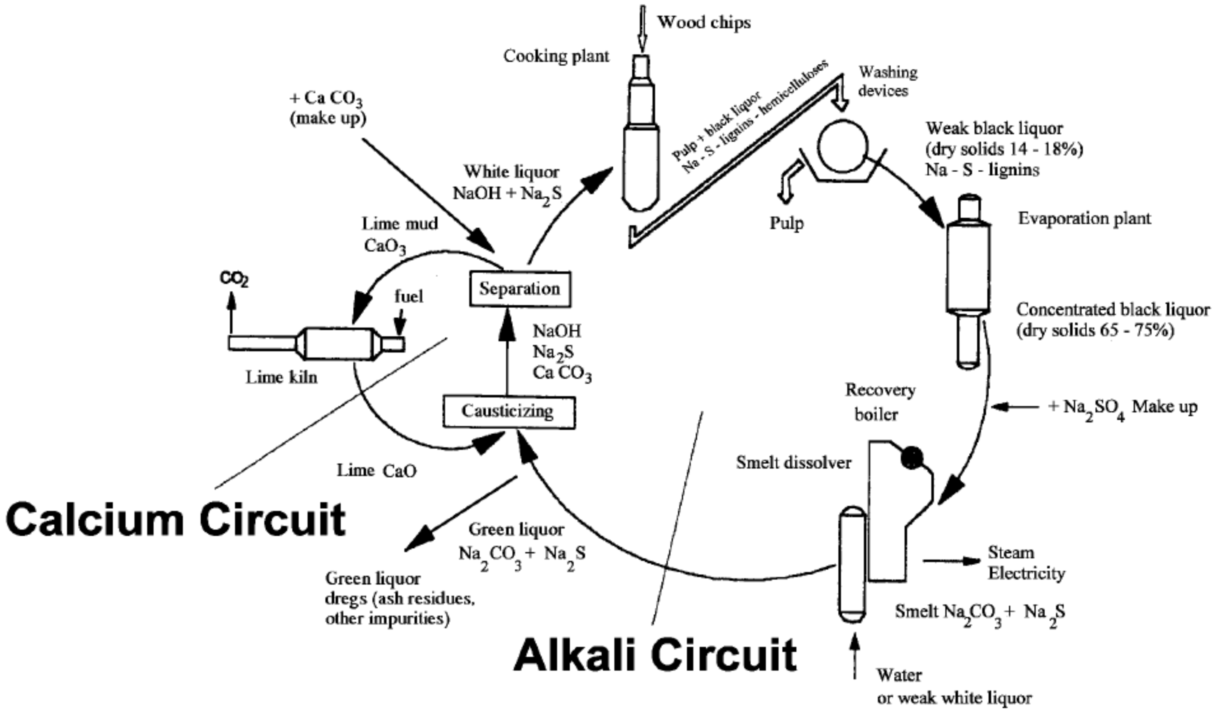


Figure 19: Material and energy flow sheet of the kraft pulping recovery process [2].

Energy demand of a kraft mill

A modern pulp mill, using a recovery system can be self sufficient or, at least almost self sufficient in steam- and electrical power generation [5]. Table 5 shows the energy balance of a non integrated Kraft pulp mill. About 10-14 GJ of heat energy and 600 – 800 GWh of electrical power are necessary for the production of one ton of bleached Kraft pulp. The most important steam consuming processes are in the cooking-, the evaporation- and the bleaching plant. More than 50% of the electrical energy is used for pumping the materials through the different stations of the pulp mill. A recovery boiler and a power boiler for bark combustion (see page **Fehler! Textmarke nicht definiert.**) produce the superheated high pressure steam, part of which is utilized in the steam turbine for electrical power generation. Medium pressure steam, extracted from the turbine and low pressure steam that exits the turbine, supply heat to the different mill operations. The ratio of electrical power generation to heat generation is in a range of 0.2 – 0.3. Fossil fuels are used for supplementary firing in the bark boiler, but mainly for heating the lime kiln. Waste heat (e.g.: from the evaporation plant) can be used as secondary heat (see page 42), recovered in hot or warm water [2].The excess energy is not sufficient to run a paper machine in case of an integrated pulp- and paper mill.

The additional energy demand has to be delivered by auxiliary boilers, fired with fossil fuels, they can also be installed to cover peaks in the energy demand of a non integrated pulp mill [2].

Table 5: Energy balance of a kraft pulp mill [5,10].

Department	**Process heat consumption/ generation [MJ/t]**	**Electric power consumption /generation [kWh/t]**
recovery boiler	+14500	
power boiler (bark combustion)	+3000	
external fossil fuel supply (e.g.: for lime kiln)	(+1500)	
turbine generator		+650
total generation (recovery boiler+power boiler)	**+17500**	**+650**
wood handling	-150	-55
cooking	-2050	-55
displacement batch cooking	-2000	-45
continuous cooking	-2100	-65
average of batch and cont.	-2050	-55
washing and screning		-50
oxygen delignification	-400	-45
bleaching (incl. bleaching chemical preparation)	-500	-90
final screening		-40
pulp drying	-2800	-100
evaporation plant	-4000	-30
recovery boiler	-610	-60
turbine generator	-2600	
causticizing		-20
lime kiln	(-1500)	-10
effluent treatment		-20
miscellaneous	-2000	-100
total consumption	**-14500**	**-675**
External supply		**+25**
Waste energy	**1500**	
Waste energy recovery by secondary heat systems	**+500**	
Excess energy	**1500**	

Black liquor gasification for chemical- and energy recovery

The aim of black liquor gasification (BLG) is to produce a combustible gas, consisting of hydrogen, hydrogen sulphide, carbon monoxide and carbon dioxide out of the organic matter of the concentrated black liquor coming from the evaporation plant. Basically, two categories of black liquor gasification can be distinguished from each other; low temperature gasification (700 – 750°C) and high temperature gasification (1000°C) [5]. Figure 20 shows the Chemrec process, one possible design of a high temperature gasification reactor.

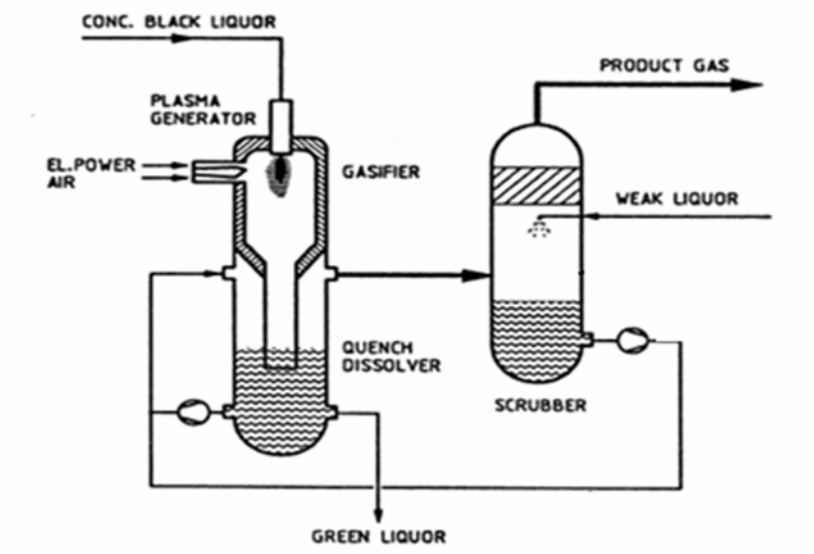


Figure 20: High temperature gasification of black liquor (Chemrec process) [2].

In the Chemrec process, preheated black liquor (130°C) with a solids content of approximately 65% is atomized and sprayed into the gasifier by air, pressurized at 12 bar. The small droplets are partially combusted in the 950°C hot atmosphere. The inorganic matters of the black liquor form small smelt droplets of sodium sulfide and sodium carbonate that fall through the gasifier to a quench cooler located at the bottom of the reactor. Water or white liquor dissolve the inorganic matters, forming green liquor that is partially recycled to the quench cooler and the rest of it is lead to the causticizing plant of the recovery system. The gas, that is generated from the organic components of the black liquor is washed with white liquor in a scrubber for the removal of hydrogen sulfide (sulphur recovery) before it is combusted in the gas turbine of a combined cycle process. The principle of such a process is shown in Figure 21 (also see Figure 58) [2].

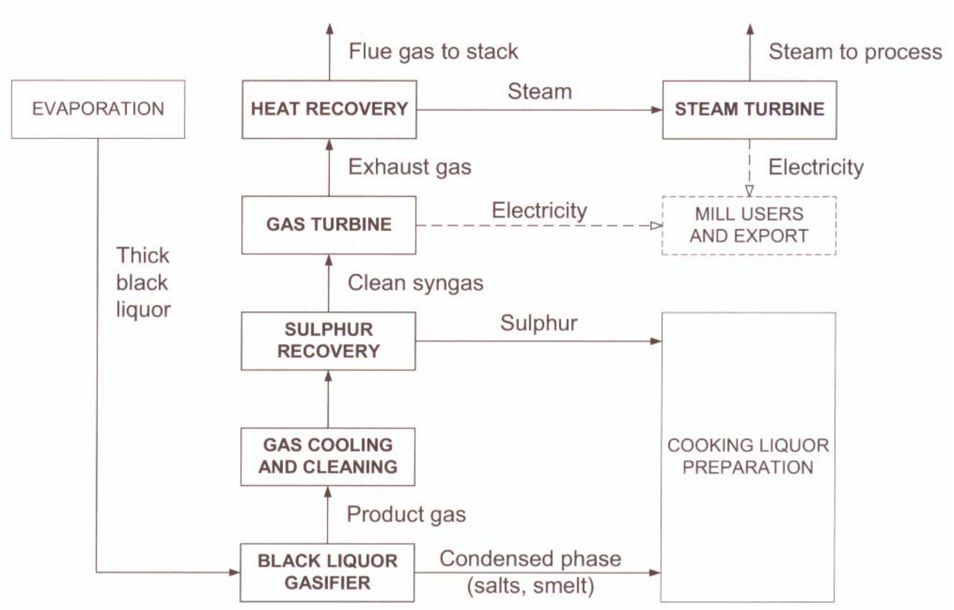


Figure 21: Combined cycle process [5].

The product gas is combusted in a gas turbine that drives a generator. The hot flue gases of the turbine produce superheated steam which drives a steam turbine, connected to a second generator. Extraction steam from the steam turbine can be used in all kind of steam consuming processes of the pulp mill, where it condenses and is pumped back to the flue gas boiler [2]. Black liquor gasification systems are still in their testing phase, the capacities of currently operated systems are less than 10% of large recovery boilers [5].

4.1.1.2 The acid sulphite process

In this process, a cooking liquor containing magnesium bisulphite $Mg(HSO_3)_2$ dissolves lignin and hemicelluloses from the wood fibres [7]. Cooking is carried out in a batch digester (technical details are explained at page 17). Figure 22 shows the flow sheet of the sulphite process [2].

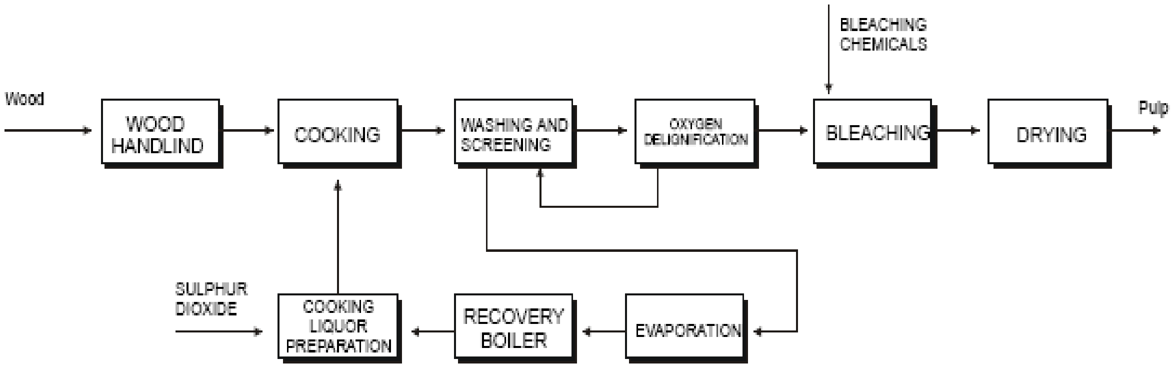


Figure 22: Flow sheet of sulfite pulping [2].

Pulp washing separates spent cooking liquor, that is lead to the recovery boiler, from the pulp, which undergoes the same screening, oxygen delignification- and bleaching operations as Kraft pulp does [2].

In the recovery system, water is evaporated from the spent cooking liquor to produce concentrated liquor (50 – 65% dry solids [5]) which is combusted in the recovery boiler for steam and electricity generation. Solid magnesium oxide and sulfur dioxide are formed and leave the boiler via the flue gas and the ash. The magnesium oxide from the flue gas is separated in electro filters and dissolved in water, thereby a magnesium hydroxide ($Mg(OH)_2$) slurry is formed. With this slurry sulfur dioxide from the flue gas is absorbed and magnesium bisulfite $(Mg(HSO)_3)_2$ is formed within the slurry. Clarification by sedimentation or filtration in order to remove undissolved soot particles as well as make up with fresh sulfur dioxide are necessary before the recycled cooking liquor is pumped back into the digester [2]. Figure 23 shows the flow sheet of the chemical-and energy recovery cycle.

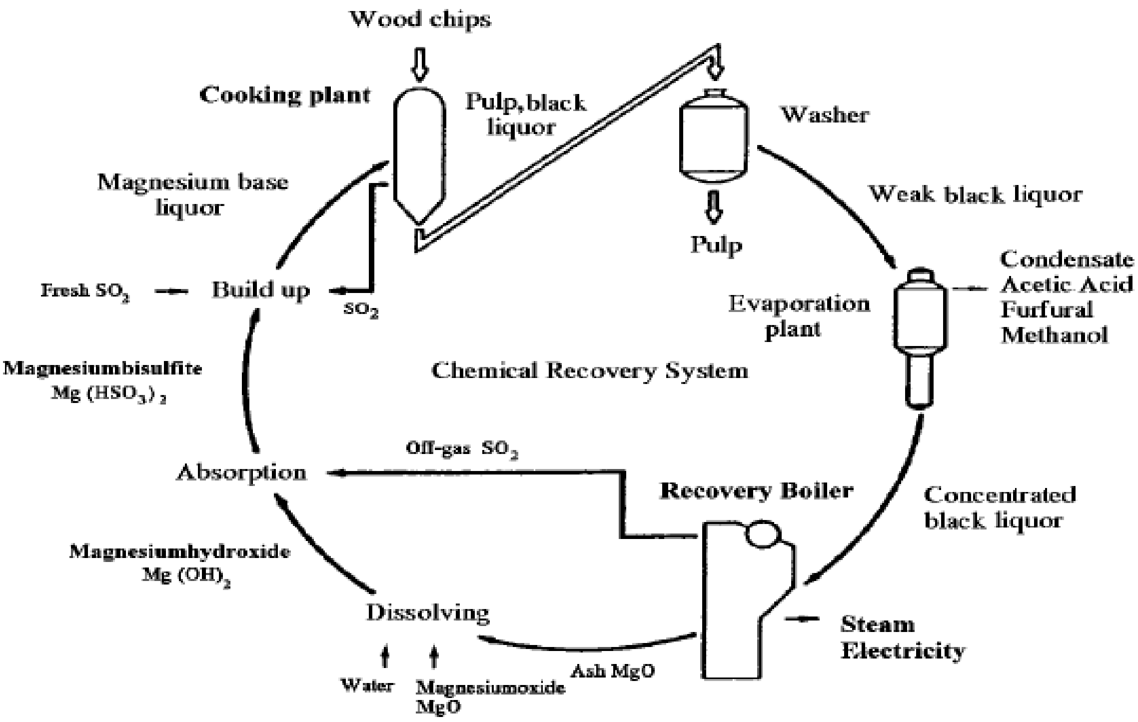


Figure 23: Chemical- and energy recovery cycle of the sulfite pulping process [2].

The major advantage of the Sulfite Pulping process is its flexibility according the pH – range in which it is operated. While the Kraft process requires highly alkaline conditions (pH – value between 13 – 14), the Sulfite process can be operated within the whole pH – range by changing the dosage and composition of the active chemicals in the cooking liquor. However, the disadvantages of the process, such as low strength of the pulp – fibres, make the Kraft process the preferred one for chemical pulping [2].

4.1.2 Mechanical pulp

Besides chemical cooking, mechanical defibration of wood is another possibility to produce pulp. The bonds between the fibres break up and single fibres, fibre bundles and fibre fragments are liberated [2]. The lignin is plasticized during the defibration process and remains in the pulp, this results in lower strength properties and a higher light-scattering and opacity compared to chemical pulp. Mechanical pulp is used for the production of short-life printing papers, hygienic papers and board. The importance of mechanically extracted fibres for the paper industry is not very high, as in 2000 mechanical pulp accounted for 9% of the worldwide produced amount of pulp. Different processes for mechanical pulping are applied in pulp mills [3].

4.1.2.1 Groundwood processes

The basic unit of these processes is a grinding stone that mechanically separates the fibres of round wood logs from each other [3]. The most important grinding principles are [5]:

- The stone groundwood (SGW or GW) process: grinding happens under atmospheric pressure, shower water with a temperature of 70 – 75°C is applied.
- The pressure groundwood (PGW) process: grinding is carried out at 2.5 bar and shower water temperatures of 100°C.
- The super pressure groundwood (PGW – S) process: grinding under a pressure of 4.5 bar and shower water temperatures slightly higher than 100°C.
- The thermo groundwood (TGW) process: shower water with 80°C or more is applied, grinding under atmospheric pressure. Figure 24 shows the operation principles of the GW, PGW and TGW process.

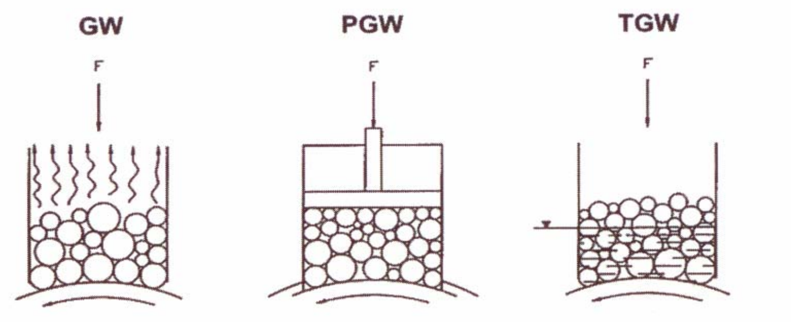


Figure 24: Comparison of grinding principles of the GW, PGW and TGW process [5].

Grinding of the water showered wood logs produces a lot of low – pressure steam and warm water which can be used as heat source for other process steps. Process waste such as bark from the wood handling plant and rejects from screening and cleaning operations can be combusted for energy generation purposes [2]. Figure 25 shows the flow sheet of a groundwood process.

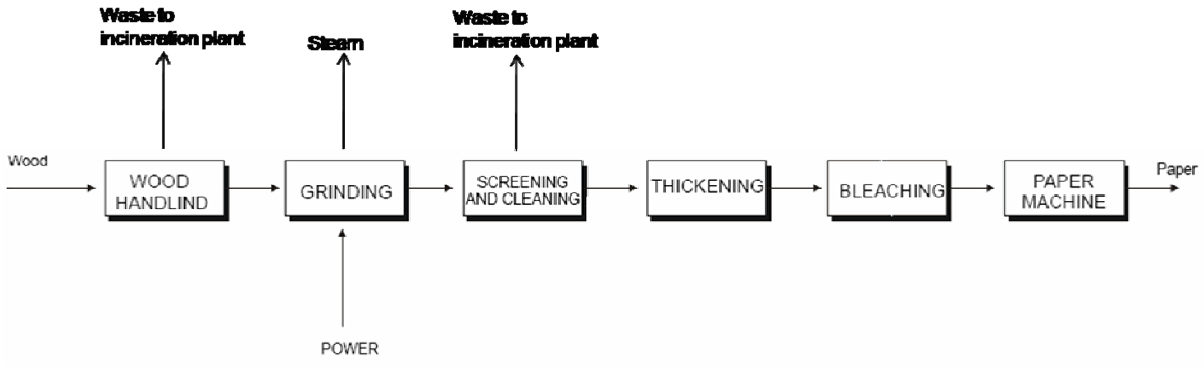
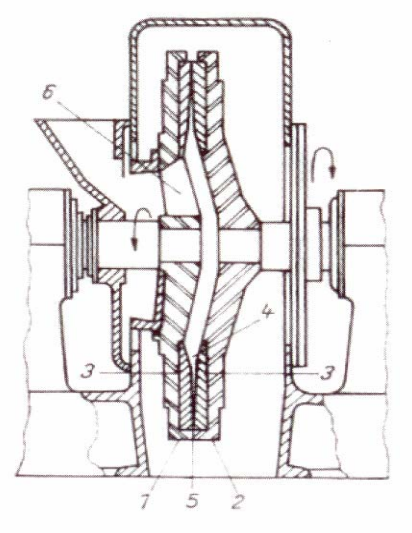


Figure 25: Flow sheet of a groundwood process [2].

4.1.2.2 Refiner Mechanical Pulp (RMP) and Thermo Mechanical Pulp (TMP)

Refining processes basically use the same operation principle of grinding out wood fibres of the matrix as the groundwood processes do. Grinding in this case however takes place in a refiner, an aggregate in which wood chips are ground between two steel discs, rotating against each other [5]. Figure 26 shows the simplified cross section of a refiner.



1 and 2: rotating discs
3: refiner plates
4: beginning of refining zone
5: outlet of refining zone
6: chip feed

Figure 26: Refiner [5].

RMP is produced at atmospheric pressure but is only of minor importance compared to TMP. In Thermo-Mechanical Pulping, washed wood chips are pretreated with steam extracted from the flash tank to soften the bonds between the wood fibres. Refining at temperatures in a range of 100 – 130°C and under an elevated pressure of 5 bar releases a lot of steam from the humid wood chips. It is separated from the pulp in a subsequent cyclone and lead to a energy recovery unit (steam converter) where it is condensed and fresh steam is produced [2,11]. Figure 27 shows the energy and material flow sheet of a thermo-mechanical pulping system.

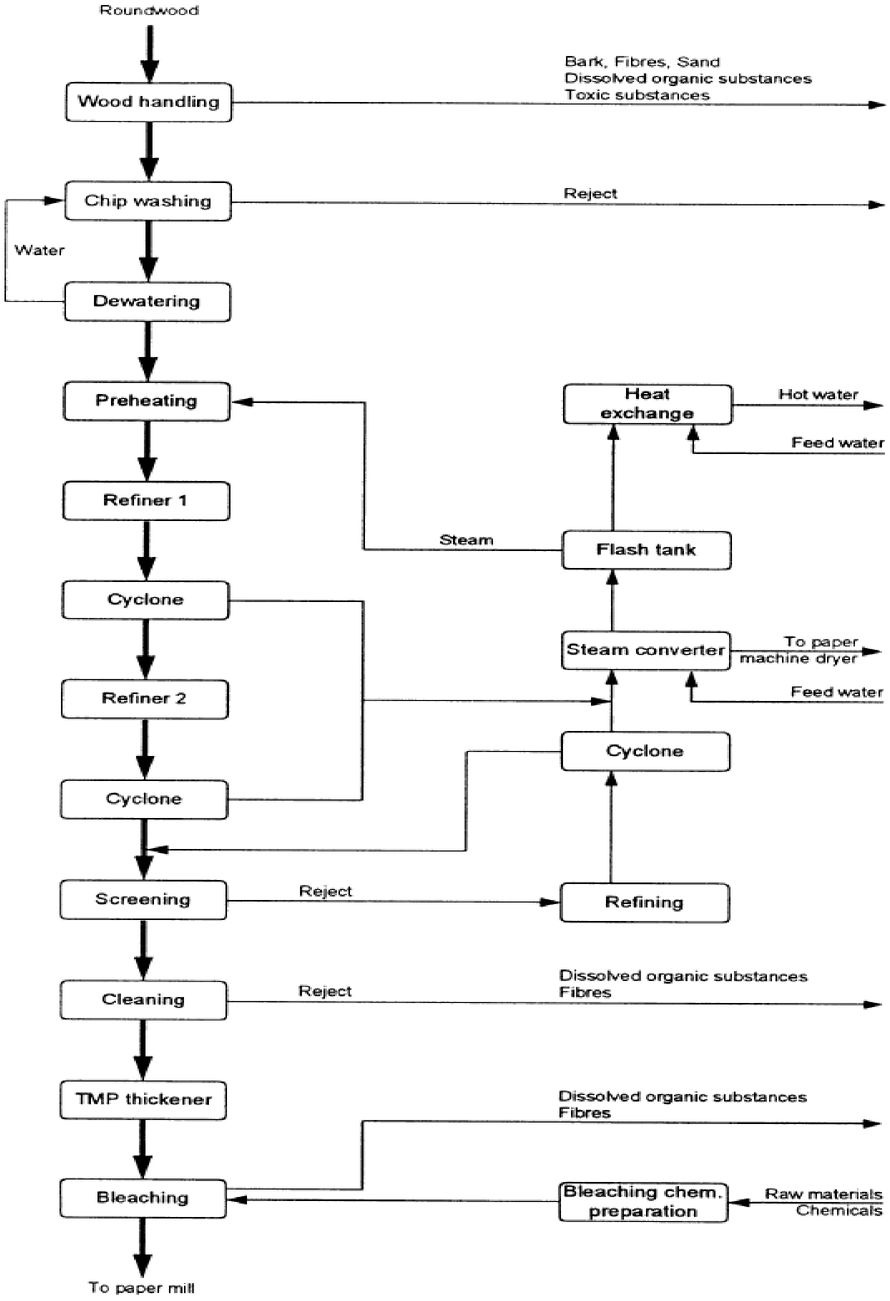


Figure 27: Flow sheet of thermo-mechanical pulping [2].

Depending on the desired pulp qualities, a second refiner is installed in most Thermo-Mechanical Pulp mills. After the second refining stage the pulp is screened to remove oversized fibre bundles (rejects) from the process. These rejects pass another refining step to generate some more steam that is collected in the steam converter. After cleaning and bleaching, the pulp can be applied to the paper machine [2,11].

Energy recovery system

The steam, produced in the refiners (TMP steam) contains a lot of impurities (e.g.: turpentine, volatile organic oils). It cannot be directly used as a heat source in other process steps. Therefore the steam is applied to a heat recovery boiler to heat fresh water and to produce new steam for impregnation of the wood chips [5]. Figure 28 shows the material and energy flow sheet of a steam converter system.

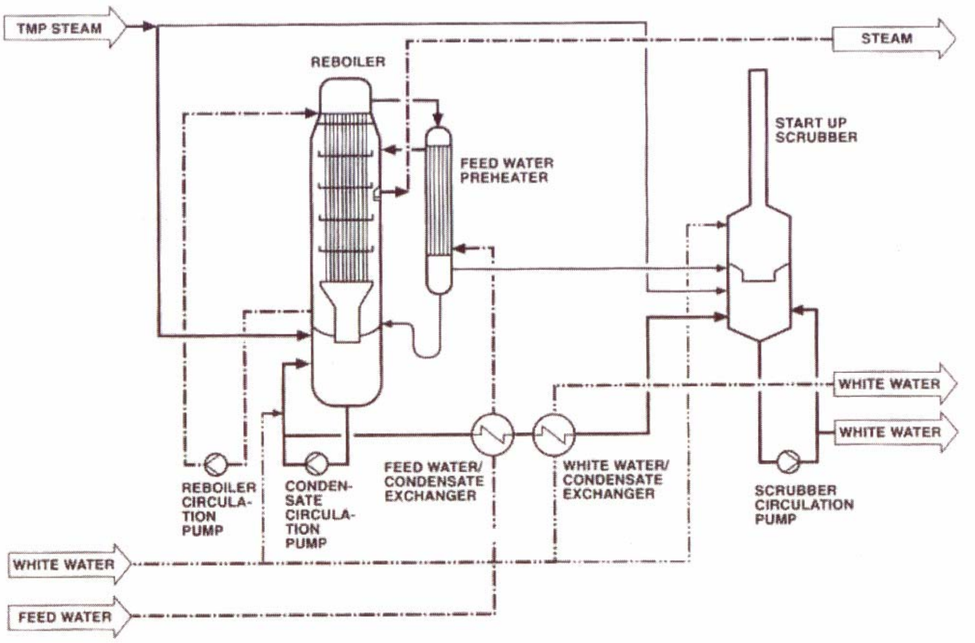


Figure 28: Flow sheet of the steam converter system [5].

The TMP steam circulates through the recovery boiler and heats fresh water. It finally condenses and is withdrawn at the bottom to be lead to the start up scrubber where all the impurities are washed out of the condensate and fresh “white water” is recycled to the process. In an integrated pulp and paper mill, some fresh steam is applied to the dryer section of the paper machine, the rest is lead to a flash tank from which steam is withdrawn for preheating of the chips and steam condensate is used for warm water generation [2]. With recovery boiler operation, 40 - 45% of the refining energy can be recovered in form of clean steam [5].

4.1.2.3 Chemi Mechanical (CMP)- and Chemi-Thermo Mechanical pulping (CTMP)

In Chemi Mechanical- and Chemi- Thermo Mechanical Pulping the input material undergoes the same operation steps as in Thermo-Mechanical Pulping. CMP, however is produced at atmospheric pressure. The difference of these processes compared to TMP is that the wood chips are chemically pre-treated with a sodium sulphite (Na_2SO_3) solution to alleviate the refining process and to improve the quality of the pulp [2]. Energy recovery systems are the same as in Thermo-Mechanical Pulping [5].

Energy demand of Mechanical Pulping

The specific energy demand of mechanical pulp production depends on the applied process, the properties of the raw material and the desired strength quality of the pulp, which is characterized by the Canadian Standard Freeness (CSF) value. The CSF indicates the drainage properties of the pulp, a low value indicates slow draining and high strength of the pulp. Due to the friction between grinder and wood or refiner and wood, mechanical energy is converted into heat and can be recovered as hot water or steam for pulp drying or, in case of an integrated pulp- and paper mill, for the paper machine [2].

Table 6: Energy demands and recovery rates for different mechanical pulps [2].

Pulp	Energy demand [kWh/t]	Recovered energy as hot water [%]	Recovered energy as steam [%]
GW	1100 - 2200	20	
PGW	1100 - 2200	30	20
TMP	1800 - 3600	20	40 - 45
CTMP	1000 - 4300	20	40 - 45

Table 7 shows a rough energy balance of a Thermo- Mechanical Pulp mill, using recovered steam from the energy recovery system and from a power boiler combusting wood residues.

Table 7: Energy balance of a TMP mill [2].

department	Process heat consumption/ generation [MJ/t]	Electric power consumption/ generation [kWh/t]
pulp mill		
recovered steam	+3450	
power boiler (wood residues + fuel oil)	+2900	
turbine generator		+100
total generation	**+6350**	**+100**
wood handling	-150	-55
refining		-2100
washing and screning		-50
bleaching (incl. Chemical preparation)	-400	-80
final screening		-40
power boiler		-35
turbine generator	-400	
total pulp mill consumption	**-950**	**-2360**
paper mill		
stock preparation		-235
paper machine	-5300	-350
total paper mill consumption	**-5300**	**-585**
Effluent treatment		**-39**
total consumption per ton of paper	**-6250**	**-2984**
External supply		**+2884**
Excess energy	**+100**	

4.1.3 Pulp from recovered paper

Different recovered paper grades have to be prepared for a smooth operation of the paper machine and to fulfil quality requirements of the final product. Stock preparation of pulp from recovered paper takes place in many unit processes, that are adapted to one another [3]. The following process steps may be applied:

- **Repulping/Slushing:** In the first step a pump able suspension is produced out of the input material in a so called pulper, a device, that breaks down the recovered paper into its fibres by dissolving it in water. Ink particles and impurities such as foils, textiles, plastic bags or wood pieces are separated from the suspension.
- **Screening:** Solid substances (plastics and paper flakes) that are different in size or shape from the fibres are separated as the suspension passes a screen.
- **Fractionation:** According to defined criteria such as size or deformability, fibre fractions are separated from each other (e.g.: long fibres from short fibres) in flat or cylindrical screens.
- **Centrifugal cleaning:** In this step particles with different gravity to the fibres such as small stones, glass, nails or staples are removed from the suspension in hydrocyclones.
- **Selective Flotation:** Impurities such as printing ink particles and coating pigments are removed by injecting air into the suspension. The generated bubbles catch one or more particles and transport them to the surface, where the resulting foam is withdrawn.
- **Bleaching:** The objective of bleaching is to give brown or yellow fibres the required brightness and luminance. Bleaching can be carried out as oxidative bleaching, using peroxide as bleaching agent.
- **Washing:** The washing process is applied to wash out dissolved and colloidal organic and inorganic substances smaller than 30 µm.
- **Dispersion:** The tasks of this process step are for example to reduce the size of dirt specks, to disintegrate fibre bundles or to detach ink or toner particles from fibres. Disk dispergers which heat up the material to 90 – to 130 °C apply shear forces to the fibres. Often bleaching is processed in combination with dispersion.
- **Mixing and Storing:** The pulp is mixed with coatings and fillers before it is applied to the paper machine.

The total energy consumption for recovered paper processing is lower than for the production of mechanical or chemical pulp [2]. Typical energy demands are shown in Table 8.

Table 8: Energy demand for the production of pulp from recovered paper [2].

department	**Process heat consumption [MJ/t]**	**Electric power consumption [kWh/t]**
pulping		16
washing and screening		50
deinking	200	175
bleaching (incl. bleaching chemical preparation)		75
stock preparation		235
paper machine	5300	350
effluent treatment		32
specific energy consumption	**5500**	**933**

Possibilities for energy recovery

The impurities removed during the recycling process, can be combusted for energy generation purposes. Typical solid wastes from the recovered paper pulping process are: rejects (consisting of: 45% plastics, 2% wood, 2% textiles and leather, 2% metals, 46% fibres and 3% of all other kind of materials), deinking sludge (consisting of 19% printing inks, 37% clay and other fillers, 19% calcium carbonate and 15% of fibres and other components), sludge from the effluent treatment plant and fibre sludge. Rejects, deinking sludge and fibre sludge are commonly dewatered, for example by belt- or screw presses (see Figure 29 and Figure 30) before they are forwarded to the combustion plant or used in other branches of the industry for energy generation or material production processes. Deinking sludge and its combustion ashes are, due to the high content of inorganic compounds, make it a preferred raw material for:

- cement- and concrete production,
- brick manufacturing,
- mortar and sand lime brick production and
- road construction purposes [3].

Anaerobic treatment of effluents from recovered paper pulping is most commonly used in the European pulp and paper industry. So called upflow anaerobic sludge blanket (UASB-)

reactors convert the solids, collected at the first step of the effluent treatment plant into biogas for further energetic use. Net heating values of biogas from anaerobic waste water treatment vary from 6 kWh/m³ to 7.5 kWh/m³ [3]. Table 9 shows the composition of biogas from an upflow anaerobic sludge blanket reactor for the treatment of effluents from recovered paper pulping.

Table 9: Typical composition of biogas from anaerobic waste water treatment [23].

Component	Vol-%	Component	Vol-%
CH_4	60 – 75	H_2	<1%
CO_2	30 – 40	O_2	<1%
H_2S	<1	N_2	<4%
H_2O	saturated		

The sludges formed at other steps of the effluent treatment plants must be dewatered before they are combusted, composted together with bark, or used in agriculture as fertilizer. Dewatered sludge also finds its application in industry, as porousing agent in the manufacturing of bricks, as additive for the fiberboard production and in cat litter. Sludge dewatering is usually carried out in two stages. Gravity tables or drum- and disk thickeners are used in the first step, belt filter presses and screw presses in the second one.

In a belt filter press the sludge is applied between two wire belts and direct pressure forces as well as shearing forces squeeze the water from the sludge. Screw presses remove water by a slowly rotating screw, transporting the sludge against discharge restriction [3]. Figure 29 and Figure 30 show the basic functions of a filter belt- and a screw press.

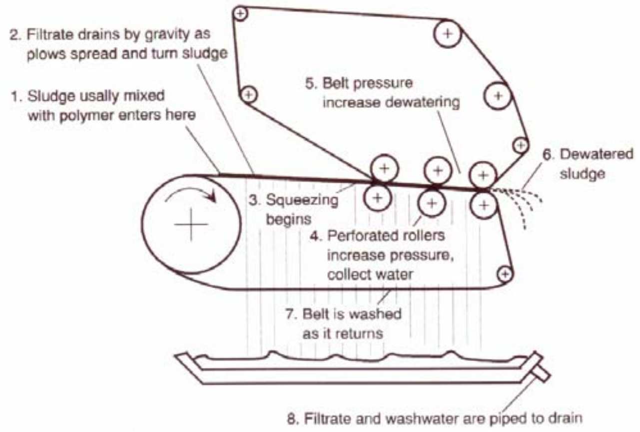


Figure 29: Filter belt press [3].

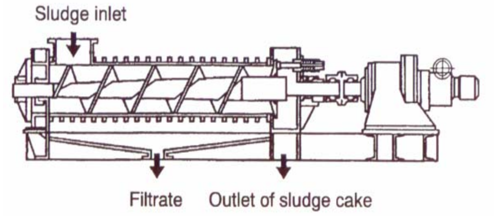


Figure 30: Screw press [3].

After dewatering, wastes from the pulping process can be utilized for electricity and heat generation (cogeneration, see page 55). Figure 31 shows the overall flow sheet of the

SIPAPER REJECT POWER System, invented by the Siemens Industrial Solutions Company and installed at an Austrian paper mill [9].

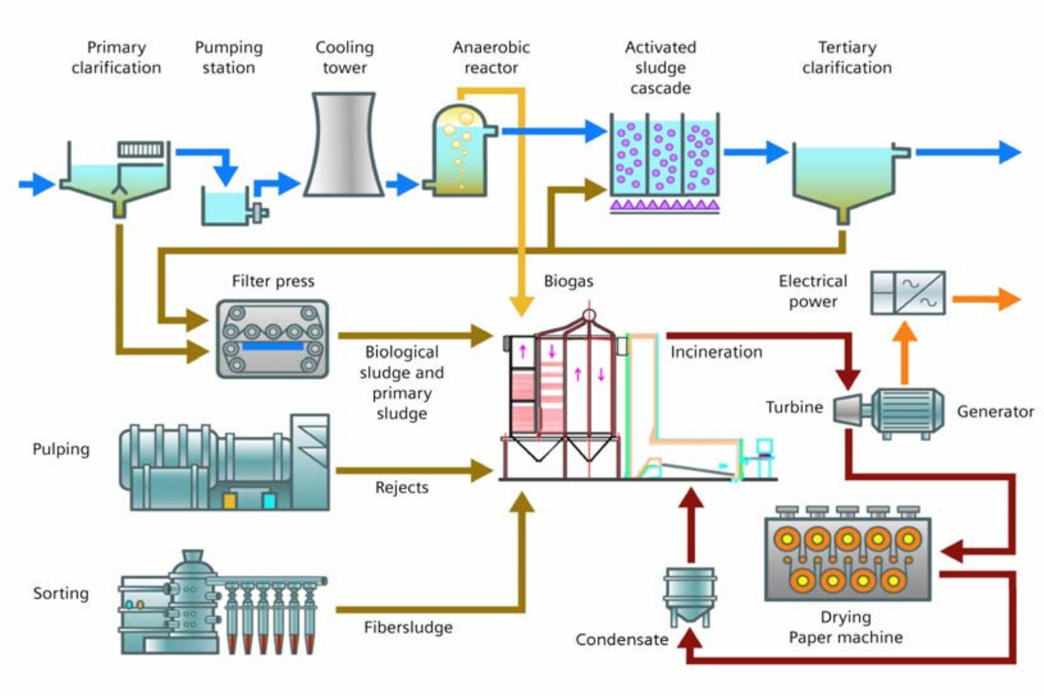


Figure 31: Material and energy flows of energy recovery from rejects [9].

Before being combusted, the rejects are shredded and screened to a size of approximately 40 mm². Metal detectors and over belt magnets remove metals before and after screening. To achieve an optimized heating value, a mix of different fuels is prepared and distributed evenly across a combustion grid by a spinning wheel [9]. Figure 32 shows the schematic of fuel mixing.

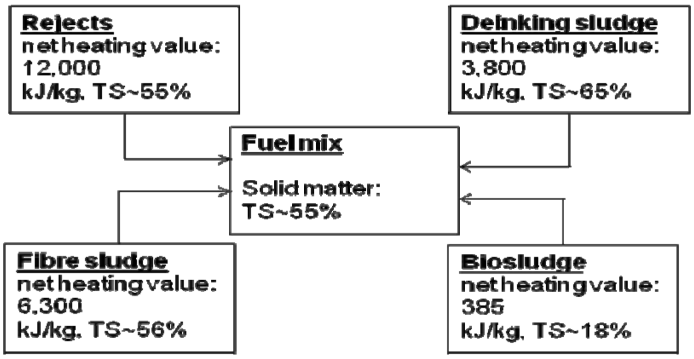


Figure 32: Fuel mix preparation [31]

4.1.4 Secondary heat systems

Secondary heat is defined as heat from a process at a temperature of 45 – 110°C. The excess secondary heat of modern pulp mills can be used as heat source within the process, in district heating or district cooling systems. This chapter describes the most important secondary heat systems. Since in pulp mills no chemical energy is bound into the product, all the energy that goes into the process also comes out at a lower temperature level as heat in the product flow or as secondary heat in side streams that is transferred into warm water (35 – 50°C) or hot water (60 – 80°C). The percentage of secondary heat can be expressed by the following equation [10]:

Secondary heat as % = $Q_3/Q_1*100 = Q_3/(Q_2 + Q_3)*100$

with Q_1: heat in the feed, Q_2: heat in the product flow and Q_3: secondary heat [10].

4.1.4.1 Secondary heat from the continuous cooking plant

Figure 33 shows the mass and energy flows through a secondary heat system at the continuous digester of a kraft pulp mill.

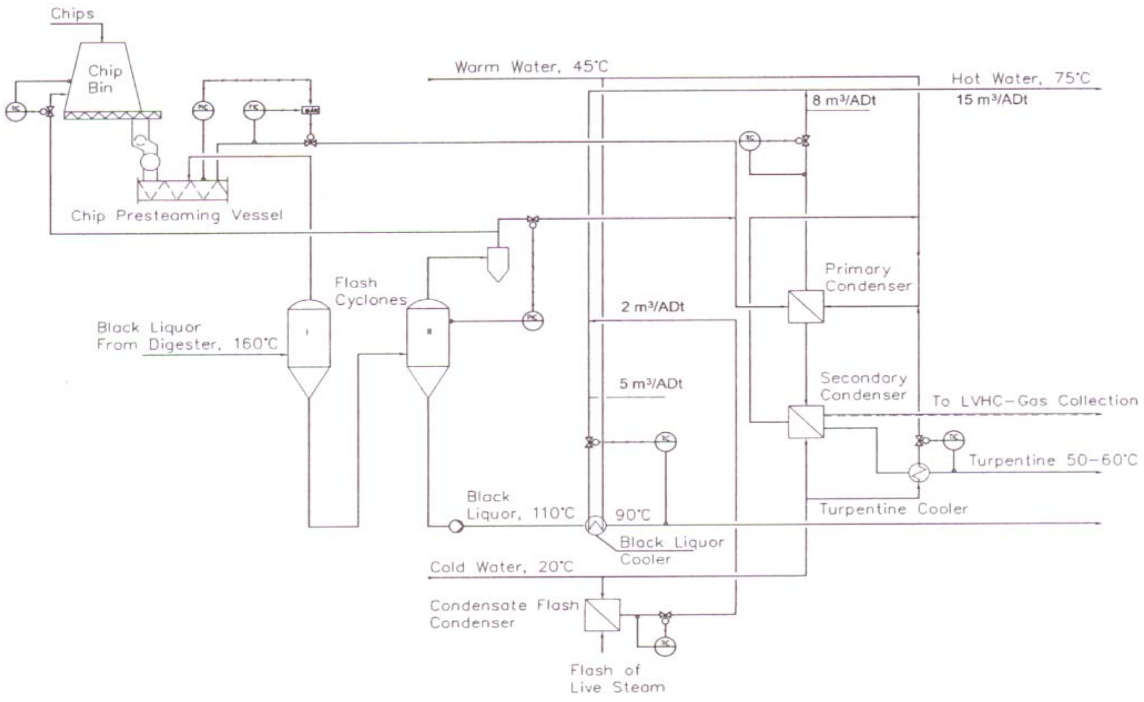


Figure 33: Secondary heat from the continuous digester of a kraft pulp mill [10].

Steam is separated from the black liquor of the Kraft process, coming with a temperature of 160°C from the continuous digester (see page 16), in the steam recovery system by flash cyclones.

Part of the steam is lead back to the process for chip pre - steaming, the rest of it is condensed together with excess steam from the chip pre – steaming vessel in the primary condenser for hot water production. Excess steam from the primary condenser, containing lots of turpentine is condensed in the secondary condenser and further cooled in the turpentine cooler, which also provides heat to the hot water system. Cold water with a temperature of 20°C is lead through the secondary and the primary condenser to be heated up to hot water at 75°C. If necessary, also some live steam can be condensed in a flash condenser for hot water production. Black liquor, coming from the flash cyclones is cooled from approximately 115°C to 90°C in the black liquor cooler, thereby heating warm water with 45°C up to 75°C and is stored in a tank at the evaporation plant for further treatment steps [10].

4.1.4.2 Warm water production from the surface condenser at the multi effect evaporation plant

Steam from the last evaporator enters the surface condenser of the multi stage evaporation system (see page 20). The amount of warm water Q, produced from the condensation of the steam can therefore be calculated by the following formula:

$Q = q*f*i/[n*(T_2 – T_1)*c_p]$ [10].

with:

Q: the warm water amount produced in the condenser by condensing the steam from the evaporation plant, kg/s;

q: the evaporation capacity of the multi effect evaporator, kg/s;

f: flash factor, the vapour amount coming from the last evaporator to the condenser is higher than the average evaporation per effect of the evaporator, usually in a range of 1.1 – 1.15;

i: latent heat of the vapour from the last stage of the evaporator, kJ/kg vapour;

n: number of evaporation stages (number of evaporators);

T_2: warm water temperature out, °C;

T_1: cooling water temperature in, °C;

c_p: specific heat of water, kJ/kg.

The term “$(q*f*i)/n$” is the amount of steam that condenses inside the surface condenser, “$(T_2-T_1)*c_p$” stands for the transferred heat amount to the incoming cool water.

4.1.4.3 Secondary heat from the recovery boiler flue gas scrubber

Flue gas from the recovery boiler passes the electrostatic precipitator (ESP) where dust is removed from the gas stream and is forwarded to a flue gas scrubber to wash out remaining ash- and dust particles.

By direct or indirect contact (plate heat exchangers) of cold water with the flue gas, hot water of 50 – 65°C is produced. A flue gas scrubber for hot water production basically consists of two sections as shown in Figure 34. In the lower section the flue gas enters the scrubber and it is washed, before it is forwarded to the upper section where the heat transfer is carried out. Contaminated washing water is mixed with sodium hydroxide and lead to the causticizing plant [10].

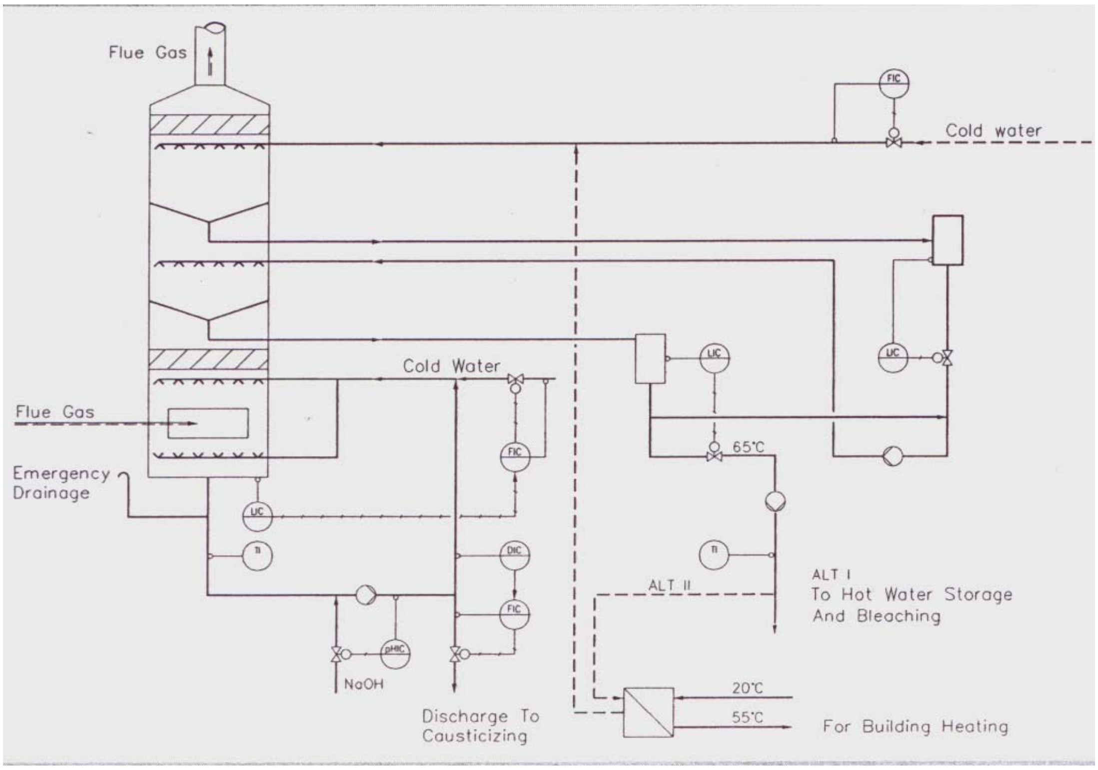


Figure 34: Secondary heat production from the flue gas scrubber [10].

The hot water amount Q, that leaves the scrubber can roughly be estimated as the sum of the cooling water amount into the scrubber Q_1 and the water amount condensed from the flue gas Q_2 by the formula:

$$Q = Q_1 + Q_2$$

Q_1 can be expressed in the following way:

$$Q_1 = G_1 * (i_1 - i_2) / (T_2 - T_1) * c_p$$

with:

G_1: dry flue gas amount, kg/s;

i_1: inlet flue gas enthalpy, kJ/kg;

i_2: outlet flue gas enthalpy, kJ/kg;

T_1: cooling water temperature, °C;

T_2: hot water temperature, °C;

c_p: specific heat of water, kJ/kg.

The water amount that condenses from the flue gas inside the scrubber is defined by the different moisture contents of inlet- and outlet gas.

$$Q_2 = (x_1 - x_2)*G_1$$

with:

x_1: moisture content of the inlet gas, kg water/kg dry flue gas;

x_2: moisture content of the outlet gas, kg water/kg dry flue gas;

G_1: amount of dry flue gas, kg/s.

4.2 Sheet formation on the Paper machine

This chapter describes the transformation of pulp into paper. A paper mill basically consists of the paper and board machine and the supplementary systems around it. Although there is a series of different paper and board grades and types, all paper and board machines are similar in design and comprise: [3,4]

- the headbox, where the suspension of pulp, water and chemicals with a solids content of 1% is distributed across the machine width,
- the wire section, here dewatering elements increase the solids content to 15 – 20% and form an endless paper web out of the suspension,
- the press section pressing out water of the paper web and increasing the solids content to 45 – 50%,
- the dryer section, where residual water is evaporated to reach a final solids content of 90 – 95%,
- the sizing unit, where pigments are applied to the web,
- coating sections,
- the final calender to smooth the surface of the paper or board,
- supplementary systems, such as water circulation systems.

Figure 35 shows a simplified flow sheet of a paper machine.

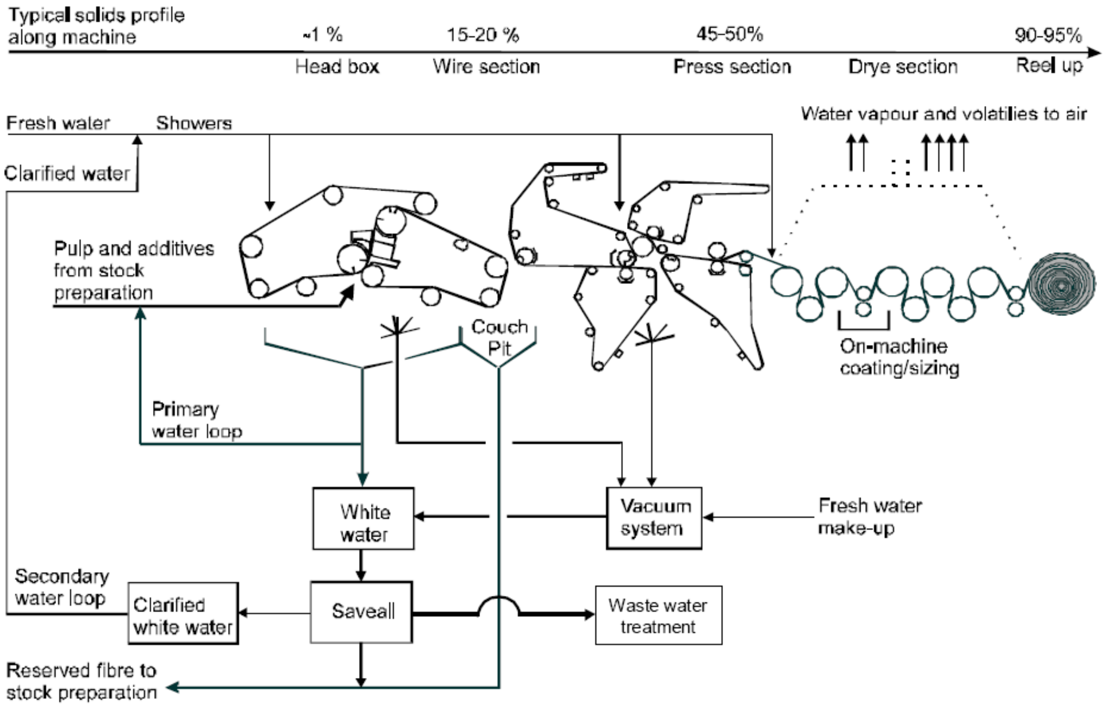


Figure 35: Simplified flow sheet of a paper machine (twin wire former) [2].

Examples for supplementary systems of a paper machine are the broke system for the recovery of broke paper from the process and water circulation- and clarifying installations. All the drained and pressed out water from the paper web is led to the “Saveall”, where it is clarified and lead back to the process. Excess water is forwarded to the waste water treatment plant [2]

Most European paper mills are non – integrated mills, which means that the pulp is delivered from a separated pulp mill in bales or as loose material. Other raw materials, fillers and pigments, chemical additives and coating colors, are delivered to the mill too. They are applied to the stock preparation system, where the final suspension for the paper machine is prepared [3]. The paper machine forms the paper web and determines the specific properties of the final product. The commonly used Fourdrinier process, in which the fibrous suspension is applied to one continuous wire has become more and more replaced in recent years by twin wire formers, that use two wires operating at the same speed. Typical machine speeds are in a range of 1500 m/min – 2000 m/min for a paper web width of 10 m. The fibre slurry that enters the paper machine at the headbox has a consistency of 0.2 – 1.5% and is first of all drained by dewatering elements such as rolls foils and vacuum boxes in the wire section to a solids content of 15- 20%. In the press section the solids content is further increased to 45 - 50% before the paper web enters the dryer section [2].

The dryer section

More than 90% of all the heat energy consumed in a paper mill is used for the dryer section of the paper machine. 80% of the heat that is required for the evaporation of water from the wet paper web is delivered by steam, the rest is coming as drying air and with the paper web. The solids content of the web is increased to 90-98% by evaporation of water in the dryer section. In addition to dewatering, the dryer section increases the strength of the paper as hydrogen bonds are formed between the fibres during the drying process. The most common drying principle is contact drying by steam heated cast iron- or steel cylinders, this means, that steam condenses at the inner surface of the cylinder wall and the heat is transferred trough the wall to the paper web, which is heated and water is evaporated. An air stream takes up the evaporated water. The condensate at the inside of the cylinder is removed by siphons in form of a two phase flow of steam and water [3].

For an energy efficient operation of paper machines, heat recovery systems are installed above the dryer section. The hot, steam containing exhaust air from the dryer section is used for heating purposes within the paper machine [2]. Figure 36 shows the schematics of a heat recovery system.

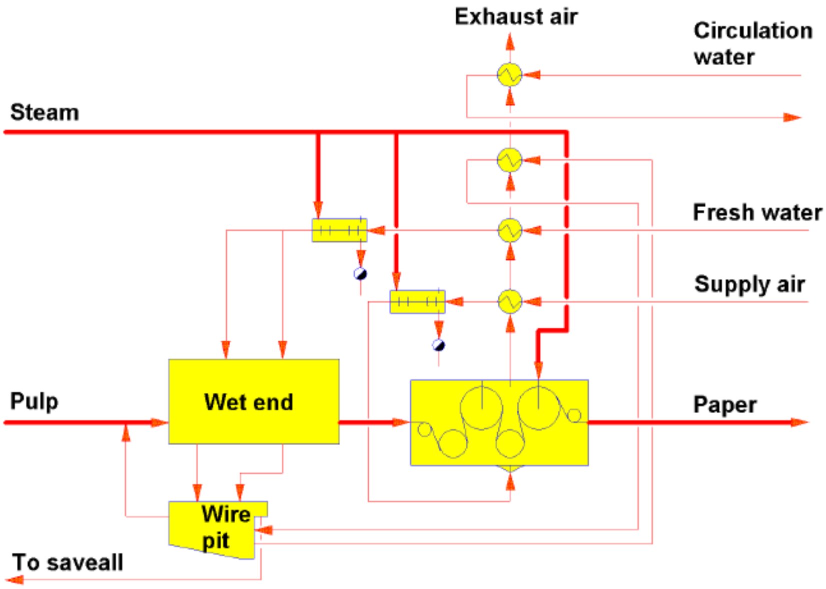


Figure 36: Heat recovery system of the dryer section [2].

The temperature of the exhaust air is up to 90°C and the moisture content about 140 – 160 grams of water per kilogram of dry air. In the first two heat exchangers shown in Figure 36, the incoming supply air and the fresh water that is applied to the paper machine are heated to their final operation temperatures of 90 – 95°C and 45 – 60°C respectively. If necessary, wire pit water (water drained from the paper web at the wire section), can be heated too.

Before the exhaust air is released to the atmosphere, it passes the last heat exchanger for the paper machine circulation water, this may not be necessary for paper mills in very warm countries. For better understanding, Figure 37 gives a more detailed overview of a heat recovery unit for the paper machines dryer section [2].

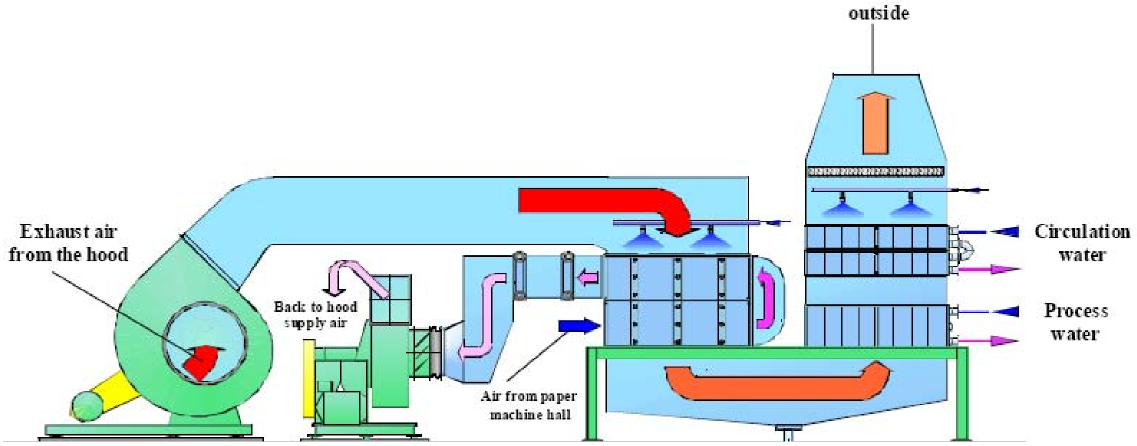


Figure 37: Operation principle of a heat recovery system [2].

With these measures approximately 50% of the energy in the exhaust air can be recovered, i.e. about 640 kWh per ton of paper (at winter conditions). Figure 38 shows a Sankey diagram for the heat recovery system of a newsprint paper machine with a production capacity of 980 t per day.

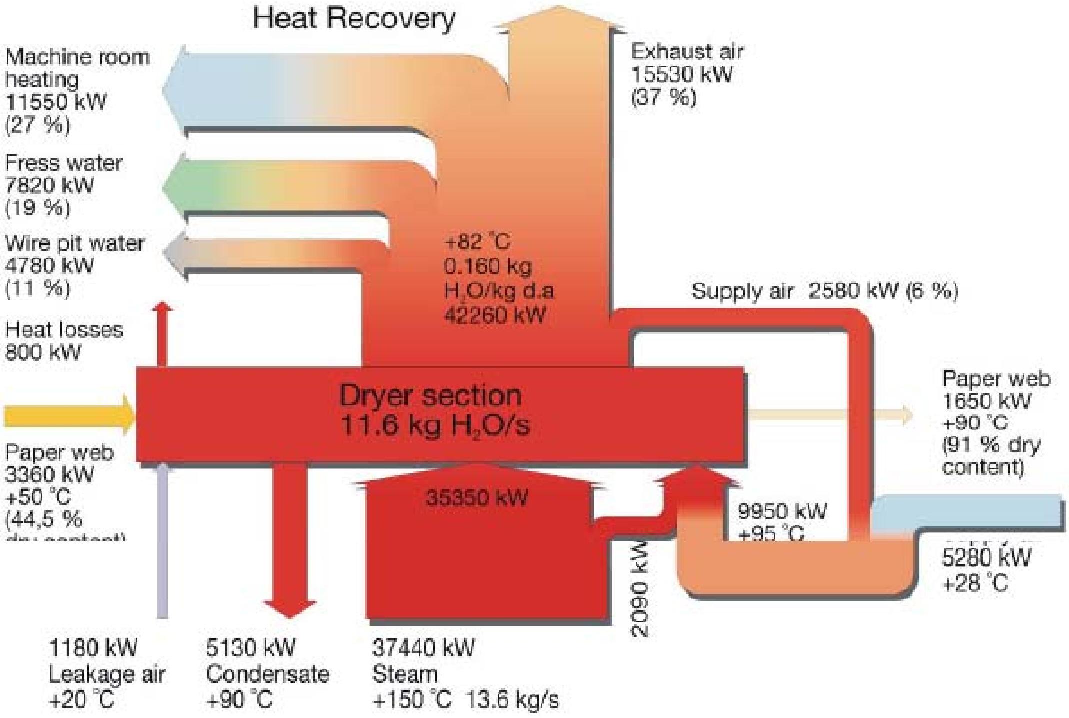


Figure 38: Sankey diagram for a heat recovery system of a paper machine [2].

5 Handling of waste from the production process

Data from Germany’s paper industry show that already in 2001 about 35% of solid wastes (bark and wood residues, all kind of rejects) were used for energy generation, 18% were composted or biologically treated, 41% were reused as raw material in other branches of industry and only 6% came to final disposal at landfills. The importance of combusting waste from the production process increases due to high costs for fossil fuels, stricter environmental legislation and high landfill costs [3]. The pulp and paper industry is the largest producer and consumer of alternative fuels such as sawdust, bark and other wood residues [15]. This chapter describes commonly used combustion technologies.

5.1 Waste Combustion systems

Grate-, fluidized bed-, and multiple hearth firing systems are commonly used combustion technologies in the pulp and paper industry. The following paragraphs explain the operation principles of these combustion systems.

5.1.1 Grate firing

Until the 1970`s grate firing was the most important technique for the combustion of wood wastes and bark in the pulp and paper industry. A common design for grate firing systems is the travelling grate shown in Figure 39 [10]. Single, chain-connected grate elements (10 cm x 40 cm) are moved through the furnace by a motorized sprocket wheel and form a slowly moving level. Wastes and bark are constantly applied to the grate at one end of the furnace and pass the single steps of the combustion process; drying, pyrolysis and the final combustion of char at a temperature of approximately 1200°C as shown in Figure 39.

Ashes and other combustion residues exit the furnace system at the ash gate. The fuel layer can have a thickness of 30 – 90 cm when for example wood is combusted [10].

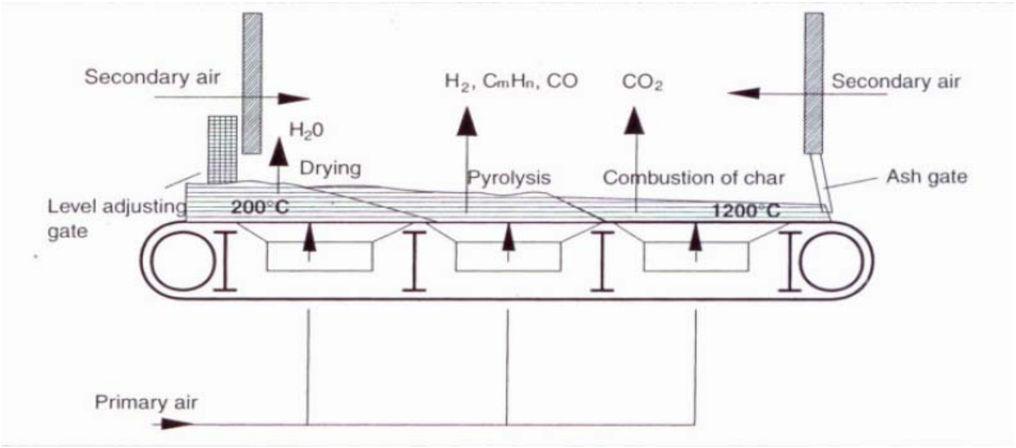


Figure 39: Travelling grate [10].

Another grate firing technology is the mechanically inclined grate. Horizontally back and forward moving grate elements, that are installed in an angle of 15° to the horizontal, transport the fuel through the combustion chamber [10]. Figure 40 shows the principle of a mechanically inclined grate.

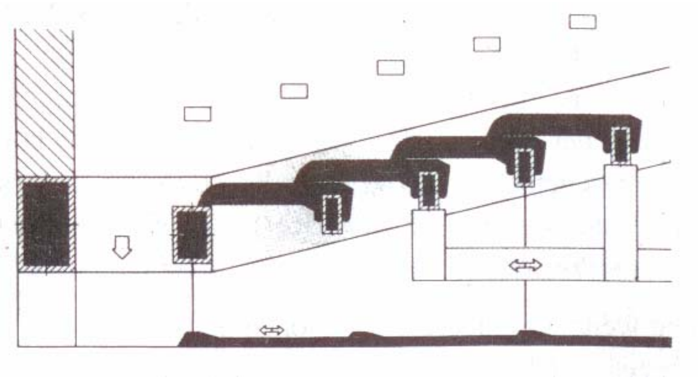


Figure 40: Principle of a mechanically inclined grate [25]

For grate firing systems the achieved fuel effects per grate area are the following [10]:

- Coal (travelling grate): 1.6 MW/m²
- Bark and wood with a moisture content of 60%: 0.4 MW/m²
- Bark and wood wastes with a moisture content of 30%: 0.8 MW/m²

5.1.2 Fluidized bed furnaces

Today fluidized bed furnaces are commonly used in the paper industry for the combustion of bark and wood residues since they offer a lot of advantages compared to grate firing systems. They provide better fuel efficiency, lower SO_2 and NO_x emission levels and allow the efficient combustion of low grade fuels with high moisture content, such as sludge and of fuels with high ash content, for example bark. Different fuels can be combusted simultaneously by the use of various waste feed nozzles. The fluidized bed is created by air, blowing through a bed of fine solid particles (e.g.: sand) laying on an air distributor grid. The particles are transformed into a fluid like state. The air velocity at which this occurs is called the minimum fluidizing velocity U_{mf} which depends on many factors such as particle diameter, density and shape as well as the gas density [10].

$$U_{mf} = \frac{\mu_g}{d_p * \rho_g} * \left[\sqrt{33.7^2 + 0.0408 * \frac{d^3{}_p * \rho_g * (\rho_p - \rho_g) * g}{\mu^2{}_g}} - 33.7 \right]$$

with μ_g = dynamic viscosity,

d_p = particle diameter,
ρ_g = gas density
ρ_p = particle density
g = gravitational acceleration

Two types of fluidized bed boilers, the bubbling fluidized bed boiler (BFB) and the circulating fluidized bed boiler (CFB), are used in the pulp and paper industry, they are shown in Figure 41. The fine solid particles lead to an excellent heat transfer between the hot inert bed material and the fuel applied to the furnace and function as a kind of a heat reservoir to compensate changes in the heating value of different fuels [10].

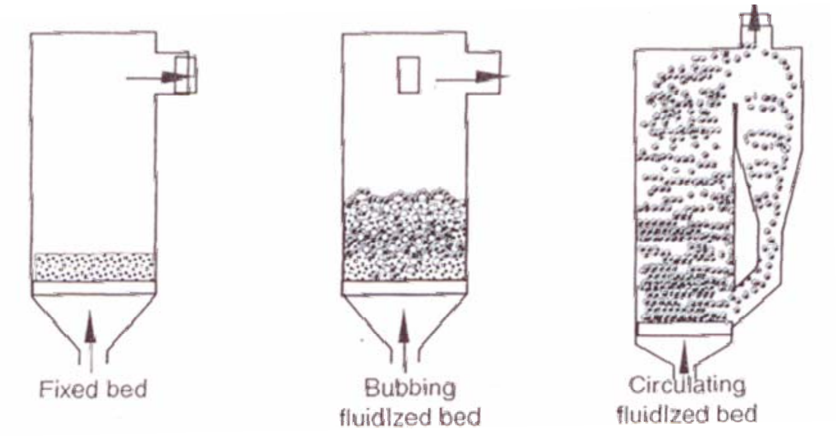


Figure 41: fluidized bed firing systems [5]

When a BFB boiler is operated, fluidizing velocities between 1 m/s and 2.5 m/s are necessary for the formation of the 0.4 - 0.8 m high fluidized bed. Fuels are applied directly to the fluidized bed of sand particles (SiO_2; particle diameter ~ 1 mm). A mixture of 98% sand and only 2 % fuel is necessary to ensure the optimized combustion conditions. The temperature within the combustion area is in a range of 800°C to 950°C [24].The high volume heat load of the boiler (0.1 - 0.5 MW/m³) even enables the combustion of wet bark and other wood wastes.

Air or screw conveyors are necessary for the fuel transport from bins and silos to the furnace, several rotary fuel feeders usually apply bark and wood residues evenly across the full bed area. Spent bed material and coarse ash is removed by drain pipes that are located in the grid of the boiler. The ash can be separated from the sand, to return the useable bed material to the boiler. The fine ash exits the boiler as fly ash and has to be removed in the flue gas cleaning system. Secondary air (30 – 70 % of the total air flow) is distributed across the boiler by air nozzles that are located above the bed level. When the boiler is started up, oil- or gas burners heat the fluidized bed to a temperature between 400°C and 600°C before the waste fuels can be applied to the boiler [10].

A CFB Boiler is operated with a fluidizing velocity in a range of 5 – 10 m/s, using fine sand with a particle size of 0.2 to 0.4 mm as inert bed material. The fluidized bed does not have a defined height, but is distributed throughout the boiler, as shown in Figure 41 [24]. This results in excellent mixing of- and contact between bed material, combustion gases and fuel which enables the efficient combustion of moist fuels such as bark or even sludge. The bed material as well as unburned fuel are separated from the flue gas in the hot cyclone and returned to the circulating bed. The volume heat load can be up to 0.3 MW/m³ and combustion temperatures in a range between 850°C and 900°C are achieved [10]. Figure 42 shows the flow sheet of a CFB boiler.

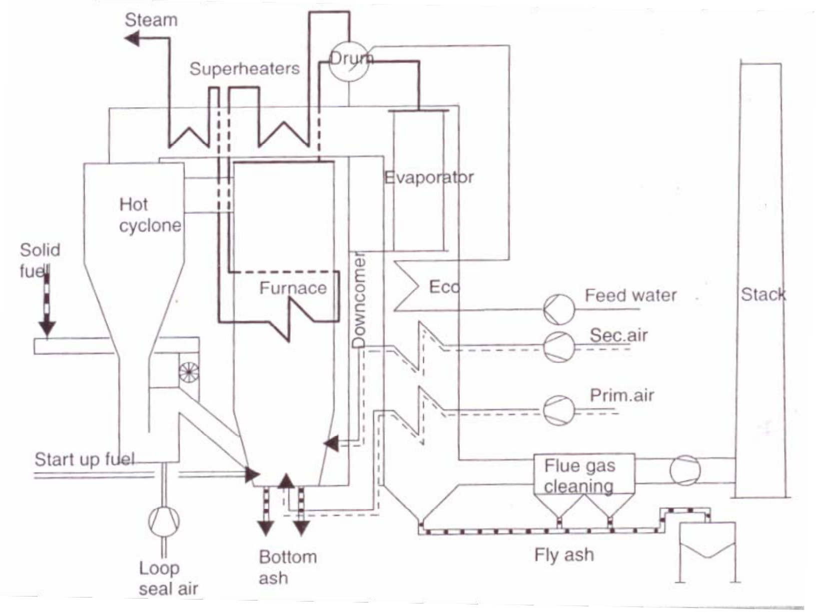


Figure 42: Flow sheet of a circulating bed boiler [10].

Coarse ash particles are collected at the bottom of the boiler (i.e. bottom ash) and carried out of the system. Similar to the bubbling bed boiler, primary combustion- and fluidizing air is blown through nozzles in the bottom of the boiler. Secondary air (10 – 50% of the total combustion air) is applied in a height of 2 – 5 m from the bottom.

The flue gas that exits the hot cyclone passes a series of heat exchangers, feed water- and air pre - heaters ,their arrangement can vary from one circulating bed boiler to the other. Feed water is preheated in the economizer and vaporized in the evaporator. In modern boilers the furnace wall tubes form the evaporator. Figure 43 shows the construction principal of the CFB Boiler wall that consists of tubes filled with water (risers). The water evaporates within the tubes and process steam is generated [10].

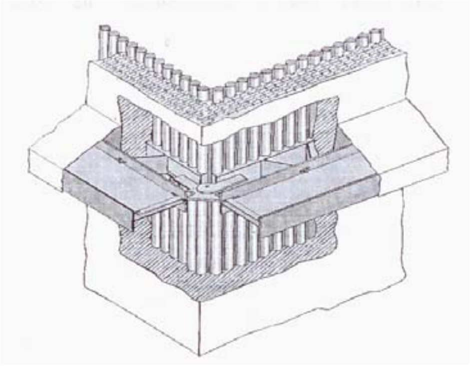
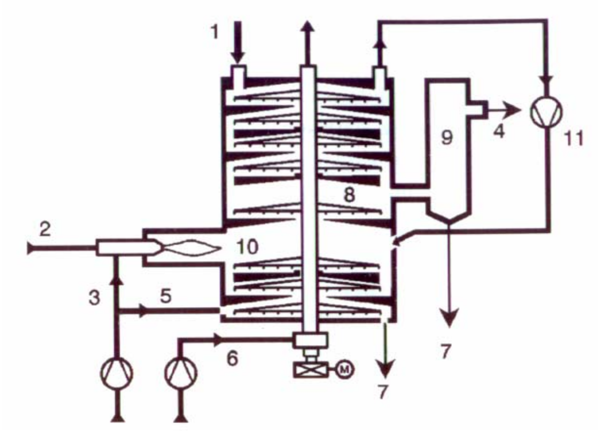


Figure 43: Boiler wall construction of a CFB boiler [10].

5.1.3 Multiple hearth furnaces

Multiple hearth furnaces have been in use for decades in the paper industry for energy production from moist and pasty wastes such as sludge from the effluent treatment plant. Co – combustion together with bark is often carried out [3]. In a multiple hearth furnace, rabble arms that are connected to a central shaft driven by a variable speed drive, agitate and move the material, which is applied at the top of the boiler, from one hearth to the next. The rabble arms and the vertical shaft are made of stainless steel and cooled by air. The furnace is heated to the operation temperature of approximately 1000°C by one single gas burner, as shown in the schematic below, or one gas burner at each hearth [26]. Combustion gases are lead through a post combustion chamber before they pass the flue gas cleaning plant, consisting of wet scrubbers to remove dust and sulphur compounds [3]. Figure 44 shows the schematic of a multiple hearth furnace.



1: Waste feed
2: Fuel
3: Combustion air
4: Flue gas
5: Ash cooling air
6: Cooling air
7: Ash
8: Multiple hearth furnace
9: Post-combustion chamber
10: Start-up combustion chamber
11: Recirculation fan

Figure 44: Multiple hearth furnace [3].

5.2 Steam production

In the production of paper and pulp, steam and hot- or warm water function as energy carriers [10]. The advantages of steam are its low toxicity, high efficiency, easy transport and high specific energy. Most of the energy in steam is stored as latent heat. Therefore steam supplies large quantities of thermal energy at a constant temperature, which is very useful for process heating applications. The heat transfer coefficient of steam is higher than 10 000 W / m² °C. Data of the EU – 15 from 1994 shows, that in this year, the industry used approximately 5988 PJ of steam energy; this is 34% of the total energy use. Almost 39% of the steam energy was consumed within the pulp and paper industry. The data also shows, that 83% of the total final energy used for the production of pulp and paper was used in form of steam [27]. Several process steps such as the dryer section of the paper machine use steam for heating purposes (see Table 10). Furthermore steam turbines are operated to produce electricity. Steam is generated by heat exchange between hot flue gases from combustion processes and water [11].

Table 10: Steam types used in pulp and paper production [12].

Steam / water type	temperature [°C]	pressure [bar]	use
Superheated steam	~540	70 - 100	Steam turbine
High pressure steam	450 – 500	60 - 100	Steam turbine
Medium pressure steam	~205	11 - 13	e.g.: chip cooking
Low pressure steam	150 – 170	3 - 6	e.g.: evaporation plant
Hot water	60 – 80	atmospheric	e.g.: heating applications
Warm water	40 - 60	atmospheric	e.g.: heating applications

5.2.1 The basic operation principle of steam power plants: the Rankine Cycle

Figure 45 shows the ideal Rankine cycle and its T-s (Temperature – entropy) diagram. It describes the ideal operation principle of a steam power system and comprises four internally reversible process steps [29]:

- Step one (1) – step two (2): isentropic (no change in entropy) compression of water in a pump. Work $W_{pump,\ in}$ has to be done by the pump.
- Step two (2) – step three (3): heat addition q_{in} at constant pressure in a boiler. Water is evaporated and saturated steam is formed.
- Step three (3) – step four (4): isentropic expansion in a turbine. Work $W_{turbine,\ out}$ is done by the system. The temperature of the vapor is decreased.
- Step four (4) – step one (1): Heat rejection in a condenser at constant pressure and teperature. Heat q_{out} is rejected to the surrounding of the system. Vapor is condensed to a saturated liquid.

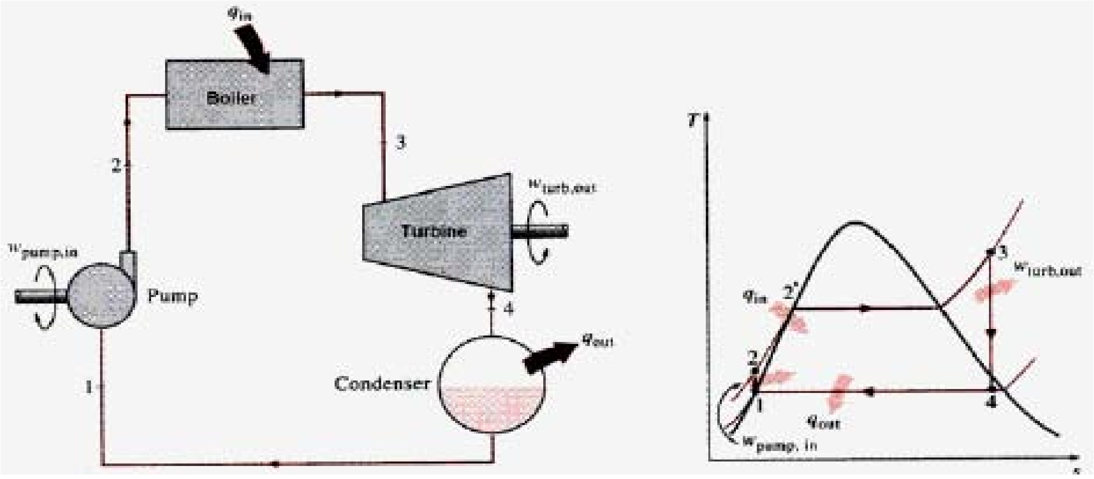


Figure 45: Operation principle and T-s diagram of the ideal Rankine cycle [29].

The thermodynamic efficiency of the process can be calculated [29]:

$$\eta_{th} = \frac{W_{turbine,out} - W_{pump,in}}{Q_{in}}$$

with:

η_{th} : thermodynamic efficiency;

$W_{turbine,out}$: turbine work done by the system;

$W_{pump,in}$: pump work applied to the system;

Q_{in} : heat addition in the boiler.

Increasing the cycle efficiency by generation of superheated steam

Superheating the steam to temperatures over 500°C (see Table 10) by increasing the average temperature (from 3 – 3´, see Figure 46) at which heat is applied to the steam, increases the performance of the vapour power cycle as shown in Figure 46. The increase in net work W_{net} is represented by the shaded area in the diagram [29].

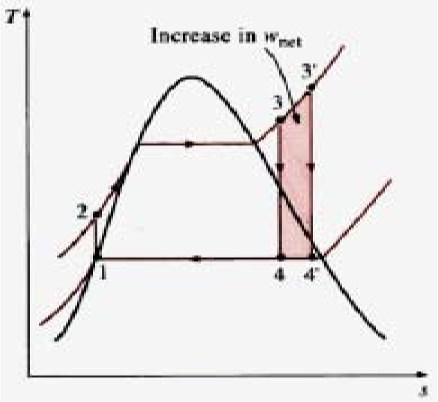


Figure 46: T-s diagram for the generation of superheated steam [29].

5.2.2 Boiler types

Modern power plant boilers are designed as water tube boilers, that means, water is evaporated inside tubes. Water tube boilers can be designed as natural- or forced circulation boilers or once-trough boilers [10]. Figure 47 shows different boiler designs.

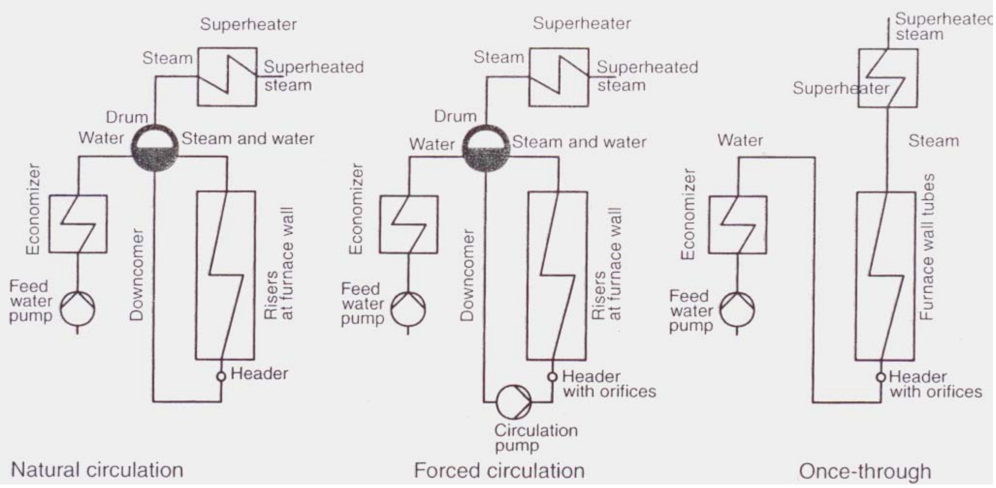


Figure 47: Steam boiler principles [10].

5.2.2.1 Natural circulation boiler

In a natural circulation boiler the feed water is pumped by the feed water pump through the economizer, where it is heated close to the saturation temperature, to the steam drum. The circulation of water and steam is caused by their different densities. The furnace heats and vaporizes the water in the risers, which are located at the furnace wall.

The density of the water in the risers is lower than the density of the water in the downcomer, so that it rises and flows to the steam drum. There, water is separated from the steam, which flows to the superheater. The remaining water from the steam drum flows through the downcomers back to the risers. Temperatures in a range between 450 – 540°C and a pressure in the range of 70 – 100 bar are typical operation parameters for superheated steam that exits from a natural circulation boiler.

Figure 48 shows the temperature levels and temperature differences in a fluidized bed boiler and the amount of heat transferred by different heat exchanging units. Approximately 40% of the energy released by combustion are transferred to the evaporating water in the wall tubes of the furnace, another 20% are transferred to the superheaters. Flue gas leaving the superheater still has a temperature of 600 – 800°C. It is further cooled in the economizer, where the feedwater enters the boiler at a temperature of 150 – 250°C and in the combustion air pre - heaters (incoming combustion air: 25 – 45°C) to improve the overall boiler efficiency. It finally leaves the stack with approximately 130°C – 150°C. At this temperature, the flue gas heat loss is normally around 10% [10].

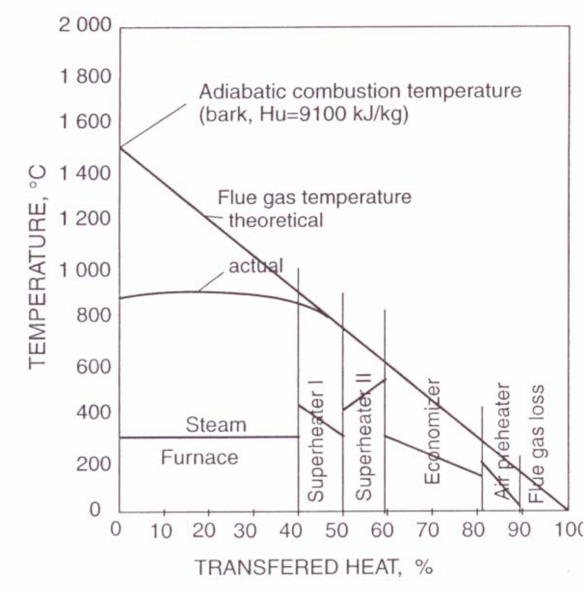


Figure 48: Heat flow diagram for a bark fired fluidized bed boiler [10]

5.2.2.2 Forced circulation boiler

In a forced circulation boiler, a feed water pump supplies fresh water to the system. The feed water is preheated in the economizer and forwarded to the steam drum. A circulation pump pumps water from the steam drum through the risers at the furnace wall, where it is heated, back to the steam drum. Steam is separated from the water and lead through the superheater. This type of boilers generates steam with higher pressure than natural circulation boilers; up to 190 bar are possible. However, forced circulation boilers and also once – through boilers are not commonly operated in power plants of modern pulp and paper mills [10].

5.2.3 Cogeneration systems

Cogeneration is the simultaneous generation of electrical power and heat in one single, integrated system (combined heat and power generation). With waste heat from electricity generation, drying or heating in subsequent process steps is achieved. Thus, the amount of waste energy is reduced and primary fuels, as well as emissions to air can be saved. This means, that the overall efficiency of a cogeneration process is higher compared to conventional separate electricity and steam generation (see Figure 49) [21].

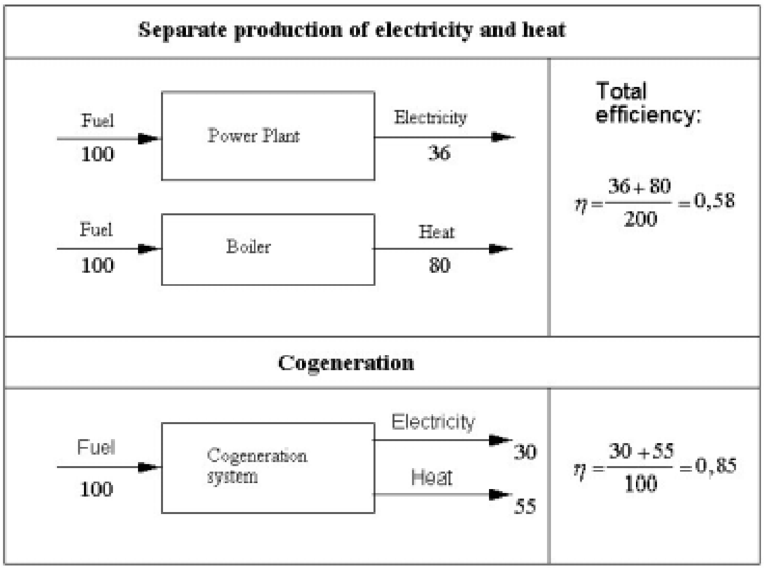


Figure 49: Comparison of efficiency between cogeneration and separate production of electricity and heat [12].

Operation principles of cogeneration systems

Superheated steam from the boiler is led through a back pressure turbine (see next page),where its temperature and pressure decrease and the heat energy is converted to mechanical energy. The shaft of the turbine is connected to a generator that transforms the mechanical energy to electricity. Steam that exits the turbine is led to the paper making process for heating purposes. In the steam and heat consuming points (e.g.: dryer section of the paper machine) steam condenses and releases its energy to the process. The condensate is pumped back to the boiler to be vaporized again. This process is called a cogeneration steam cycle (combined heat and power generation) and is illustrated in Figure 50 [10].

Back pressure steam turbine

A back pressure steam turbine, expands superheated steam from the boiler to the specific pressure which is necessary due to the temperature required for subsequent heating purposes, thereby generating electricity [29].

Depending on this specification of the process steam, it exits the turbine at atmospheric pressure or somewhat higher. The enthalpy of the steam is higher compared to steam that exits an extraction condensing steam turbine in which the steam is expanded until a pressure of down to 0.05 bar is reached.

Back pressure turbines are operated when big amounts of steam e.g. for heating purposes are constantly necessary to run the process. The main purpose of a back pressure turbine is the production of steam for the thermal applications in the plant, the generation of electricity is controlled by the thermal load to the turbine [12]. Figure 50 shows the simplified flow sheets of a back pressure steam turbine system.

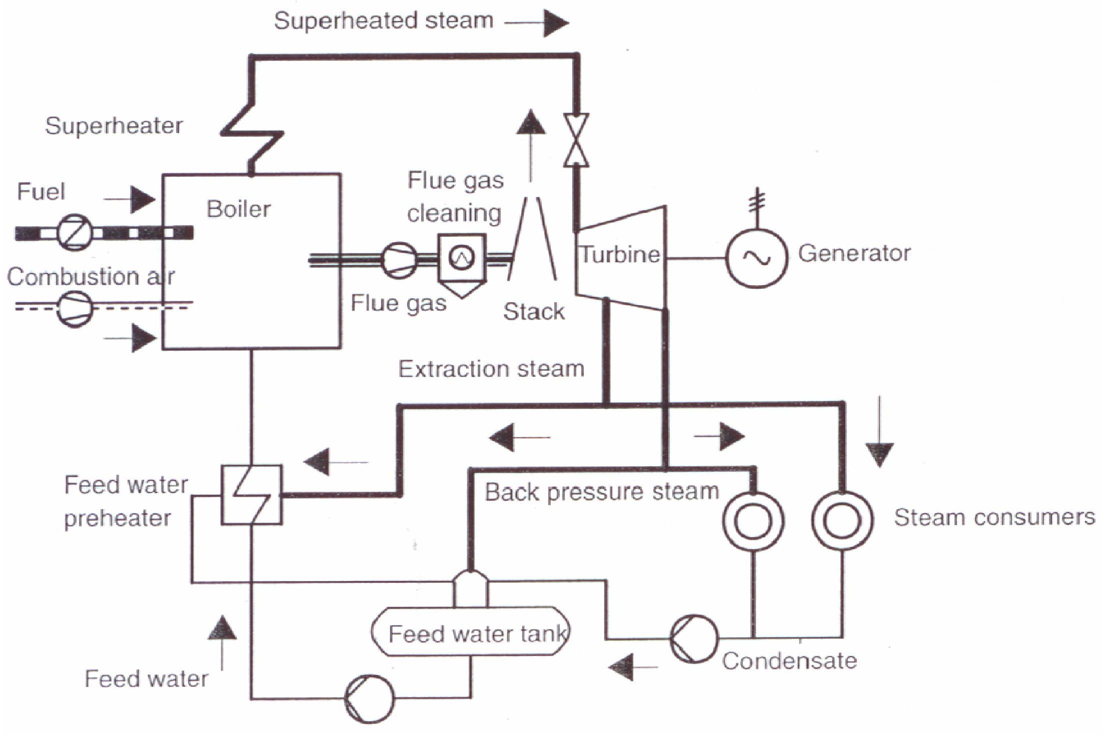


Figure 50: Flow sheet of waste combustion for steam and electricity generation [10].

Extraction condensing steam turbine

In the condensing steam turbine system, steam for process heating purposes is obtained by extraction of one or more intermediate stages of the turbine at the appropriate pressure and temperature. Steam that exits at the end of the turbine (0.05 bar with the corresponding condensing temperature of 33°C) is condensed to boiler feed water releasing its heat to the environment since there is hardly any need for such low temperature heat.

With this system, the electrical power generation is higher compared to the back pressure system since the steam is expanded to a lower pressure. Additionally, the power output can be controlled independently to some certain extend by auxiliary valves. However, the total efficiency of the back pressure system is higher compared to extraction steam turbine due to the fact that there is no heat rejection to the environment, which makes it the preferred one for the applications within the paper industry [12]. Figure 51 shows the simplified schematic of an extraction condensing turbine.

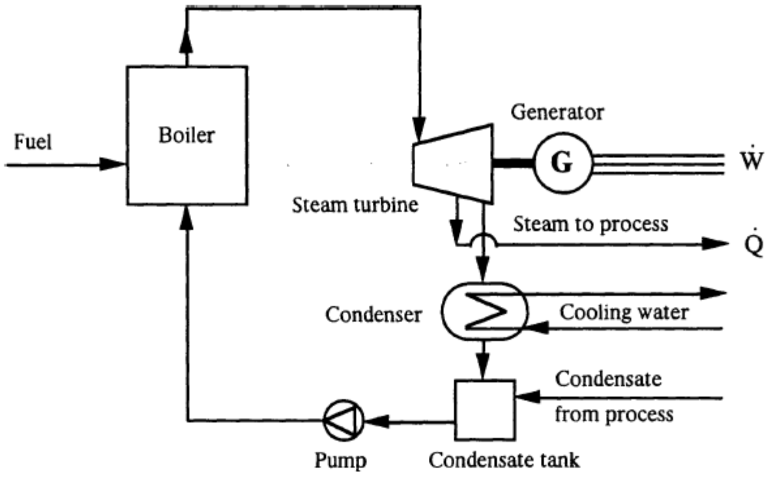


Figure 51: Simplified flow sheet of an extraction condensing steam turbine [12].

5.3 Gasification of solid wastes

A gasification process converts solid fuels into a combustible gas by partial oxidation [29]. In a pulp mill, combustible gases can be supplied to the lime kiln of the recovery system to reduce the demand of fossil fuels. Figure 52 shows the overall flow sheet of solid waste gasification in a circulating fluidized bed gasifier for the lime kiln process. Wet fuels, such as bark and wood residues have to be dried by the hot flue gases, that exit the lime kiln. Dry fuels are directly supplied to the gasifier [10].

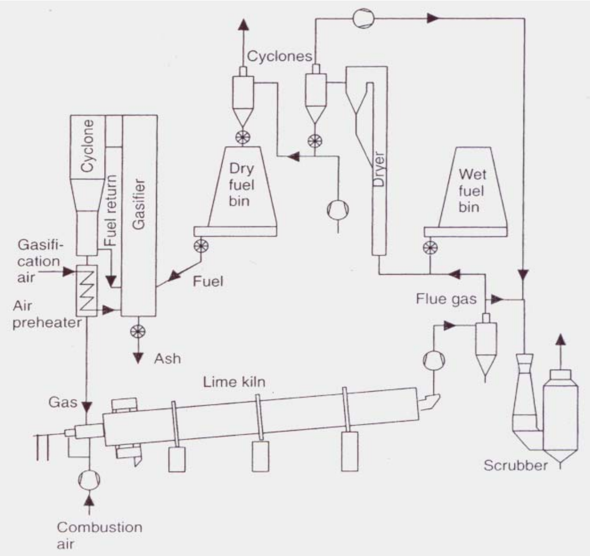


Figure 52: Flow sheet of solid waste gasification at the lime kiln plant [10].

The gasifier (see Figure 53) is designed similar to a circulating fluidized bed furnace, it comprises a reactor, where the gasification takes place, a cyclone to separate the bed material from the flue gas and a returning pipe to lead the bed material back to the reactor. Preheated air (850°C – 950°C) is blown through the bottom of the reactor and fluidizes the bed material. Typical operation temperatures of a circulating fluidized bed gasifier are in a range of 800 – 1000°C. Fuel, supplied to the lower part of the reactor by a screw feeder, is dried and pyrolysed. It is converted into gases, charcoal and tars. Some parts of the charcoal flow down the reactor, are oxidized to CO and CO_2 and heat is generated [29]. The product gas and its remaining solids enter the cyclone to be separated from each other. The solids are returned to the reactor and carbon is burns to control the gasifying temperature. The product gas (650°C – 750°C) leaves the cyclone and passes the air pre heater to heat the fluidizing air to its operation temperature [10].

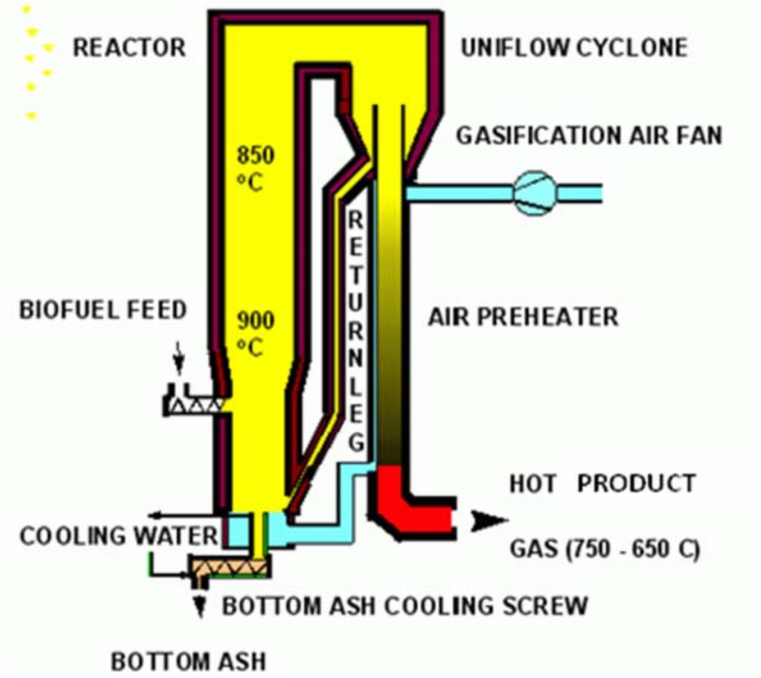


Figure 53: Circulating fluidized bed (CFB) gasifier for waste gasification [29].

Table 11 shows the typical gas composition for product gas from a CFB gasifier, operated at the waste gasification step of the lime kiln plant [10].

Table 11: Composition of product gas from wood gasification

Gaseous component	**Vol % (dry gas)**	**Net heating value [MJ/m³]**	**Gas production rate [m3/t of waste]**
Carbon Monoxide (CO)	21-22	6 - 8	~2400 m³
Carbon Dioxide (CO_2)	10-11		
Methan (CH_4)	5-6		
Hydrogen (H_2)	15-16		
Nitrogen (N_2)	46-47		

6 Combustion of fossil fuels

In addition to bark and other wastes from the production process, fossil fuels, such as natural gas, coal and fuel oil, supply energy to pulp and paper mills. Fossil fuels can be co-combusted with wastes, for example in fluidized bed boilers, or can be applied to separate power boilers. The operation of a separate, fossil fuel fired power boiler or gas turbine in addition to a bark boiler and a recovery boiler is a popular possibility for energy generation in a kraft pulp mill. Such a system is shown in Figure 54 [10].

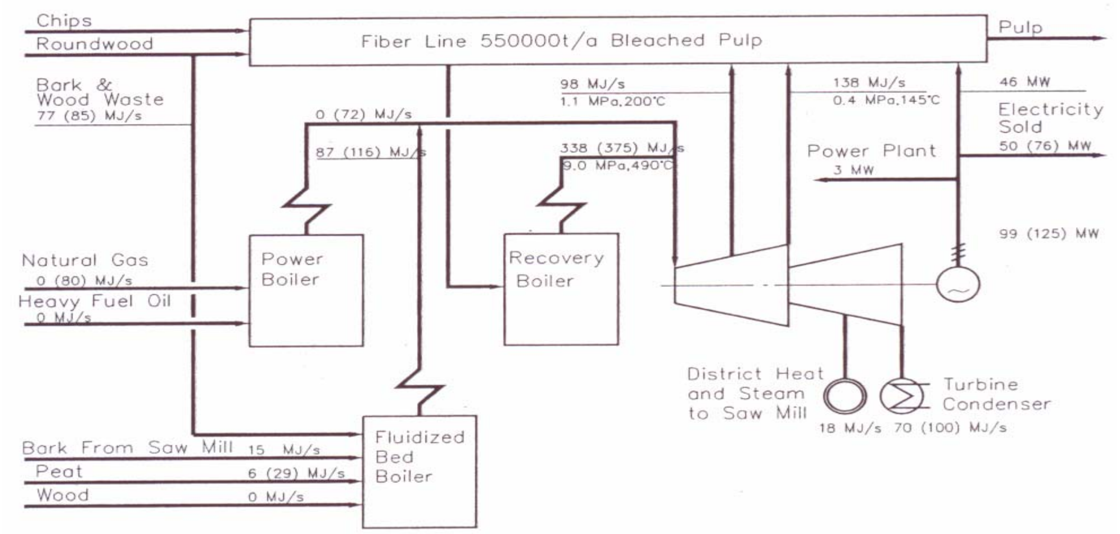


Figure 54: Energy flow sheet of a pulp mill with separate bark and power boilers [10].

Gas turbines

Gas turbines transform chemical bound fuel energy to mechanical rotation energy which is used to drive a generator for electric power generation. The electric power of a gas turbine system can be in a range of some hundred kilowatts to many hundred megawatts. Gas turbines are suitable for the combustion of various gaseous fuels, such as natural gas, biogas, and gas from gasification units, as well as liquid fuels, for example fuel oil. Gas turbines reach efficiencies of up to 39% [12].

Cogeneration systems with gas turbines

Gas turbines are also applied in cogeneration systems, which can be designed as open-, closed- or combined cycle systems [12].

Open cycle system

A compressor applies combustion air to a combustion chamber, where the natural gas is injected and combusted. The exhaust gases exit the combustor at temperatures that can be up to 1300°C and oxygen concentrations of 15–16%. The efficiency of an open cycle system is directly connected to the temperature of the combustor off gas.

The off gas is expanded to atmospheric pressure and transfers its heat energy into mechanical work in the gas turbine that is connected to the compressor and the generator. The gas stream leaving the turbine at a temperature in a range of 450–600°C is forwarded to heat recovery steam generator (HRSG), which can also be supported by a backup burner for supplementary firing. This HRSG produces steam for heating and drying in the pulp or paper mill. The temperature of the exhaust gas from the HRSG is around 90°C. The power to heat ratio of an open cycle system lies within 0.5-0.8 and the overall efficiency is typically up to 80% [12]. Figure 55 illustrates the schematic of an open cycle system.

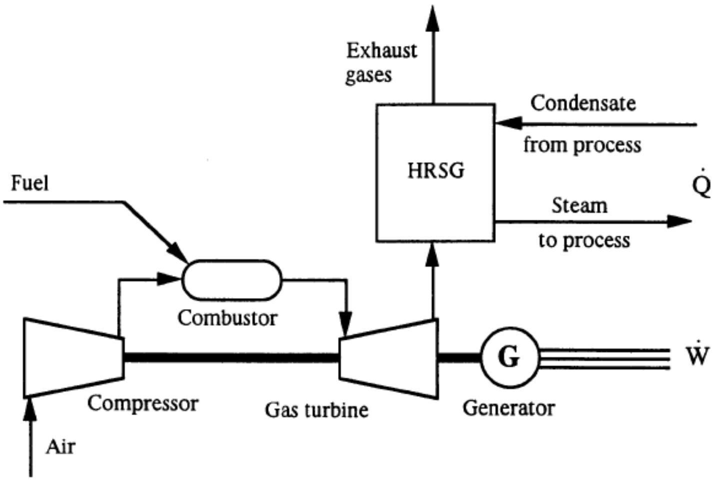


Figure 55: Simplified flow sheet of an open cycle gas turbine [12].

Closed cycle system

In a closed cycle system (Figure 56), helium or air is used as working fluid. The working fluid is heated by a heat source, which can be any combustion process, or even nuclear or solar energy, before it enters the gas turbine to expand and transform its heat energy into mechanical energy. The remaining heat is used to produce hot water as heat source for any application within the production process. The electric output is in a range of 2 – 50 MWe [12]. The ideal cycle that the working fluid undergoes in a closed cycle system is called Joule or Brayton Cycle and comprises four internally reversible steps as shown in Figure 56 [29].

- Step 1 – step 2: isentropic compression of the working fluid in a compressor, which is connected to the turbine.
- Step 2 – step 3: heat addition (heat from a boiler) to the working fluid via a heat exchanger at constant pressure.
- Step 3 – step 4: isentropic expansion of the fluid, work W_{net} is done by the system.
- Step 4 – step1: heat rejection in a condenser at constant atmospheric pressure. The heat can be used to generate steam for the production process.

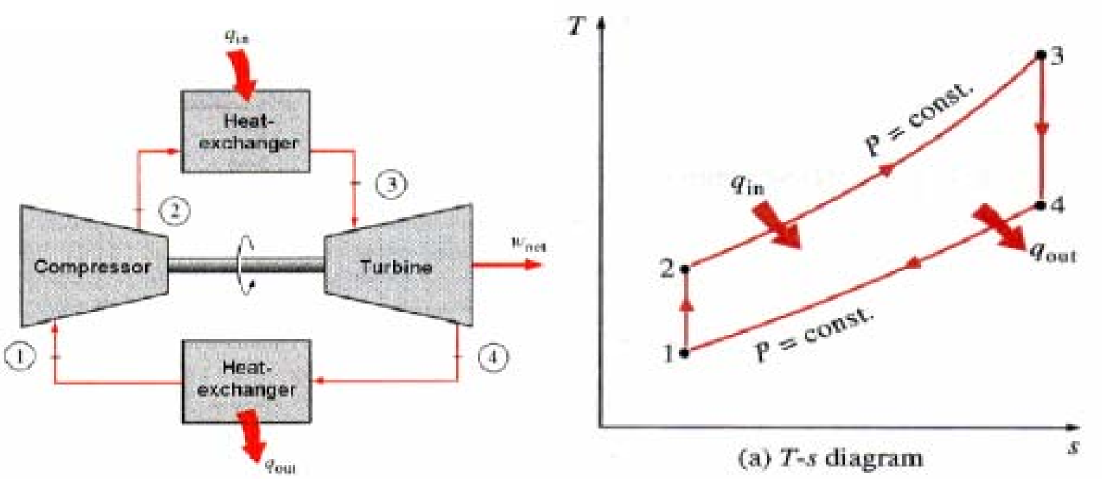


Figure 56: Operation principle and T-s diagram of a closed cycle system [29].

Combined cycle system (Combined Joule – Rankine cycle)

Basically the efficiency of a process can be improved by raising the maximum temperature in the cycle and by decreasing the temperature of the waste heat. A combined cycle comprises two cycles, one with high process temperatures (gas turbine cycle), the other one with a so called “cold end” (steam turbine cycle) is the best possibility to increase the process efficiency [29]. Figure 57 shows the T-s diagram of an ideal combined cycle.

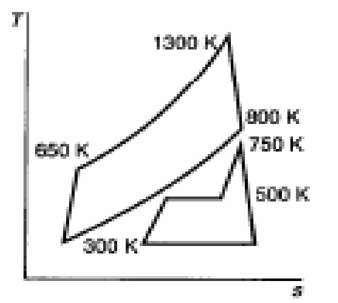


Figure 57: T-s diagram of an ideal combined cycle [29].

The waste heat from the high temperature gas turbine cycle (topping cycle) is recovered at the low temperature steam turbine cycle (bottoming cycle) [12]. Electricity generation can be increased by the factor two compared with conventional power generation with just one turbine [5]. Figure 58 shows some details of a combined cycle system with a double pressure boiler, which means, that high pressure steam (H.P.steam) and low pressure steam (L.P.steam) are applied to the steam turbine. Supplementary firing in the steam boiler can increase the steam temperature to 540°C and its pressure over 100 bar [12].

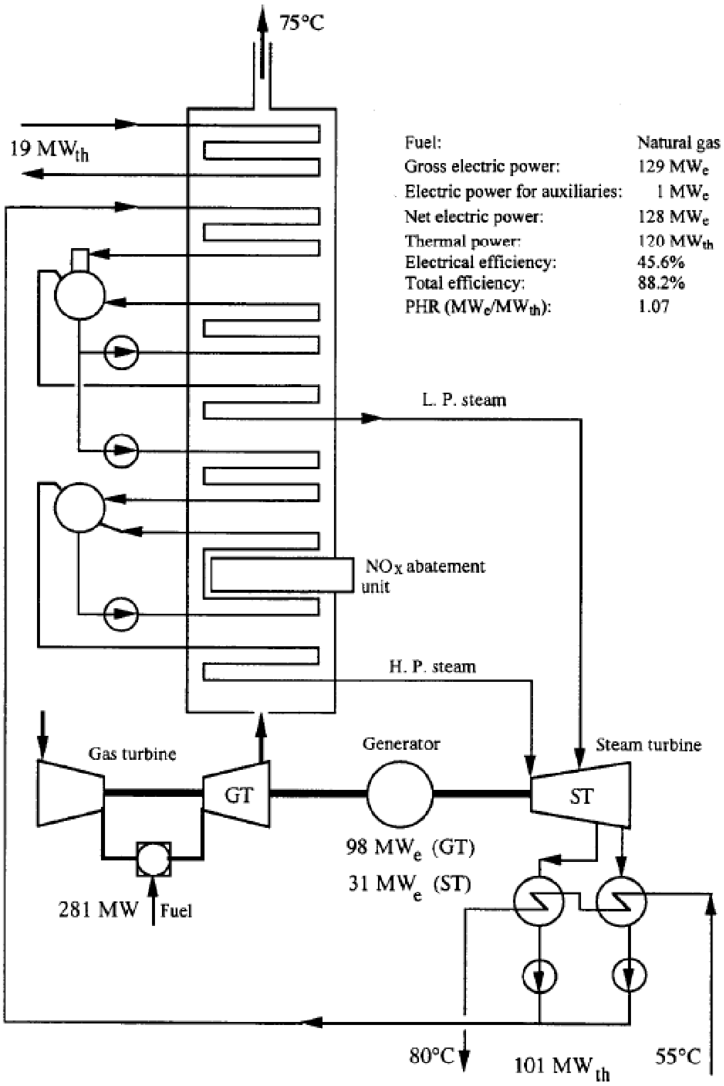


Figure 58: Combined cycle process [12].

7 Flue gas cleaning

This chapter describes technologies to reduce emissions from combustion plants for energy generation. Especially the removal of particulate matter, sulphur dioxide and nitrogen oxides are key tasks for flue gas cleaning systems [10].

7.1 Reduction of particulate matter

During combustion, the mineral matter of fuels is partly converted into fly ash and leaves the boiler via the off gas stream. Cyclones, electrostatic precipitators (ESP), fabric filters and wet scrubbers are often used for the flue gas cleaning of large combustion plants [29].

7.1.1 Centrifugal precipitation (cyclones)

Cyclones use gravitational forces to remove dust- and ash particles from the flue gas stream. they are only used as pre-cleaning technique in combination with other particulate matter reducing techniques [29]. Leading blades at the gas inlet of the cyclone lead it to a spiral path toward the bottom of the cyclone. By mass action, the dust particles are thrown to the cylinder wall and slip down to the outlet of the cyclone [10]. Pre-cleaned air escapes through a central tube at the top of the cyclone [29].

7.1.2 Electrostatic precipitators

Dust and ash particles pass an ionizing zone and receive a negative charge. Subsequently the particles are separated from the flue gas by the electric field between the positive and the negative electrodes and are collected on the positive charged collector plates. The electric field is generated by a voltage of 30 – 70 kV between the electrodes. Figure 59 shows how electric precipitation works [10].

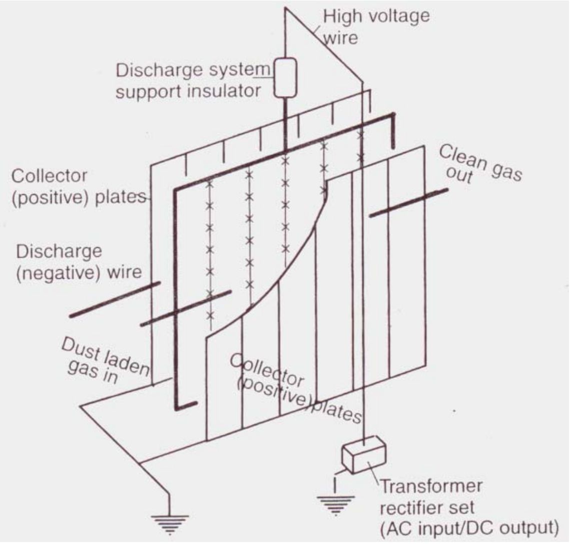


Figure 59: Electrostatic precipitator [10].

7.1.3 Fabric filters (baghouses)

A baghouse consist of compartments of filter tubes or bags, as shown in Figure 60. The dust- and particle -laden gas stream passes through the fabric filter and particles are retained by adhesion. Fabric filters have to be cleaned periodically, dust accumulated on the surface of the fabric has to be removed and finally disposed off. Filter cleaning can be carried out by reverse air flow, mechanical shaking of the filters or compressed air pulsing [29].

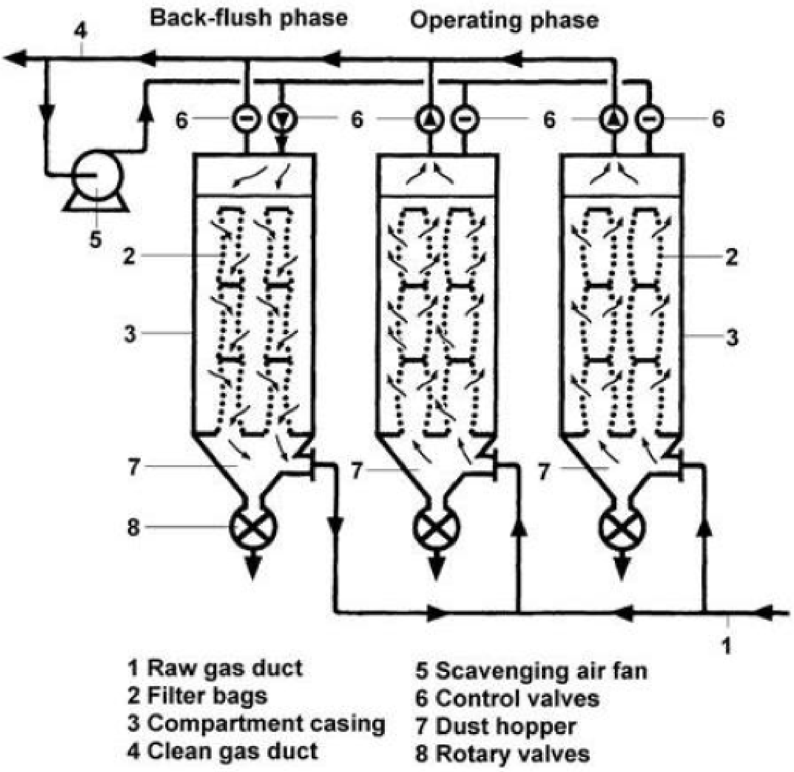


Figure 60: Cross section of bag house containing fabric filters [29].

7.1.4 Wet scrubbers

Wet scrubbers utilise a liquid to separate particulate matter from the flue gas. The most commonly applied technique is the venturi scrubber [29]. The scrubbing liquid is applied at the top of the venturi scrubber and is lead through a venturi throat together with the flue gas. Thereby the scrubbing liquid is atomized into small droplets and gets in contact with the dust-laden flue gas. The collisions of small droplets and dust particles lead to the formation of larger and heavier particles. A cyclone separator separates the flue gas from the dust laden liquid, which is recycled to the venturi scrubber. Figure 61 illustrates the basic operation principle of venturi scrubbing [29].

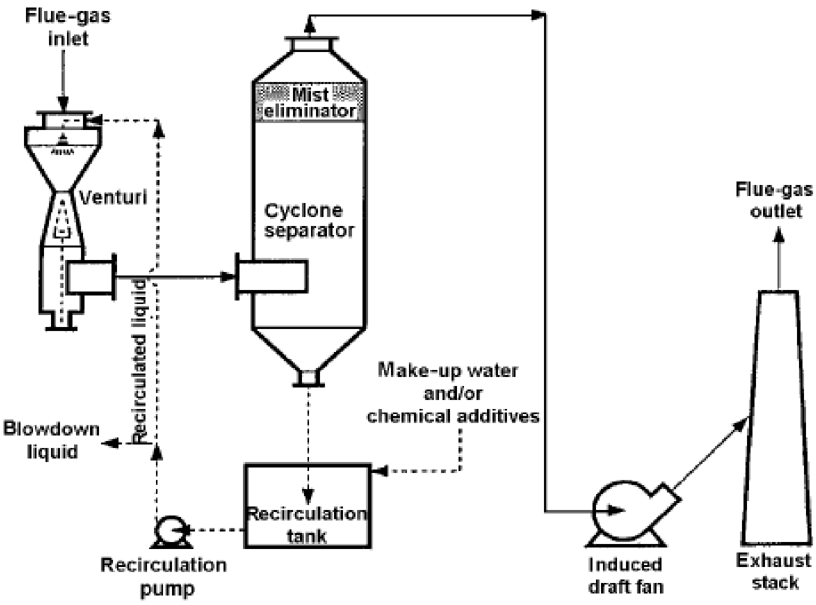


Figure 61: Wet scrubbing with venturi scrubber to reduce particulate matter emissions from combustion [29].

7.2 Reduction of sulfur dioxide (SO_2)

The combustion reaction oxidizes the fuels sulfur content to sulfur dioxide (SO_2), a part of which (1/40 – 1/80) is further oxidized to sulfur trioxide (SO_3). Sulfur trioxide and water form highly corrosive sulfuric acid (H_2SO_4). In addition, sulfuric emissions are harmful to the environment, causing acidification of soil and water.

7.2.1 Use of adsorbents in fluidized bed combustion systems

Adding limestone ($CaCO_3$) or calcium hydroxide (CaOH) to the furnace removes sulfur dioxide from the flue gas. Pulverized limestone that is directly applied to the gas stream of the boiler, changes into calcium oxide and carbon dioxide due to the high boiler temperatures of approximately 850°C [10]. The surface of these reactive particles reacts with SO_2 to form calcium sulphite ($CaSO_3$) and calcium sulphate ($CaSO_4$). The reaction products are captured together with the fly ash or other particles in an Electrostatic precipitator or any other particulate matter reduction technique. Figure 62 shows the principle of sulphur emission reduction by limestone [29].

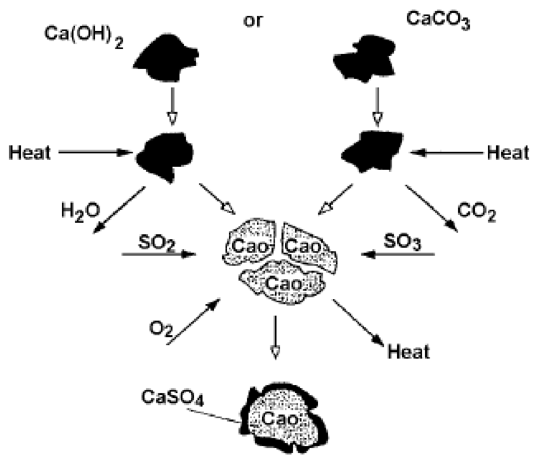


Figure 62: Principle of sulphur reduction by adding limestone or calcium hydroxide to the furnace [29].

7.2.2 The wet limestone scrubber

Flue gas from the particulate matter control unit (e.g. electrostatic precipitator) is forwarded to an absorber. SO_2 is washed out from the flue gas by direct contact with an limestone solution, sprayed into small droplets by nozzles at the top of the absorber. The sulphur dioxide finally forms a gypsum slurry. It is withdrawn from the bottom of the boiler, dewatered and can be used as raw material for cement or wallboard production. Figure 63 shows a wet limestone scrubber [29].

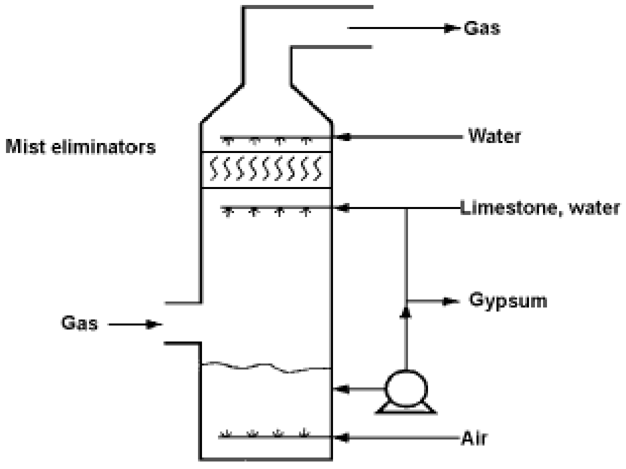


Figure 63: Operation principle of a wet limestone scrubber [29].

7.3 Removal of Nitrogen oxides (NO_x)

The term NO_x comprises the nitrogen compounds nitrogen monoxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O), whereas NO contributes to approximately 90% of the total NO_x [29]. Also NO_x emissions are responsible for the acidification of the environment. NO is formed in the furnace and is further oxidized to NO_2 in the atmosphere [10]. For combustion processes, three different kinds of NO_x – emissions can be identified [24]:

- thermal NO_x: is formed at temperatures higher than 1100°C by nitrogen and oxygen contained in the combustion air
- prompt NO_x: occurs due to specific reactions of hydrocarbon radicals, forming substances such as HCN and nitrogen radicals(NH^* and NH_2^*) which may react to form NO in a temperature level of more than 1100°C
- fuel NO_x: is created due to the oxidation of nitrogen contained in the fuel at somewhat lower temperatures.

Since the combustion temperatures of fluidized bed- and grate furnaces (~ 950 – 1200°C) prevent in large part the formation of thermal and prompt NO_x, emissions occur due to nitrogen in the fuel [10].

7.3.1 Primary measures to reduce NO_x emissions

There are many measures (modification of combustion) to reduce the formation of NO_x in the furnace. The most important techniques are mentioned and shortly explained within the next paragraphs [29].

Air staging

The furnace is divided into two combustion zones, a primary combustion zone with a lack of oxygen and a secondary combustion zone with excess oxygen. By the reduced amount of oxygen in the primary combustion zone, the formation of fuel NO_x is suppressed. As a consequence of the substoichiometric oxygen amount, the peak flame temperature is lower than under stoichiometric conditions which results in reduced formation of thermal NO_x. In the secondary combustion zone, 10-30% of the combustion air are injected above the combustion zone. This results in an increased flame volume, but not in increased flame temperatures, which limits the formation of thermal NO_x [29].

Flue gas recirculation

The recirculation of flue gas to the combustion chamber directly cools the flame, thereby decreasing the flame temperature und reduces the available amount of oxygen in the combustion zone.

A part of 20-30% is withdrawn from the flue gas stream at a temperature of 350-400°C, mixed with combustion air and recycled to the boiler. This principle is illustrated in Figure 64 [29].

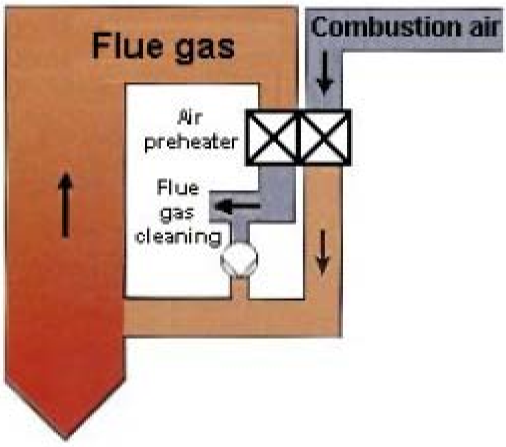


Figure 64: Principle of flue gas recirculation for NO_x emission reduction [29.]

7.3.2 Secondary measures to reduce NO_x emissions

Commonly used flue gas cleaning techniques to reduce the NO_x emissions already formed in the combustion zone, are based on the injection of ammonia or urea into the flue gas stream to react with the nitrogen oxides and form molecular nitrogen [29].

Selective catalytic reduction (SCR)

The selective reduction of NO_x to molecular nitrogen takes place at the surface of a catalyst (e.g. base metal oxide catalyst) at temperatures usually between 170-450°C. Ammonia, injected into the flue gas stream is the reducing agent, that converts NO_x into molecular nitrogen [29].

$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$

$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$

Figure 65 shows the operation principle of a selective catalytic reduction reactor (DENOX reactor) [29].

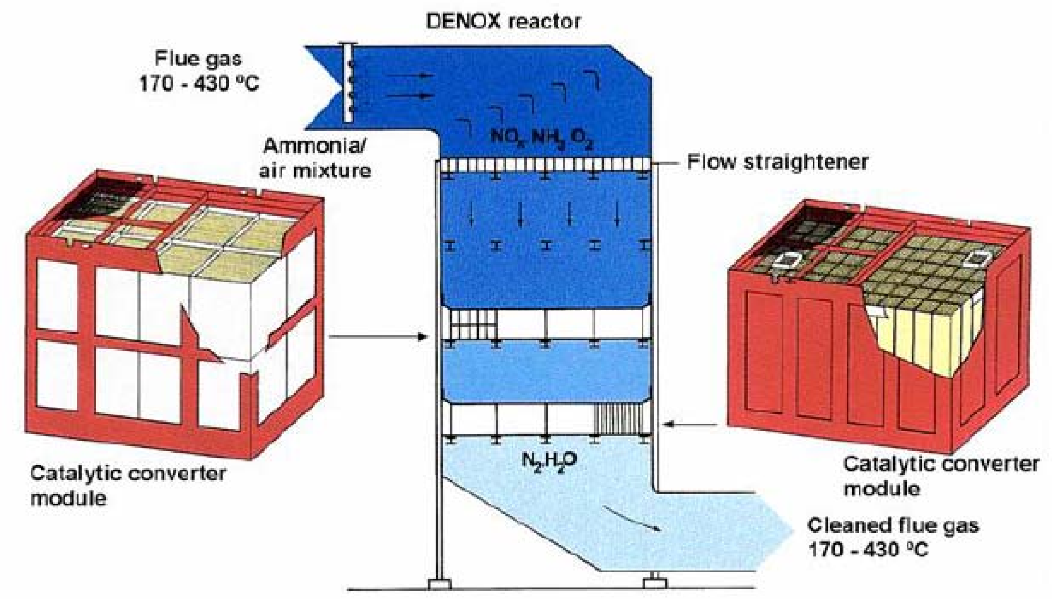


Figure 65: Principle of selective catalytic reduction to reduce NO_x emissions [29].

Selective non catalytic reduction (SNCR)

SNCR works without a catalyst. The reducing agent (ammonia or urea) is injected by different nozzles (see Figure 66, A, B, C) into the flue gas stream (850-1100°C) directly after the boiler. The reactions:

$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$

$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$

convert NO_x into molecular nitrogen [29, 10].

Figure 66 shows the operation principle of selective non catalytic reduction.

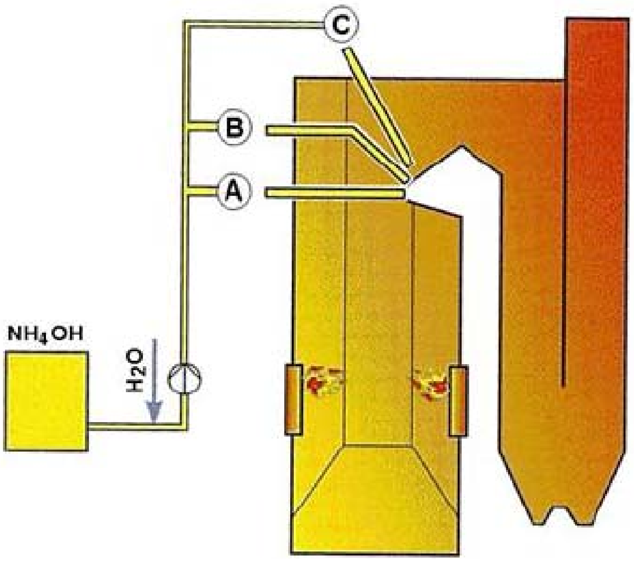


Figure 66: Principle of selective non catalytic reduction to reduce NO_x emissions [29].

8 The Life cycle of paper

The power of the sun drives the pulp and paper eco cycle; it converts water, nutrients, solar energy and carbon dioxide to wood fibres in growing trees. The forest is a renewable resource of raw materials providing both wood fibres for paper production and bio fuels for energy generation [15]. Figure 67 shows the basic steps of the paper life cycle.

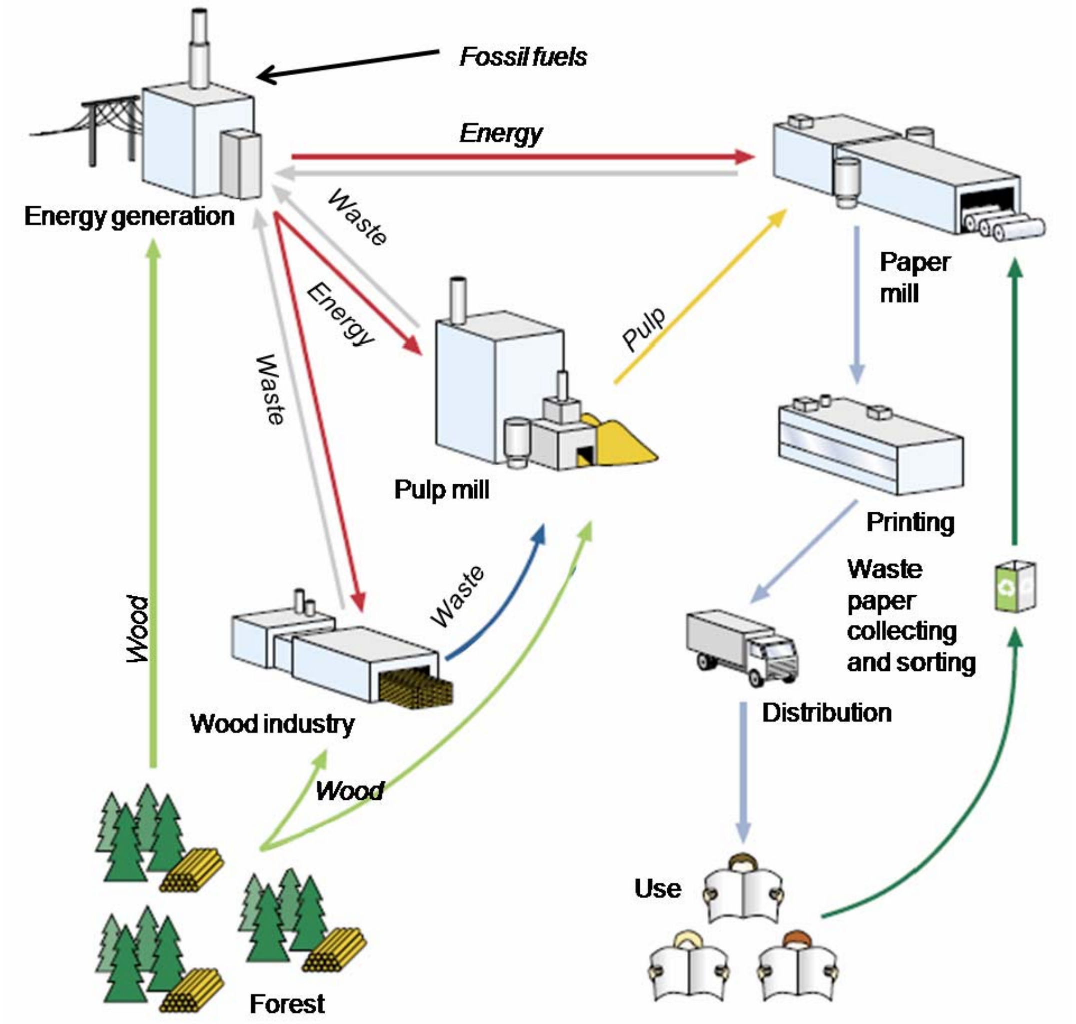


Figure 67: Life cycle of paper [22].

Wood as well as by-products from the wood industry are transported to the pulp mill where the separation of the cellulose fibres from the other wood components takes place. The extracted fibres (pulp) are mixed with water and chemicals to be applied to the paper machine in the paper mill. Wastes from the wood industry and from pulp- and paper mills are combusted in energy generation plants to save fossil fuels and reduce the amount of land filled waste. Waste paper is collected and sorted after use and subsequently gets recycled to the production process [22].

8.1 Recycling vs. incineration

Recycling contributes a lot to a sustainable paper production; however it is always necessary to bring fresh fibres from the forest into the paper cycle for make up. Waste paper contains lots of broken and destroyed fibres that cannot be reprocessed any more [8]. At each cycle of reprocessing, 10–20% of the fibres become too small for reuse and have to be replaced [13]. Paper that cannot be reprocessed any more can be combusted together with other domestic wastes in municipal incinerators. The paper positively influences the incineration process since it burns easily and therefore reduces the demand for supplementary fossil fuels [13]. Combusting one ton of waste paper substitutes approximately 600 liters of fuel oil [17].

Since municipal incinerators commonly generate energy, for example steam for district heating systems and electrical power, the incineration of waste paper that cannot be recycled any more is another part of an energy efficient paper cycle.

8.2 Paper recycling vs. fresh fibre use

The environmental impacts of paper production are numerous; this chapter will illustrate the most basic and commonly known influences of pulp and paper manufacturing on the environment. Despite the many different paper grades and the various production processes for pulp and paper, several European and US American experts claim, that paper that is manufactured from recovered fibres is less harmful to nature than paper produced from virgin fibres. [9, 10, 19, 25, 26]

Table 12 shows the different environmental impacts of the production of one tonne paper from primary fibres (Scenario A) compared to one tonne from secondary fibres (Scenario B). Serious impacts on the nature are:

- Greenhouse gases: such as carbon dioxide (CO_2) and methane (CH_4) contribute to climate change by trapping energy from the sun in the earth’s atmosphere [19].

- Particulates: small particles (< 10 µm) that are dispersed into the atmosphere during combustion can cause asthma and other respiratory illnesses or even cancer when inhaled [19].

- Sulphur dioxide: SO_2 results from combusting sulphur containing fuels (coal, oil) and leads to air pollution problems like acid rain or smog [19].

- COD: The Chemical Oxygen Demand (COD) determines the amount of oxygen that is necessary for the oxidation of **total organic substances** and certain inorganic matter (e.g. ammonia and nitrite) of a waste water sample. The water sample is mixed with a chemical oxidant (potassium dichromate $K_2Cr_2O_7$) and stored under specific conditions for a certain period of time [19, 35].

- BOD: The Biochemical Oxygen Demand is another standard test for determining the organic matter load of effluents. However it only indicates the **amount of oxygen consumed by micro organisms** when degrading organic material in the effluent.

  Knowing the amount of oxygen consumed for the oxidation of organic matter in the COD or BOD test, the amount of organic pollutants in the effluent can be determined. COD and BOD do not always measure the same type of pollutants. For example certain dissolved organic compounds such as acetate cannot be measured with the COD, but with BOD. Cellulose on the other hand, can only be measured during a COD test. Discharging effluents with high BOD or COD contents results in the reduction of dissolved oxygen in the water and adversely affect fish and other organisms [14, 35].

- AOX: Adsorbable organic halogens: are an indirect measure of chlorinated organic compounds, some of which are toxic [19].

Table 12: Comparison of environmental impacts between paper produced from fresh fibres and paper produced from recovered paper [19,32,33].

	A: 100% fresh fibres	**B: 100% recycled fibres**
Raw materials		
Wood	2,200 kg	-
Used paper	-	1,100–1,300 kg
Minerals (e.g.chalk)	100 kg	25 kg
Chemicals (e.g. pigments, fillers)	230 kg	130 kg
Water	30,000-100,000 l	10,000-20,000 l
Energy consumption		
From combusting wood residues	3-4 MWh	
From combusting process waste		0.5-1 MWh
Additional (e.g.: fossil fuels)	0.5-1 MWh	1-2 MWh
Total	3.5-5 MWh	1.5-3 MWh
Emissions to water		
COD	5-50 kg	2-10 kg
BOD	1.8-2.1 kg	1.6-2 kg
AOX	<0.5 kg	<0.5 kg
Emissions to air		
Greenhouse gases (CO_2 equivalents)	1,200-2,500 kg	900-1,400 kg

Particulates	4-5 kg	2.5-3 kg
Sulfur dioxide	10-12 kg	9-11 kg

Regarding energy efficiency of the paper cycle, fibre recovery is less energy consuming than producing paper from virgin fibres. However it is likely that greater external inputs of energy from fossil fuels are involved in recycling processes since manufacturing processes that use virgin fibres, use a lot of wood as alternative fuels [18].

9 Results and Discussion

On the one hand the term “energy efficiency” in pulp and paper production, is strongly connected to the thermal treatment of wastes from the production process. To call some examples, the combustion of bark, wood residues and rejects as well as recovering the chemicals from the cooking process, minimize waste from the process and decrease the demand of fossil fuels. These measures don`t make a production process more energy efficient. They prevent, however, that the energy content bond in the waste is disposed off on landfills. Several state of the art technologies for waste combustion and gasification are described in this study.

On the other hand, several technologies such as the use of waste heat, for example in the paper machine dryer section or in secondary heat systems, as well as steam recovering installations in mechanical pulp mills and in wood chip cooking systems, decrease the waste heat amount released to the environment. These measures increase the overall efficiency of a pulp- or paper mill by decreasing the demand for energy input to the system.

Taking a look at the development of paper production and primary energy use of the paper industry within the last two decades (see Table 13), it can be estimated that, despite the difficult economical situation that can be seen at the moment, on a long term view, the production capacity of pulp-, paper- and cardboard mills as well as the demand of energy for the industry will increase steadily.

Table 13: Development of pulp and paper production and primary energy consumption in the Cepi countries from 1990 – 2006 [25].

	1990	1995	2000	2005	2006	% Change 2006/2005	% Change 2006/1990
Production of market pulp and paper (´000 tonnes)	71 335	84 448	100 452	111 495	115 566	3.7	62.0
Total primary energy consumption (TJ)	932 820	1 069 250	1 153 204	1 278 568	1 322 872	3.5	41.8
of which biomass utilization	409 705	477 429	566 509	636 682	687 881	8.0	67.9
Total electricity consumption (GWh)	88 657	97 899	112 865	115 655	119 773	3.6	35.1
CO_2 emissions (kt)[1]	36 894	38 664	39 564	39 685	39 605	-0.2	7.3

[1] Excluding Switzerland

With the background of steadily increasing prices for primary energy, further measures will be necessary to minimize the specific energy consumption and CO_2 emissions for paper- and board products. One possibility to reduce the energy demand of the paper industry is to force the recovered paper utilization for pulp production, since the energy demand for one tonne of paper from recovered fibres can be up to 40% smaller than for one tonne of paper from fresh fibres (see Table 12). In this context, Cepi aims to increase the European paper recycling rate to 66% by the end of 2010.

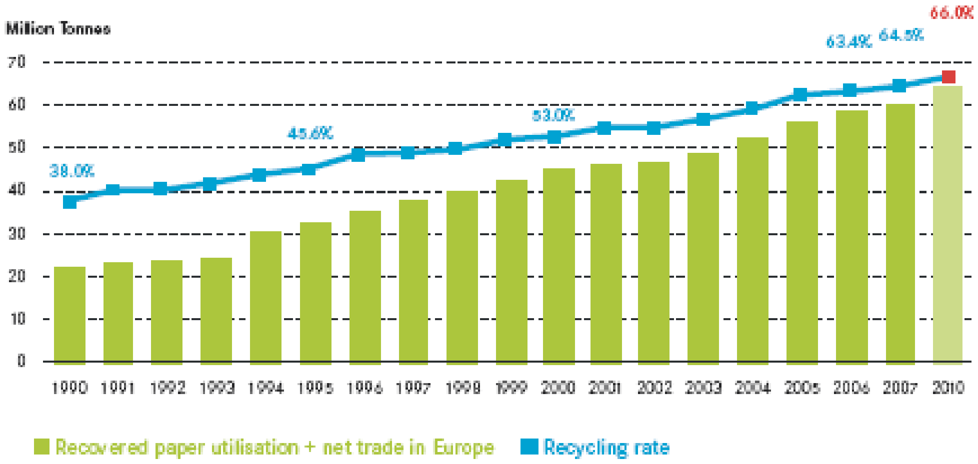


Figure 68: Development of Recovered paper utilization and recycling rate of Cepi Countries [34]

If this target is reached, further energy savings and also prevention of CH_4 emissions from paper rotting on landfills can be achieved. Detailed estimations for this saving potentials could not be found. However, also collection and transport of recovered paper require the input of financial resources and primary energy. The question is, at which level a collection and recycling rate will be reached, where the financial and management effort for collection and distribution overcome the environmental benefits.

Another target of the Confederation of European paper industries is to increase the share of biomass fuel to 56% of total primary energy in order to reduce the demand of fossil fuels and carbon dioxide emissions [34].

Other, process related changes that have energy saving potentials are possible throughout all different steps of the production process, some of them are mentioned in the following paragraphs [33].

Wood handling system

Energy savings are still possible by:

- Improved wood chip sorting: the more uniform the size distribution of the wood chips applied to the cooking system is, the less energy is necessary in the refiner or in the cooking plant (saving potential of 1-2%).

- The operation of belt conveyors instead of pneumatic conveyers. This implicates energy savings of up to 80%. However, maintenance costs are higher and belt conveyors have a maximum inclination angle, which makes it often difficult to transport wood chips at the top of the cooker.

Mechanical Pulping

- Increasing the refining or grinding speed reduces the energy demand (energy savings: up to 10%).
- Forced use of double disc refiners instead of single disc refiners (saving potential:15%). However, double disc refiners require shorter maintenance intervals and are more expensive.

Chemical Pulping

- Cooking at lower temperatures (iso – thermal cooking): a reduction of the cooking temperature of 10°C reduces the steam demand about 0.2 – 0.3 GJ/t of pulp. Of course, lower temperatures implicate longer cooking times, therefore a compromise between energy reduction and production capacity has to be found.
- Increasing the number of stages of the evaporation plant (page 21): A 6-stage evaporator is state of the art, by an additional, seventh evaporation step, further energy savings can be achieved. Table 14 shows this correlation.

Table 14: Steam economy and specific heat consumption of a multi effect evaporation plant depending on the number of evaporation steps [33].

Number of stages	Specific heat consumption	
	GJ/t evaporated H_2O	GJ/ton of pulp
4	630-650	4.7-4.9
5	550-570	4.1-4.3
6	460-480	3.4-3.6
7	390-400	2.9-3.0

Recovered Paper Pulping

- High consistency pulping: when the consistency inside the pulper is increased, the energy demand decreases as expressed in Table 15.

Table 15: Specific energy consumption of recovered paper pulping in correlation to the consistency in the pulper [33].

	Consistency in % solids	Specific energy demand in kWh/t
Low consistency pulping	4-6	50-70
Medium consistency pulping	10-15	30-50
High consistency pulping	18-20	17-25

General measures

- Speed – controlled and more efficient electric motors and pumps.
- More energy efficient lighting systems.
- Forced combustion of wastes from the production process.
- Highly efficient compressed air systems (for example by sealing of leakages).

Which measures lead to an ecological improvement and economical success on the long run has to be estimated for each company case by case. It always has to be considered, that changes in process are cost intensive and have to be repaid over years by the energy savings that can be achieved.

10 Summary

Basically the production process of paper can be divided into two steps:

- Production of pulp: extraction of fibres out of wood or out of recovered paper.
- Sheet formation on the paper machine: pulp, chemicals and water are the main components of a suspension that is applied to the paper machine and is transformed into paper.

Numerous technologies contribute to an efficient use of energy and to a minimized demand of primary energy and other natural resources for the production process of pulp and paper.

10.1 Wood pulp production

Fibres can be extracted chemically or mechanically from the wood.

10.1.1 Chemical pulping: sulfate process (kraft process)

Wood logs or wood chips are delivered to a pulp mill. Wood logs have to be debarked and chipped. Wood chips are screened in order to achieve a uniform size distribution for an efficient operation of the subsequent process steps. In a continuous or batch digester, the wood chips are impregnated with cooking chemicals (NaOH and Na_2S) to separate the cellulose fibres from lignin and other wood components. Further treatment of the fibres, such as washing and bleaching is necessary to remove impurities. The remaining liquid, comprising spent cooking chemicals and organic matter from the wood is called “black liquor” and can be recycled in a recovery system in order to obtain chemicals and energy. After evaporation of water, the thickened black liquor is combusted in a recovery boiler, the released heat energy is used for steam production. The spent cooking chemicals form a smelt at the bottom of the boiler and are lead to subsequent recovering steps where they are prepared for reuse. The recovery plant recovers more than 90% of the chemical- and 70% of the energy input to the cooking plant.

Black liquor gasification can considered an alternative to the conventional recovery boiler, this systems are still in their testing phase, however.

10.1.2 Chemical pulping: sulfite process

The sulfite process is operated with magnesium bisulphite $(MgHSO_3)_2$ as cooking chemical. Only 10% of all, world - wide produced chemical pulp is sulphite pulp. Energy- and chemical recovery operations are similar to the Kraft process.

10.1.3 Mechanical pulp: groundwood pulp

In groundwood pulping, debarked wood logs are grinded by a grinding stone to obtain single wood fibres and fibre bundles which have to be cleaned and bleached. The grinding process produces low pressure steam that is used as heat source for other process steps.

10.1.4 Mechanical pulp: refiner pulp

Wood chips are impregnated with steam in order to soften their structure and subsequently applied to the refiner. A refiner comprises one or two discs, rotating against the refiner housing or against each other and thereby grinding the wood chips into fibres. The rotation energy of the refiner produces steam that cannot be used directly as a heat source due to its high content of impurities. It is condensed in a recovery boiler, heating and vaporizing fresh water. Further fibre treatment comprises cleaning, screening and bleaching.

10.1.5 Recovered paper pulp production

In order to extract the fibres from the recovered paper, it has to be dissolved in water. Recovered paper is applied to a vessel filled with water (pulper) and fibre slurry is produced. Different processes remove impurities from the fibre slurry and transform it into the recovered pulp. In many cases these impurities, called rejects (i.e. plastics, foils, wood, staples, sand, etc.) are combusted to produce steam and electricity.

Also other kind of wastes from the production process, such as bark and wood residues are combusted together with fossil fuels in grate-, fluidized bed- and multiple hearth furnaces. Cogeneration systems, with an overall efficiency of approximately 85%, convert the heat into superheated-, high pressure-, medium pressure and low pressure steam and electrical power. Excess steam can be used in municipal district heating systems, excess electrical power is delivered to the grid.

10.2 Sheet formation on the paper machine

Pulp from wood or recovered paper is mixed with different fillers, coating chemicals and water to form slurry with a dry solids content of 1%. This slurry is dewatered by mechanical pressure and thermal heat in the paper machine; thereby the paper web is formed. The dryer section evaporates water from the paper web to increase the solids content to 99%. The heat content of the evaporated water is recovered to heat incoming supply water and supply air to the paper machine.

10.3 Paper lifecycle and future potentials

Paper recycling reduces the environmental impacts of the paper lifecycle. Generally speaking, producing paper from recovered fibres consumes less energy and raw materials and causes fewer emissions to air and water compared to paper produced of wood. Further improvements of the overall sustainability of the paper lifecycle, for example by enhanced recovered paper utilization and forced use of biomass as primary energy carriers, as well as process related changes can still be achieved.

11 Glossary

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11.2 Symbols and abbreviations

Symbols

%	Percent
°	Degree
°C	Degree Celsius
Ŋ	Efficiency
dH	Reaction enthalpy
k	Particle diameter
U_{mf}	Minimum fluidizing velocity

Abbreviations

AOX	Adsorbable organic halogens
BFB	Bubbling fluidized bed boiler
BLG	Black liquor gasification
BOD	Biological oxygen demand
CEPI	Confederation of European Paper Industry
CFB	Circulating fluidized bed boiler
cm	Centimeter
CMP	Chemi- mechanical pulp
COD	Chemical oxygen demand
CSF	Canadian standard freeness
CTMP	Chemi – thermo – mechanical pulp
e.g.	For example (exempli gratia)
EU	European Union
EU – 25	25 member states of the European Union until the end 2006
EU – 27	27 member states of the European Union since 2007
GJ	Gigajoule
GW (=SGW)	Groundwood pulp (=Stone groundwood pulp)
GWh	Gigawatt hours
HHV	Higher heating value
HRSG	Heat recovery steam generator
kg	Kilogram
kJ	Kilojoules
kWh	Kilowatt hours
l	Liters
m^2	Square meter
m^3	Cubic meter
m	Meter
min	Minute
MJ	Megajoule
mm	Millimeter
MW	Megawatt
MW_e	Megawatt electrical
MWh	Megawatt hours
m/s	Meters per second
MW_{th}	Megawatt thermal

nm	Nanometer
Nm^3	Dry standard cubic meter
NO_x	Nitrogen oxides
PGW	Pressure groundwood pulp
PGW-S	Super pressure groundwood Pulp
PJ	Pentajoule
Q	Heat energy
RMP	Refiner mechanical pulp
s	Enthalpy
SCR	Selective catalytic reduction
SGW (=GW)	Stone groundwood pulp (=Groundwood pulp)
SNCR	Selective non catalytic reduction
SO_2	Sulfur dioxide
t	Tonne
TGW	Thermo groundwood pulp
TMP	Thermo mechanical pulp
TS	Solid matter
TWh	Terawatt hours
Vol-%	Percent by volume
W	Watt

Chemical elements and compounds

$Al_4(OH)_8(Si_4O_{10})$	Hydrous kaolin (China Clay)
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
$Ca(OH)_2$	Calcium hydroxide
$CaSO_4$	Calcium sulfate (gypsum)
CO	Carbon monoxide
CO_2	Carbon dioxide
H_2O	Water
H_2S	Hydrogen sulfide
H_2SO_4	Sulfur acid
HCN	Hydrogen cyanide
$Mg(HSO_3)_2$	Magnesium bisulphite
MgO	Magnesium oxide

$Mg(OH)_2$	Magnesium hydroxide
$Mg_3(OH_2)(Si_4O_{10})$	Talc
N	Chemical symbol for Nitrogen
NaOH	Sodium hydroxide
Na_2CO_3	Sodium carbonate
Na_2S	Sodium sulfide
Na_2SO_4	Sodium sulfate
NH^*, NH_2^*	Chemical symbols for nitrogen radicals
O_2	Molecular oxygen
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide
TiO_2,	Titanium dioxide

11.3 Tables

11.4 Figures