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Energy efficiency and GHG emissions: Prospective scenarios for the pulp and paper industry

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Energy efficiency and GHG emissions: Prospective scenarios for the pulp and paper industry

This study analyses the role of technology innovation in the European pulp and paper industry from 2015 to 2050. The baseline scenario describes a decrease in energy consumption and GHG emissions by 14 % and 63 %, respectively, in a context in which the demand grows by 7 %. Without the technological improvement the respective variations would register an increase of 1 % and 5 %. Unlike the biorefineries concept, the carbon capture and storage technology does not become cost effective; although higher CO_2 prices and rewarding the bio-CO_2 captured could turn the industry into a carbon sink.

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Authors

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Executive summary

One of the political guidelines of the current EU Commission is the need to bring industry's contribution to the EU GDP back to 20% by 2020. In EU-28, the industry accounts for a quarter of EU emissions and energy consumption, contributing 15% to GDP directly, and acting as the foundation for many value chains.

The European pulp and paper industry, the 4th largest industrial energy user in EU, has the potential to contribute to the main objectives (stemming from the global commitments) to combat climate change, that are a 20%, 40% and 80% reduction in GHG emissions compared to 1990 by 2020, 2030 and 2050, respectively. The 2011 roadmap sets a EU industry trajectory of 43% reduction in direct emissions by 2023 compared to 2005. The main policy instrument to guide the achievement of these objectives is the EU Emissions Trading System Directive (ETS). Note that also the EU Climate policy provides tools to support low-carbon innovation in industry. After 2020 ETS allowances will be put aside to create an innovation fund or support the large scale demonstration of highly innovative low carbon technologies.

Regarding energy efficiency, one of five dimensions of the EU's Energy Union strategy, the EU has set itself a 20% energy savings target by 2020 (when compared to the projected use of energy in 2020). The revised energy efficiency directive includes a new target for 2030 of 32.5% with an upward revision clause by 2023.

The aim of this study is to analyse the contribution of technology innovation in the pulp and paper sector to the energy consumption and GHG emission savings until 2050. This is achieved using a bottom-up model to analyse the cost effectiveness of technological improvements at facility level for all pulp and paper products covered by the ETS. As a boundary condition for a baseline scenario, this study uses a growth of the demand and energy prices that stem from the 2016 reference scenario of the European Commission. The contribution of the technological improvement makes that the demand growth, by 7% from 2015 to 2050, goes hand in hand with a decrease in energy consumption and GHG emissions of 14% and 63%, respectively. While most of the energy improvement comes from the incorporation of the state-of-the-art technologies to new facilities, most of the CO_2 savings come from switching fossil fuels to biofuels. Otherwise, without the technological improvements, the energy consumption and GHG emissions will be in 2050 around 1 and 5%, respectively, higher than in 2015.

Among the technological options analysed, there are seven potential configurations of biorefineries; three producing dimethyl ether, three biofuels and an additional configuration producing a mixture of alcohols. All but the last configuration are cost-effective during the simulation. However, the deployment of the biorefineries is analysed apart from the baseline scenario, with which all the remaining alternative scenarios are compared. The approach followed in this study considers only the benefits of the technologies to the pulp and paper industry, taking for granted the demand of the biofuels or feedstock from petroleum refineries, chemical industry or transport sector. The results show that the biorefineries could produce 270 PJ (6.4 Mtoe) of biofuels. In this case, although the GHG emissions and energy consumption of producing these biofuels take place in the pulp and paper industry, these carbon-free fuels would reduce GHG emissions in some other sectors.

Each alternative scenario analyses the effect of different trends of the prices of electricity, CO_2 allowance or fuels. In each of them, the corresponding price of the baseline scenario is scale up linearly, doubling its final prices in 2050. The GHG emissions of these alternative scenarios are quite similar because in all of them, even in the baseline scenario, fuel-switching is equally deployed. Practically the same happens regarding energy consumption, proving that all energy savings are already delivered under the conditions of the baseline scenario. Although the amine-based post-combustion CO_2 capture (used as the CCS technology) is included in the model, it does not become cost effective in any mill, not even in the scenario that doubles the final CO_2

price in 2050. However, in an alternative scenario in which we contemplate the possibility (not in the EU ETS) of rewarding the industry by the bio-CO_2 captured (with the same price as the CO_2 allowance), the CCS becomes cost effective when the CO_2 price is higher than EUR 92.4 per tonne.

The findings of this study may deserve to be revisited if there were more details than the existing ones in the already very detailed database used for this study (from RISI), and more importantly, if there were more details about technological performance (and associated costs) of breakthrough technologies that are currently at a very early stage of research. Moreover, the interest to invest in some of the technological options considered in this study could be reinforced if some of the collateral benefits brought to other sectors were acknowledged to the industry, enabling those indirect savings. Therefore, this study underlines the interest of using a holistic approach to grasp in its full extent the potential contribution of this industry to the European targets.

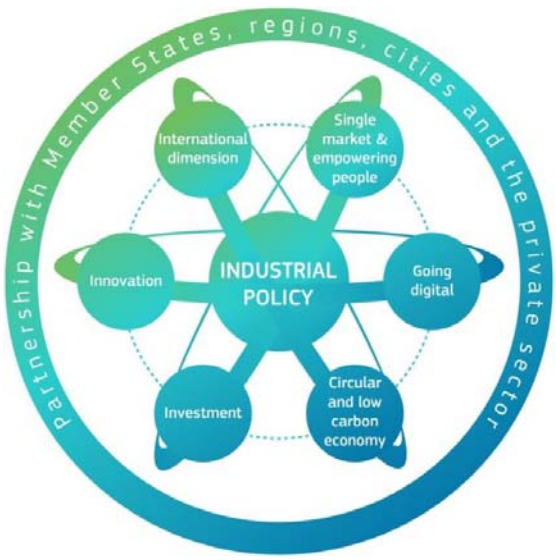
1 Introduction and policy context

'Putting energy efficiency first' is one of the main goals that the European Commission proposed in the package *'Clean energy for all Europeans*', which aims at keeping the EU competitive in the clean energy transition (European Commission, 2016a). In line with the perspective for moving to a competitive low-carbon economy in 2050, the EU leaders set in 2014 new targets for 2030 on the reduction of greenhouse gas emissions (GHG) (at least 40%, from 1990 levels, increasing to 80% by 2050), on the improvement of energy savings (at least 27%, which could increase to 30%) and on the promotion of renewable energy (at least 27% share in final energy consumption).

All sectors need to contribute to the achievement of these targets and consolidate the transition to a low-carbon economy according to their technological and economic potential. For example, the energy intensive industries (e.g. steel and car industries) will need to maintain their efforts towards improving the energy efficiency of the production processes, while promoting innovative solutions, fostering competitiveness and creating new jobs and growth.

The transformation of the European industrial base towards more sustainable and resource-efficient business models is a key element of the renewed EU industrial policy strategy (European Commission, 2017a). The overall goal of industrial strategy is to make the EU industry stronger and more competitive by investing in smart, innovative and sustainable technologies (Figure 1).

Figure 1. Main elements of the EU industrial policy strategy



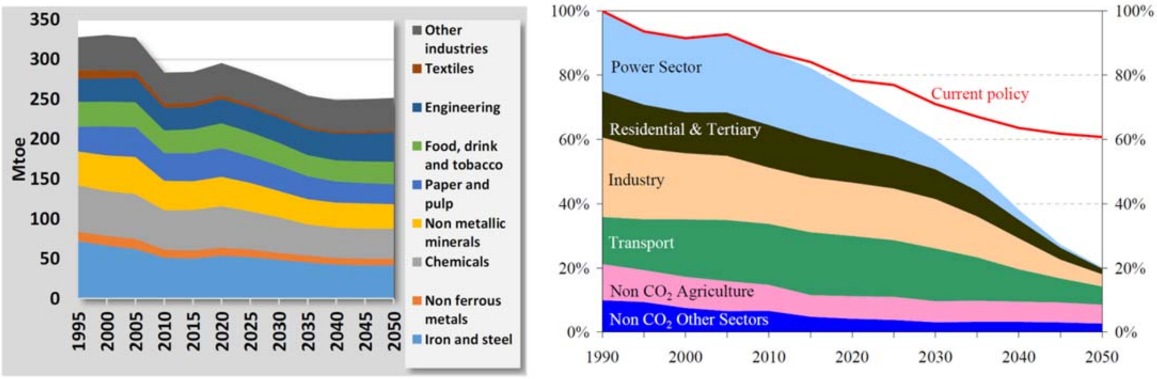
Source: European Commission, 2017a.

The shift of the industry towards higher value added and less energy-intensive products will promote the decrease of energy consumption. According to the estimations of the EU Reference Scenario 2016 (European Commission, 2016b) on the future trends and developments in the EU energy system and in greenhouse gas emissions, energy demand by industrial activity will decrease in the medium term from 295.3 million toe (tonnes of oil equivalent) ([1])) in 2020 to 269.7 million toe in 2030 and stabilise by 2050 to 251.8 million toe (Figure 1, below left). Two main factors will drive the decrease in energy consumption: a) replacement of old equipment at the end of its lifetime with more energy efficient technologies b) switching towards higher value added and less-energy intensive production processes.

([1]) *toe* is the abbreviation for tonne(s) of oil equivalent, which represents a normalised unit of energy equivalent to the approximate amount of energy that can be extracted from one tonne of crude oil.

Currently, the industry is the third largest source of greenhouse gas emissions in the EU after power sector and transport (Figure 2, below right). In terms of reducing greenhouse gas emissions, the EU roadmap for 2050 low-carbon economy shows that the energy intensive industries could cut more than 80% of emissions by 2050 by implementing the energy-efficiency measures (European Commission, 2011).

Figure 2. Estimation of final energy consumption in industry (left) and possible cut in greenhouse gas emissions in the EU main sectors (right)



Source: European Commission, 2016a (left image) and 2011 (right image).

This cut could be achieved through adoption of more advanced resource and energy-efficient industrial processes and equipment, increased recycling, as well as abatement technologies for non-CO_2 emissions. In this respect, the European Commission provides some of the necessary tools and policies. For example, the EU Emissions Trading System is the most important tool to drive the energy efficiency and GHG reductions in industry.

New energy-efficient production technologies will contribute to the modernisation of EU's industrial base, help the transition to a low-carbon and resource efficient economy, and also play an increasingly role in determining the ability of European business to compete globally. The overall transition to a low-carbon energy system is supported by the Strategic Energy Technology Plan (SET-Plan), which is the technology pillar of the EU's energy and climate policy aiming at acceleration the development and deployment of low-carbon technologies.

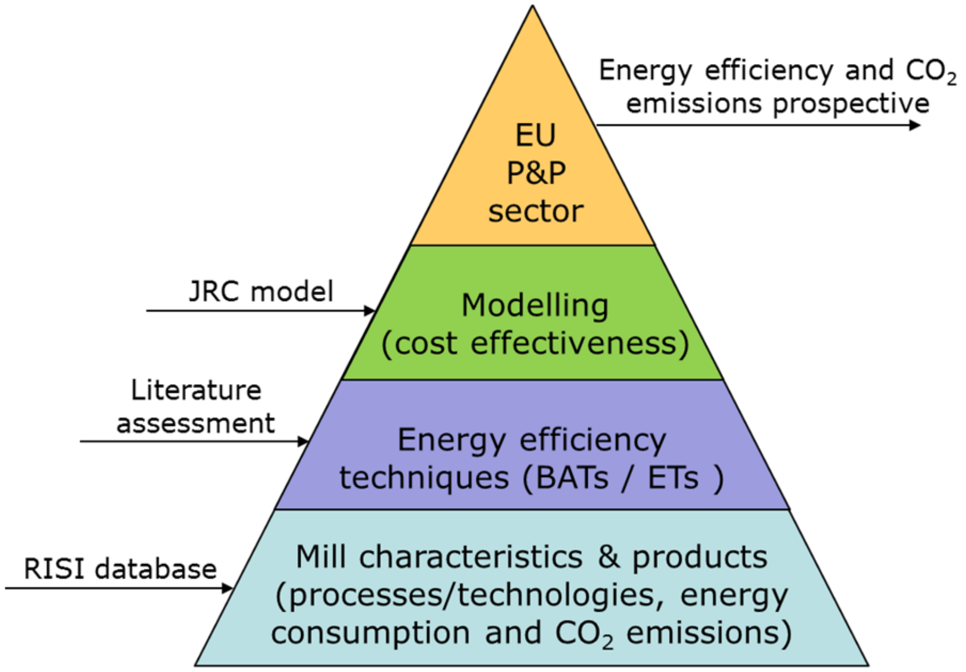
The role of technological innovation in improving energy efficiency and reducing GHG emissions by European energy-intensive industries was already addressed by the Joint Research Centre for cement (Moya et al., 2010), iron and steel (Pardo et al., 2012), aluminium (Moya et al., 2015) and chemicals industries (Boulamanti and Moya, 2017). Following a similar methodological approach, in this report we analyse the potential energy savings and GHG reduction in the pulp and paper industry.

2 Scope of the study and methodology

This study analyses the role of technology innovation in improving the energy efficiency and reducing CO_2 emissions of pulp and paper industry taking into account the cost-effectiveness of the retrofits of the main processes at the mill level in the timeframe 2015-2050. This analysis is based on the most accurate set of information available at facility level for the pulp and paper industry as developed by RISI ([2]), and the prospective breakthrough technologies that the industry could incorporate in the frame of the 35 years ahead. The information to accomplish this part comes from the scientific literature, mainly from the International Energy Agency (IEA, 2007, 2009, 2014 and 2015) and others (e.g. Larson et al., 2006). RISI's Asset Database comprises information about the equipment, processes and technologies used in the production of pulp and paper in all integrated and non-integrated mills in the EU, as well as the process/mill-specific consumptions (electricity and fuel consumption). More details about the RISI dataset are provided in sub-chapter 3.3.

The information provided in the RISI dataset were used as input data to a model developed in-house and integrated with additional information about the cost of technologies installed.

Figure 3. The bottom-up approach used in this report — Methodology overview used in this study



Source: JRC representation.

The following chapters give an overview of the EU's pulp and paper industry (Chapter 3), current energy consumption and GHG emission by the sector (Chapter 4), measures for improving energy efficiency and reducing GHG emissions through adoption of best available technologies (BATs) and emerging technologies (ETs) (Chapter 5), bottom-up model and assumptions (Chapter 6), assessment and results of energy/GHG saving potentials (Chapter 7). The main finding of this study and conclusions are presented in Chapter 8.

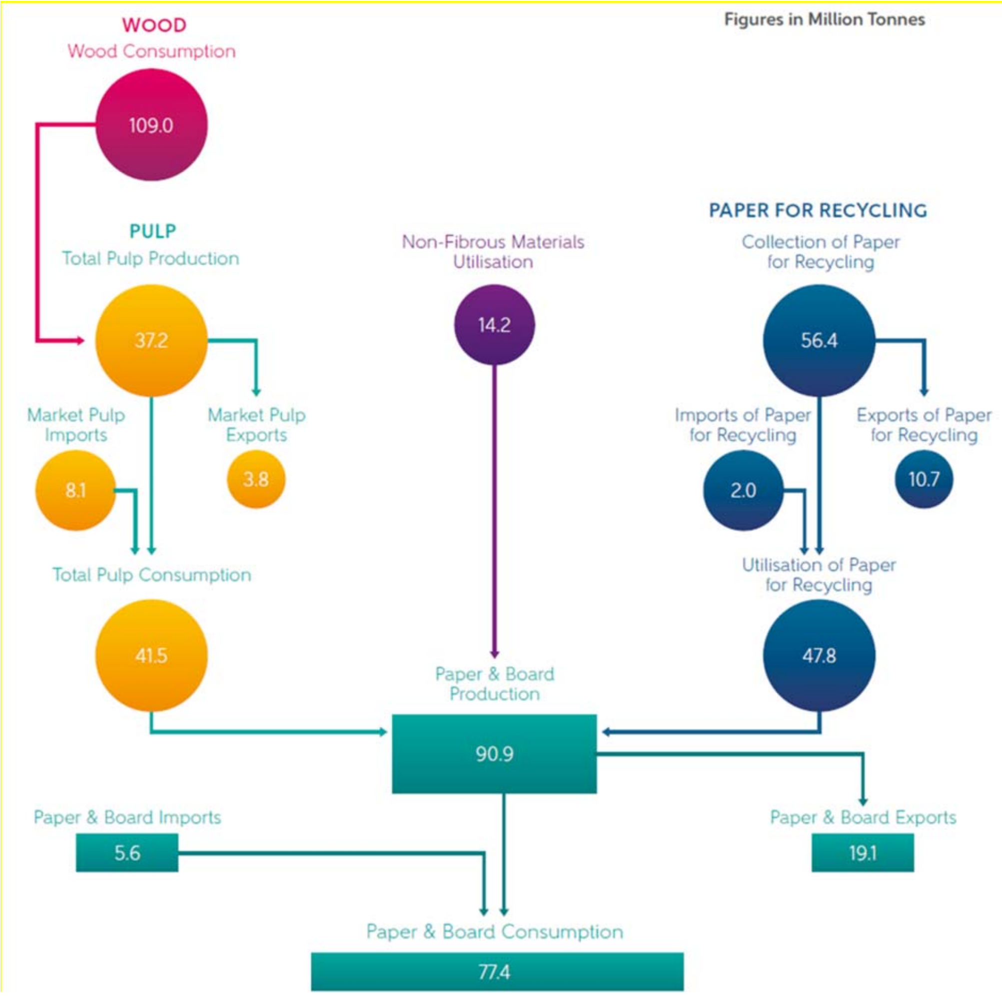
([2]) The RISI database was developed by the RISI company (https://www.risiinfo.com/) under the contract with the Joint Research Centre, reference number IET/2012/F06/008-NC-C109337 'NL-Petten: Database of the pulp and paper industry in the EU', followed by an update in 2015.

3 Overview of the EU's pulp and paper industry

The European pulp and paper manufacturing industry is energy- and raw-materials intensive, overall employing 647 000 workers in 21 000 companies (European Commission, 2017b). The annual turnover from the production of pulp, as well as graphic, hygienic, packaging and specialised paper grades and products is estimated at around EUR 180 billion.

In Europe, the pulp and paper industry is represented by the Confederation of European Paper Industries (CEPI), which currently gathers 18 national associations ([3]). In 2016, CEPI represented 92 % of the European pulp and paper industry in terms of production. The total production reported in 2016 by the 18 CEPI's associations (CEPI, 2017) was 37.2 million tonnes of pulp and about 91 million tonnes paper and board (Figure 4).

Figure 4. CEPI pulp and paper industry in 2016



Source: CEPI, 2017.

Based on the CEPI statistics, in 2015, 24.5 % of global production of pulp and 26.1 % of global paper and board production was made by European companies (CEPI, 2017). Overall, the EU is a net importer of market pulp and a net exporter of recycled paper and paper and board products.

([3]) CEPI member countries: Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.

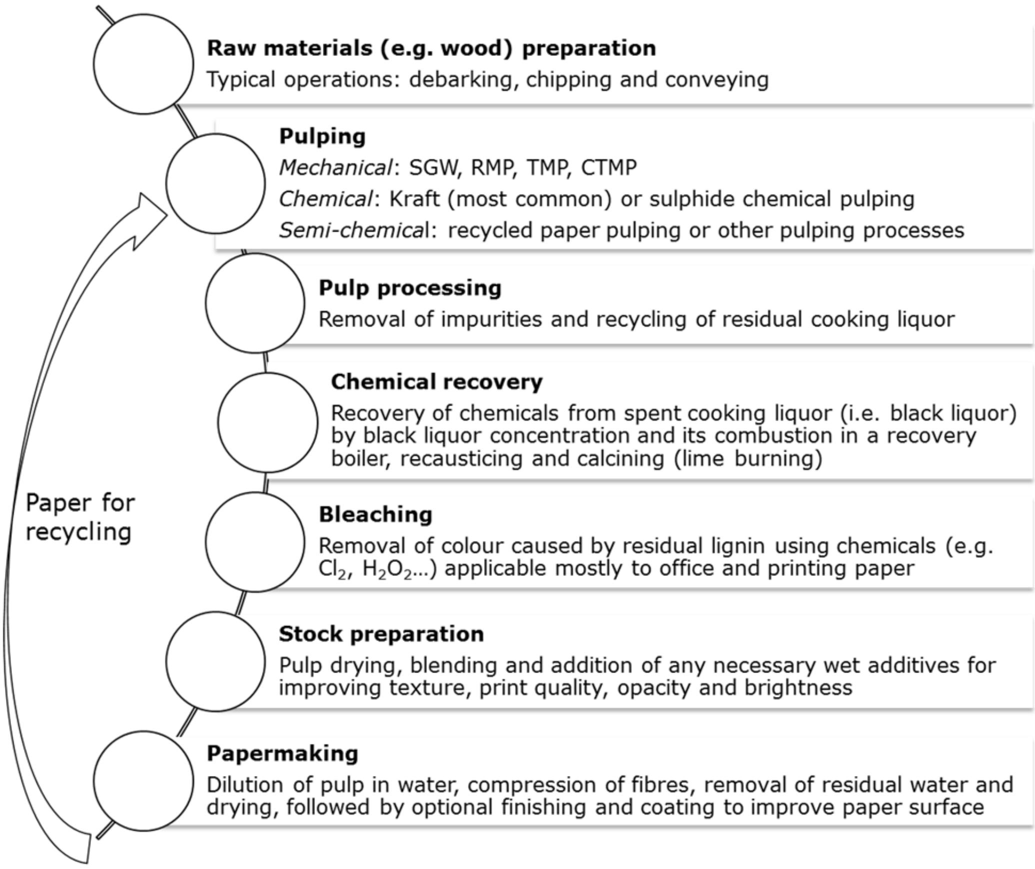
3.1 Manufacturing processes

The paper and paperboard are made from different forms of pulp, which in turn is obtained mainly from wood, recycled paper or other cellulose-bearing material such as straw, hemp, grass, cotton and other (e.g. bagasse, bamboo, reeds, jute, flax, etc.). Pulp can be also produced by repulping of the recycled paper.

The EU is a forerunner in paper recycling. In 2015, the recycling rate reached 71.5 % and it is foreseen to increase further to 74 % by 2020, close to the maximum theoretical limit of 78 % (EPRC, 2017). In 2015, the recovered paper utilisation rate (representing how much recovered paper is used in the total production of paper and paperboard) was 52.5 % for the CEPI countries (CEPI, 2017).

The process flow in pulp and paper manufacturing operations is illustrated in Figure 5.

Figure 5. Major steps in pulp and paper manufacturing processes ([4])



Source: JRC representation with information from Bajpai, 2016.

The main raw material (i.e. wood) is first debarked and chipped uniformly in order to maximise the quality and efficiency of the pulping process. Then, the harvested wood is processed by adding water and heat so that the individual cellulose fibres are separated from the lignin (an intercellular material that binds the fibres together in wood). Pulp is mainly produced mechanically or chemically, or using a combination of them.

- **Mechanical pulping**. It is the oldest form of pulping which uses mechanical energy to weaken and separate fibres from wood via a grinding action. 95 % of the mechanical pulp capacity is installed in integrated and semi-integrated paper

([4]) SGW — stone groundwood pulping, RMP — refiner mechanical pulping, TMP — thermomechanical pulping and CTMP — chemi-thermomechanical pulping.

mills. The mechanical pulping is characterised by a high yield (85-95%). However, the resulted fibres are often weak, short and unstable. Therefore, the mechanical pulp is used for lower grade papers such as newsprint, magazines, books, etc. Several mechanical-based processes can be used for pulp making such as: stone groundwood pulping (SGW), refiner-mechanical pulping (RMP), thermomechanical pulping (TMP) and chemi-thermomechanical pulping (CTMP). The SGW, RMP and TMP are the most used processes in the production of mechanical pulp. While in the SGW the logs are pressed against a rotating grinder stone with simultaneous addition of water, in the RMP and TMP the defiberising of the wood chips takes place between refiner disks (Ullmann, 2005).

Electricity is the main source of energy in producing mechanical pulp and most of it is converted into heat. Some of this heat can be recovered and used in other processes or for district heating.

- **Chemical pulp**. In this process, fibres are extracted from the wood in a digester under pressure with the use of 'cooking' chemicals and separated by washing. The chemicals dissolve most of the lignin and hemicelluloses present in the wood, resulting in better separation of the cellulose fibres. Although the chemical process has a low yield (40-55%), the pulp consists of long, strong and stable fibres, suitable for high quality papers such as office paper, packaging and high-strength paper and board. Based on the type of chemicals used for digesting (breaking the fibres bonds), two main processes are known: Kraft (or sulphate) and Sulphite. Kraft chemical pulping uses a highly alkaline solution (white liquor) containing sodium hydroxide (NaOH) and sodium sulphide (Na_2S) for digestion, which can take place in batches or continuous digesters. Sulphide chemical pulping, uses an acidic mixture of sulphurous acid (H_2SO_3) and bisulphite ion (HSO_3) (sulphite cooking liquor). Kraft pulping is the most common pulping process. In 2016, around 67% of the total pulp produced in the EU was obtained by kraft pulping compared to 27% for mechanical and semi-chemical pulp and about 5% for sulphite pulp (CEPI, 2017). The so-called 'black liquor' resulted during the wood cooking and further treated in the recovery cycle is a high-energy content by-product of the chemical pulping containing wood waste, chemicals and other impurities. This liquor is burned in recovery boiler (present in all kraft mills) producing steam that can be later used to produce power in a steam turbine. In general, the chemical pulping process generates more energy than it uses.

In the EU, over half of the paper and board is produced from pulp coming from recycled paper (Figure 4). With the exception of high grade paper, all other paper and board products can be produced from fibres coming from recycled paper (secondary fibres). The main advantage of using recovered paper is that the energy requested is much lower compared to wood-based pulp (see later Figure 19 and Figure 20).

An important step in the chemical pulping process is the recovery of chemicals from the spent cooking liquor. This result both in a significant cost reduction associated with purchasing of fresh chemicals and generation of steam by combusting the organic residue from the black liquor during refining process. According to Bajpai, the chemical recovery process consists of 4 main stages (Bajpai, 2016):

— *Black liquor concentration*; process in which water is evaporated from the black liquor making thus the combustion process more efficient.

— *Combustion of black liquor in a recovery boiler*; steam is produced by combustion of the organic fraction contained in the black liquor with generation of steam used further in heating applications within the mill or for on-site electricity generation.

— Recausticising; the inorganic fraction resulted after the combustion (known as molten smelt) is firstly mixed with a weak alkaline solution (e.g. sodium hydroxide and sodium sulphite) and then recausticised by adding calcium hydroxide to form sodium hydroxide and calcium carbonate (known as lime mud).

— Calcination; after washing and drying, the lime mud is calcined in a lime kiln to regenerate the lime.

Depending on the end use, pulp could be bleached with various chemicals (e.g. chlorine dioxide, hydrogen peroxide, oxygen, caustic and sodium hypochlorite) to remove any colour and processed into the stock used for paper making.

Before turning into paper, pulp undergoes several steps known as stock preparation, depending on whether the paper is produced at integrated or non-integrated mills. For example, at non-integrated mills, the pulp arrives dried and baled, while at integrated mills, the paper mills use the pulp manufactured on-site.

The stock preparation may also include blending and addition of any necessary additives (e.g. resigns, waxes for water repellence as well as certain inorganic chemicals) for improving texture, print quality, opacity and brightness. Integrated mills are more energy efficient than the non-integrated ones because the latter require a pulp drying stage avoided in the former that also shares common auxiliary systems, such as steam, electric generation.

Paper is made through several operations called wet end and dry end (Bajpai, 2016). In the wet-end operation, the slurry of pulp containing more that 99% water is deposited onto a moving belt that draws the water from the slurry, moving then through additional rollers that compress the fibres and remove the residual water. The most common technology is the Fourdrinier (50%) followed by Crescent (14%), Gap Former (12%), Hybrid former (11%), Twin-wire (6%), and inclined (1%). All papermaking machines are made of some basic elements: the headbox, wire section, press section, dryer section and reel. Twin wire and cylinder formers are alternative methods to the traditional Fourdrinier wire for the sheet formation. While in the twin wire formers, the pulp suspension is led between two wires that rotate at the same speed and is drained through one of both sides, in the cylinder former, web formation occurs on a wire-covered, water-permeable cylinder (Ullmann, 2005).

The dry-end section consists of up to 100 steam-heated drying cylinders, bringing the finished paper web to only 5-8% water (which is the normal moisture content).

To improve its surface quality, the paper could go through additional processes such as finishing and coating. Coating can be made with coloured substances such as pigments and binders. A further smoothing of the paper is achieved through a process called calender (‘ironing effect’). In the finishing process, the rolls of paper are cut into smaller rolls by a reel cutter.

From the energy consumption view, producing one tonne of paper products requires on average about 11.5 GJ of primary energy, which is comparable to that of other energy-intensive products such as steel or cement (Suhr et al., 2015). However, unlike other energy-intensive industries, the pulp and paper sector uses a high share of biomass as primary energy source.

Due to the wide range of pulp and paper products, the energy used in their manufacturing varies for different products and processes, depending on the raw materials used, paper quality and techniques applied. The average energy required in different manufacturing processes is shown in Figure 6.

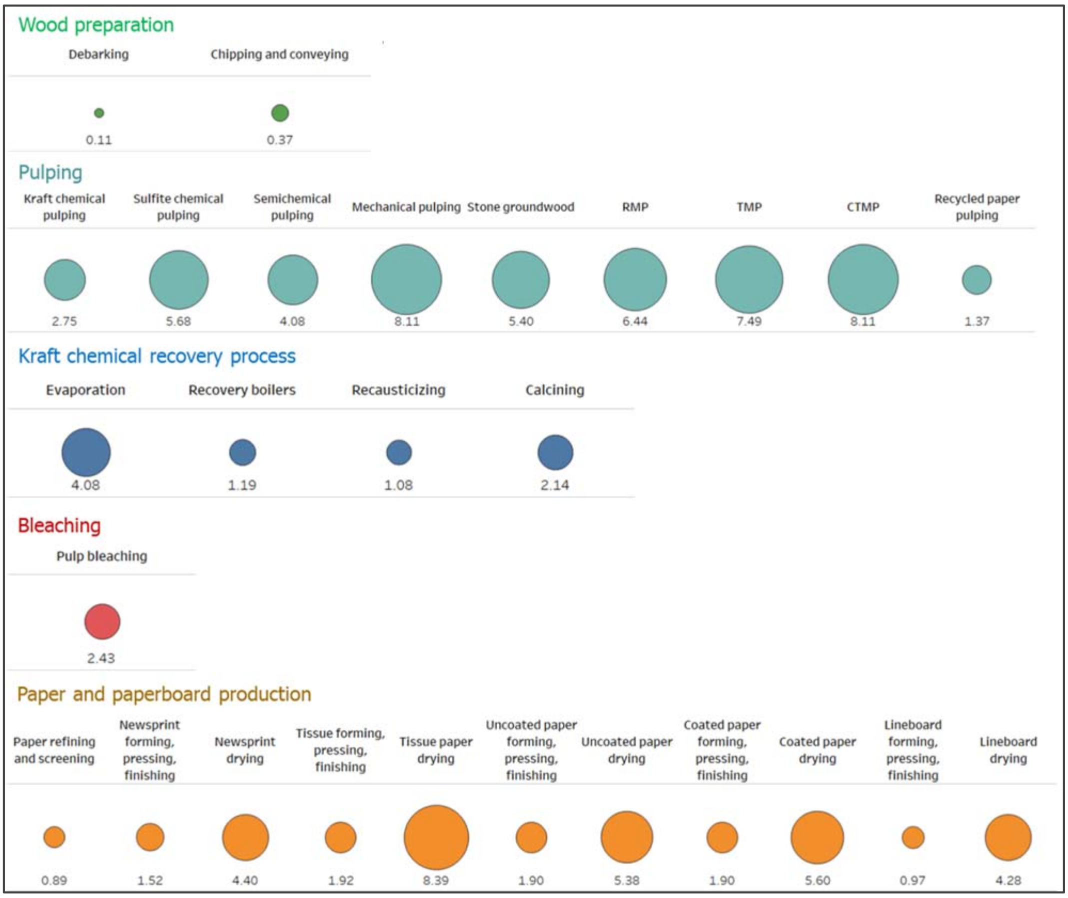
It should be noted that the for the same process the specific energy consumption can vary widely due to different feedstock composition, various practices in process operation and use of different technologies.

The amount and type of energy used in pulping varies largely by process. While chemical and semi-chemical pulping relies widely on steam, the mechanical (SGW) and thermomechanical pulping (TMP) use mostly electricity for driving the grinding equipment. On the other hand, heat and electricity can be generated by burning the biomass residues resulted as by-product in the chemical pulping. As Figure 21 later shows, pulp mills can produce more electricity than they need.

In the papermaking process, drying is the most energy intensive step (Figure 6) accounting for about two thirds of total energy use in paper production (Kramer et al., 2009).

More information about specific energy consumption by the European mills for making the pulp and paper products analysed in this study is presented in Chapter 4.

Figure 6. Average energy consumption (GJ/tonne) estimated for pulp and paper manufacturing processes.



Source: JRC representation with information from Bajpai, 2016.

3.2 Pulp and paper products

For this study the JRC has counted on detailed information at facility, process and product level provided by RISI. The information about the European pulp and paper production is arranged around the same 12 products with carbon emissions benchmark (European Commission, 2011) in the EU Emission Trading System (ETS). Table 1 provides the twelve pulp and paper products and their definition (according to the carbon leakage decision).

Pulp and paper products can be made in integrated mills or separated mills, or both (semi-integrated). A fourth category called 'recycled' can be used to cover the paper production from recycled paper. In this study, the mill configuration is divided into four categories as follows:

- **Integrated** — a mill that purchases less than 10% of its fibre needs.
- **Semi-integrated** — a mill that purchases anything between 10-90% of its fibre needs.

- **Non-integrated (separated)** — a mill that purchases between 90-100% of fibre needs.
- **Recycled** — a mill that uses mostly recycled fibre (more than 90%).

Table 1. Pulp and paper products included in this analysis.

Product	**Description**
Pulp (*)	
Short fibre kraft pulp	Wood pulp produced by the sulphate chemical process using cooking liquor, characterised by fibre lengths of 1-1.5 mm, is mainly used for products which require specific smoothness and bulk, as tissue and printing paper.
Long fibre kraft pulp	Long fibre kraft pulp is a wood pulp produced by the sulphate chemical process using cooking liquor, characterised by fibre lengths of 3-3.5 mm, which is mainly used for products for which strength is important, as packaging paper.
Sulphite pulp, thermo-mechanical and mechanical pulp	Sulphite pulp produced by a specific process, e.g. pulp produced by cooking wood chips in a pressure vessel in the presence of bisulphite liquor. Sulphite and mechanical pulp can be either bleached or unbleached. Two mechanical pulp grades are included: TMP (thermomechanical pulp) and groundwood. Chemi-thermomechanical and dissolving pulp are not included in this category.
Recovered paper pulp	Pulps of fibres derived from recovered (waste and scrap) paper or paperboard or of other fibrous cellulosic material.
Paper and paperboard (**)	
Newsprint	Specific paper grade (in rolls or sheets) used for printing newspapers produced from groundwood and/or mechanical pulp or recycled fibres or any percentage of combinations of these two. Weights usually range from 40 to 52 g/m^2 but can be as high as 65 g/m^2. Newsprint is machine-finished or slightly calendered, white or slightly coloured and is used in reels for letterpress, offset or flexo-printing.
Uncoated fine paper	Covers both uncoated mechanical and uncoated wood-free: • Uncoated wood-free papers suitable for printing or other graphic purposes made from a variety of mainly virgin fibre furnishes, with variable levels of mineral filler and a range of finishing processes. This grade includes most office papers, such as business forms, copier, computer, stationery and book papers. • Uncoated mechanical papers cover the specific paper grades made from mechanical pulp, used for packaging or graphic purposes/magazines.
Coated fine paper	Coated fine paper covers both coated mechanical and coated wood-free papers: • Coated wood-free papers made of fibres produced mainly by a chemical pulping process which are coated in process for different applications and are also known as coated freesheet. This group focuses mainly on publication papers. • Coated mechanical papers made from mechanical pulp, used for graphic purposes/magazines. The group is also known as coated groundwood.

Product	**Description**
	Paper and paperboard (**) *(continued)*
Tissue	Tissue papers cover a wide range of tissue and other hygienic papers for use in households or commercial and industrial premises such as toilet paper and facial tissues, kitchen towels, hand towels and industrial wipes, the manufacture of baby nappies and sanitary towels.
Testliner and fluting	Testliner covers different types of paperboard that meet specific tests adopted by the packaging industry to qualify for use as the outer facing layer for corrugated board, from which shipping containers are made. Testliner is made mainly from fibres obtained from recycled fibres. Fluting refers to the centre segment of corrugated shipping containers, being faced with linerboard on both sides.
Uncoated cartonboard	This category covers a wide range of uncoated products which may be single or multiply. Uncoated cartonboard is mainly used for packaging applications which the main needed characteristic is strength and stiffness, and for which the commercial aspects as information carrier are of a second order of importance. Cartonboard is made from virgin and/or recovered fibres, has good folding properties, stiffness and scoring ability. It is mainly used in cartons for consumer products such as frozen food, cosmetics and for liquid containers; also known as solid board, folding box board, boxboard or carrier board.
Coated cartonboard	This category covers a wide range of coated products which may be single or multiply. Coated cartonboard is mainly used for commercial applications that need to bring commercial information printed on the packaging to the shelf in the store in applications such as food, pharma, cosmetics, and others.
Packaging paper	Contains those products that are classified as Kraft papers and are used for various packaging applications.

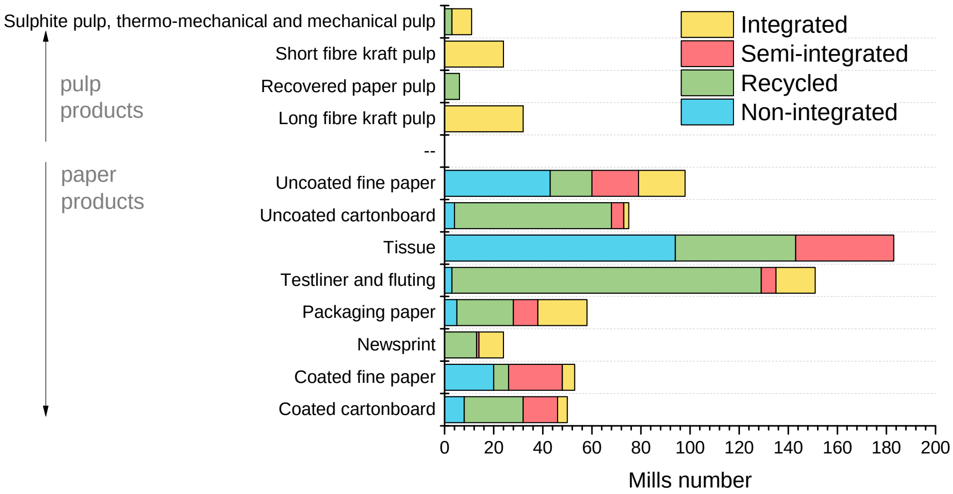
(*) Includes the following production processes: pulp mill, recovery boiler, pulp drying section and lime kiln and connected energy conversion units (boiler/CHP)). It excludes other activities on site that are not part of this process, such as: sawmilling activities, woodworking activities, production of chemicals for sale, waste treatment (treating waste onsite instead of offsite (drying, pelletising, incinerating, landfilling), PCC (precipitated calcium carbonate) production, treatment of odorous gases, and district heating.

(**) Includes the processes which are parts of the paper production process, such as: paper or board machine and connected energy conversion units (boiler/CHP) and direct process fuel use). Other activities on site that are not part of this process such as sawmilling activities, woodworking activities, production of chemicals for sale, waste treatment (treating waste onsite instead of offsite (drying, pelletising, incinerating, landfilling), PCC (precipitated calcium carbonate) production, treatment of odorous gases and district heating are not included.

Source: JRC compilation from RISI and the carbon leakage decision (RISI, 2016).

The distribution of pulp and paper products per type of mills is shown in Figure 7.

Figure 7. Type of mills for pulp and paper products in the EU

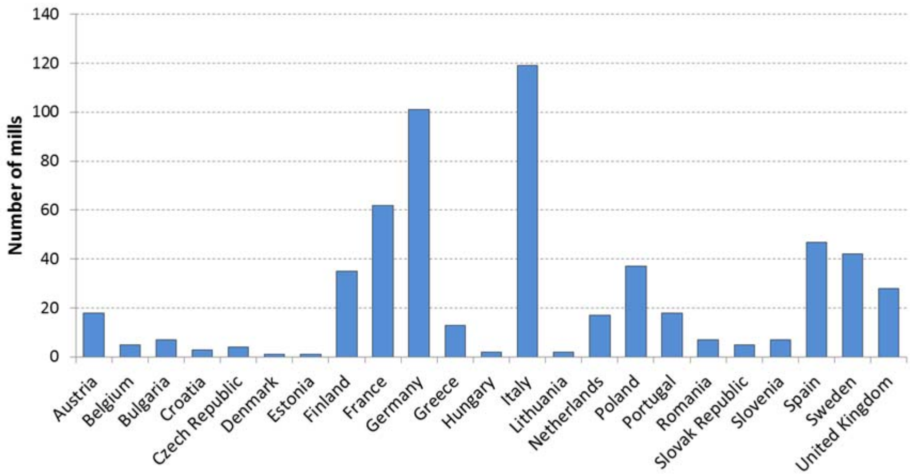


Source: JRC representation with information from RISI, 2016.

Kraft pulp (short and long fibres) is produced exclusively in integrated mills. Regarding the paper products, 79% of testliner and fluting and uncoated cartonboard products are produced in those mills that mostly use recycled fibres. Overall, the 'recycled' mills cover the whole spectrum of paper products manufacturing (Figure 7).

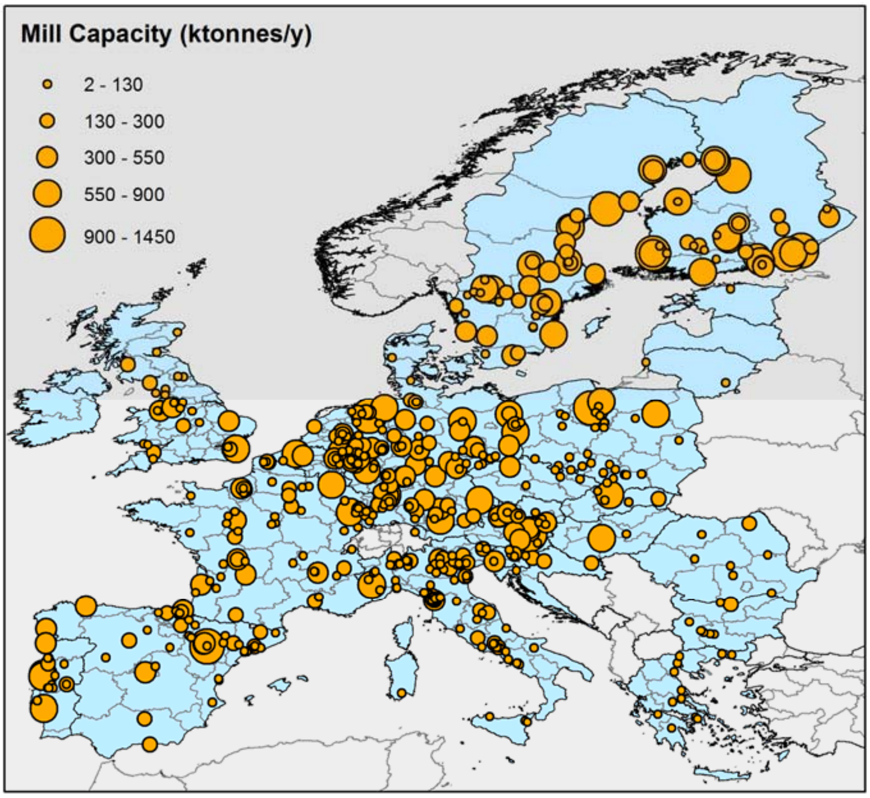
According to the RISI database, in 2015 there were 581 mills operating in the EU for producing the pulp and paper products listed in Table 1 (Figure 9). These mills are distributed in 23 Member States, mainly in Italy (119 mills), Germany (101 mills), France (62 mills), Spain (47 mills), Sweden (42 mills), Finland (35 mills) and the UK (28 mills) (Figure 9). All other Member States have less than 20 mills or none at all.

Figure 8. Distribution of pulp and paper mills per EU Member State



Source: JRC representation with information from RISI, 2016.

Figure 9. Geographically location of pulp and paper mills in the EU

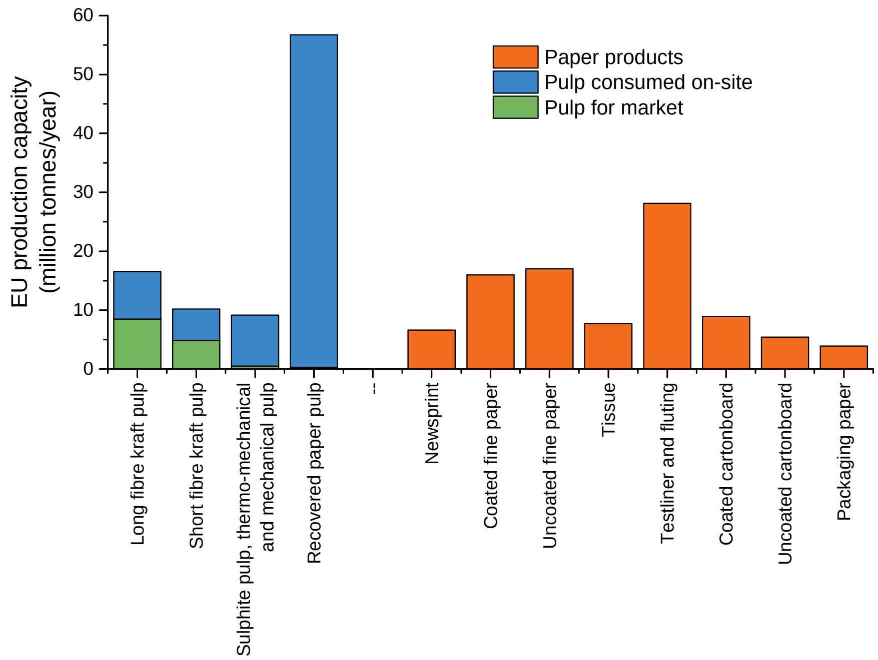


Source: JRC representation with information from RISI, 2016.

In 2015, the total production capacity of pulp in the EU was estimated at about 36.9 million tonnes virgin pulp and 56.7 million tonnes of recycled pulp (RISI, 2016). About 85% of the total capacity of pulp (virgin and recycled) is used for on-site transformation of pulp into paper products in integrated, semi-integrated and recycled mills, while 15% of production capacity is allocated to market pulp, mainly at non-integrated mills. In the same year, the estimated total production capacity of paper products was about 93.6 million tonnes (RISI, 2016).

The EU production capacity per pulp and paper products is shown in Figure 10.

Figure 10. Production capacity of pulp and paper products in the EU, 2015



Source: JRC representation with information from RISI, 2016.

The EU has a large capacity of pulp production from recycled paper, about 56.7 million tonnes per year, which amounts to 61% of total EU pulp production capacity. Regarding paper products, testliner and fluting have the largest production capacity (30% of the total paper production capacity), followed by uncoated fine paper (18.2%) and coated fine paper (17%). The capacity share of each of the remaining paper products is below 10%.

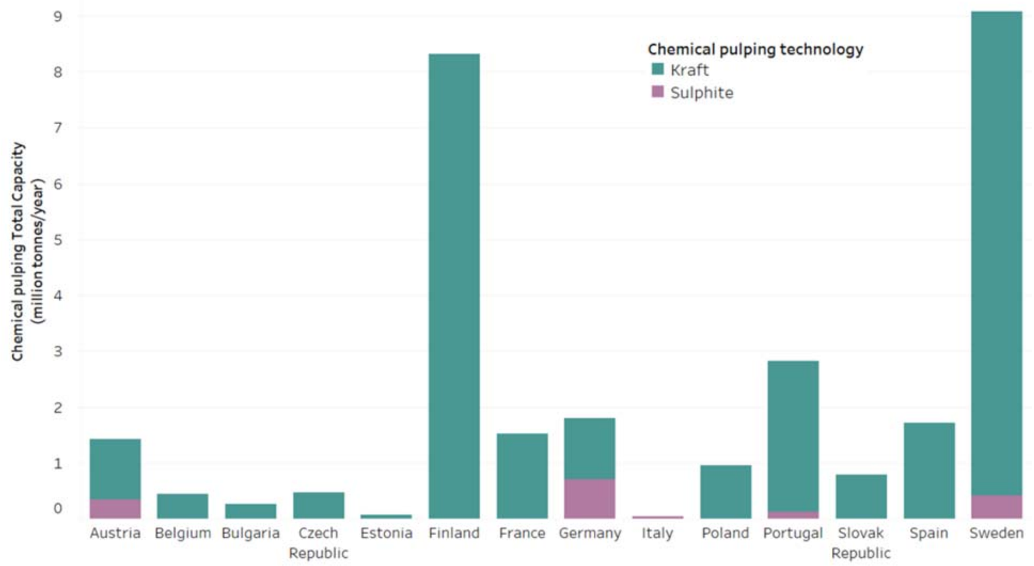
The following charts give information per EU country of the production capacity of virgin pulp (chemical pulping — Figure 11, and mechanical and chemi-mechanical pulping — Figure 12) and repulping of imported pulp, mechanical cleaning of recovered paper and deinking equipment for recovered paper (Figure 13).

In the EU, chemical pulping is spread over 14 countries, while mechanical and chemi-mechanical pulping is produced in 13 countries. The largest production capacity of chemical pulping is located in Sweden and Finland, together accounting for about 17.7 million tonnes per year (Figure 11). Portugal, Germany, Spain and Austria are also large producers of chemical pulp. About 95% of total chemical pulping capacity in the EU is based on the Kraft technology. Sweden and Finland are also the major producers of mechanical and chemi-mechanical pulping, followed by Germany, Italy and Austria (Figure 12).

Apart from virgin pulp production, the EU has a relatively large capacity for repulping the imported pulp and other pulp substitutes. The European production capacity for repulping accounts for over 19 million tonnes, being Germany, Italy and Finland the leading countries. The repulping process takes place mainly in non-integrated mills (Figure 13a).

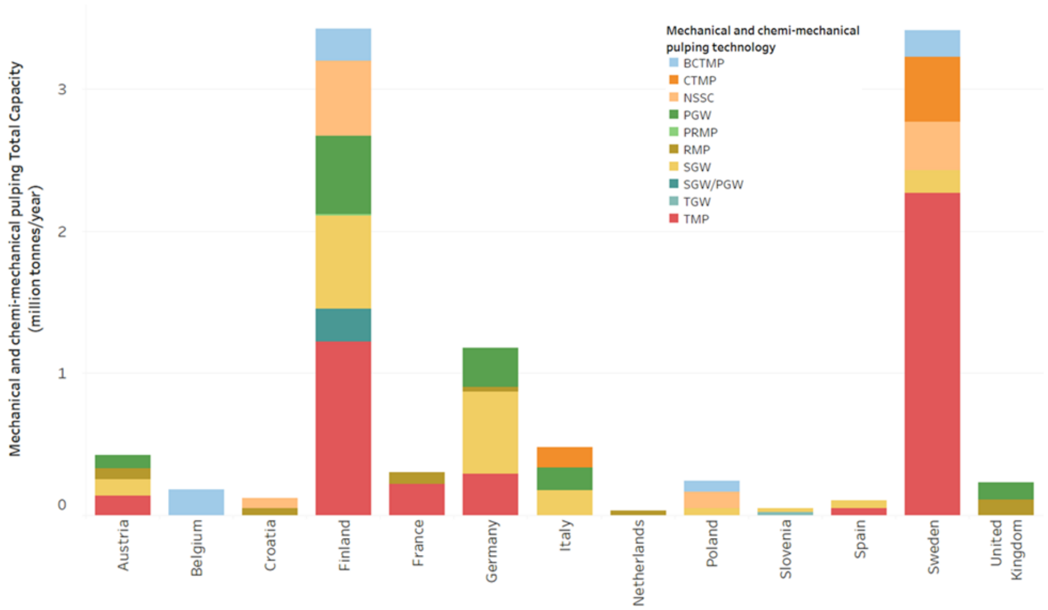
The EU is a forerunner in paper recycling. Mechanical cleaning and deinking are two important processes in paper recovery. For both, Germany is the leading country in terms of installed capacity and equipment (Figure 13b, c). The total EU capacity of mechanical cleaning and deinking equipment for recovered fibre is estimated at 31.4 and 11.5 million tonnes of finished pulp per year, respectively. The mechanical cleaning and deinking take place mainly in recycling mills.

Figure 11. Production capacity of chemical pulping per EU Member State



Source: JRC representation with information from RISI, 2016.

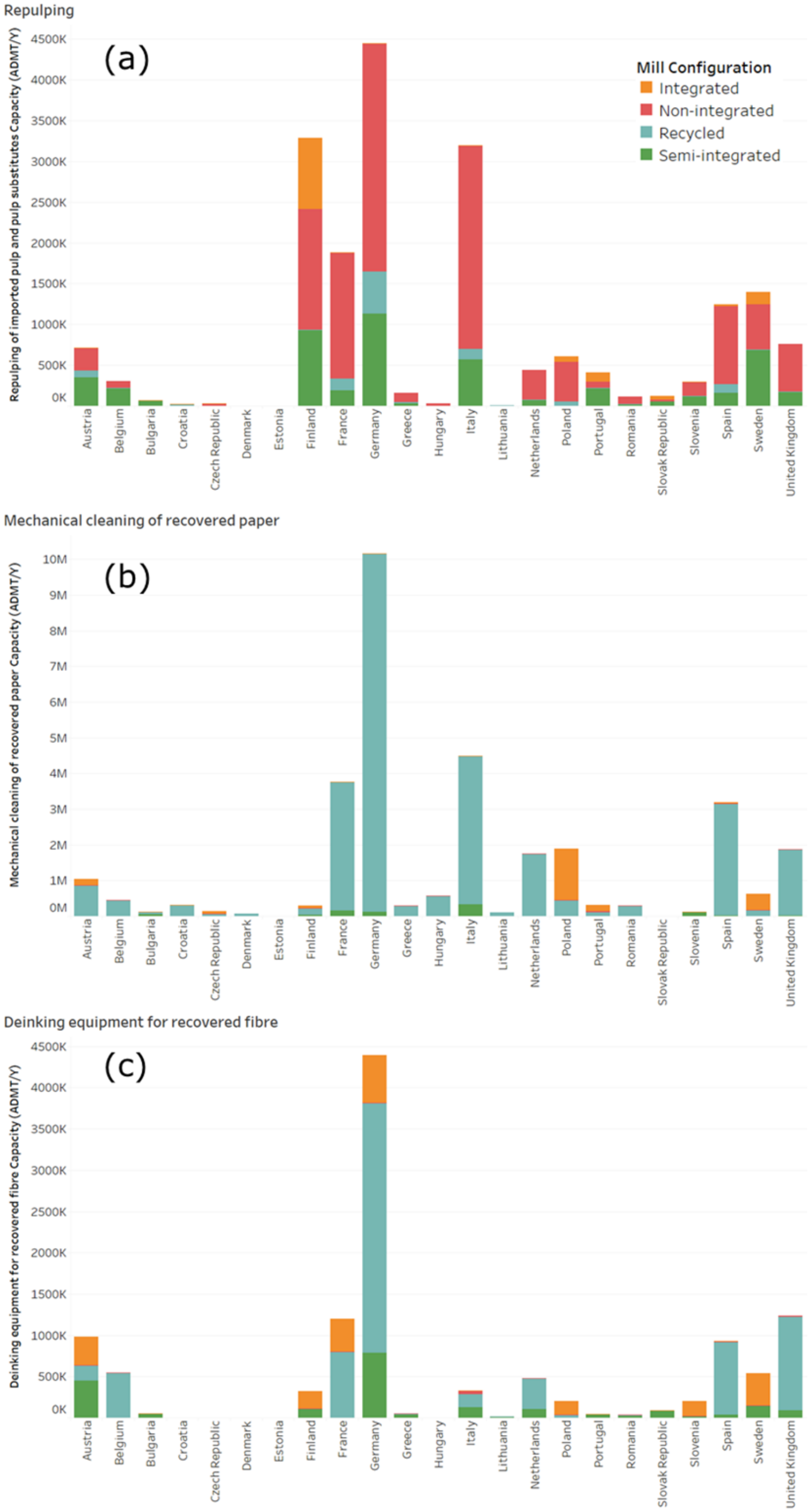
Figure 12. Production capacity of mechanical and chemi-mechanical pulping per EU Member State (5)



Source: JRC representation with information from RISI, 2016.

(5) PGW = Pressure Groundwood, SGW = Stone Groundwood, (P)RMP = (Pressurised) Refiner Mechanical Pulp), TMP = Thermomechanical Pulp, (B)CTMP = (Bleached) Chemi-Thermomechanical-Pulp) and NSSC = Neutral Sulphite Semi Chemical Pulping.

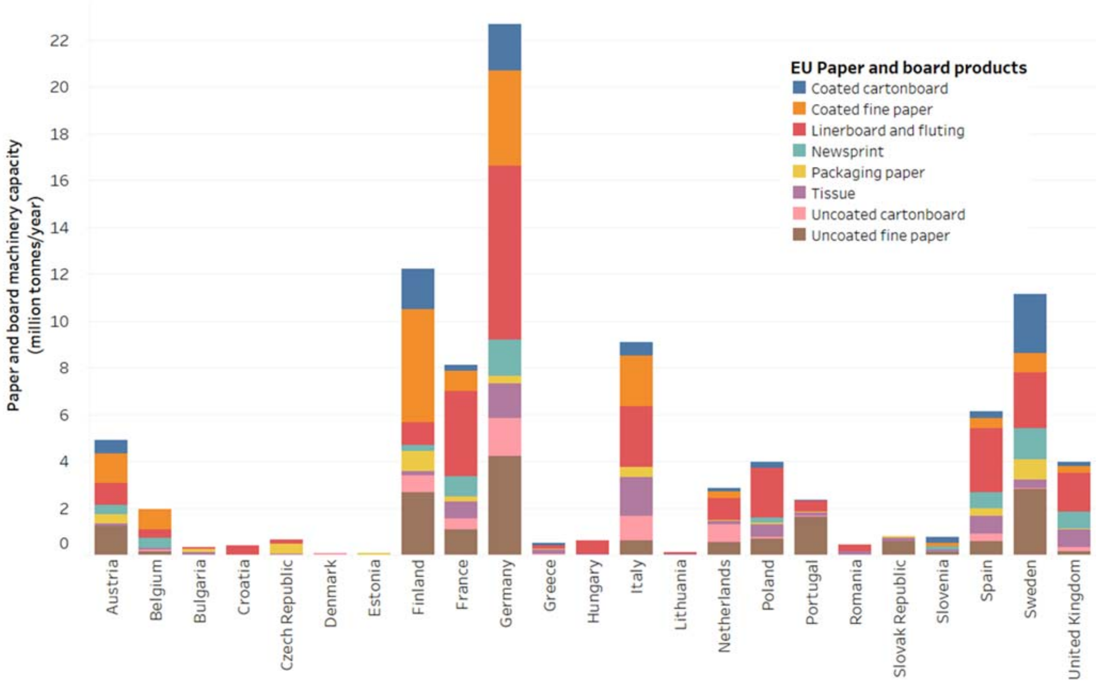
Figure 13. Production capacity of repulping of imported pulp and pulp substitutes (a), mechanical cleaning of recovered paper (b) and deinking equipment for recovered fibre (c)



Source: JRC representation with information from RISI, 2016.

Among the 23 EU Member States that manufacture various grades of paper, Germany is the main player in terms of paper and board machinery capacity, followed by Finland, Sweden and Italy (Figure 14). These three countries account for about half of the total production capacity for paper in the EU.

Figure 14. Production capacities of paper products



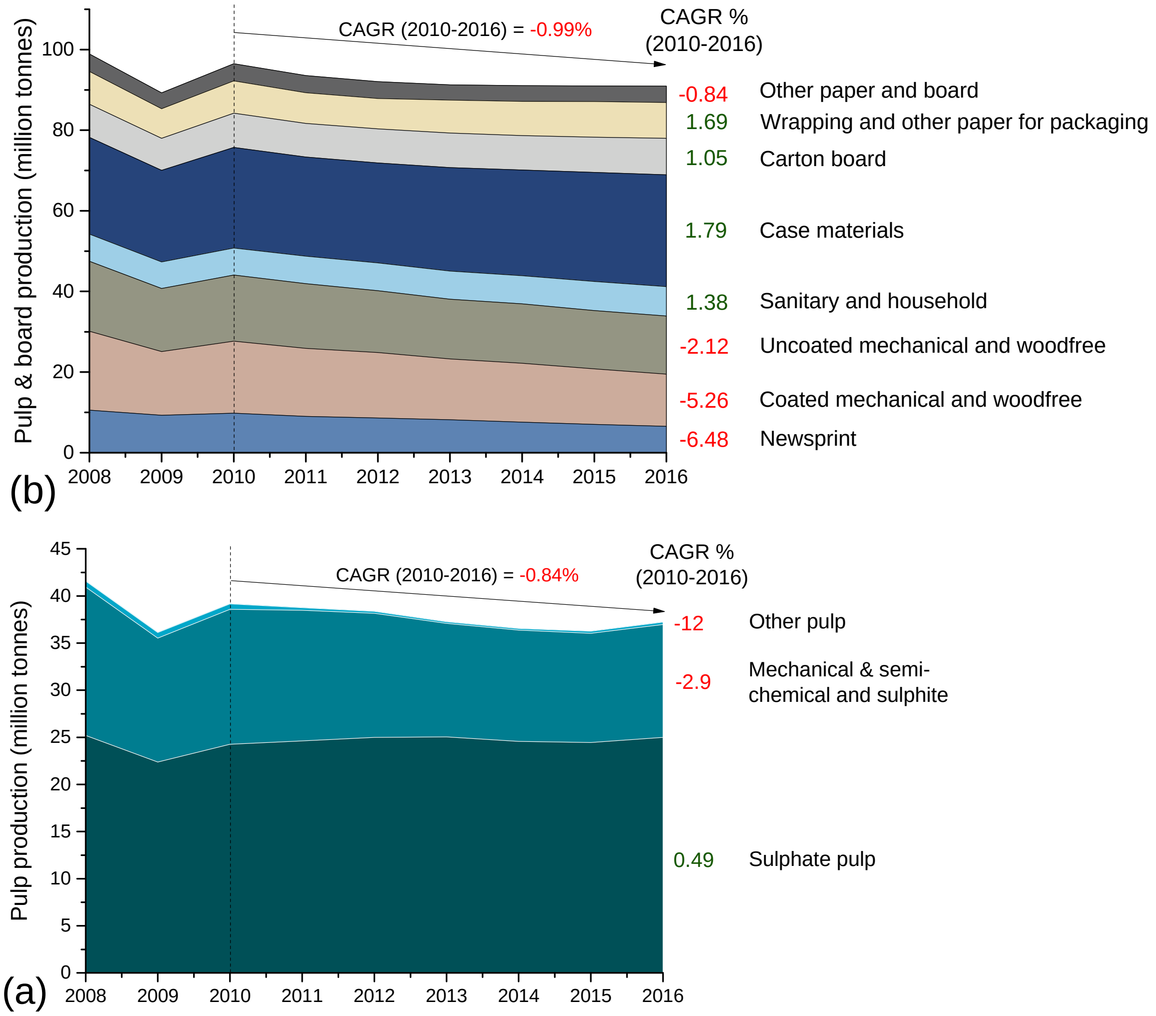
Source: JRC representation with information from RISI, 2016.

3.3 Production of pulp and paper in the EU and prospective production scenarios to 2050

Despite a partial recovery after the global financial crisis, up to now the European pulp and paper production remained below the maximum peak register in 2007. According to CEPI statistics, the total annual production of CEPI member countries has decreased during the period 2010-2016 at a compound annual growth rate (CAGR) of -0.84% for pulp and -0.99% for paper products (Figure 15). However, this trend was not the same for all pulp and paper products. In spite of the overall decline of the mechanical and semi-chemical and sulphite pulping production (in volume) at a CAGR of -2.9% during 2010-2016, the chemical sulphate (Kraft) pulping registered a 0.49% increase from 2010 (Figure 15a). In the EU, the recycling rate of paper waste has also improved to 71.9% in 2015 (from 62% and 68.7% in 2005 and 2010, respectively).

A significant decline in production was registered between 2010 and 2016 for graphic grade papers such as newsprint (CAGR = -6.48%), coated mechanical and wood-free products (CAGR = -5.26%) and uncoated mechanical and wood-free products (CAGR = -2.12%). This decline was also affected by the overall changes in the industry landscape, including digitalisation (Figure 15b). Due to increasing in demand for consumer goods packaging, tissues and hygiene products, the production of packaging grade papers (e.g. case materials, cartonboard, wrapping and other paper for packaging) and sanitary and household products grew by a CAGR > 1% over the same period of time.

Figure 15. Production of pulp (a) and paper (b) products by CEPI member countries, 2008-2016



Source: JRC representation with data from CEPI statistics.

In 2015, the global production volume of paper and cartonboard was 407.6 million tonnes (Statista, 2017). Driven by increasing global consumption, especially in Asia, and based on the assumption of per-capita demand in different regions, it is expected that the world paper production will increase to about 700 million tonnes in a low-demand case and over 900 million tonnes in a high-demand case by 2050 (IEA, 2009). To meet this increasing demand, the worldwide pulp and paper industry will need to go through structural changes (e.g. switching paper machines from graphic paper into cartonboard) and consolidate the market segments that are well positioned for growing (McKinsey, 2017). For example, over the next decade the demand market for tissue and consumer/industrial packaging is expected to grow almost on par or somewhat below GDP. On the other hand, the global demand for graphic paper will decline further as consequence of digital communication.

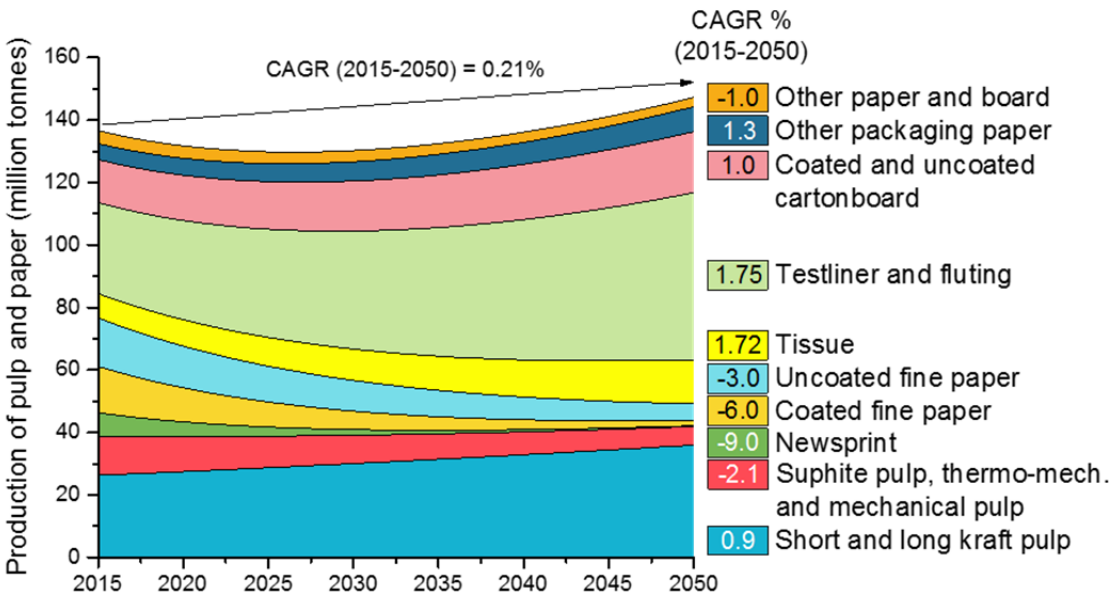
In the medium term, the increasing requirements for stronger, lighter-weight packaging paper will drive the demand for both short (hardwood fibre) and long (softwood fibre) kraft paper and the waste paper recovery will continue to improve. Moreover, pulp market for textile applications will also be growing.

The European market for pulp and paper products will follow somewhat the global trend. The growth rates of the market demand among different segments for the main global regions by 2021 were analysed in a recent study carried out by McKinsey and Company

(McKinsey, 2017). According to McKinsey estimations, in the west European countries, the market demand for graphic paper (i.e. mechanical, newsprint and wood-free) and long fibres (softwood) kraft pulp will continue to decrease in the next years, while tissue, packaging paper and short fibre (hardwood) kraft pulp will increase at a CAGR ranging between 0 – 2 %. In eastern Europe, the market demand for all products mentioned above will increase at a CAGR > 2 %, with exception of newsprint (CAGR < 0 %) and graphic paper wood-free (CAGR = 0-2 %).

The total production of pulp and paper in EU is projected by ICF Consulting Limited to increase slowly at a CAGR of 0.21 % from 2015 to 2050 (ICF, 2015). In this study, the same growing rate has been assumed for the overall pulp and paper production in EU as of 0.21 % CAGR (2015-2050). In order to estimate the increasing/decreasing rates of different production segments in the EU by 2050, we have taken into account the historical data from 2008 to 2016, according to CEPI statistics, as well as the growth prospects of market demand by 2021 (McKinsey, 2017). These trends were integrated with the increasing added value of pulp and paper sector estimated at CAGR = 0.79 % from 2015 to 2050 in the EU Reference Scenario (European Commission, 2016b). The contribution of each pulp and paper product to the sectoral added value by 2050 was calculated based on the average prices in 2015 as retrieved from the Eurostat's Prodcom list (Eurostat, 2017). In order to estimate the future European pulp and paper production, we assume that use external trade will remain constant at 2015 values during the whole simulation. The estimated growth rates are presented in Figure 16.

Figure 16. Assumption of production growth rates of pulp and paper in the EU by 2050.



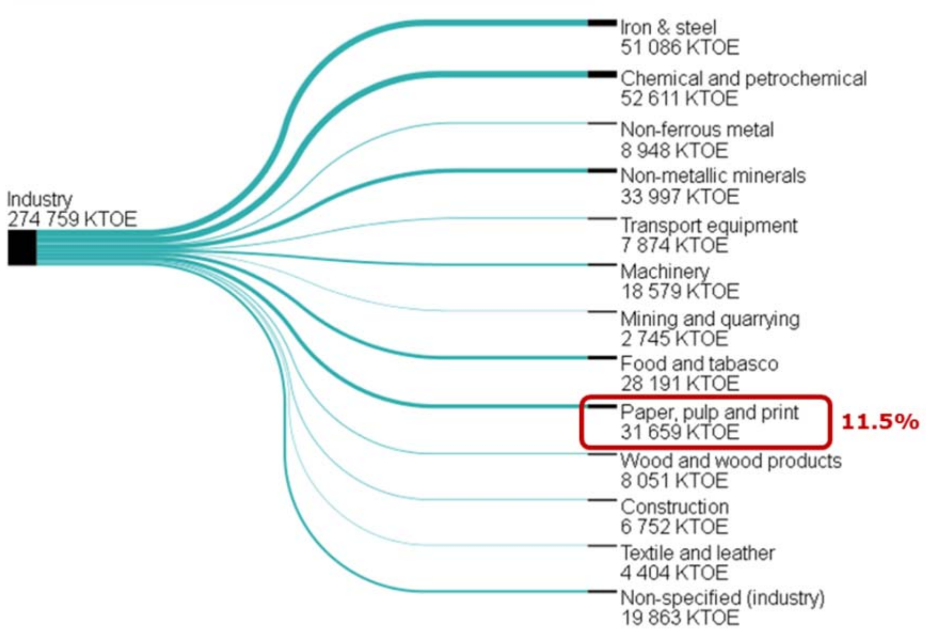
Source: JRC analysis.

In the simulation presented in Chapter 7, we assume positive growth rates for chemical kraft pulping and for a series of paper products such as tissue and packaging grade papers (testliner and fluting, and cartonboard). Production of sulphite pulp, thermo-mechanical and mechanical pulp is estimated to decrease in the EU by 2050, as well as for newsprint and fine paper.

4 Current energy consumption and GHG emissions

The pulp, paper and printing manufacturing is the fourth largest industrial energy user in the EU after chemical and petrochemical, iron and steel and non-metallic minerals sectors (Figure 17). In 2014, this sector consumed 31 659 ktoe (equivalent of 1 325.5 PJ), accounting for 11.5 % of final industrial energy consumption in the EU (Eurostat, 2016).

Figure 17. Sankey diagram of final energy consumption in the EU industrial sectors in 2014



Source: Eurostat, 2016.

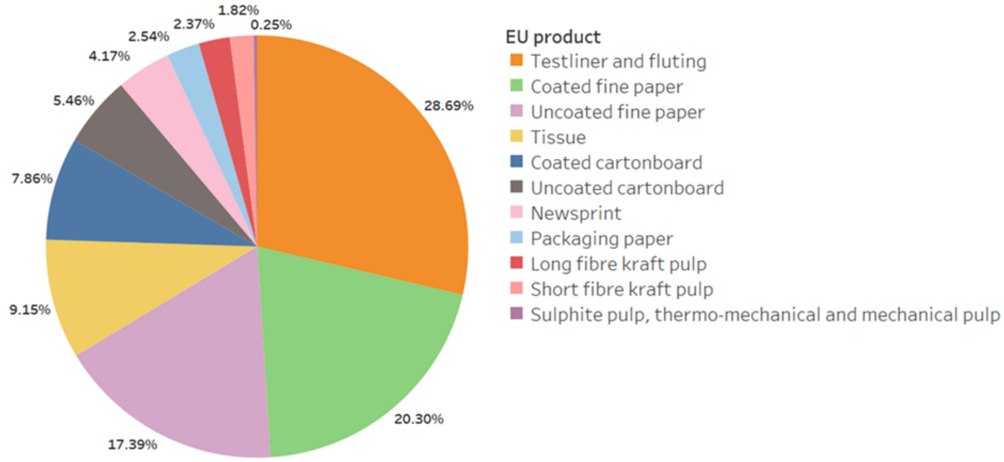
Despite its high energy consumption, the pulp and paper industry is one of the least CO_2 intensive industrial sectors in Europe and worldwide. This is due to the large utilisation of biomass as a primary energy source, which is considered as carbon-neutral by the Intergovernmental Panel on Climate Change (IPCC). In 2015, 57.7 % of total fuel consumption in the CEPI's member countries originated from biomass, followed by natural gas (34.7 %), coal (3.9 %), fuel oil (1.7 %) and other type of fuel (2 %) (CEPI, 2017).

The pulp and paper sector can play an important role to the decarbonisation of the EU economy by adopting new energy efficient technologies and by making more efficient use of bioenergy. Modernisation of old mills, fuel switching to carbon neutral/renewable energy and improving productivity and quality of products represent additional solutions for reducing energy consumption and CO_2 emissions.

Apart from the direct CO_2 emissions generated at the pulp and paper mills, additional emissions are associated with the off-site production of energy (i.e. steam and electricity) that is purchased and transferred to the mills. The total CO_2 emissions generated in 2015 by the European forest fibre and paper industry accounted for 49 million tonnes, of which 65.3 % come from direct emissions and 24.5 % from indirect emissions (CEPI, 2016). According to the '2050 Roadmap to a low carbon bio-economy' developed by the CEPI, it could be possible to bring down the CO_2 emissions to 12 million tonnes by 2050 (CEPI, 2016). However, this CO_2 reduction might happen under certain circumstances and with the adoption of emerging and breakthrough technologies.

According to RISI's model (RISI, 2016), the fossil fuel CO_2 emissions based on the installed capacity of the European pulp and paper mills are around 39.7 million tonnes per year The breakdown of fossil CO_2 emissions per product is shown in Figure 18. These emissions have been calculated based on the specific consumption of fuel (e.g. oil, natural gas, liquefied natural gas, peat and coal) used when all mills are operating practically at their full capacity. Production capacity of testliner and fluting, together with coated fine paper account for about half of the total yearly CO_2 emissions followed by uncoated fine paper, tissue and coated cartonboard.

Figure 18. Fossil CO_2 emissions per production capacity of pulp and paper products in the EU

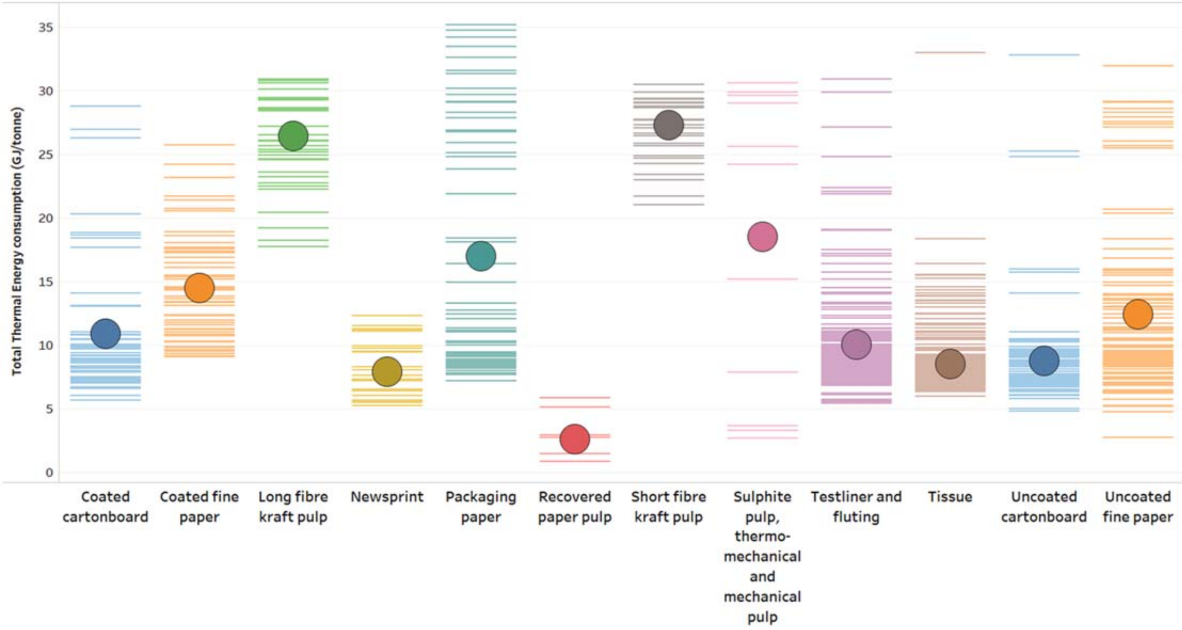


Source: JRC representation with information from RISI, 2016.

Overall, about 93 % of the total energy consumption by the European pulp and paper sector is as heat power, used mainly for the generation of pressurised steam, and about 7 % as electricity. The thermal energy in the form of steam is used for heating of various products (e.g. water, pulp fibres, air, chemicals, cooking liquor, etc.), evaporation of water from spent liquors and in the dryer section of a paper machine, dispersion of fibres derived from recycling paper, drying of coated paper, etc.

The specific thermal energy consumption varies largely between different technologies and products, depending on the process used, fibre quality and grade of paper needed to be produced. Figure 19 shows the specific thermal energy consumption per mill's capability to produce the 12 pulp and paper products analysed in this study, the average energy consumption as well as the energy used by the best available technology.

Figure 19. Specific thermal energy consumption per pulp and paper capacities in the EU. Circles denote the average energy consumption



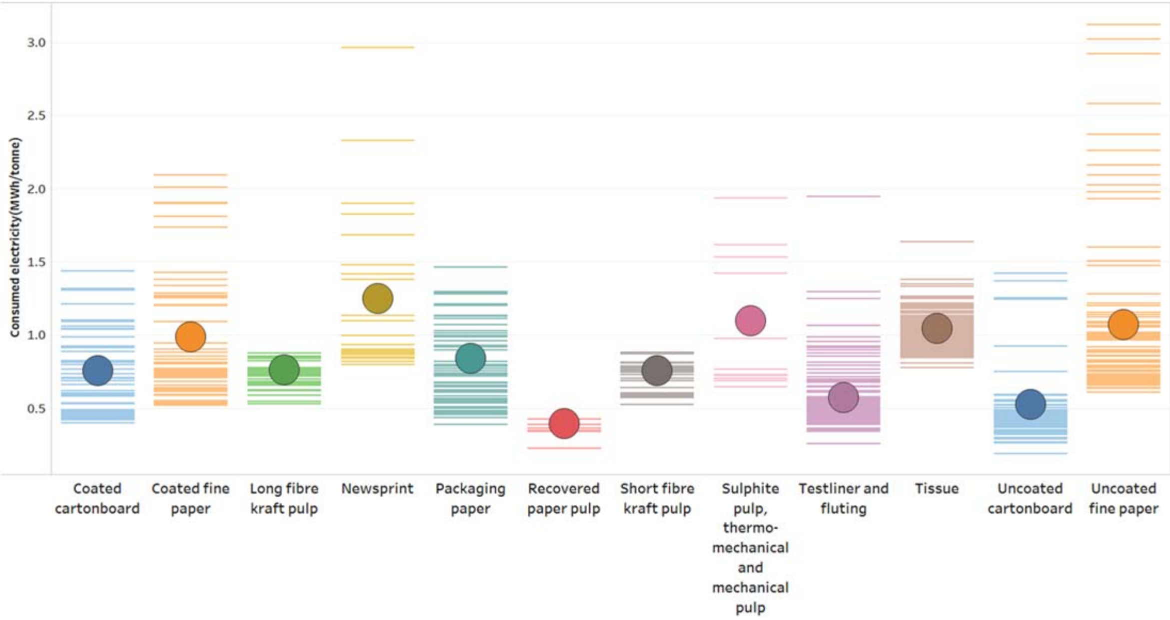
Source: JRC representation with information from RISI, 2016.

According to RISI's model/data, when operating at its full capacity, the total thermal energy consumption of the European pulp and paper industry amounts to 1 522 PJ (RISI, 2016). The thermal energy consumption for each product varies between wide ranges. For example, the thermal energy needed to produce 1 tonne of packaging paper can vary from 35.2 GJ/t to 7.3 GJ/t. This means that there is a high potential for energy reduction through adopting more energy-efficient processes and technologies. Pulp production, especially kraft pulping, has the highest average energy intensity. For example, the average thermal energy consumption for making kraft pulp is 26.4 GJ/t, which is about 1.4 times higher compared to sulphite, thermomechanical and mechanical pulping (18.4 GJ/t) and 8.3 times higher than the energy used for repulping the recycled paper (3.2 GJ/t). However, energy can be recovered from both chemical and mechanical pulping. Heat can be recuperated from mechanical pulping process in the form of hot water or steam and further used, either for paper drying in an integrated mill or in district heating. Thermal energy and electricity can also be recovered from chemical processes by burning the by-products such as bark and black liquor. This allows modern non-integrated kraft pulp mills to be more energy sufficient, or even become net energy suppliers.

Among paper products, packaging and fine paper are the most thermal energy intensive; On average, the energy consumption per either tonne of packaging paper, coated fine paper or uncoated fine paper of is 17 GJ/t, 14.6 GJ/t or 12.6 GJ/t, respectively.

Although the average electricity consumption range for different pulp and paper products is much narrow in comparison to the thermal energy, for the same product the consumption of electrical power varies broadly between different mills' capabilities (Figure 20). Overall, the average electricity consumption ranges between 1.23 MWh/t for newsprint to 0.35 MWh/t for recovered paper pulp.

Figure 20. Specific electricity consumption per pulp and paper capacities in the EU. Circles denote the average power of the electricity consumption

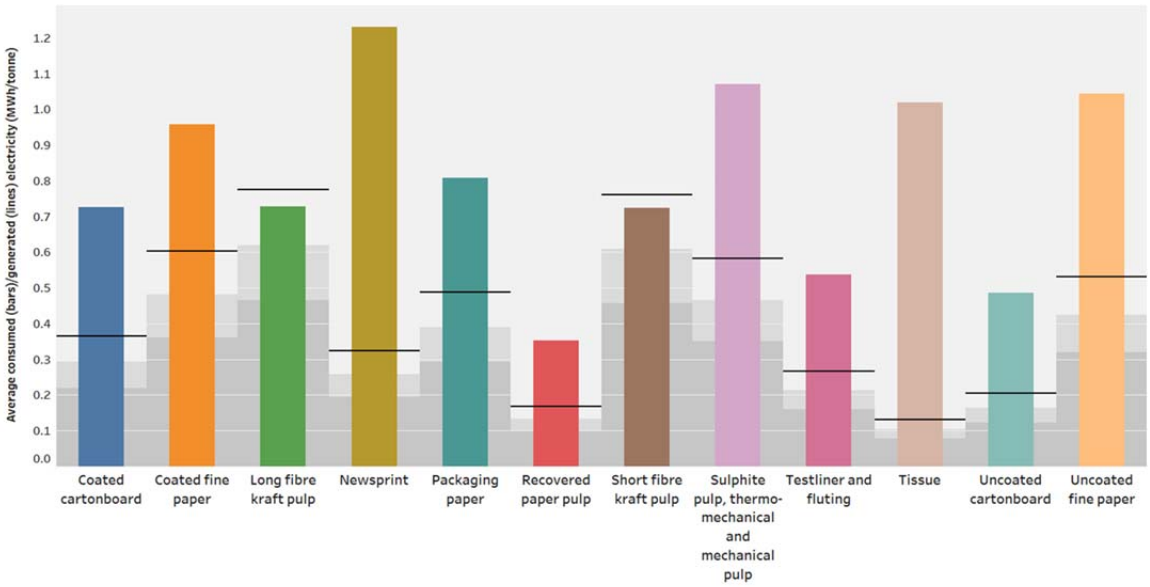


Source: JRC representation with information from RISI, 2016.

In mechanical pulping, the electricity is mainly used for separation of wood fibres, and in paper machines, for pressing and drying of coatings. According to CEPI statistics, 52.3 % of the total electricity consumption (i.e. 99 937 GWh) by its members was produced on-site in 2015, which accounts for 52 308 GWh, (CEPI, 2017).

On average, kraft pulping produces more electricity than it consumes (Figure 21).

Figure 21. Average specific electricity consumed (bars) and produced (horizontal lines) on site per product capacity



Source: JRC representation with information from RISI, 2016.

The potential of reducing energy demand through improved process integration and adopting more efficient equipment in pulp and paper mills is the subject of the following chapters.

5 Measures for improving energy efficiency and reducing GHG emissions

Most GHG emissions in this sector are related to energy consumption through on-site combustion of fuels and off-site generation of steam that is purchased and transferred to the mill. Additionally, there are non-energy related GHG emissions derived, for example, from lime kiln chemical reactions and wastewater treatment.

Many opportunities already exist and other will become available in the future to reduce energy consumption and GHG emissions in the pulp and paper sector. These opportunities can be divided as follows:

— general measures, such as energy management systems, process integration, new equipment and efficient modes of operation;

— increasing on-site use and production of energy from biomass residues (fuel switch) and expanding the adoption of combined heat and power (CHP) technology;

— retrofitting the existing mills with energy-efficient technologies (e.g. BATs). In general, BATs have low- to medium costs with relatively short payback periods and energy savings; however, the investment cost and competitiveness remain determinant factors in adopting these technologies;

— increased use of recovered paper and paper recycling; a reduction of about 37 % in CO_2 emissions is estimated by substituting virgin wood with recycled fibres (Roth et al., 2016);

— development and adoption of emerging and breakthrough technologies;

— development and growth of new bio-based products from renewable solutions, etc.

To achieve the reduction targets of GHG emissions of 75.5 % by 2050 compared with 2015 as proposed by CEPI in the '2050 Roadmap to a low-carbon bio-economy' (CEPI, 2011), all these measures need to be tackled.

Implementing the best available technologies, switching from fossil fuel to biomass in combination to CHP and adopting breakthrough technologies are identified as the most effective measures for reducing the CO_2 emissions from the European forest fibre and paper industry. According to the industry (CEPI, 2016), by 2050, direct emissions from this sector can be cut by 20 million tonnes CO_2 by adopting these three measures, the equivalent of 62.5 % of the direct emissions registered in 2015 (CEPI, 2016). In particular, it is estimated that the adoption of energy efficient technologies might lead to a reduction of 7 million tonnes of CO_2, fuel switch to 8 million tonnes of CO_2 and breakthrough technologies to 5 million tonnes of CO_2 by 2050 (CEPI, 2016).

Regarding the reduction of energy consumption, a previous study conducted by ICF Consulting Limited showed that despite a gradual increase in pulp and paper production through 2050, there is a potential to achieve relevant improvements on energy efficiency (ICF, 2015). According to this reference, under a business-as-usual (BAU) scenario, the maximum energy saving potential technically feasible in the EU pulp and paper sector can reach 17 % by 2050 (5.5 Mtoe) based upon the application of current available energy saving opportunities (ESOs), regardless of its economic viability.

All the numbers provided in previous paragraphs may be used as a reference to contrast the results provided in this study, in which we analyse the role of technology and its implementation at mill level in the EU pulp and paper industry, based on a bottom-up model. This aim of this study is to determine the potential evolution of energy consumption and CO_2 emissions for the industry up to 2050 under certain assumptions, its variability and impact of technology and policy options.

This chapter describes the best available technologies (BATs) and emerging (breakthrough) technologies (ETs) that the pulp and paper might adopt leading to increasing the process energy efficiency.

5.1 Best available technologies

Best available technologies (BATs) represent the most effective and advanced (state-of-the-art) technologies that can be applied in different stages of an industrial process aiming at improving the efficiency of environmental protection. These technologies indicate the practical suitability of a particular measure which can enable a significant reduction in energy consumption and CO_2 emissions as well as reduction of emissions of pollutants to water, material waste, etc. This section discusses the BATs identified from the literature, their investments costs and energy savings. The model described and used in next two chapters limits the analysis of the applicability of BATs to those whose presence is identifiable at facility level in the RISI database.

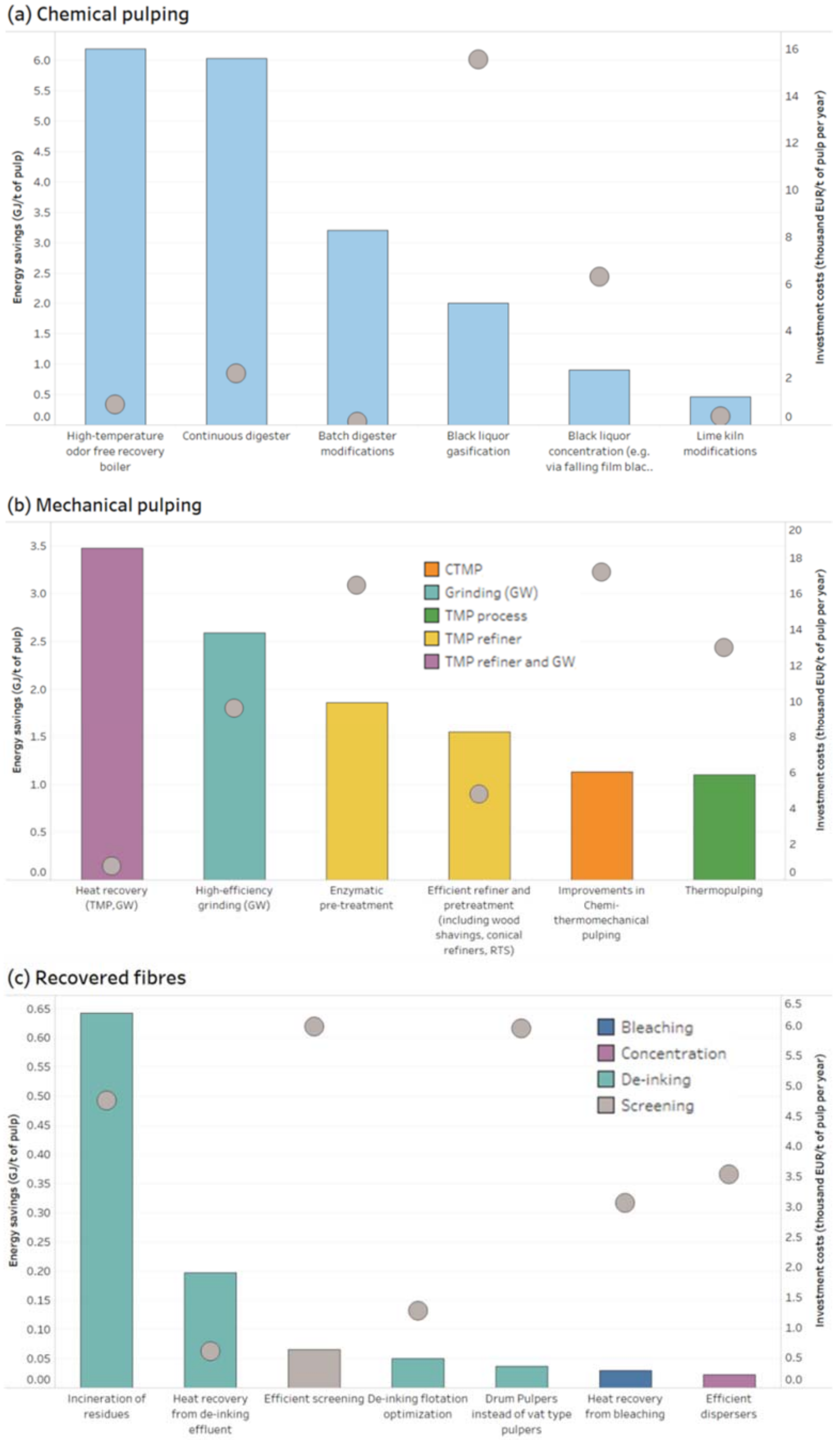
In Europe, the European Commission's IPPC Bureau establishes under the Industrial Emissions Directive (IED)/2010/75/EU the best available techniques reference documents, the so-called BREFs that have to be adopted by the industries. For the production of pulp, paper and board, a new BAT conclusions reference document was published on September 2014 containing the legally binding requirements needed to be considered and adhere to them by all European pulp and paper mills (European Commission, 2014). 62 best available techniques were identified in relation to reduction of fuel and energy consumptions (thermal and electrical), and increasing energy efficiency in power generation for the production of pulp, paper and board (Annex 1). These BATs are applicable to various activities performed by industrial installations in integrated and non-integrated mills for production of pulp from wood or non-wood fibrous material and paper or cartonboard with a production capacity higher than 20 tonnes per day. They cover the five major types of mills existing in pulp and paper sector, such as: (i) kraft pulp mills, (ii) sulphite pulp mills, (iii) mechanical and chemi-mechanical pulp and paper mills, (iv) mills that process paper for recycling and (v) non-integrated mills including speciality paper mills.

The adoption the BATs, operational improvements alongside with advanced process monitoring and management systems will increase energy efficiency. Energy management system technique includes the following features: (i) assessment of the mill's overall energy consumption and production, (ii) locating, quantifying and optimising the potentials for energy recovery and (iii) monitoring and safeguarding the optimised situation for energy consumption. For example, when applying the energy-saving measures for Kraft pulping, the indicative electrical energy consumption that can be achieved for a market pulp mill can vary in range of 660 – 750 kWh/air dried tonne (ADt) (Suhr et al., 2015). This value does not include the energy required for producing the bleaching chemicals and if it performed on-site adds 100 kWh/ADt to the previous indicative level. Due to the higher yield of eucalyptus wood compared to softwood, recently built eucalyptus market kraft pulp mills have a lower electrical energy demand. The indicative energy consumption levels for eucalyptus pulp are 550 – 700 kWh/ADt.

While the legally binding decision published on 26 September 2014 (European Commission, 2014) request all European pulp and paper mills to consider the new BAT conclusions by October 2018, their adoption and penetration might depend on several factors such as cost effectiveness, payback period, age of mills and equipment, existing capital stock, investment cycles, location of the plant, etc. In practice, companies will move towards BATs depending on their rate of investments in new technologies either at the end of the economic life of a component of the mill or when a major retrofitting is required.

The International Energy Agency (IEA) underlines the energy efficiency investments for pulp and paper sector and gives information about energy saving potential and investment cost for the most relevant best available technologies (IEA, 2014). In total, IEA describes 31 BATs related to the main processes of the industry: pulping (chemical, mechanical and recovered fibres) (Figure 22) and papermaking (Figure 23). In the following figures, the values provided in the previous reference have been converted from USD to EUR in 2015.

Figure 22. Energy saving potential (bars) and investment costs (circles) for pulp production by chemical (a), mechanical (b) and from recovered fibres (c)



Source: JRC representation with information from the IEA, 2014.

For the chemical pulping process, there are several technologies by which significant savings in production costs and additional revenue generation can be achieved. Heat recovery boiler (high temperature) and continuous digesters are two relevant BATs that offer the greatest opportunities for energy savings, of about 6 GJ per tonne of paper each, at reasonably low investment cost (EUR 860/tonne pulp per year for high-temperature recovery boiler, and EUR 2 190/tonne pulp per year for continuous digesters). The **recovery boilers** contribute to increasing the energy generation at a plant by firing black liquor with high dry solids content. Most high energy-efficient boilers have an increased power-to-heat ratio by utilising feedwater heating, combustion air preheating, flue-gas heat recovery and especially higher steam temperatures and pressures, which allow achieving up to 560-600 °C and 110 bar (Suhr et al., 2015). If all features are incorporated into the boiler design, the total power generation can increase by 16 % compared to the baseline case (Suhr et al., 2015).

Separation of the wood fibres during the cooking process can take place either in batch digesters or in a **continuous digester**. Improving digester performance can lead to significant reduction of operation cost and production losses, while improving the paper quality and energy/environmental emissions efficiency. Wood and chemical charge, retention time, and the temperature in the cooking zone are several parameters which influence the pulp quality (e.g. low lignin content). The energy performance of the cooking process can be improved in by several **modification methods**, such as modified continuous cooking (MCC), extended modified continuous cooking (EMCC), isothermal cooking (ITC), and low solids cooking (LSC). These modification methods can be applied also to batch digesters in smaller mills, where it might be not operationally efficient to switch to larger batch or continuous digesters, leading to energy savings of 3.2 GJ/tonne of pulp at a low investment cost of EUR 130/t of pulp per year (IEA, 2014).

The most effective energy-efficient technique for mechanical pulping is the **heat recovery** produced as a by-product, especially in the thermomechanical (TMP) process. This BAT combines a high energy saving (about 3.5 GJ/t of pulp) with a low investment cost (EUR 780/t of pulp per year) (IEA, 2014). Payback periods for this method can be a few months, depending on capital cost (Kramer et al., 2009). Most of the energy used in mechanical pulping is converted into heat through friction, as only a portion of the mechanical work is used to separate fibres from the wood. This heat can be recovered by using specific equipment and used further as hot water or steam. The methods used in heat recovery include: (i) mechanical vapour recompression used in integrated mills for dryer section, (ii) generation of hot water in direct contact heat exchangers, (iii) production of clean process steam in reboilers and (iv) other techniques such as thermos vapour recompression, cyclotherm, heat pump systems (Kramer et al., 2009). The applicability of these methods depends on the type of refiners and design of the TMP plant. Old mills that use pressurised refining are at first instance suitable for this technology, as the most modern TMP mills are already designed with heat recovery systems. The highest potential for heat recovery is from processes carried out in pressurised refiners. For example, for a TMP process operating at 6 bar, up to 2 tonnes of steam per tonne of pulp can be produced, the equivalent of 1 tonne of steam per MWh of the refiner (Suhr et al., 2015). In general terms, up to 80 % of energy input could be recovered as steam from TMP and an additional 10-20 % as hot water (Suhr et al., 2015). Heat can be recovered also from other mechanical pulping processes (e.g. groundwood pulp (GW), pressure groundwood pulp (PGW), chemi-mechanical pulp (CMP) or chemi-thermomechanical pulp (CTMP). However, the share of energy recovered as steam from these processes is much lower compared to TMP.

Other BATs for mechanical pulping are: **high-efficiency grinding (GW), enzymatic pre-treatment, efficient refiner and pre-treatment, improvements in chemi-thermomechanical pulping and thermopulping**, but these opportunities are associated with higher investment costs (Figure 22b).

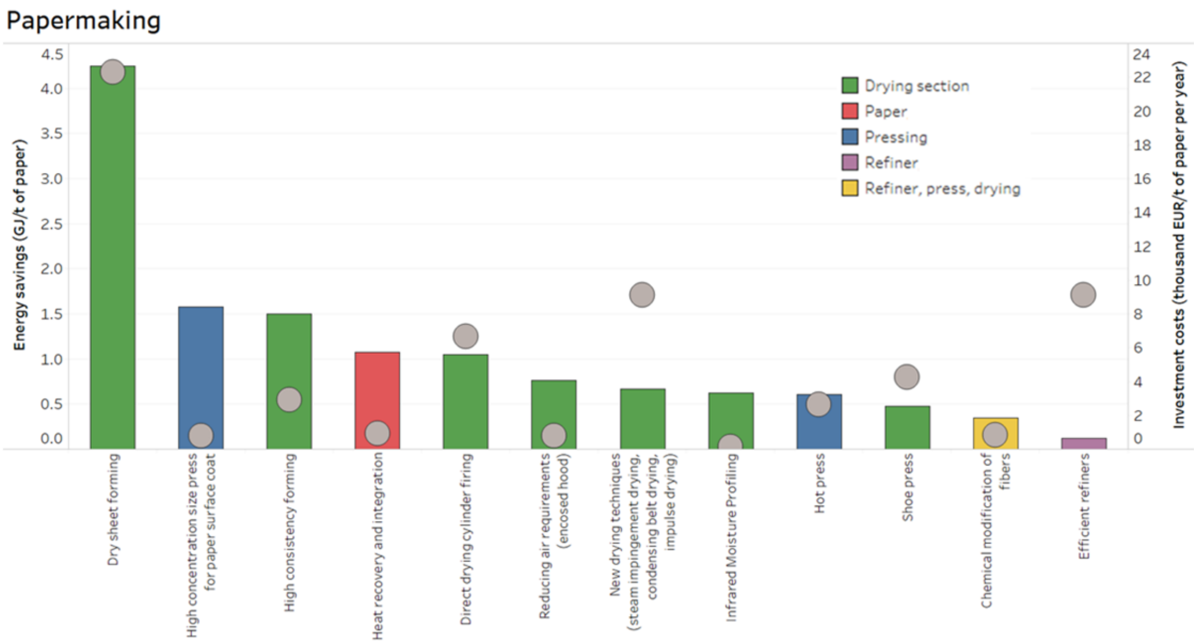
Although the total energy needed for repulping of recovered paper (secondary fibres) is much lower compared to chemical or mechanical pulping, the processing of recycled fibres still require substantial amount of steam and electrical power for heating the ingredients for repulping, removal of impurities and especially for drying of final paper products. Since in many cases the energy comes from fossil fuels, the production of pulp from recovered fibres is often more CO_2 intensive than the production of chemical pulp. In general, two main processes are used for processing of recycled paper, depending of the paper grade and type of furnish used: (i) processes using mechanical cleaning without deinking (e.g. for paper products like testliner, uncoated board and cartonboard) and (ii) processes using mechanical cleaning and deinking (e.g. for newsprint, tissue, coated board, etc.).

Removing the ink from recycled fibres contributes to increasing the brightness and cleanliness of paper. Deinking is a necessary step in the plants producing paper grades from recycled fibres for which brightness is important, such as printing paper, newsprint and tissue. Various types of deinking technologies can be applied depending on the type of recycled paper and requirements of the new product. The ink can be removed by washing and flotation. The recovered pulp could be further brightened through a bleaching process using different chemical agents such as hydrogen peroxide and sodium dithionite.

In terms of specific energy savings, **incineration of residues** and **heat recovery from deinking effluent** are two relevant techniques linked to deinking process of recovered fibres (Figure 22c). The investment cost for their installation is proportional with the energy savings. Combustion of residues derived at the deinking plant could contribute to increasing the heat or power generation at mills amounting for 0.64 GJ/tonnes of pulp.

A possible source of low-grade heat recovery in a typical pulping mill from recycled fibres represents the deinking effluent which usually is discharged at high temperature. By installation of heat exchangers in the effluent circuit some of this heat can be recovered and used further in the mill. Circa 0.2 GJ/tonne of recovered fibres pulp were estimated to be saved through heat recovery from deinking effluent with a yearly investment cost of EUR 610/tonne of recovered pulp (IEA, 2014).

Figure 23. Energy saving potential (bars) and investment cost (circles) for papermaking



Source: JRC representation with information from IEA, 2014

Other BATs associated with the deinking process are **optimisation of the flotation** process and by installation of **drum pulpers**. The drum pulper has lower energy requirements than the conventional vat-type mechanical pulpers which operate in a batch method. The drum pulpers have a rotating, inclined design with baffles and therefore are able to mix more effectively the mixture of recovered fibres, water and deinking chemicals. Overall, the specific energy savings of these BATs are relatively low (Figure 22c).

Additional BATs in the recovered fibres process are associated with an **improved screening** for removing the contaminants in the first stage of the stock preparation, more **efficient dispersers** during concentration and **heat recovery from blenching**.

Among the main sections of a paper machine (i.e. headbox, wire, press and dryer), the paper drying is one of the most energy-intensive processes in a paper mill. Overall, water is removed in three successive steps: in the wire (the solid content reaches up to 1520% by dewatering by gravity and vacuum/suction), press (45-50% solid content on the wet web achieved by mechanical forces) and dryer (90-95% solid content by drying the web by evaporation of water on steam-heated cylinders).

Significant energy reduction is possible by introduction of more efficient water removal devices, new drying technologies and by combining of new forming technologies with increased pressing designs and thermal drying. Out of 12 BATs shown in Figure 23, 7 BATs are connected with drying section. A highly effective method to decrease energy consumption for paper drying is to optimise water removing before the dryer section, for example in the forming section. It has been shown that the energy required to remove one pound of water in the dryer section could be 25 times higher than to remove the same amount of water in the forming section (Bajpai, 2016). Despite the high investment cost (EUR 22 300/tonne of paper per year), around 4.2 GJ/tonne of paper can be saved by adoption of so-called **dry sheet forming** (IEA, 2014). The most common paper machine is based on the Fourdrinier forming process, but thin wire and gap formers are two examples of new forming designs (Martin et al., 2000). Dry sheet forming allows the production of paper without the addition of water. This can be achieved either by dispersion of fibres through carding or using air laying techniques.

An efficient way to reduce the water content in the pulp stock and vacuum pumping requirements is to increase the consistency of the furnish slurry before the forming stage. **High consistency forming** technology can double the consistency of the furnish pulp (3%) compared to the one obtained in normal conditions. Such system can reduce the energy consumption by 1.5 GJ/tonne of paper at a yearly investment cost of 2920 EUR/tonne of paper (IEA, 2014).

Paper drying is normally done using steam-heated cylinders. Fuel savings of 1.05 GJ/tonne of paper are estimated by eliminating the intermediate step of steam production and introduction the **direct drying cylinder firing** technique to heat the cylinders by burning for instance natural gas (IEA, 2014).

New **paper drying technologies** such as steam impingement drying, condensing belt drying, impulse drying, etc. can offer several advantages over the conventional cylinder drying. Among this, the condensing belt drying (known as Condebelt drying) has the potential to increase the drying rate by 5-15 times compared to the conventional steam drying by using steel belt as heat transfer medium (Martin et al., 2000).

Infrared moisture profiling is an additional BAT associated with drying section, which allows optimisation of moisture content in the web.

Another technique that can remove more efficiently the water loading in the pressing section, thus leading to reduce energy requirements in the dryer is the **shoe press**. This BAT consists of increasing pressing area by using a big concave shoe instead of one of the rotating cylinders. Moreover, the evaporation load in pressing step can be reduced by pre-heating the water in the paper sheet to about 80 °C or more before the paper sheet goes to pressing. This technique is called **hot pressing** and the water is pre-heated through steam showers. Cost of this BAT is estimated to be 2660 EUR/tonne of paper per year bringing potential energy savings of 0.61 GJ/tonne of paper (IEA, 2014). Additional benefits are brought by increasing web temperature, such as reduction of viscous resistance of water and increasing compressibility of the fibre material.

When paper's surface needs to be improved, depending on its end-use, pigments, binders, plastic, etc. are usually added through a coating process. The energy consumed in this specific step can be reduced by adoption of the **high concentration press**, which enables a high concentration and speed of coating (about 1.6 GJ/tonne of paper can be saved at an investment cost of EUR 780/tonne of paper per year (IEA, 2014)).

As in the case of pulping process, it is possible to reduce the consumption of primary energy of a paper mill by **heat recovery and integration** of thermal energy from steam and waste heat, especially in the paper drying process. Approximatively, 1.07 GJ/tonne paper can be saved by applying different types of heat recovery systems, such as installation of heat exchangers for heating hood supply air or by recovery waste heat using heat pumps, mechanical vapour decompensations and replacing the dryers with stationary siphons in the paper machine. The annual investment cost of this BAT is estimated to be about EUR 910/tonne paper (IEA, 2014).

A further potential method to reduce the steam consumption in a mill is by optimisation the fibres properties and controlling water retention in the fibre through **efficient refiners**. This method is relatively costly (EUR 9 090/tonne paper per year) and is able to achieve moderate energy savings of 0.12 GJ/tonne of paper (IEA, 2014).

Besides the BATs mentioned in this report, there are some other technologies that could have an impact on energy savings in the pulp and paper industry. For instance, the Industrial Efficiency Technology Database contains information about technologies and measures that improve productivity and profits while reducing energy consumption and CO_2 emissions in several industries including pulp and paper (IETD, 2017).

Combined heat and power (CHP) systems

Apart from increasing use of recycled paper and introduction of energy-efficient technologies, the pulp and paper industry can reduce the overall primary energy consumption using on-site generation of electricity and heat through increasing their (already high) adoption of combined heat and power (CHP), or cogeneration. Compared to other industries, the European pulp and paper industry is one of the largest user of CHP. Around 10% of the total CHP capacity in Europe is within the pulp and paper industry, representing the third largest industrial sector after oil refining and chemical (Minett, 2006).

In 2015, the European pulp and paper mills (represented by CEPI members) produced 50 268 GWh electricity through CHP, representing 50.3% of the total electricity consumption by the sector (CEPI, 2017). The pulp and paper sector also sells the excess power to the grid. In 2015, the sector sold 11 109 GWh electricity (CEPI, 2017). The availability and cost of natural gas, long-term system reliability and the size of the site are other determining factors for up-taking of CHP technology. The payback period for a new CHP system installed in a large mill could be about 3 years (Finning, 2017), but the exact value depends on the price of electricity and fuels within the country/mill.

Traditional steam turbines and/or gas turbines are the most common systems of installed CHP capacity in the pulp and paper industry. Steam turbines are connected to boiler-based systems which produce high-pressure steam by firing on-site fuels (i.e. black liquor, bark, waste, liquid, solid or gas fuels). Gas turbines, unless hot flue-gases are used in a dryer, are combined with heat recovery steam generators.

A variety of CHP configurations can be applied depending on the specific conditions at the plant aiming to provide the better energy efficiency and flexibility at the lowest life-cycle cost. For example, the steam generated can be fed to different steam consumers in a *simple cycle* or the gas turbines/heat recovery steam generators can be combined with a back-pressure steam turbine or an intermediate steam extraction condensing turbine in a *combined cycle*.

Investment costs for CHP systems depend on the size of the plant and type of CHP installed and can vary from EUR 1.5 million for 1 MW simple cycle with gas turbine and production of 3 t/hr saturated low-pressure steam, up to EUR 54 million for 48 MW combined cycle with gas turbine (CCGT) and production of 90 t/hr of saturated low-pressure steam (Suhr et al., 2015).

In terms of efficiency, the CHP plants using fossil fuel or biofuels (this is the case for most pulp mills) can achieve 85-90% with a back-pressure turbine or even higher (85-92%) when producing CHP with a combined cycle gas turbine unit (Suhr et al., 2015).

Despite the widespread use of CHP in the EU's pulp and paper industry, the last chapter will examine the opportunity to further exploit this technology, taking advantage of the large number of solid fuel boilers that will reach the end of their expected operational life by 2020 (Sipilä et al., 2009).

For all technologies finally included in the study, either best available technologies or the emerging technologies of next section, the investment cost for each new investment is particularised using the following expression:

$$Inv_{BAT,IT} = \left(\frac{C}{C_{ref}} \right)^n \cdot Inv_{ref}$$

Where 'Inv_{ref}' is the reference investment corresponding to the capacity 'C_{ref}'; 'C' is the capacity corresponding to the new investment '$Inv_{BAT,IT}$' and n is a scale factor that we set to 0.6 for all cases.

5.2 Emerging technologies (ET)

New methods, processes and technologies for pulp and paper production might be developed through innovation in mid- and long-terms, leading to creation of added-value products, reduce product costs, increase reliability, improve profit margins, productivity and sector operations. Emerging or breakthrough technologies are often discussed within the wide range of innovative opportunities. As the commercial status is under development, pilot/demo phase, semi-commercial or commercialised with little or not at all market penetration, in general, these technologies cannot be considered as BATs yet.

Several studies looked at the diffusion of innovation in the pulp and paper sector, in particular at the introduction of the emerging technologies at the mills for improving energy efficiency and abatement of CO_2 emissions. We collected in Annex 2 a list of the emerging technologies as found in literature. These technologies are applicable in different steps of the pulping and papermaking processes, including those for reutilisation of waste heat, emerging by-product (e.g. black liquor) and fuel switch (e.g. biomass).

Out of the emerging technologies listed in Annex 2, this study takes into account only those that have a large potential for energy savings and reduction of CO_2 emissions in the EU by 2050, and have been demonstrated at industrial scale or are close to commercialisation in the short- and medium term, and are evaluated as the most promising according to the International Energy Agency (IEA, 2009) This group can be considered in Technology Readiness Level (TRL) 8-9. It includes: CO_2 capture and utilisation, black liquor gasification, biorefineries and new paper-drying technologies.

5.2.1 CO2 capture and storage (CCS)

Despite the uncertainties surrounding the diffusion of CCS, carbon capture technology will be important to large CO_2 emitting industries. While an important part of the capacity in the power production sector can be replaced with renewable energy, for energy-intensive industries there is no other alternative to cut emissions from processes.

In the pulp and paper industry, the majority of CO_2 emissions originate from the combustion of biomass, which can be considered carbon neutral in certain conditions. The capturing and storing of CO_2 emissions could give the pulp and paper industry the possibility to act as a potential carbon sink, so called bio-CCS. It is estimated that 73% of

CO_2 emissions from the European pulp and paper industry arise at the Kraft pulp mills, with mean emissions of over 0.5 $MtCO_2$/year (Leeson et al., 2017).

The CO_2 emissions are generated in the mill plant mainly from the recovery boiler, multi-fuel boiler and lime kiln processes. Several studies assess the performance and cost of integrating CCS technology in pulp and paper mills under different configurations. For example, Onarheim et al. showed that the retrofit of a post-combustion CO_2 capture plant into a pulp mill increases the steam demand by 1-8 GJ/air dried tonne (ADt) pulp (Onarheim et al., 2017a). This will result in a reduction in the amount of electricity exported to the grid. While the steam demand for the CCS plant can be covered in a standalone mill by the excess steam produced; for an integrated mill, the addition of an auxiliary boiler will be required. The total negative emission potential amounts to about 2.0 $MtCO_2$ per mill. According to Onarheim et al., the incorporation of CCS into a pulp mill will increase the levelised cost ([6]) of pulp by 4 – 30 % in a standalone mill and by 4-37 % in an integrated mill (Onarheim, 2017b). The amplitude of previous ranges is explained by the wide variation of cases considered (capturing CO_2 from the flue gases of the recovery boiler, power boiler, lime kiln or a combination of these for both mills: the standalone and the integrated mill). To maintain the levelised cost of pulp similar to the reference mill without CCS, a negative CO_2 emission credit of EUR 60 – 70 per tonne CO_2 for a standalone pulp mill and EUR 70 – 80 per tonne CO_2 for an integrated mill will be needed. Therefore, implementation of bio-CCS in the pulp and paper industry can be incentivised by the recognition and rewarding of negative CO_2 emissions as well as by tacking the relevant financial, economic and regulatory barriers. According to IEA, CCS would be economically feasible for integrated pulp and paper mills at a price of CO_2 varying from USD 30-50/t (IEA, 2009).

In the model we analysed the cost-effectiveness up to 2050 in the European industry of some of the different alternatives of CCS included in literature (Onarheim, 2017a and 2017b). These references focus their analysis in CCS in two mills, one producing only pulp and other with integrated production of board. According to literature, the mills are net electricity exporters to the grid, though the amount strongly depends on the configuration of the mill (Onarheim, 2017a). In our analysis we retain the separation between the cases of integrated and non-integrated mills, and consider the capture of fossil CO_2 in the lime kiln and simultaneously in the recovery boiler, power boiler and in the lime kiln. Chapter 7 presents the results of the model and also analyses how the deployment of CCS in the industry would be affected if the capture of bio-CO_2 was compensated from the CO_2 allowances of the EU ETS. This option would open the possibility to capture also the bio-CO_2 from the recovery and power boiler, increasing the amount of the CO_2 to be captured. The results presented in Chapter 7 differ from those of Onarheim et al., mainly because the expected increase in the CO_2 price that rewards the investment goes hand in hand with an increase in the price of the energy and resources required to implement the CCS.

5.2.2 Black liquor gasification (BLG)

BLG is an emerging commercial technology able to obtain energy more efficiently from the organic content in the black liquor through gasification, producing a combustible gas which after upgrading and conditioning results in a mixture of hydrogen and carbon monoxide known as syngas, while recovering the inorganic chemical. The hot flue gases from BLG can be used to generate steam in a heat boiler, resulting in high pressure steam for power generation in a steam turbine. Alternatively, the syngas can be used as feedstock for production of biofuels such as dimethyl ether (DME), Fisher-Tropsch (FT) fuel, methanol, etc., turning the paper mill into a ‘refinery’. The EU demonstration project BioDME proved the production of DME from biomass and its utilisation in transport and

([6]) Levelised cost of pulp refers to the price which enables the present value from the sales over the economic lifetime of the plant to equal the present value of all the cost of building, maintaining and operating the plant over its lifetime. In short, the levelised cost of pulp is the break-even price of the pulp when the net present value is set to zero.

industrial sectors (BioDME FP7, 2017). Although less steam is produced compared to the conventional recovery boiler (e.g. Tomlinson boiler), the black liquor gasification is considered a future key alternative for the recovery boiler as it provides high value products (e.g. syngas) or more electricity. About 1.75 tonnes of black liquor (measured as dry content) per tonne of pulp can be produced in a bleached kraft pulp mill, representing a potential energy source of 250-500 MW per mill (IEA bioenergy, 2007).

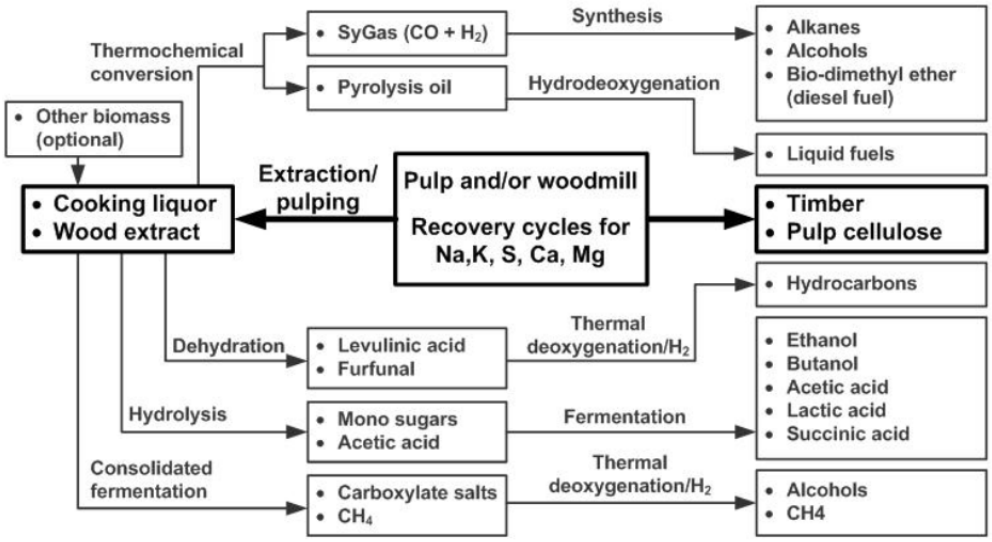
A possible configuration is the integration of the gasification with a steam turbine in a combined cycle, so-called black liquor gasification combined cycle (BLGCC). BLGCC technology could reach a power efficiency of about 30% (based on the heat value of the black liquor), which is double compared to the conventional recover boiler (IETD, 2017). Therefore, the BLGCC technology is able to produce 900 kWh/tonne pulp more compared to a recovery boiler system, however the heat production is reduced by 4 GJ/adt (IETD, 2017).

The capital cost for the black liquor gasification technology depends on the final configuration into the mill, and it is likely to be two times higher than for a conventional recovery boiler, ranging from USD 200-400 million (Bajpai, 2016). Larson et al. calculated an installed capital cost for the BLGCC technology equivalent to EUR 243.5 million (relative to 2015), which is 1.6 times higher compared with the conventional Tomlinson boiler (EUR 152 million) (Larson et al., 2006). Despite the larger investment cost compared to a new Tomlinson boiler recovery system, a BLG in a combined cycle (BLGCC) or integrated with a synthesis unit (biorefinery) would have higher energy efficiency, lower air emissions, and a diverse range of products and an attractive internal rate of return (IRR). According to the IEA, the black liquor gasification technology could be a competitive alternative to standard recovery boilers with capacities above 800 tonnes of solids per day that are older than 20 years or have not extensively renovated in the last 20 years (IEA bioenergy, 2007).

5.2.3 Biorefineries

The BAT reference document (BREF) for the production of pulp, paper and board makes reference to the development of the biorefinery as one of the emerging techniques for this industry that will bring significant technological, economic and social advantages. Different biorefinery pathways, utilising biomass as raw material, can be applied to the pulp and paper sector by integration of new technologies such as black liquor gasification, biomass gasification, lignin/hemicellulose production and processing/synthesis units, to provide a wide range of pulp, paper, energy, fuel and chemical products using biomass as feedstock (Figure 24). Possible feedstocks include wood extract, spent black liquor, forest biomass, agro-lignocellulosic products and sludge.

Figure 24. Biorefinery concepts within pulp and paper mills



Source: Suhr, 2015.

An optimal biorefinery design depends on several mill characteristics such as type of plant, energy (steam) balance, size, available investment capital and geographical location. The value of processed products, fuel price and policy instruments will also influence the design of a biorefinery. Some biorefinery technologies have already been constructed on a demonstration scale. Therefore, despite a series of challenges still to overcome, it is likely that some biorefinery concepts will be implemented on a full commercial scale in the near future and the integration of pulp mills with other facilities will increase (Suhr, 2015). The potential of adoption of the biorefinery concept in the EU and the integration level of biorefineries within the existing and new industry sectors, including the pulp and paper industry, were assessed through several EU projects (e.g. Biorefinery Euroview ([7]), Eurobioref ([8]), Biorefine-2G ([9]), etc.).

An integrated forest biorefinery will allow a significant added value to the pulp and paper traditional business and will improve the sector's energy sustainability and economic viability. A promising long-term route is the conversion of kraft mills to biorefineries with production of different classes of motor biofuels via Fisher-Tropsch synthesis (FT), dimethyl ether (DME), methanol and hydrogen. This configuration is often referenced as black liquor gasification motor fuel (BLGMF). The investment cost of the BLGMF technology was estimated to be just 1.18 times higher compared to BLGCC for the same flow capacity of black liquor, with almost 10 times more operating cost for BLGMF (IEA, 2015).

A biorefinery is capital-intensive and this is why only a few operate today on a commercial scale. Overall, the investment cost of a biorefinery depends on the size of the mill, fuel/raw material input, black liquor flow, steam surplus/deficit, etc. Moreover, the investment cost is largely dependent on the biorefinery design and configuration. Black liquor gasification is found as one of the technologies with the highest level of integration with the pulping process. Larson et al. examined in detail the technical and commercial viability as well as the environmental and energy impact of gasification-based biorefinery for liquid fuel production at kraft and paper mills, and concluded that biorefineries could bring important economic benefits to the pulp and paper industry (Larson et al., 2006). The authors also estimated the installed capital costs of seven different BLG-based biorefinery designs for production of DME, FT and mixed alcohol (MA). No other more

([7]) https://cordis.europa.eu/result/rcn/47386_en.html
([8]) http://www.eurobioref.org/
([9]) http://www.biorefine2g.eu/

recent studies were found with this high level of details. All process design of these configurations include the following basic equipment: BLG, biomass gasification, syngas heat recovery and clean-up, fuel synthesis and power unit. Depending on the design parameter values of biorefinery, the installed capital cost can vary from EUR 280.5-462.8 million for DME production, EUR 367.7-559 million for FT production and EUR 441.2 million for MA production (Larson et al., 2006). Although the upgrading of a pulp mill to a biorefinery might be economically feasible for production of specific high market value chemicals and biofuels at lower volumes, a substantial effort is however needed for integration of materials, processes and facilities into the biorefinery plant in order to spread the high investment cost and mitigate the risks. In the model we use the same seven configurations considered by Larson et al. to analyse the cost effectiveness of any of those concepts in each European kraft mill under the changing conditions up to 2050 (Larson et al., 2006). Three out of these seven configurations analysed in Chapter 7 produce DME, three FT and there is an additional one producing a mixture of alcohols.

5.2.4 LignoBoost

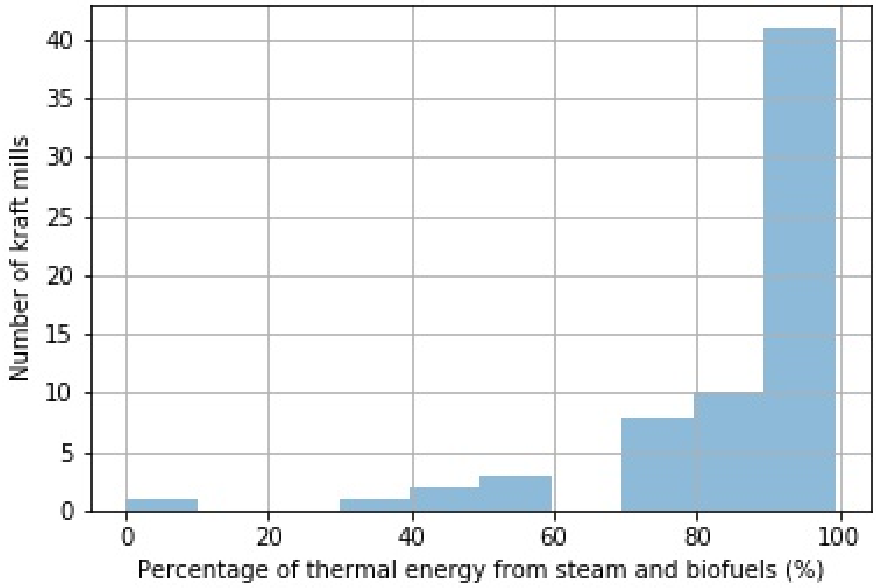
This process is an emerging technology in which up to 25-50 % of the lignin ([10]) is extracted from the kraft black liquor via precipitation at low pH with CO_2 and dewatering, and used in other profitable applications such as production of chemicals and materials (e.g. carbon fibres, activated carbon or phenols). The lignin extraction would be facilitated and its purity increased by extraction of the other wood constituent — hemicellulose, either from black liquor or prior pulping. Hemicellulose can be used in upgrading processes for production of a wide range of value-added products.

A partial removal of lignin from black liquor allows kraft mill to increase pulp production by up to 50 %, since the pulping process is currently limited by the size of recovery boilers (IEA, 2009).

Based to its high lower heating value (25-26.5 MJ/kg), the recovered lignin can be used onsite as fuel in a power plant boiler/recovery boiler or to replace the fossil fuel in the lime kiln. According to the literature, up to 50 litres of fuel oil per tonne of pulp (1.95 GJ/t) can be saved in a lime kiln by using lignin as fuel (Bajpai, 2016). However, as Figure 25 shows, most of the European kraft mills already rely on biofuels, and therefore, the possibility to replace fossil fuels by any other biofuel is limited.

([10]) Lignin is an organic substance binding the cells, fibres and vessels elements of plants and wood, with a content between 20 and 30 % of dry weight of wood.

Figure 25. Number of kraft mills with a certain percentage of thermal energy from biofuels



Source: JRC analysis.

The model treats this potential breakthrough, assuming that as much as 1.95 GJ of fossil fuels can be replaced by lignin, and in the (likely) case that the kraft mill had a lower consumption of fossil fuels, it is assumed that the remaining is lignin sold. Although currently much of the lignin is not extracted yet, it is burned in the chemical recovery boilers to provide steam for power and heat production. Therefore, if the lignin were extracted, the steam production in the recovery boiler would decrease due to reduction of organic content in the black liquor.

The extracted lignin from the kraft black liquor can be used as renewable raw material by the chemical industry for production of dyes, food, plastics, etc. Therefore, pulp mills can derive additional profit by selling any potential surplus of lignin. The benefits of the LignoBoost were demonstrated by integration of this technology at commercial scale in two pulp mills, such as at Plymount, North Carolina (United States) and Stora Enso Sunila (Finland), this last plant having a capacity of 50 000 tonnes of dry (95 % dry solid) lignin per year. The investment costs for a LignoBoost lignin plant of capacity of 50 000 tonnes of dry lignin/year can vary from about EUR 10.8 million (excluding drying, pulverising, palletising and storage) (Tomani, 2010) up to EUR 32 million for a complete plant of the same capacity including the dryer, lignin dust burners in the lime kilns and a packing line (Tomani, 2013). As the specific investment cost decreases with the size, about EUR $7.2*LR^{0.6}$ (LR – lignin extraction rate in kg/s) million investment cost and EUR 5.8 /MWh annual operating cost were estimated for a lignin extraction plant (IEA, 2015).

5.2.5 Emerging drying technologies

The drying section represents the most energy-intensive process in the papermaking stage where about 67 % of the total energy required in papermaking is used to dry paper, the equivalent of 25-30 % of the total energy used in the pulp and paper industry (IEA, 2009). The conventional drying method uses steam heated rollers which compress and dry the paper sheets through evaporation (circa 1-2 kg of water per kilogram of paper or paperboard needs to be evaporated in the drying section) (Bajpai, 2016). As a consequence of using steam to heat the metal cylinders, the paper drying accounts for the majority of thermal energy use in papermaking. A series of technologies and new process designs, already available or close to commercialisation, are able to improve the efficiency of drying process, paper forming and recovering the heat waste. For example, dry sheet and high consistency forming, direct drying cylinder firing, reducing air requirements, infrared moisture profiling, shoe press and new drying techniques (steam impingement drying, condensing belt drying and impulse drying) are considered best available technologies for increasing water removal in the papermaking process, able to provide large energy saving to the industry (Figure 23).

Boost dryer and **microwave drying** are two selected techniques often mentioned as emerging technologies for the drying section of the paper machines, which currently are in pilot (TRL 6-7) and development (TRL 3-4) stages, respectively. For example, the boost dryer technology is able to improve by about 12% the drying efficiency and drying capacity compared to the conventional systems (Kong et al., 2016). This is achieved by combining condensation and press drying processes through incorporating a dryer cylinder and a pressure hood. Boost dryer technology is mostly suited for board and packaging paper production, bringing additional benefits in terms of paper quality, drying time, space required and specific energy consumption. In the case of microwave drying, an electromagnetic microwave field can be applied as a drying technique in the papermaking process. It can be applied either in the press section to preheat the web and reduce the water load delivered to the dryer section, or directly in the dryer section to preheat and complement the conventional heated cylinders (Bajpai, 2016). This technique is especially suited for drying high basis weight paper grades. Overall, it reduces the dryer energy consumption by 12% by increasing the temperature and drying efficiency (although higher electricity consumption is needed to produce microwaves), it enhances the paper surface smoothness and productivity (the paper machine's speed can increase by 30%), and it reduces the operation and maintenance costs based of the reduction in number of cylinders relative to the conventional dryer section). As these techniques are at the early stages of development, the information about the investment costs is rather scarce.

Reducing water content in the main sections of a paper machine or replacing water as the forming medium will also bring significant energy saving benefits. For example, **Supercritical CO_2** is new process design that will potentially eliminated the need for heat and steam in the drying section, contributing to reducing the fossil CO_2 emissions by about 45% and with about 20% primary energy savings by 2050 compared to 2011 baseline (CEPI, 2013).

Deep Eutectic Solvent technology came out of the 'Two team project' led by CEPI to be the most promising long-term breakthrough research concept for decarbonisation of the pulp and paper industry (CEPI, 2013). This technology could replace the traditional chemical and mechanical pulping techniques by enabling dissolving the wood and extraction lignin, hemicellulose and cellulose at low temperature and at atmospheric pressure. Deep eutectic solvent could be applied to pulp production from both wood and recovered paper with minimal energy consumption, CO_2 emissions and residues (e.g., fossil CO_2 emissions could be reduced by 20% compared to 2011 baseline and deliver 40% primary energy savings to the sector by 2050) (CEPI, 2013).

These new concepts — supercritical CO_2 and deep eutectic solvent — require additional research and demonstration before being in a position to market uptake. It is yet premature to make estimations or find data on the investment cost and potential capacity.

6 Bottom-up model for the assessment of GHG emissions and energy efficiency scenarios

This chapter introduces the bottom-up model that has been used to analyse the trends of GHG emissions and energy consumption of the European pulp and paper industry up to 2050. Bottom-up means that the model works at facility level, and uses the cost-effectiveness of technological improvements in each European facility to estimate the overall trend of the whole industry.

The JRC uses the estimations of energy consumption and GHG emissions from the RISI model to build up a random forest model that replaces the solutions provided by RISI's model. Both models include the technological layout of all European facilities, providing their GHG emissions, energy and raw materials' consumption, etc. Since the JRC's model leans on RISI's model to provide its estimations, both share the same limitations. The replacement of RISI's model by a proxy allows the JRC to provide its own analysis and estimations.

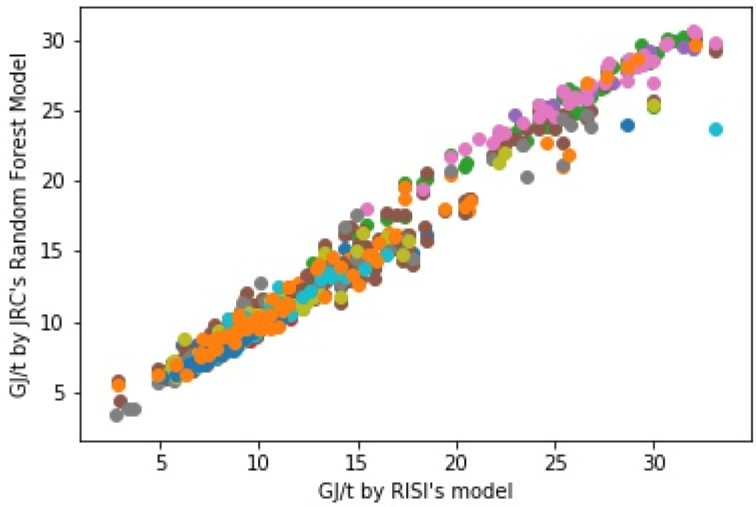
The random forest model is an extension of tree-based methods for regression. These methods involve segmenting the solution space into regions, and make predictions for a given facility, or change in that facility, based on the mean of the average of the training facilities on the region to which that observation belongs. The random forest model combines a large number of trees in order to improve dramatically the prediction accuracy, at the expense of some loss of interpretation.

The JRC's model is programmed in Python using the function 'RandomForestRegressor' of the package 'skleran.emsemble'. The interested reader can find a more detailed description of tree-based methods and applications in the following references: (James et al., 2013) and (VanderPlas, 2016).

In practical terms, the JRC has designed two sets of random tree models, one for the specific energy consumption (consumption per tonne of product) that includes a dedicated model per each product, and another set to model the electricity consumption, again, with one model per product. The models estimating the specific energy consumption include all fuels consumption in each pulp and paper facility, including fuels consumed for self-generated power. Similarly, the models estimating the electricity consumption include the consumption of self-generated power.

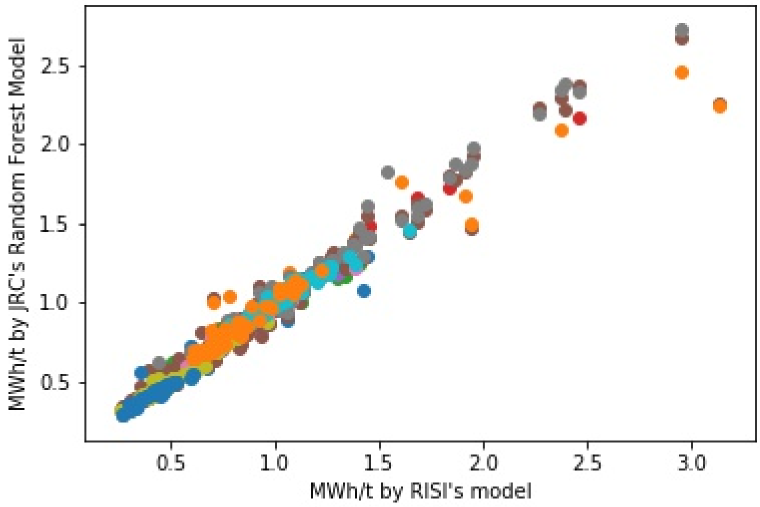
The following figures show the capacity of the different random tree models (one colour per product and model) to resemble the values provided by the RISI's model. The closer the values to the diagonal the better is the adjustment. The root-mean-squared error (RMSE) of these models, between 0.7 and 1.4 GJ/t for the thermal energy consumption and 0.032 and 0.155 MWh/t for the electricity consumption, show the goodness the adjustments. In view of the ranges of variation of the thermal energy and electricity consumptions (see Figure 26 and Figure 27), these errors are quite reasonable.

Figure 26. Thermal energy consumption estimated by the random-forest model vs data from RISI's model



Source: JRC analysis.

Figure 27. Electricity consumption estimated by the random-forest model vs data from RISI's model



Source: JRC analysis.

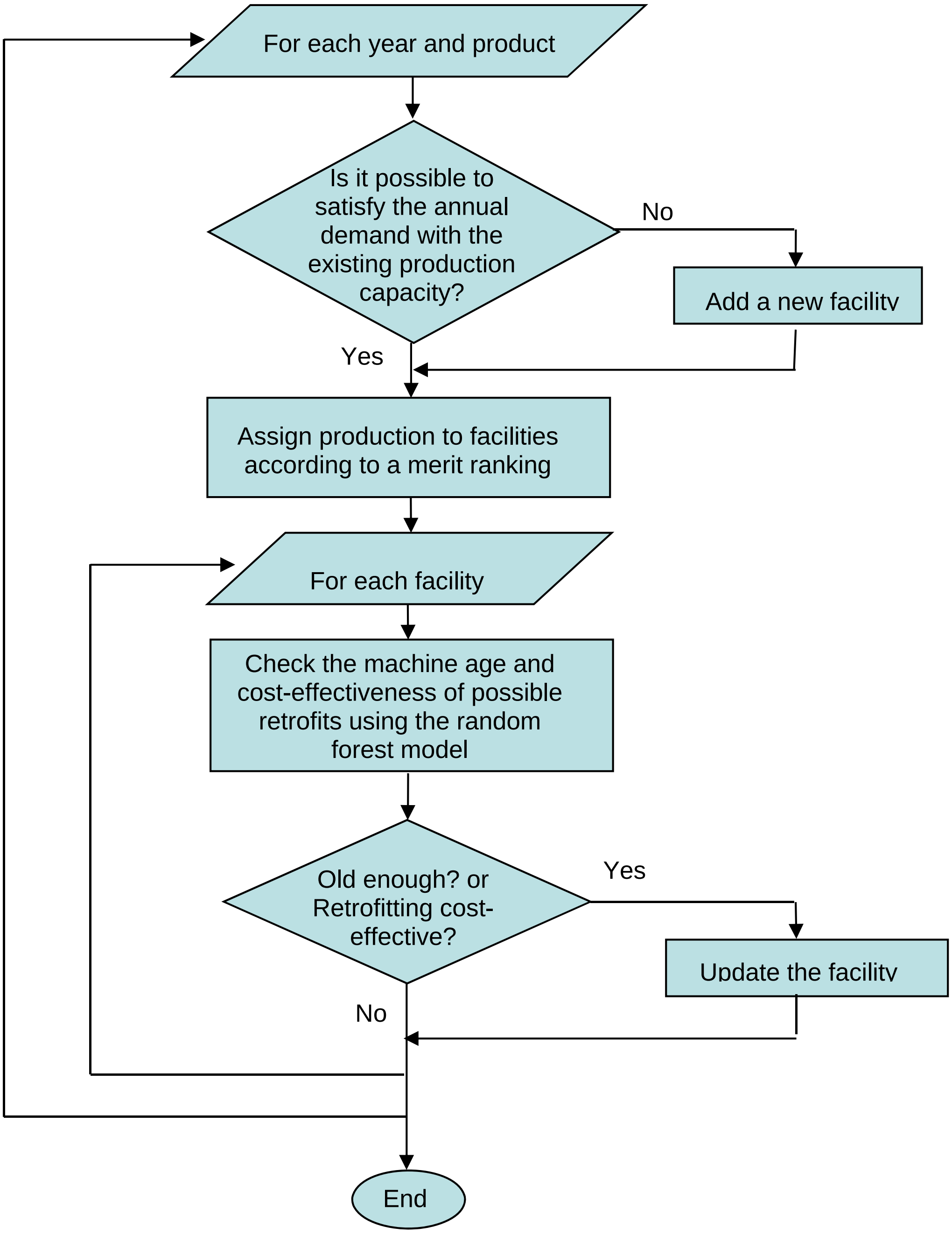
6.1 Model and decision-making criterion

This section describes first the JRC's model, leaving for next chapter the discussion of the results of the energy consumption and GHG emissions of the European pulp and paper industry up to 2050.

The JRC's model uses as input the expected evolution of the demand of the European pulp and paper industry (see Figure 16) assuming equivalence between the European demand for pulp and paper and the European production (keeping in mind that we consider the external trade exchange frozen at current values). The aim of the model is to analyse the potential margin for energy end GHG emissions reduction in a cost effective fashion at facility level.

As Figure 28 shows, the first step of the model is to adjust the annual demand with the production.

Figure 28. Algorithm used in this study



Source: JRC representation.

The model assumes that all facilities contributing to the production are operating at their maximum capacity for 357 days a year, leaving 8 days for maintenance operations. The facilities with highest production costs (not necessary to match the demand) are assumed idle that year. The last facility (last, according to production costs) needed to satisfy the demand, is used to match the production and annual demand. If the total installed capacity for a product is not able to match the annual demand, the model will add a new facility with the same performance as the best of the existing facilities. For the purpose of matching production and demand, energy costs are used as a proxy for the production costs.

The random forest model is used to estimate the effect of the retrofits in the overall performance of each facility. With this information, for each year, product and facility, we carry out a cost-benefit analysis of all possible retrofits. The payback period is used as the decision-making criterion for accepting or rejecting investments.

The formula used to calculate the payback period is:

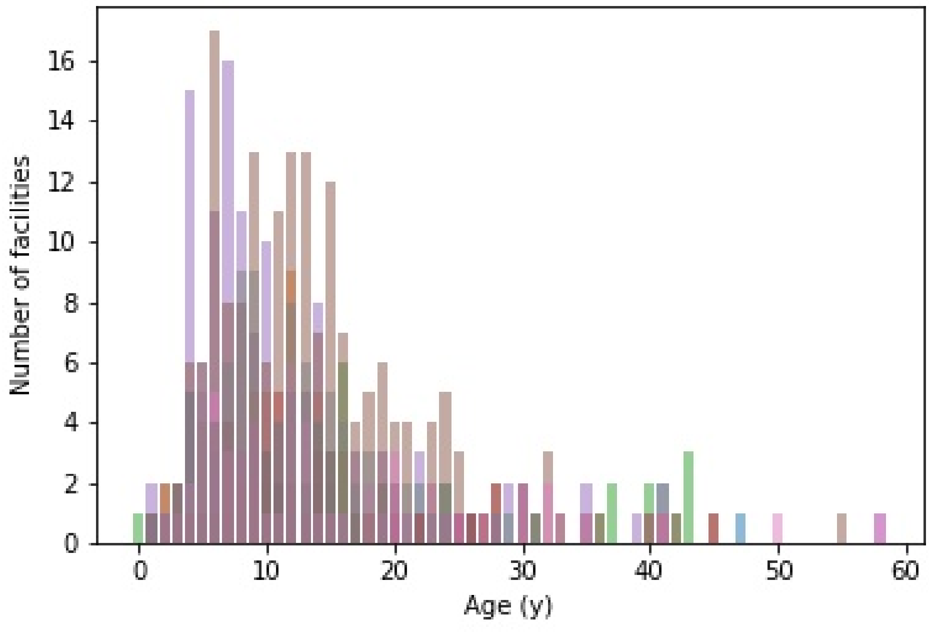
$$PayBackPeriod = \frac{INV_{\mathrm{Retrofit}}}{COP_{Before\,\mathrm{Retrofit}} - COP_{After\,\mathrm{Retrofit}}} \quad (1)$$

Where, $INV_{Retrofit}$ is the total investment cost of retrofitting, $COP_{Before\ Retrofit}$ is the annual operational cost (O & M, fuels, materials, CO_2 cost ...) before retrofitting, and $COP_{After\ Retrofit}$ is the annual operational cost (O & M, fuels, materials, CO_2 cost ...) after retrofitting.

6.2 Expected life span of the paper machines in the model

Besides the decision-making criterion for the adoption of innovations, there are some other parameters configurable by the user, such as the maximum age of the paper machine. RISI's database on the European pulp and paper industry contains information about 900 machines for paper manufacture distributed in 580 mills. There is also information about the age of the processes involved in pulp manufacture (practically all mills include one form of production of the pulp products considered). The random forest model combines all machines producing the same product in each facility in a single fictitious machine whose characteristics are estimated weighting (according to capacity) the corresponding parameter of the related machines. Figure 29 shows the age of these representative machines (there is one histogram per product) for all paper machines. Figure 30 shows the same information for the ages of the four processes involved in pulp production.

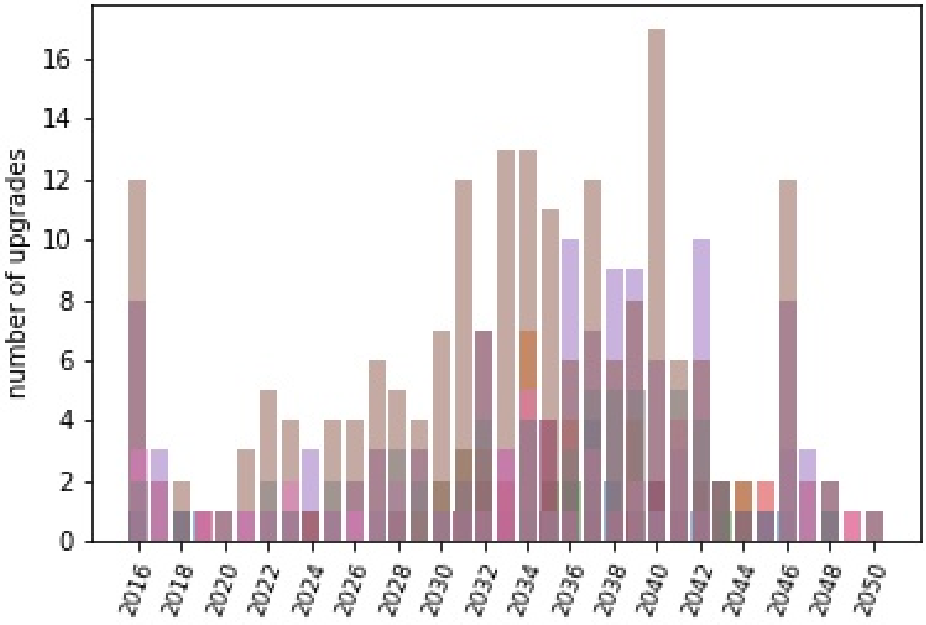
Figure 29. Histogram of the average age of the paper machines of the European mills. Each colour corresponds to one of the nine paper products included in this study



Source: JRC analysis.

With this information, we selected 30 years as the maximum age reachable by any machine; after that age, the model assumes that the corresponding machine is automatically upgraded. Figure 30 shows that this upgrade rate does not impose a number of upgrades at the beginning of the simulation different to the maximum number of upgrades that would be obtained in some other years.

Figure 30. Number of simultaneous upgrades of paper machines when the maximum allowed age is 30 years

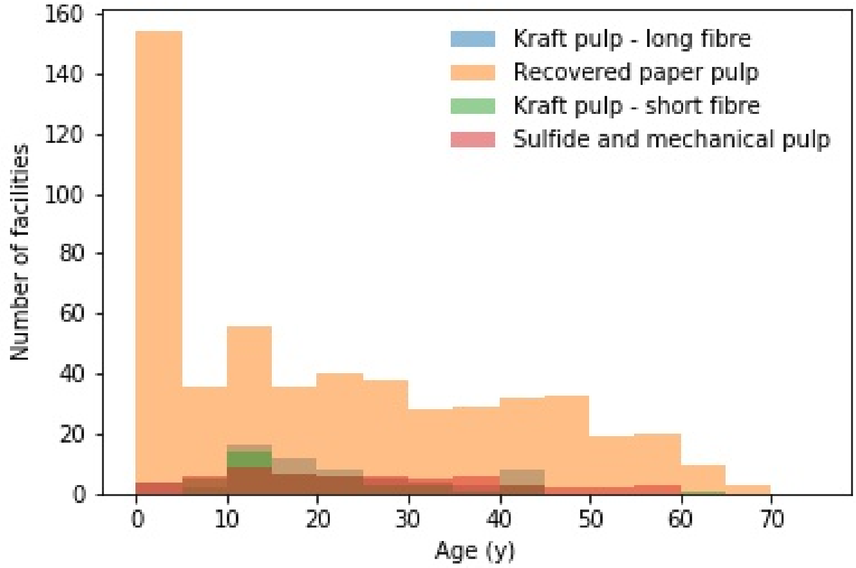


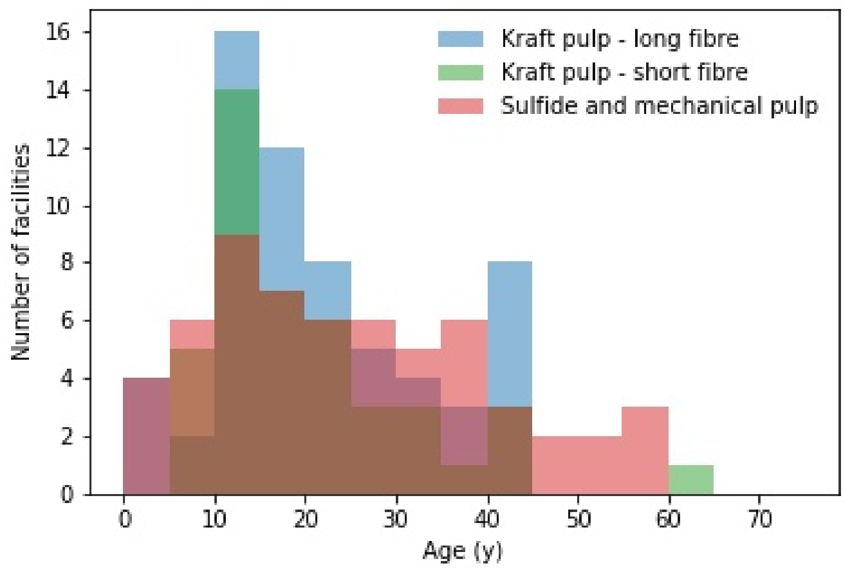
Source: JRC analysis.

Figure 31 represents the same kind information as Figure 29, but in this case for pulp processes. The overwhelming presence in European mills of the pulp recycling capacity is reflected in the dominance of that pulp production process in the upper pane of Figure 31, whereas the bottom pane allows make out the age of the remaining pulp production processes once the pulp recycling is excluded. Apparently, pulp mills last without upgrading around two times the paper machines' life span.

We used 60 years as the maximum life span for pulp producing processes. When selecting 50 years, the maximum number of simultaneous retrofits (about 30) takes place at the beginning of the simulation. Whereas using 60 years, as shown in Figure 32, the maximum number of simultaneous retrofits occurs in 2020 and not at the beginning of the simulation.

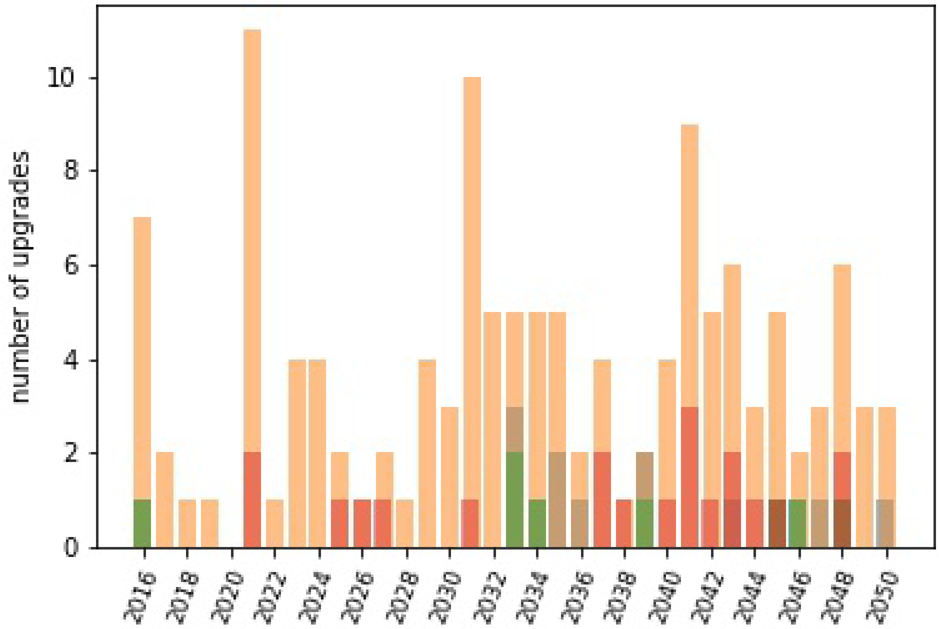
Figure 31. Average age of the pulp producing processes of European mills





Source: JRC analysis.

Figure 32. Number of simultaneous upgrades of pulp processes when the maximum allowed age is 60 years



Source: JRC analysis.

6.3 Maximum annual implementation rate of BATs/ETs

As already mentioned, the model uses the cost-effectiveness of the investment to decide when an investment is carried out. However, in the case that this results in an overwhelming sudden inversion in those technologies, we need to add an additional constraint to limit the rate of uptake of BATs or ETs in a way that resembles the investment behaviour of the industry. We can resort to the information contained in the database about the commissioning data and date of last upgrade to obtain a valid maximum of simultaneous investments in a single technology in a single year.

For example, there are 327 mills with at least one turbine (out of a total of 580 mills in RISI's database and JRC's model). The highest number of turbines in a single mill is five; Each mill can combine more than one technology of turbines (see Table 2).

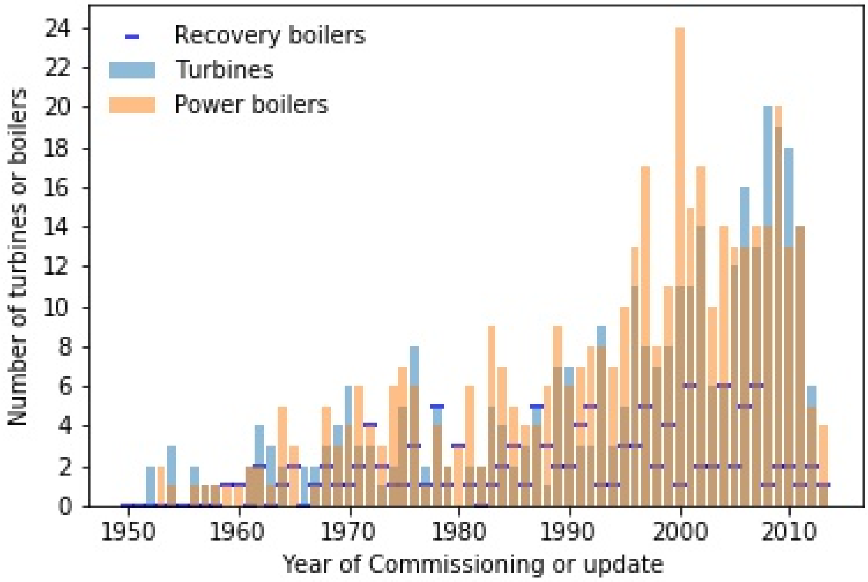
Table 2. Installed capacity of turbines per technology

Number of turbines	Technology	Total capacity (MW)
225	Gas	3 270
86	Hydro	120
419	Steam	6 607
11	Wind	40

Source: JRC compilation with information from RISI's database.

For some components like the turbines, the recovery and power boilers, the RISI's database includes the commissioning date and date of last upgrade (see Figure 33). Based on this information, we select 20 as the maximum number of simultaneous cost-effective investments at any single year of the simulation. For the case of new investments in turbines, it means that if all potential new turbines were cost-effective since the beginning of the simulation, it will take 12 years to install all required turbines before fully exploiting this BAT in the industry. In any case, note that since the investments cost depends on the capacity, it is highly unlikely that all pending investments in any BAT are simultaneously cost-effective.

Figure 33. Histogram of commissioning dates or date of last upgrade of turbines, power boilers and recovery boilers



Source: JRC analysis.

7 Simulation results

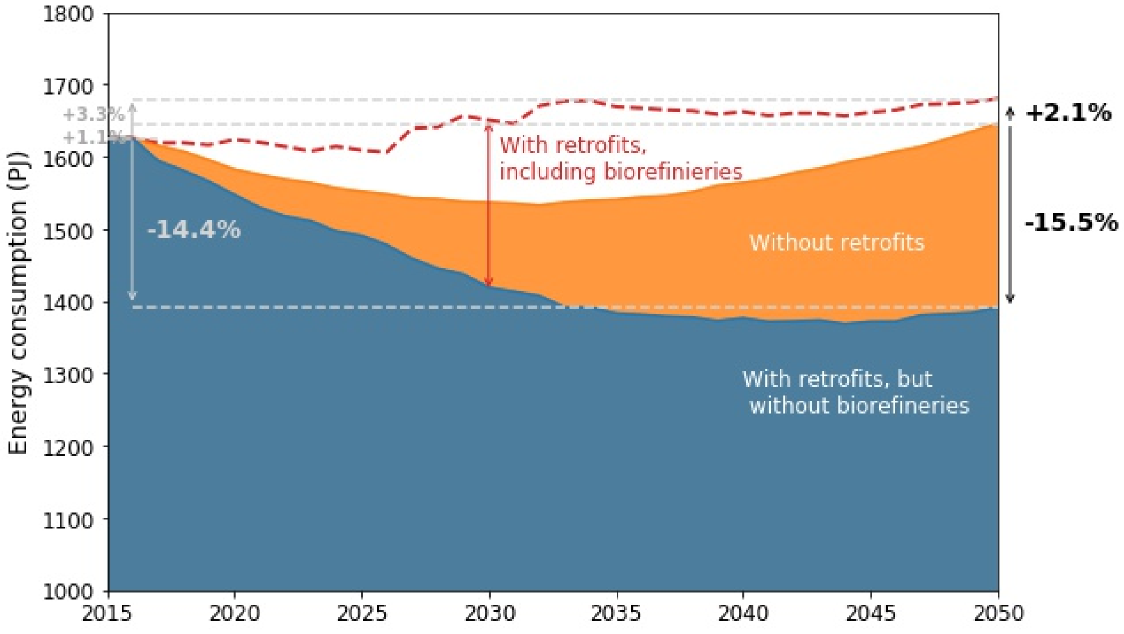
This chapter presents the results of the model under different scenarios. The first section shows the results of a baseline scenario that uses the same trends in prices and demand up to 2050 according to the EU Reference Scenario 2016 (European Commission, 2016b). The second section analyses the effect of some 'what if' or alternative scenarios. In them, we do not assign any credibility to the final values that some parameters reach (mainly prices) but they are used to check their effect on the variability of energy consumption and GHG emissions from the EU pulp and paper industry.

The prospective deployment of some technologies considered in previous sections, such as the biorefinery concept, will depend on factors that are beyond the pulp and paper industry. For example, the demand for — and therefore, the deployment of — new products or biofuels, to be used in the transport or chemical sectors, might be limited by a growing share of electrical vehicles or a sustained demand of those chemical products. Although we checked whether the deployment of biorefineries may be cost-effective, this deployment is considered only as an alternative to a baseline scenario that does not take for granted their deployment.

7.1 Baseline scenario

The baseline scenario uses the trends of energy, resources and demand up to 2050 coming from the EU Reference Scenario 2016 (European Commission, 2016b). The results for the energy consumption (thermal energy and electricity) of the baseline scenario correspond to the blue area in Figure 34. The dashed red line shows the increase of energy consumption due to the production of some bio fuels that occur when we give credibility to the deployment of cost effective biorefineries; not included in the baseline scenario. Moreover, and in order to contrast the role of the technology innovations, we also include a scenario without retrofits (orange area) in which the new facilities required to satisfy a growing demand have the average performance of current facilities. The direct GHG emissions corresponding to these three cases are provided in Figure 35.

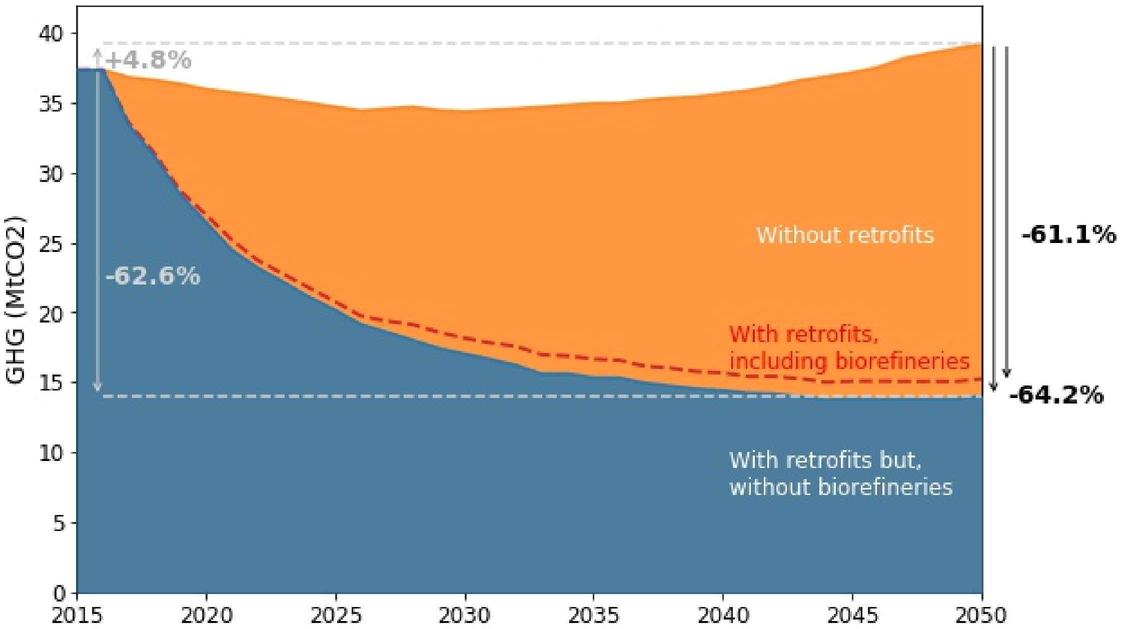
Figure 34. Energy consumption (thermal energy([11]) and electricity) in the pulp and paper industry



Source: JRC analysis.

([11]) Including fuels consumed (around 200 PJ in 2015) for self-generated power.

Figure 35. Direct GHG emission from the pulp and paper industry with and without retrofits



Source: JRC analysis.

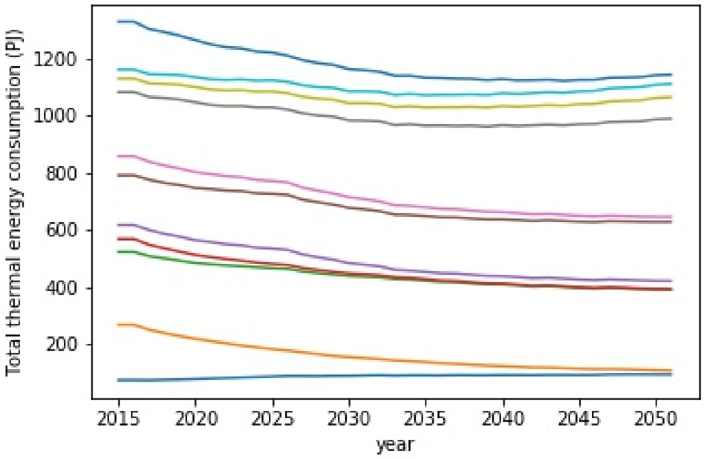
The model uses as input an overall increase in the production by 7.6 % (0.21 CAGR) from 2015 to 2050. When no technological improvement is allowed (orange area of Figure 34 and Figure 35), this increase goes hand in hand with an increase in the energy consumption of just 1.1%. The practically decoupling in the growth of the demand and energy consumption is due to variation in the share of final pulp and paper products with different energy intensity. The evolution of the energy consumption per each product can be seen in Figure 36 that breaks down the energy consumption according to the final thermal energy and electricity consumption in the processes, providing also the contribution from each product, even for the GHG emissions. In each panel of Figure 36 the energy consumption or GHG emission for each product is the value between two correlative curves.

The cost-effectiveness of technology innovations is such that the energy consumption in 2050 is 14.4% lower than in 2015 (or 15.5% lower than the energy consumption in 2050 if no retrofits were allowed) (Figure 34).

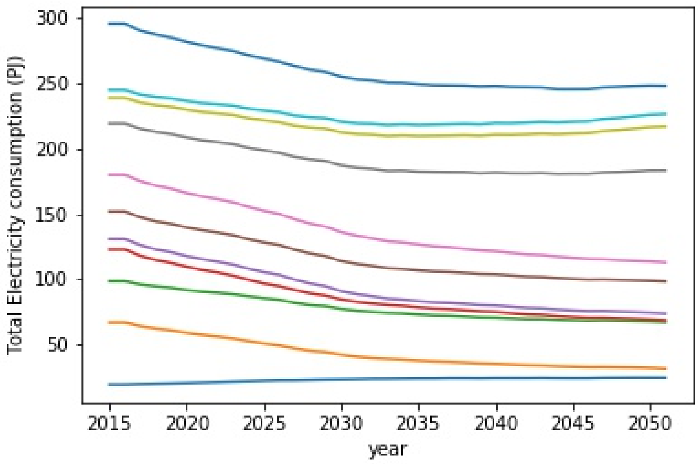
When the biorefinery concept is incorporated into the simulation, the valorisation of the by-products in another sectors makes this technology cost-effective — as advanced by (Larson et al., 2006) — and therefore, it is adopted by the model. Six out of the seven configurations of the biorefineries analysed become cost-effective at some point of the simulation, but the selection of just the most cost-effective one (e.g. producing biofuels via Fischer–Tropsch synthesis) prevents the adoption of the other alternatives. Note in Figure 34 that, in this case, the increase in the energy consumption compensates the energy savings produced by the rest of the improvements, making the energy consumption in 2050 3% higher than in 2015. However, this increase in the energy consumption by the pulp and paper industry is employed in the production of almost 270 PJ of biofuel (to be shipped to a conventional petroleum refinery for processing or refined onsite into ‘clean diesel’ and naphtha fractions, and consumed in some other sectors).

Figure 35 also shows that the GHG emissions are not affected by the biorefineries as much as the energy consumption. In both cases (with or without biorefineries) the decrease from 2015 to 2025 is above 60%. In both cases the fuel switching from fossil fuels to biofuels is primarily responsible for this decrease of GHG emissions.

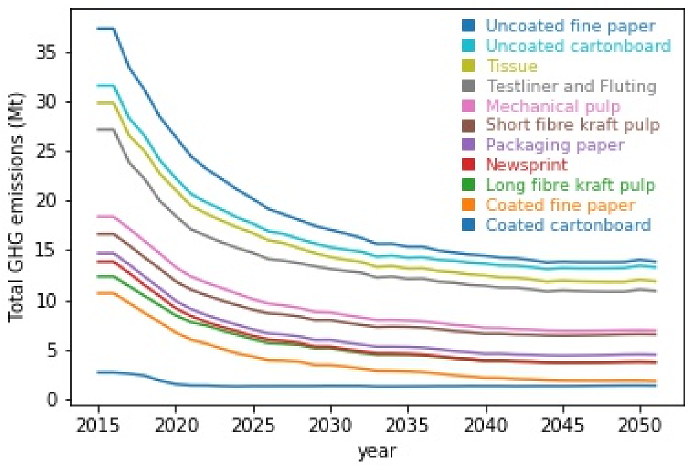
Figure 36. Evolution of thermal energy (a) and electricity consumption (b), and direct GHG emissions (c) for the EU pulp and paper industry per product



(a)



(b)



(c)

Source: JRC analysis.

7.2 Alternative scenarios

This section discusses the results of the model and how these results are affected by the variation of some input parameters, that is, it shows how sensitive the model is. Each of these variations are arranged in scenarios that can also be seen as 'what if' scenarios. That is, we do not assign any credibility to the final value of the parameter varied, but check its effect on the energy consumption and GHG emissions of the industry.

There are three alternative scenarios varying only one parameter each (the remaining parameters keep the values of the baseline scenario). The varying parameter is scaled up linearly to obtain the final price in 2050. We prove the effect of doubling the final prices in 2050 of CO_2 allowances, electricity and fuels. These scenarios are coded as 'CO_2x2', 'MWhx2' and 'FuelsX2' in Figure 37 and Figure 38. These figures show the results for energy consumption and direct GHG emissions.

There is an additional scenario that analysis the effect of rewarding the bio-CO_2 captured on the deployment of CCS, and its consequences in terms of energy consumption and GHG emissions. However, note that this possibility is not contemplated in the EU ETS. This scenario is coded as 'CO_2 with CCSneg' in Figure 37 and Figure 38.

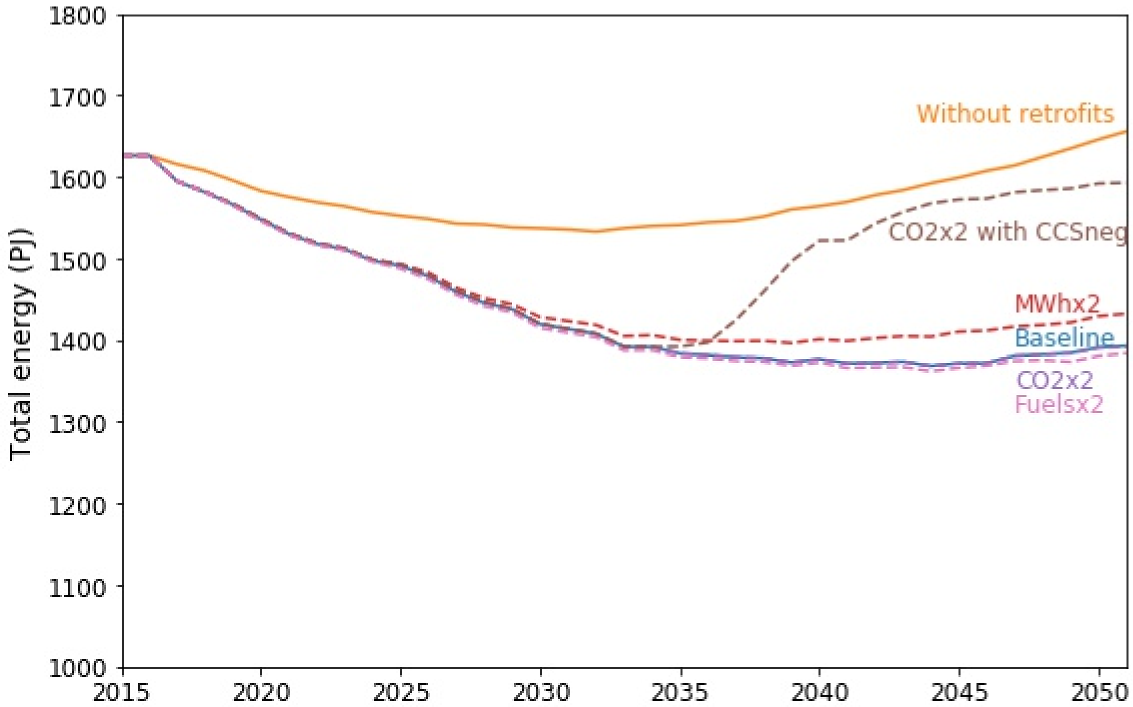
It is worth noting that although the baseline scenario considers the possibility to capture the fossil CO_2 emissions, e.g. from the lime kiln, this technology does not become cost-effective under the conditions of the baseline scenario, not even in the ('CO_2x2' scenario) that doubles the final CO_2 price in 2050. In the baseline scenario the CO_2 prices vary between 2015 and 2050 from EUR 7.2 per tonne CO_2 to EUR 87.6 per tonne CO_2. The main reason is that the simultaneous increase in the cost of resources and energy prevents CCS investments from becoming cost-effective (using as decision-making criterion for new investments, and cost-effectiveness, a payback period lower than five years)

However, the assignation of a monetary reward (equal to the expected price of the CO_2 allowance) to the bio-CO_2 captured (together with the rest of conditions of the 'CO_2x2' scenario') would make the CCS cost-effective from 2035 onwards (for CO_2 prices higher than EUR 92.4 per tonne). The results of this scenario are coded in Figure 37 and Figure 38 as 'CO_2x2 with CCSneg'. The retribution of bio CO_2 captured would give the chance to capture the CO_2 from the recovery and power boiler (not contemplated in the usual CCS). Figure 37 shows that the capture of CO_2 emissions is not energy free; the increase of energy consumption practically balance the energy savings delivered by the rest of BATs and innovations. In fact, the extra energy costs associated to CCS is one of the reasons that the CO_2 price at which this technology becomes cost effective in this study is different from the values provided in literature (Onarheim, 2017b). In any case, as shown in Figure 38 the resulting GHG emissions in the 'CO_2x2 with CCSneg' scenario could turn the pulp and paper industry in a carbon sink.

It is also worth noting that the black liquor gasification would double its implementation in the 'MWhX2' scenario compared to the baseline. Also in the 'MWhX2' scenario the CHP is implemented in nine mills, versus the three new cases in the rest of scenarios, except in the 'FossilX2' in which there are only 2 new CHP. There is an increase in the energy consumption in the scenario 'MWhx2' compare to the baseline. This happens because technologies that produce electricity at the expense of higher consumption of final energy are favoured by higher electricity prices. The GHG emissions are not affected because of the fuel switching neutralises the emissions from the increased energy consumption. In fact, this last technology equals the CO_2 emissions of all the alternative scenarios (with the logical exception of the 'CO_2x2 with CCSneg').

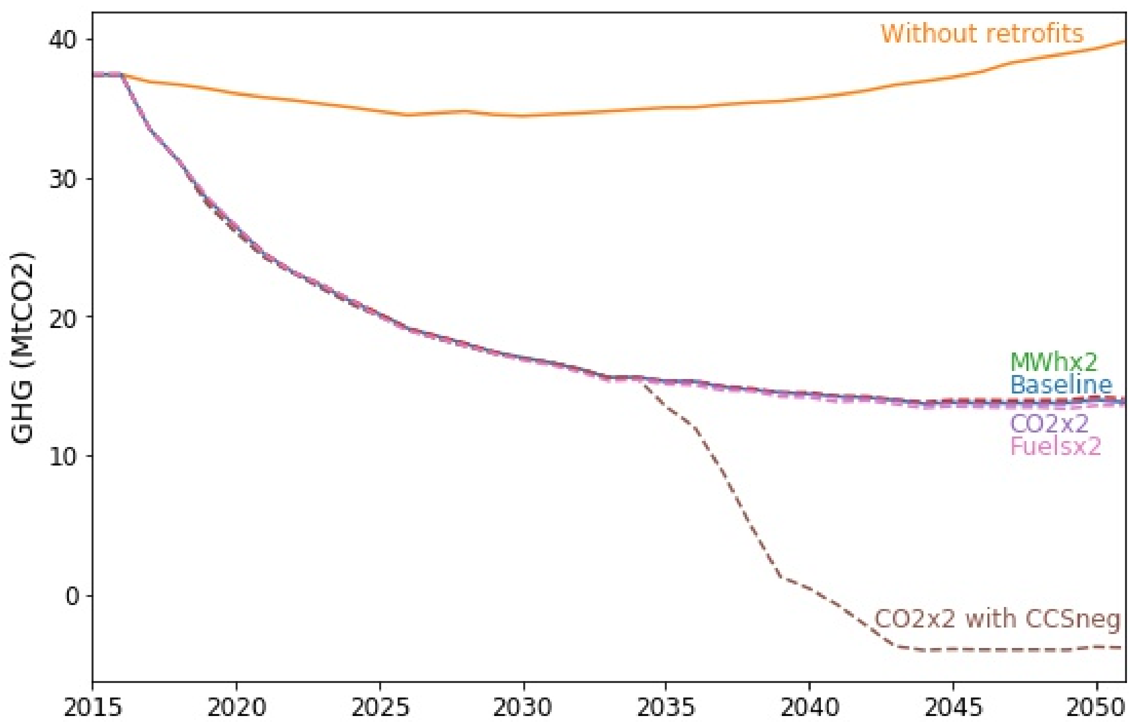
Even though in the baseline scenario none of the drying technologies become cost effective, the 'drying infrared moisture profiling' is adopted in 12 mills in the 'FossilX2' scenario and in 2 mills in the 'CO_2x2' scenario.

Figure 37. Energy consumption (thermal energy and electricity) in the alternative scenarios



Source: JRC analysis.

Figure 38. Direct GHG emissions in the alternative scenarios



Source: JRC analysis.

8 Conclusions

The main aim of this study is to analyse the role of the technological innovation in the European pulp and paper industry and how it can contribute to decreasing the energy consumption and GHG emissions up to 2050. This was achieved using a bottom-up model that takes into account the technological detail of each facility, by checking the cost effectiveness of the technological options available and the uptake of breakthrough innovations. The results reveal the cost effectiveness of achieving savings of around 14% in energy consumption and 63% decrease in GHG emissions from 2015 to 2050. This decrease could take place in the context in which the demand grows by 7% in the same period. These estimations rely on a growth of the European pulp and paper demand, as well as an evolution of fuels and resources prices in line with the reference scenario 2016 of the European Commission. If the contribution from the technological improvement is disregarded, the combination of the growth in the demand with the energy intensity of the different products would produce an increase in the energy consumption and GHG emissions by 1% and 5 %, respectively.

The emerging technologies are considered available during the whole simulation. However, the model set aside technologies such us the boost dryer, microwave drying, supercritical CO_2 and deep eutectic solvent for which the public information available is very limited. Although it is acknowledged that in some cases, several of those emerging technologies may have a high potential impact in the long-term.

This study also includes an analysis of the cost effectiveness of some biorefineries concepts as well as of the CCS technology. For this last technology we also estimate the effect of rewarding for the bio-CO_2 captured (option not contemplated currently in the EU ETS). The effect on the results of doubling the prices of electricity, fuels and CO_2 allowances by 2050 was also investigated. Assigning a monetary reward (equal to the expected price of the CO_2 allowance) to the bio-CO_2 captured (together with the rest of conditions of the 'CO_2x2' scenario') would make CCS cost-effective from 2035 onwards (for CO_2 prices higher than EUR 92.4 per tonne), those conditions could turn the pulp and paper the industry into a carbon sink (capture more CO_2 than the purely coming CO_2 from fossil origin).

All but one of the seven configurations of biorefineries considered in this study are able to recover the investment in a shorter time than the payback period of five years that is used as decision-making criterion for considering the investments cost-effective. The model also limits the simultaneous number of annual investments per technology, and automatically upgrades facilities once they reach certain age. The aim of this constrains/upgrades is to resemble the historical rate of renewal/investments from the industry. When including biorefineries, the pulp and paper industry is able to produce 270 PJ of biofuels (6.4 Mtoe) equivalent of around 1.6% of total energy consumed by the transport sector in 2015. In this case, the biorefineries of the pulp and paper sector would be contributing to a decrease in GHG emissions in the transport sector. The alternative scenarios, which show the effect of varying final prices of fuels, electricity and CO_2 are quite consistent with the results of the baseline scenario, showing that the implementation of the technological improvement in the baseline hardly leaves any improvement margin to the industry.

The technological options included in the model are constrained in some cases by the availability of detailed information about their presence at facility level. Moreover, the lack of energy and mass balances, and economical details of some potential breakthrough technologies, which are in early stages of research, the dependence (and consequences) of some technologies (such as biorefineries) on factors that are beyond the scope of the pulp and paper industry, together with the potential contribution from the CCS when rewarding the capture of bio-CO_2 are factors that may affect the results and it may make worthy to revisit this study once more information becomes available.

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List of abbreviations and definitions

BAT	best available technology
BLG	black liquor gasification
CAGR	compound annual growth rate
CCGT	combined cycle with gas turbine
CCS	Carbon capture and storage
CEPI	Confederation of European Paper Industries
CHP	combined heat and power
CTMP	chemi-thermomechanical pulping
ET	emerging technology
GHG	greenhouse gas emissions
GJ	gigajoule, 10^9 joules
GWh	gigawatt hours, 10^9 watt hours
MW	megawatt, 10^6 watts
MWh/t	megawatt hours per tonne
O & M	operation and maintenance
PGW	pressure groundwood
PJ	petajoule, 10^{15} joules
TMP	thermomechanical pulping
toe	tonne of oil equivalent
SGW	groundwood pulping

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Annexes

Annex 1. BATs applicable in the pulp and paper industry according to the BREF

Processes and activities	BAT	Applicability
General	1. Energy management system	Generally applicable
General	2. Recovery of energy by incinerating the wastes and residues from the production of pulp and paper that have high organic content and calorific value	Only applicable if the recycling or reuse of wastes and residues from the production of pulp and paper with a high organic content and high calorific value is not possible
General	3. Cover the steam and power demand of the production processes by cogeneration of heat and power (CHP)	Applicable for all new plants and for major refurbishments of the energy plant. Applicability in existing plants may be limited due to the mill layout and available space
General	4. Use excess heat for the drying of biomass and sludge, to heat boiler feedwater and process water, to heat buildings, etc.	Applicability of this technique may be limited in cases where the heat sources and locations are far apart
General	5. Use thermo compressors	Applicable to both new and existing plants for all grades of paper and for coating machines, as long as medium pressure steam is available
General	6. Insulate steam and condensate pipe fittings	Generally applicable
General	7. Use energy efficient vacuum systems for dewatering	Generally applicable
General	8. Use high efficiency electrical motors, pumps and agitators	Generally applicable
General	9. Use frequency inverters for fans, compressors and pumps	Generally applicable
General	10. Match steam pressure levels with actual pressure needs	Generally applicable
Kraft and sulphite pulping	11. High dry solid content of bark, by use of efficient presses or drying	n.a.
Kraft and sulphite pulping	12. High efficiency steam boilers, e.g. low flue-gas temperatures	n.a.
Kraft and	13. Effective secondary heating systems	n.a.

Processes and activities	BAT	Applicability
sulphite pulping		
Kraft and sulphite pulping	14. Closing water systems, including bleach plant	n.a.
Kraft and sulphite pulping	15. High pulp concentration (middle or high consistency technique)	n.a.
Kraft and sulphite pulping	16. Recovery and use of the low temperature streams from effluents and other waste heat sources to heat buildings, boiler feedwater and process water	n.a.
Kraft and sulphite pulping	17. Appropriate use of secondary heat and secondary condensate	n.a.
Kraft and sulphite pulping	18. Monitoring and control of processes, using advanced control systems	n.a.
Kraft and sulphite pulping	19. Optimise integrated heat exchanger network	n.a.
Kraft and sulphite pulping	20. Ensuring as high a pulp consistency as possible in screening and cleaning	n.a.
Kraft and sulphite pulping	21. Optimised tank levels	n.a.
Kraft and sulphite pulping	22. High recovery boiler pressure and temperature (in new recovery boilers used in Kraft pulping, the pressure can be at least 100 bars and the temperature 510 °C)	n.a.
Kraft and sulphite pulping	23. Outlet steam pressure in the back-pressure turbine as low as technically feasible	n.a.
Kraft and sulphite pulping	24. Condensing turbine for power production from excess steam	n.a.
Kraft and sulphite pulping	25. High turbine efficiency	n.a.
Kraft and sulphite pulping	26. Preheating feedwater to a temperature close to the boiling temperature	n.a.
Kraft and sulphite pulping	27. Preheating the combustion air and fuel charged to the boilers	n.a.
Kraft pulping	28. High efficiency evaporation plant	n.a.
Kraft pulping	29. Recovery of heat from dissolving tanks e.g. by vent scrubbers	n.a.
Kraft pulping	30. Heat recovery from the flue gas from the recovery boiler between the ESP and the fan	n.a.
Kraft pulping	31. Use of speed control of various large motors	n.a.

Processes and activities	**BAT**	**Applicability**
Kraft pulping	32. Use of efficient vacuum pumps	n.a.
Kraft pulping	33. Proper sizing of pipes, pumps and fans	n.a.
Kraft pulping	34. High black liquor dry solid content (increases boiler efficiency, steam generation and thus electricity generation)	n.a.
Mechanical and chemi-mechanical pulping	35. Use of energy efficient refiners	Applicable when replacing, rebuilding or upgrading process equipment
Mechanical and chemi-mechanical pulping	36. Extensive recovery of secondary heat from TMP and CTMP refiners and reuse of recovered steam in paper or pulp drying	Generally applicable
Mechanical and chemi-mechanical pulping	37. Minimisation of fibre losses by using efficient reject refining systems (secondary refiners)	Generally applicable
Mechanical and chemi-mechanical pulping	38. Installation of energy saving equipment, including automated process control instead of manual systems	Generally applicable
Mechanical and chemi-mechanical pulping	39. Reduction of fresh water use by internal process water treatment and recirculation systems	Generally applicable
Mechanical and chemi-mechanical pulping	40. Reduction of the direct use of steam by careful process integration using e.g. pinch analysis	Generally applicable
Paper processing for recycling	41. High consistency pulping for disintegrating paper for recycling into separated fibres	Generally applicable for new plants and for existing plants in the case of a major refurbishment
Paper processing for recycling	42. Efficient coarse and fine screening by optimising rotor design, screens and screen operation, which allows the use of smaller equipment with lower specific energy consumption	
Paper processing for recycling	43. Energy saving stock preparation concepts extracting impurities as early as possible in the repulping process, using fewer and optimised machine components, thus restricting the energy intensive processing of the fibres	
Papermaking	44. Energy saving screening techniques (optimised rotor design, screens and screen operation)	Applicable to new mills or major refurbishments

Processes and activities	**BAT**	**Applicability**
Papermaking	45. Best practice refining with heat recovery from the refiners	
Papermaking	46. Optimised dewatering in the press section of paper machine (wide nip press)	Not applicable to tissue paper and many speciality papers grades
Papermaking	47. Steam condensate recovery and use of efficient exhaust air heat recovery systems	Generally applicable
Papermaking	48. Reduction of direct use of steam by careful process integration using e.g. pinch analysis	Generally applicable
Papermaking	49. High efficient refiners	Applicable to new plants
Papermaking	50. Optimisation of the operating mode in existing refiners (e.g. reduction of no load power requirements)	Generally applicable
Papermaking	51. Optimised pumping design, variable speed drive control for pumps, gearless drives	Generally applicable
Papermaking	52. Cutting edge refining technologies	Generally applicable
Papermaking	53. Steam box heating of the paper web to improve the drainage properties/dewatering capacity	Not applicable to tissue paper and many speciality papers grades
Papermaking	54. Optimised vacuum system (e.g. turbo fans instead of water ring pumps)	Generally applicable
Papermaking	55. Generation optimisation and distribution network maintenance	Generally applicable
Papermaking	56. Optimisation of heat recovery, air system, insulation	Generally applicable
Papermaking	57. Use of high efficient motors (EFF1)	Generally applicable
Papermaking	58. Preheating of shower water with a heat exchanger	Generally applicable
Papermaking	59. Use of waste heat for sludge drying or upgrading of dewatered biomass	Generally applicable
Papermaking	60. Heat recovery from axial blowers (if used) for the supply air of the drying hood	Generally applicable
Papermaking	61. Heat recovery of exhaust air from the Yankee hood with a trickling tower	Generally applicable
Papermaking	62. Heat recovery from the infrared exhaust hot air	Generally applicable

Source: JRC compilation with information from Suhr et al., 2014.

Annex 2. Emerging energy efficiency technologies of the pulp and paper industry according to selected literature sources

Processes and activities	**Energy Start guide** (Kramer et al., 2009)	**International Energy Agency** (IEA, 2009)	**CEPI's Two team project** (CEPI, 2013)	**BREF*** (Suhr, 2015)	**Kong et al., 2016**	**Bajpai, 2016**
General	Magnetically-coupled adjustable-speed drivers	CO_2 capture and storage (CCS)	Toolbox to replicate	Direct drive systems (+ +)		
				More precise dimensioning (+ +)		
				Forward-looking control methods (+ +)		
				Low friction materials (+ +)		
				New vacuum system (+ +)		
Raw materials pre-treatment	Directed green liquor utilisation pulping			Fractionation methods to add value (+)	Directed green liquor utilisation pulping	Directed green liquor utilisation pulping
	Microwave logs			Fibre modification methods (+)	Chemical pre-treatment with oxalic acid	Chemical pre-treatment with oxalic acid (for mechanical pulping)
	Biotreatment			Higher consistency processing (+)	Biological pre-treatment	Bio-pre-treatment for mechanical pulping
				Enzymes (to reduce the size and tackiness of stickies)/biochemical (+ +)	Microwave pre-treatment	Enzymatic debarking
Pulping	Steam cycle washer for unbleached pulp		Deep eutectic solvents	New mechanical pulping (+ ++)		Enzymatic refining
				Efficient pulp washing technology (+)		Enzymatic pre-bleaching
				New energy-efficient TMP		Enzymatic removal

Processes and activities	**Energy Start guide** (Kramer et al., 2009)	**International Energy Agency** (IEA, 2009)	**CEPI's Two team project** (CEPI, 2013)	**BREF*** (Suhr, 2015)	**Kong et al., 2016**	**Bajpai, 2016**
Pulping — continued				Processes (e.g. high-speed and high-intensity TMP refining and chip pre-treatment)		of shives
				New energy-efficient bleached CTMP processes		Enzymes for reduction of vessels in tropical hardwoods
				Use of enzymes during the refining of TMP		
Recovered fibres	Electrohydraulic contaminant removal			Processing paper for recycling for quality improvement (+)	Recycled paper fractionation	New flotation deinking processes***
					Surfactant spray deinking	Surfactant spray deinking
						Pulsed power technology for decontamination of recycled paper
						Enzymes for drainage improvements
						Enzymatic deinking
Papermaking and finishing	Impulse drying		Flash condensing with steam	New web-forming techniques (+ +)	Impulse drying in wet pressing process	Impulse drying
	Advanced fibrous fillers		Dry pulp for cure-formed	Simplified shoe press concept (+)	New fibrous fillers	Advanced fibrous fillers

Processes and activities	**Energy Start guide** (Kramer et al., 2009)	**International Energy Agency** (IEA, 2009)	**CEPI's Two team project** (CEPI, 2013)	**BREF*** (Suhr, 2015)	**Kong et al., 2016**	**Bajpai, 2016**
Papermaking and finishing — continued			paper			
	Lateral corrugator		Functional surface	Use of cooling water as process water (+ +)	Aq-vane technology	Aq-vane technology
	Laser-ultrasonic web stiffness sensor			Simplified runnability systems (+)	High consistency papermaking	Laser-ultrasonic stiffness sensor
				Multilayer forming technologies (+ +)	Displacement pressing	Displacement pressing
				HC forming technologies (+ +)		
				Curtain coating (+)	Dry sheet forming	
				Spray coating (+)		
				Metal belt calender (+)		
				High solid sizer (+)		
				Powder coating (+ +)		
Drying	Multiport dryer	Paper drying technologies	Supercritical CO_2		Condebelt drying	Multiport dryer
	Gas-fired paper dryer		Superheated steam drying		Gas-fired dryer	Gas-fired paper dryer
					Boost dryer	Boost dryer
					Microwave drying	Microwave drying
						Air/steam impingement drying
						Infrared drying
Utilisation of by-product, heat,	Black liquor gasification	Black liquor gasification	100 % electricity	Heat recovery with heat pumps (+ +)	Black liquor gasification	Black liquor gasification

Processes and activities	**Energy Start guide** (Kramer et al., 2009)	**International Energy Agency** (IEA, 2009)	**CEPI's Two team project** (CEPI, 2013)	**BREF*** (Suhr, 2015)	**Kong et al., 2016**	**Bajpai, 2016**
renewable energy and biomass Utilisation of by-product, heat, renewable energy and biomass — continued		Lignin production from black liquor		Enhanced generation of electricity, biomass-based products and the utilisation of excess heat	Dual-pressure reheat recovery boiler	Dual-pressure reheat recovery boiler
		Biomass gasification with synfuels production		Gasification of black liquor	Biomass gasification	Membrane concentration of black liquor
		Biorefinery concepts		Biorefinery	Steam cycle washing	Steam cycle washing
				Selective removal of chloride and potassium by ESP ash treatment	Borate autocausticizing	Borate autocausticising
				Partial borate autocausticising	LignoBoost	LignoBoost
				SNCR or SCR** for reducing NO_X emissions from the black liquor recovery boiler	Extraction of hemicellulose extraction before chemical pulping	Extraction of hemicellulose extraction before chemical pulping
				Removal of chelating agents by modest alkaline biological treatment or its recovery by use of kidneys	Other biorefinery concepts	Utilisation of residuals in concrete production
				Increased system closure combined with the use of kidneys		

(*) + positive energy efficiency effect; ++ medium positive energy efficiency effect; +++ large positive energy efficiency effect.
(**) SNCR: selective non-catalytic reaction; SCR: selective catalytic reaction.
(***) e.g. OptiCell flotation™, Deaeration foam pump 4000™, Low energy flotation™, MAC flotation cell.

Source: JRC compilation with information from Kramer et al., 2009; IEA, 2009; CEPI, 2013; Suhr et al., 2014; Kong et al., 2016 and Bajpai, 2016.

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