Pulp and paper industry

Decarbonization technologies to reach neutral emissions by 2050

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Abstract

Up to 2050, the European Union (EU) aims at an 80-90% reduction of Greenhouse gas (GHG) emissions [1]. The industry is responsible for about 19% of GHG emissions, representing a priority for achieving those targets.

Pulp and paper (P&P) production is among the major industrial sectors in Europe. For this thesis, the main processes related to paper production from either virgin or recycled fibers are analyzed, giving emphasis to the final energy consumption of each process (either heat or electricity). A bottom-up model of the energy consumption of the entire process was developed, which calculates energy consumption based on the amount of P&P produced. By understanding which fuels were used in heat or electricity production, the model calculated the amount of CO_2 emitted in the production process. The model was used to calculate the CO_2 emissions of the production of the main paper grades and also the annual CO_2 emissions of the P&P industry in Austria.

The technological options to reduce fossil-CO_2 emissions due to the production of P&P were investigated. Seven of those technologies were introduced individually in the model. For each of the chosen technologies, the individual fossil-CO_2 emission reduction during the production of a specific paper grade and in the overall P&P production in Austria until 2050 were estimated. The implementation of technologies chosen results in a reduction of 18% to 80% of CO_2 emissions for the production of the specific grades they apply to.

Key-words: Pulp and paper industry, Greenhouse gas emissions, CO_2 emissions reduction, Innovative technologies.

Resumo

A União Europeia pretende reduzir as emissões de gases com efeito de estufa em 80-90% até 2050. A indústria é responsável por cerca de 19% destas emissões e é por isso um sector prioritário.

A produção de pasta e papel (P&P) encontra-se entre os sectores industriais principais na Europa. Nesta tese, os principais processos necessários para a produção de papel a partir de fibras recicladas ou de madeira foram analisados, dando enfase ao consumo de energia final de cada processo (eletricidade ou calor). Foi desenvolvido um modelo bottom-up do consumo energético de todo o processo, calculando a energia consumida tendo por base a quantidade de P&P produzidos. Sabendo os combustíveis utilizados para a produção do calor e eletricidade, foram calculadas as emissões de CO_2. O modelo foi utilizado para calcular as emissões de CO_2 para a produção dos principais tipos de papel e também para calcular as emissões anuais da indústria da pasta e do papel na Áustria.

Foram também investigadas as opções tecnológicas que permitem reduzir as emissões de CO_2 durante a produção de P&P. Sete das tecnologias estudadas foram introduzidas no modelo. Para cada uma, foi estimada a redução individual de CO_2 durante a produção de um dos tipos de papel estudados e também toda a indústria na Áustria até 2050 (individualmente). A implementação das tecnologias escolhidas resulta numa redução de 18% a 80% de emissões de CO_2 durante a produção dos tipos de papel estudados.

Palavras-chave: Indústria da pasta e papel, Emissão de gases com efeito de estufa, Redução de emissões de CO_2, Tecnologias inovadoras

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Abbreviations and Nomenclature

Abbreviations

AAGR	Average annual growth rate
AGR_y	Annual growth rate in year y
AD	Air dried (10% moisture)
BAT	Best available technologies
CAPEX	Capital expenditure
CCS	Carbon Capture and Storage
CD	Condebelt drying
CEPI	Confederation of European Paper Industries
CO_2	Carbon dioxide
CPM	Chemimechanical pulp
CTMP	Chemithermomechanical pulp
DEH	Direct electric heating
DSF	Dry sheet forming
EF	Emission factor
EU ETS	European Union emission trading system
GDP	Gross domestic product
GFD	Gas-fired dryers
GHG	Greenhouse gas
GW	Groundwood pulp
GWP	Global warming potential
ID	Impulse drying
IEA	International Energy Agency

IPCC	Intergovernmental Panel on Climate Change
IT	Innovation technologies
LCA	Life cycle assessment
LULUCF	Land use, land use change and forestry
NEFI	New Energy For Industry
OPEX	Operational expenditure
PGW	Pressure groundwood pulp
P&P	Pulp and paper
R&D	Research and development
RCF	Recycled fibers
RMP	Refiner mechanical pulp
SAT	State-of-the-art technologies
SCW	Steam cycle washing
TMP	Thermomechanical pulp

Nomenclature

- Indexes

i	Type of fuel
p	Process (a part of the production process)
x	Product (a type of pulp or paper)
y	year

- Variables

α_y	Ratio between total heat consumption and total fuel consumption by the P&P industry in year y (kWh_{heat}/kWh_{fuel})

β_y	Ratio between total electricity consumption and total fuel consumption by the P&P industry in year y ($kWh_{electric}/kWh_{fuel}$)
$CO_{2\ direct,y}$	CO_2 emissions derived from the use of fossil fuels by the P&P industry in year y (ton)
$CO_{2\ grid,y}$	Total CO_2 emissions due to production of grid electricity in year y (ton)
$CO_{2\ indirect,y}$	CO_2 emissions derived from the use of grid electricity by the P&P industry in year y (ton)
$ef_{grid,y}$	CO_2 emission factor of grid electricity consumption in year y (kg CO_2/kWh)
ef_i	CO_2 emission factor of fuel i (kg CO_2/kWh)
$E_{grid,y}$	Total grid electricity in year y (kWh)
$E_{purchased,y}$	Electricity purchased from the grid in year y (kWh)
$E_{purchased,data,y}$	Electricity purchased from the grid in year y (from data – kWh)
e_x	Specific electricity need for the production of product x (kWh/ton)
$e_{x,p}$	Specific electricity need for process p used in the production of product x (kWh/ton)
E_y	Total electricity consumption by the P&P industry in year y (kWh)
$E_{y,data}$	Total electricity consumption by the P&P industry in year y (from data – kWh)
$F_{grid,i,y}$	Total consumption of fuel i for the production the grid electricity in year y (kWh)
$f_{i,y}$	Share of fuels used in the P&P industry in year y corresponding to fuel i (%)
$F_{i,y}$	Total consumption of fuel i in the P&P industry in year y (kWh)
F_y	Total consumption of fuels in the P&P industry in year y (kWh)
$F_{y,data}$	Total consumption of fuels in the P&P industry in year y (kWh – from data)
g_y	Ratio between grid electricity consumption and total electricity consumption by the P&P industry in year y (kWh/kWh)
h_x	Specific heat need for the production of product x (kWh/ton)
$h_{x,p}$	Specific heat need for process p used in the production of product x (kWh/ton)
H_y	Total heat consumption by the P&P industry in year y (kWh)
$H_{y,data}$	Total heat consumption by the P&P industry in year y (from data – kWh)

mf	Mineral filler content in paper (%)
M_p	Mass of product p (ton)
$P_{x,y}$	Production of product p in year y (ton)
r	RCF content in pulp (%)

1 Introduction

1.1 Motivation and objectives

The recent years have been marked by unsettling climate changes: changes in the yearly seasons, the melting of the arctic ice caps, extreme weather events (such as storms and droughts) and immense fires consuming major forest areas of the planet like the Amazon and destroying both natural habitats and human patrimony. These changes make the problem of global warming more evident every day to all citizens, raising a growing concern for the future of the Planet. Acting is urgent.

Global warming is caused by the increase in the concentration of greenhouse gases (GHG) in the atmosphere. The common metric used to quantify the impact of GHG is global warming potential (GWP). "*GWP expresses the integrated radiative forcing (warming impact) of a greenhouse gas relative to that of CO_2, over a fixed period, usually 100 years (GWP_{100}). Using the relevant GWP for each different greenhouse gas, the aggregated value is then expressed as "CO2-equivalents" (CO_2-e)" [2] .* Among the main GHG are Carbon dioxide (CO_2), methane (CH_4), Nitrous oxide (NO_2) (natural gases) and Chlorofluorocarbons (CFCs – not created naturally but synthesized). The emissions of CFCs have been successfully mitigated in the past, so they are not a priority at the present. CH_4 has a GWP_{100} of 21 kg CO_2-eq and NO_2 has a potential of 310 kg CO_2-eq[3].

In the Paris Agreement of 2015, 195 countries have agreed to take action to keep global warming well bellow 2ºC. The European Union (EU) aims to position itself as the World leader in emission reduction and so it has defined a set of ambitious targets to limit the increase in temperature. Among them, the reduction of GHG emissions by 40% in 2030 relatively to 1990. Other targets establish that at least 32% of energy consumption in the same year should correspond to renewable energy and energy efficiency should increase by at least 32.5%. To 2050, the EU aims at an 80-90% reduction of GHG emissions [1]. To do that, the EU must effectively locate the source of the emissions and look for alternatives to the current processes in a short period of time.

The main sources of GHG emissions in Europe are energy production, transport, industry and agriculture, and so measures are applied to each of these sectors. In 2014, the industry accounted for 19% of emissions in Europe, representing a priority in the strategy of the EU. That is the case for most countries inside the EU. In 2016, the Austrian industry was responsible for 21% of the GHG emissions in the country.

With that in mind, the project New Energy for Industry (NEFI), a consortium of companies, research institutes and public institutions, was created in Austria, with the goal of decarbonizing the Austrian industrial sector until 2050. The current thesis project was developed under the scope of the NEFI in the University of Leoben, about a relevant sector for the industries in Austria and Portugal, the pulp and paper (P&P) industry. The project was a part of the first phase of the project, in which information about the current production processes of the several industries in Austria is being collected along with research on innovation technologies which may lead to a reduction in CO_2 emissions.

The paper production is energy and material intensive. In Europe, continued efforts have been made to decarbonize the sector and increase energy efficiency. However, paper production still accounts for 1,2 Mton and 1.8 Mton of CO_2 emissions per year in Portugal and Austria, respectively. The majority of the GHG emitted in the lifecycle of paper products correspond to CO_2 emissions during the production process, due to the high energy demand of the process. The industry uses mostly biofuels to obtain both the heat and electricity needs, using high efficiency combined heat and power cycles, so the majority of carbon emissions is related to the share of energy produced from fossil fuels, and a small share from the energy consumption from the electrical grid.

In this project, the options for decarbonization for the production process of the P&P industry were assessed, focusing on innovative technologies. The objectives of the project were the following:

1. Understand the P&P production process and identify the state-of-art technology used currently;
2. Develop a model to estimate energy consumption and CO_2 emission up to 2018, understanding which processes should be the focus of the industry to decrease CO_2 emissions;
3. Determine what are the best available technologies (BAT) and innovation technologies (IT) with potential to decarbonize the P&P industry;
4. Estimate scenarios for future energy consumption and CO_2 emissions for the P&P industry if the chosen technologies are deployed, based on the developed model. Give recommendations about which technologies will be determinant to decarbonize the paper industry.

The model was developed in a linear bottom-up approach. The specific energy consumption of each process used in production was investigated in the literature and used to calculate the annual energy consumption, considering the amount of P&P produced. The estimation of the fuel consumption to supply the energy needs was made using the ratio between the declared energy and fuel consumption for the P&P industry in Austria. Finally, CO_2 emissions were estimated based on fossil fuel emission factors.

The project is focused on the Austrian industry. Nevertheless, an introductory chapter about the Portuguese P&P industry is also included, since many of the considerations and conclusions of the study are common to both countries.

1.2 Structure of the dissertation

The thesis is structured in 5 sections, the first of them corresponding to the introduction, stating the motivation, objectives and structure of the thesis.

Following the literature review of the relevant topics will be presented, namely the evolution and current state of the paper industry in Europe (focusing on Austria and in Portugal), the P&P production process, the future scenarios developed by various authors for the industry and finally the innovative technologies.

The third section is the description of the methodology for the development of a bottom-up model to calculate the CO_2 emissions of the paper industry, based on the production of the various types of P&P.

The fourth section presents the results of the model developed for the industry in Austria. First, the results of the application of the model to the past years are presented and compared to real data, followed by the scenarios of emissions up to 2050.

Finally, in the last chapter, the conclusions of the thesis are presented.

2 Literature Review

2.1 The paper industry

The paper industry is among the most expressive industries in the World, with a production of over 400 million tons of paper annually. The process of paper production consists of three main stages: wood preparation, pulp production and paper production. All three stages have several sub-processes and can take different routes (as will be explained in detail in section 2.5) making this industry highly complex.

Paper production traces its roots to China, in the II century. The raw materials used in production were rags and later bamboo, and paper was used only for writing purposes. Wood became the main raw material only after the start of industrial paper production, in the nineteenth century, with the invention of the wood-grinding machine. The pulping process was originally done by mechanical means, which are still used nowadays for some purposes such as magazine paper. Full industrialization occurred in the twentieth century, marking also the invention of many diversified paper grades. Nowadays most of the virgin pulp produced is obtained by chemical methods since it produces a paper of higher quality. Also, a large share of pulp is produced from recycled paper. Industrial paper production started with the invention of the Fourdrinier Machine, a production line in which pulp is introduced and subjected to several processes, obtaining paper as the final product. Even though other alternatives were developed, the Fourdrinier machine is still the most used process of paper production nowadays.

This sector is very diverse. Some paper products are considered essential to society for several decades, such as graphic paper. However, nowadays the paper industry is also the source of modern highly specific grades developed to satisfy diverse purposes, such as hygiene or specialized packing of food and other goods, among many other applications. The Confederation of European Paper Industries (CEPI) divides the paper grades into the following categories:

- Newsprint and Magazine paper, suitable for press printing, generally made through mechanical pulping methods, with high percentages of recycled fibers;
- Printing and writing paper, used for graphic purposes. Printing paper is coated, a final process that provides better surface characteristics, whereas writing paper is not coated. These paper grades are commonly made from chemical pulp and have many requirements which make the production process more demanding;
- Sanitary and household papers, such as toilet paper and tissue, made from virgin pulp or recycled fibers. These grades are amongst the more energetically intensive;
- Packing material or products, which include corrugated board, folding boxboard and wrappings. These products can be done with virgin or recovered pulps, but usually have high percentages of recovered paper. Often the surface quality is not a priority, making these grades less energy-intensive.
- Specialty papers, which includes papers for different specific porpoises with lower production, such as cigarette paper, wallpaper, photographic paper, etc;

Packing materials and graphic paper (printing and writing) take the biggest shares of production. Figure 2.1 shows the evolution of paper and board production worldwide from 1990 to 2016. In 2016, 408,7 Mton of paper were produced worldwide, of which 57.4% were packing and board products, 30.4% were graphic paper and 8,2% were tissue paper. In the same year, 181 Mton of virgin pulp were produced, 76% Chemical, 18% Mechanical and 6% by other methods [4].

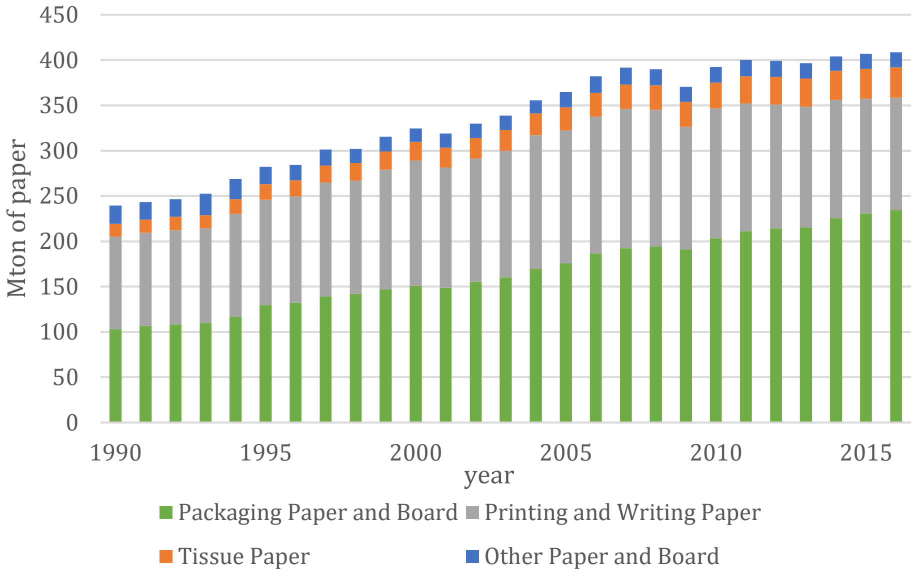

Figure 2.1: Global paper and board production by grade [5]

To produce paper, a large amount of energy is necessary, mostly in the form of steam. The average final energy consumption to produce some common paper products in the Netherlands is presented in Figure 2.2. Tissue and sanitary paper are commonly the most energy-intensive grades since a different paper drying method is required to ensure surface smoothness, whereas packing materials are usually less energy-intensive.

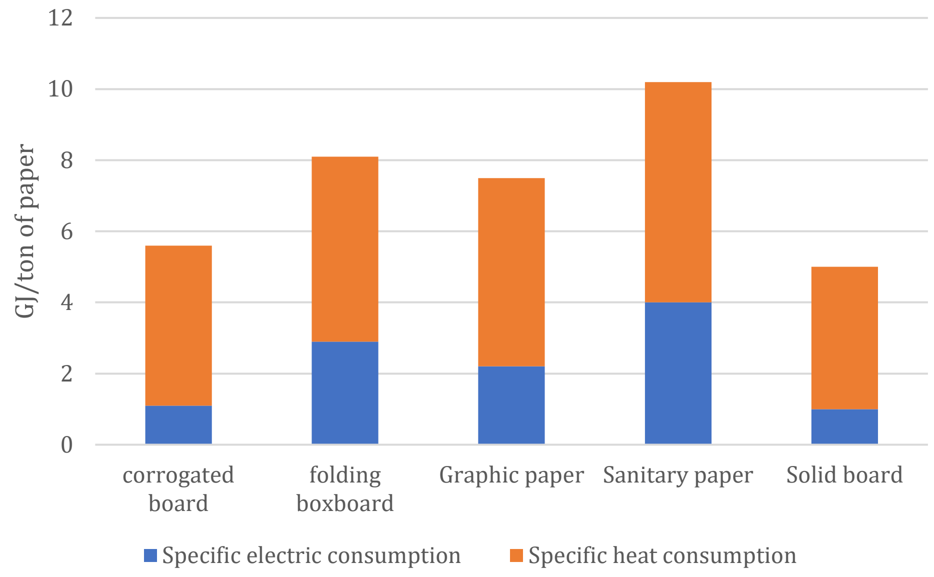

Figure 2.2: Specific energy consumption of paper products [6]

The energy consumption of each product depends on the specific production process. Products with higher recycled fiber content tend to have lower energy requirements because the production of recycled pulp consumes less energy than any virgin pulp production process. Many other factors are determinants, such as the pulping process (for virgin pulp paper) or the paper drying process.

The global paper industry has decreased its overall final energy intensity by 19.3% from 2000 to 2016 [7]. Still, paper is among the most energy-intensive industrial products. In 2016, the global paper industry accounted for 6.73 EJ – 4.38% of industrial final energy consumption worldwide [8], 34.92% of this energy was originated from fossil fuels at the paper mills, emitting 0.2Gton of CO_2 (0.5 ton CO_2/ton of paper) – 2.38% of the emissions for all industrial sectors [8] and 0.46% of the total CO_2 emissions.

2.1.1 Paper industry in Austria

Paper has been produced in Austria for many centuries. It is for long established as one of the main industrial products of the country. The first paper mill was established in 1321 in Leesdorf bei Baden and by the XVI century paper production was spread among all the territory [9]. Nowadays, according to the Austrian association of paper producers, Austropapier, there are 23 P&P mills in Austria specialized in various products. In 2017, the P&P industry contributed to 0.89% of Austria's GDP [10, 11].

The production is not uniform among facilities. More than one-third of the production is accounted to the three largest companies (34%) whereas eleven medium-sized facilities accounted for 61%. The remaining capacity (less than 6%) is produced in small firms. Energy represents 15% of the total costs of the industry [12].

Several of the P&P mills in Austria make use of CHP to produce energy from waste biomass and sell the excess heating to district heating grids, which is considered the best practice to deal with the excess low-temperature heat generated by the industry. Many of the companies are awarded quality certificates such as quality management system, environment management system certifications and system for the structured management of efficient energy generation and consumption (ISO 14001, ISO 90001 and ISO 50001).

Figure 2.3 presents the evolution of the pulp production in Austria, discriminated into 5 types: mechanical pulp, chemical pulp, textile pulp (which is pulp produced through chemical processes, but used in the textile industry, not for paper production) and deinked and non-deinked recycled paper pulp (which is not available for the year 1990). Production of mechanical pulp is decreasing in the past years, whereas the textile and non-deinked pulp productions show a growing trend. In 2018, total production of pulp in Austria was 4.33 Mton, with the following shares: 7.0% mechanical pulp, 30.6% chemical pulp, 10.5% textile pulp, 13.7% recycled deinked pulp and 38.1% recycled non-deinked pulp. Recycled paper pulp represented 57.9% of the total paper pulp produced.

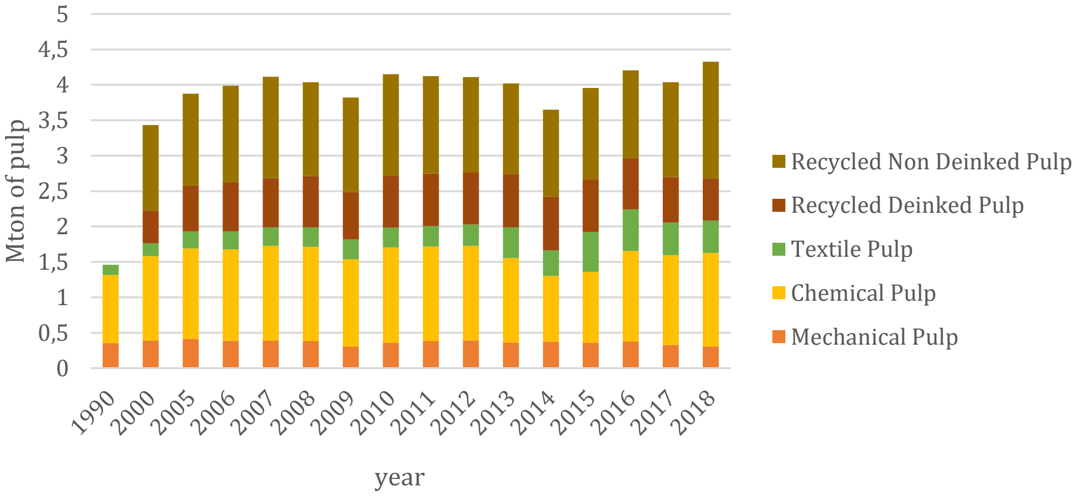

Figure 2.3: Pulp production in Austria by type [13–24]

Figure 2.4 illustrates the evolution of paper production in Austria. Whereas global production has been increasing, the production in Austria has been steady since 2009, with an average annual growth rate (AAGR – equation (2.1)) of 0.26%.

$$AGR_y = \frac{x_{y+1} - x_y}{x_y}; \ AAGR = \frac{\sum_{y=1}^{N} AGR_y}{N} \qquad (2.1)$$

In 2018 were produced in Austria 5.06 Mton of paper products in Austria, with close shares of printing and writing paper and packing paper and board (47.4% and 46.3%, respectively) and a smaller share of tissue and other products (6.3%). The production of paper is significantly higher than the production of pulp. This is due to the use of paper fillers but also the international trade of virgin pulp. In 2018, 0.527 Mton of pulp were exported and 0.718 Mton were imported.

Even though graphic paper represents still a large share of the production, it has been slowly decreasing since 2012, whereas the production on packing materials has been increasing since 2006, following the global trend already referred. This is due to the global trends of slower consumption of graphic paper and increased use of paper as packing products, strengthened by the tendency to decrease plastic use.

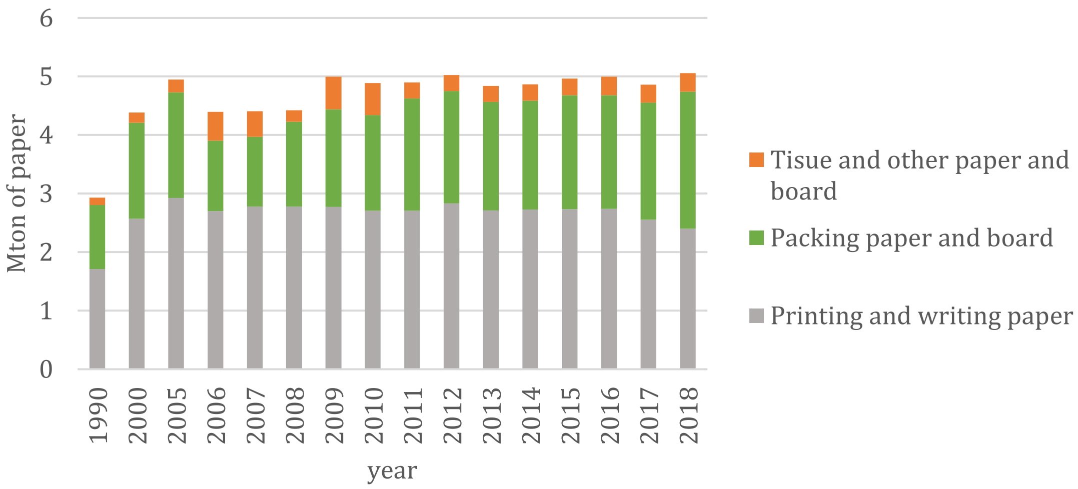

Figure 2.4: Paper and board production in Austria by grade [13–24]

In 2018, the P&P industry in Austria consumed 4535 GWh of electricity and 11918 GWh of steam as final energy. Having produced 3026 GWh and 13366 GWh of each energy, respectively [24], out of 18639 GWh of fuels, the industry was self-sufficient in terms of heat consumption and produced 67% of the electricity consumed. This would not be possible without the use of energy-efficient technology.

Table 2.1: Final energy consumed by the Austrian P&P industry in 2018.

Final Energy	**Consumption (GWh)**
Fuels	18639
Electricity	4535

The discriminated fuel consumption in 2018 and CO_2 emissions calculated with each fuel emission factor (EF) are reported in Table 2.2. The majority of fuels used in P&P mills are biofuels (mostly black liquor – a sub-product of chemical pulp production, but also waste wood), with only 40% use of fossil fuels (mostly natural gas, but also coal and oil). Biofuels are the biggest source of CO_2 emissions, but they are considered to be carbon neutral. Nevertheless, the EF of bio-CO_2 emitted when combusting biofuels (correspondent to the EF black liquor) is presented in Table 2.2: Fuels consumption and estimated CO_2 emissions by the Austrian P&P industry in 2018.

Table 2.2: Fuels consumption and estimated CO_2 emissions by the Austrian P&P industry in 2018.

Fuel	**Share (%)**	**EF (kg CO_2/kWh)**	**Total emission (kton CO_2)**
Biofuels	59.1	0.343	3778.4
Natural gas	6.49	0.199	1261.5
Oil	0.21	0.28	11.0
Coal	34.01	0.338	408.9

The electricity consumed came from both internal production from the fuel mix in Table 2.2 and grid electricity. The CO_2 emissions related to grid electricity consumption are reported in Table 2.3. Information regarding the energy mix powering the grid was obtained from the IEA and is not available after 2014, so the values of the year 2014 are used for this purpose (as explained in section 3.3).

Table 2.3: Estimated CO2 emissions due to grid electricity use by the Austrian P&P industry in 2018

Grid consumption (GWh)	Grid EF (ton CO_2/GWh)	Total emission (kton CO_2)
1805	41.4	74.7

Most of the fossil-CO_2 emissions are derived from the combustion of fossil fuels used by the industry (direct emissions – 89%), but emissions due to the use of grid electricity should also be accounted for (indirect emissions). The evolution of direct fossil CO_2 emissions is reported in the annual reports of Austropapier and is presented in Figure 2.5.

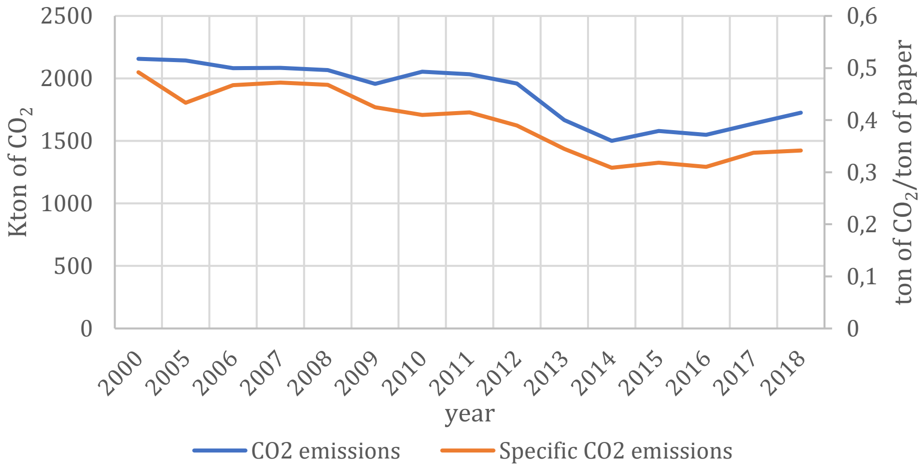

Figure 2.5: Direct fossil CO2 emissions from the Austrian P&P industry [13–24]

There was a decreasing trend in the direct emissions from 2000 to 2014 (most likely due to efficiency measures and technology renovation) when the emissions started to increase again up to the present moment. The trend for specific emissions is similar since the production was proximately constant. In 2018, the direct emissions were of 1727 kton of CO_2.

2.1.2 Paper industry in Portugal

Like Austria, Portugal is also a major producer of paper, which is among its main industrial products. Industrial production of paper started in the beginning of the 18th century. Nowadays according to the Portuguese association of paper producers, CELPA, there are nine main P&P mills in Portugal, responsible for the totality of the production of pulp and 90% of the production of paper [25]. In 2017, the paper industry contributed to 1.39% of Portugal's GDP [25].

Several of the paper mills in Portugal are equipped with CHP units, which use mostly bio-fuels. The uses of the excess heat are not used for district heating since such grids are not common in Portugal, but the excess production of electricity is sold to the national grid. In 2016, the paper industry produced 6.3% of the total electricity produced in Portugal, corresponding to almost half of the electricity produced by all the industries by means of cogeneration (49%) [25]. All paper in Portugal is produced in facilities that are certified with quality and environmental management and efficient energy systems (namely ISO 14001, ISO 90001 and ISO 50001).

Figure 2.6 presents the evolution of the pulp production in Portugal, discriminated into the 3 types of pulp produced in the country: chemical pulp and deinked and non-deinked recycled pulp. There is no information about the production of recycled paper pulp before 2002. The overwhelming majority of production corresponds to chemical pulp. In 2017, the total production of pulp in Portugal was about 2,938 Mton of pulp, out of which 93.7% corresponded to chemical pulp, 1.1% to recycled deinked pulp and 5.3% to recycled non-deinked pulp.

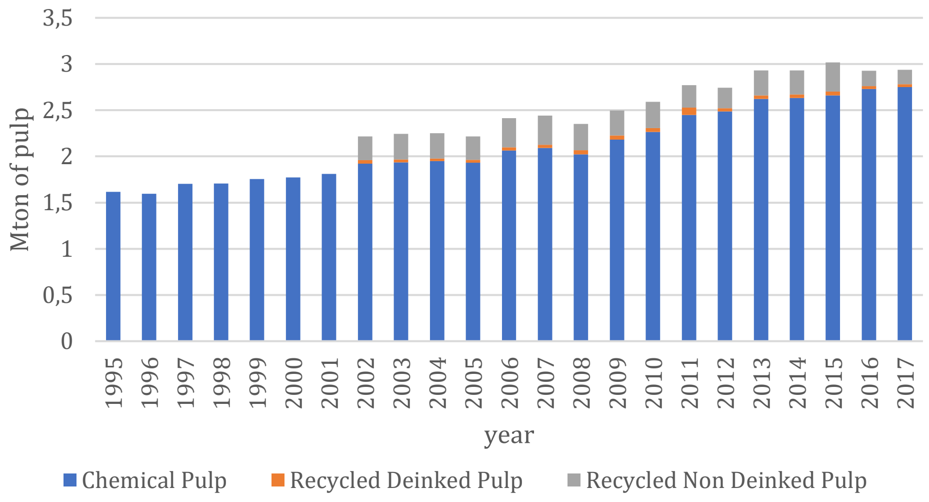

Figure 2.6: Pulp production in Portugal by type [26–42]

Figure 2.7 illustrates paper production in Portugal. Despite a slight reduction in 2017, the overall tendency since 1995 is to increase, with an AAGR of 3.7%. In 2017 the total production of paper in Portugal was of 2.1 Mton, with the following shares of paper products: 76.1% printing and writing paper; 17.5% packing paper and board; and 6.4% tissue and other grades. The production growth in the last years was mostly in the form of printing and writing paper (the production of this grade in 2017 twice the value of 2000), with a small growth of tissue papers and steady production of packing paper and board products. These trends do not correspond to the global paper industry, which is experiencing a strong increase in board products. The industry in Portugal is focusing on graphic grades, for which mostly chemical pulp is used with a low percentage of recycled paper. The typical grades produced out of mechanical pulp such as newspapers or magazines are not produced, which explains why that type of pulp is not produced.

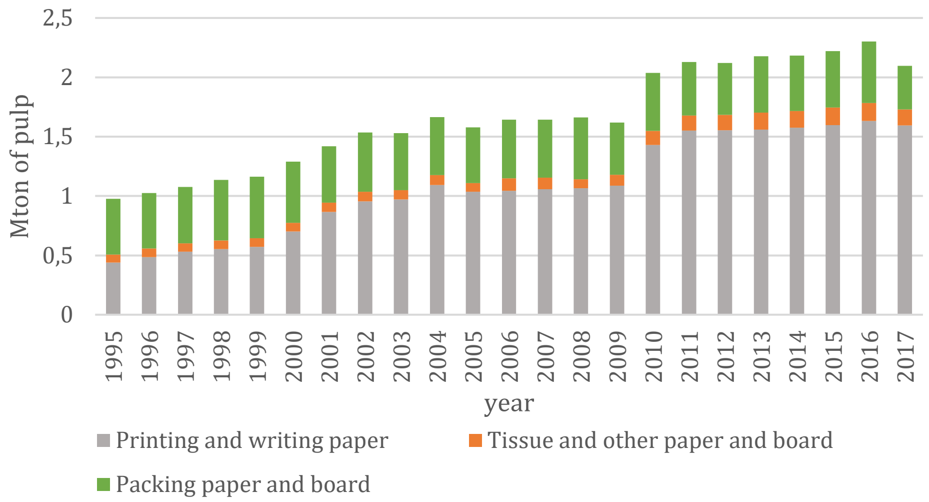

Figure 2.7: Paper and board production in Portugal by grade [26–42]

In 2017, the paper industry in Portugal consumed 19850 GWh of fuels, used mostly in cogeneration units, producing 3440 GWh of electricity. The consumption of electricity was 2620 GWh, meaning that in 2017 the paper industry was self-sufficient in terms of electricity consumption, selling 820 GWh to the grid. This has been the case since the year 2005.

Table 2.4: Primary energy consumed by the Portuguese P&P industry in 2017

Primary Energy	**Consumption (GWh)**
Fuels	19850

The discriminated fuel consumption in 2017 and CO_2 emissions are reported in Table 2.5. Like in the Austrian industry, most of the fuels used are biofuels, generating also most of the CO_2 emissions (bio-CO_2). The most used fossil fuel is natural gas. The Portuguese P&P industry does not use any coal as fuel.

Table 2.5: Fuels used by the Portuguese P&P industry in 2017 [25]

Fuel	**Share (%)**	**EF (kg CO_2/kWh)**	**Total emission (kton CO_2)**
Biofuels – Black liquor	59.48	0.343	4050.1
Biofuels – Wood waste	10.86	0.403	684.8
Natural gas	25.41	0.199	1003.7
Oil	2.62	0.28	145.4
Deisel	1.63	0.28	90.5

Figure 2.1 shows CO_2 emissions by the paper industry (absolute and specific values) derived from energy production. Specific values are only available after 1995 since there is no previous record of paper production.

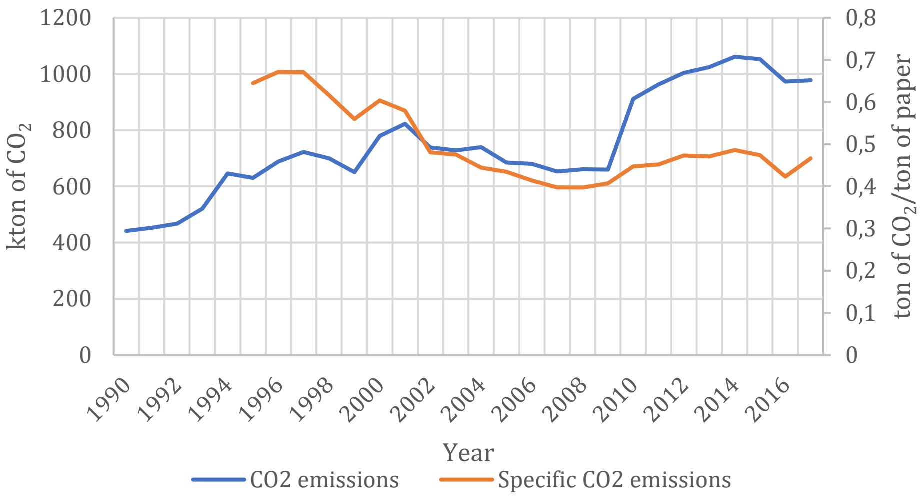

Figure 2.8: Direct fossil CO2 emissions from the Portuguese P&P industry [26–42]

The CO$_2$ emissions present a growing trend until the year 2000, due to the increase of production in P&P in that period. After that point and until 2009 there is a slight reduction in emissions. Even though the overall emissions increased, the specific emissions of CO$_2$ have a decreasing trend from 1996 up to 2009, indicating the technological progress of the sector in this period towards more sustainable production.

In 2010 the paper production increased considerably (25%). Since pulp production did not follow the same trend, the biofuels share decreased in that year from 74% to 69% (since most of the biofuels used are biomass waste or black liquor from chemical pulp production), increasing the share of fossil fuels used which caused a drastic increase in emissions (38% in that year). The growing trend continued until 2013, after which the emissions started to decrease again.

2.2 Emissions throughout the life cycle of paper products

The starting point to reduce the CO$_2$ emissions by the P&P industry is to understand what the sources of those emissions are along the life cycle of paper. A tool which is often used for this purpose is Life cycle assessment (LCA), which is an analysis of a product "from cradle to grave", calculating the impacts caused by each phase of the life cycle of the product, according to different impact categories. This way, industry experts can locate which phase of the life cycle of paper causes the most emissions.

For the purpose of understanding the life cycle of paper products and how it may change according to factors such as local conditions, business model, recycling rate, etc, eight different scenarios were considered, all considering the production of office paper from virgin (kraft) and/or recycled pulp:

1. Virgin fiber paper produced, consumed and disposed of in Portugal – Pt [43];
2. Virgin fiber paper produced in Portugal and exported to Germany, where it is disposed of after use – G [43];
3. Paper imported and consumed in the UK, produced in Europe, from either virgin fibers (57%), recycled fibers (40%) or closed-loop recycled fibers (produced and recycled after use in the same facility, in Germany – 3%) – UK_BaU [44];

4. Paper imported and consumed in the UK, produced in Europe only from closed-loop recycled fibers – UK_CLRec [44];
5. Paper imported and consumed in the UK, produced in Europe, form either virgin fibers (25%) or closed-loop recycled fibers (75%) – UK_CLRec +Virgin [44];
6. Paper imported and consumed in the UK, produced in Europe only with virgin fibers – UK_Virgin [44];
7. Paper imported and consumed in the UK, produced in Europe only with recycled fibers (not closed-loop) – UK_Rec [44];
8. Paper produced and consumed in the USA, from virgin pulp (96%) and recycled fibers (4%) – USA [45].

Typically, LCA studies about the P&P industry distinguish the following main stages of paper life-cycle (shown in Figure 2.9):

1. Raw material production and extraction – consists mostly of forestry-related activities and transport of the materials to the industrial sites;
2. P&P production;
3. Transport to consumer;
4. Final product use;
5. End-of-life – for paper products, the end-of-life may be one of three alternatives, recycling, incineration or landfilling.

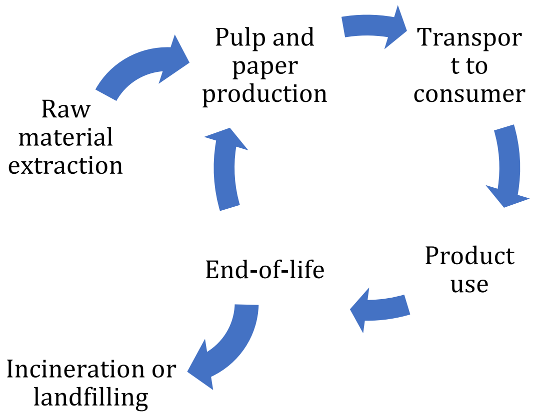

Figure 2.9: Stages of the life-cycle of paper.

Different studies may expand these stages into more specific ones, according to the goals of the study. For example, the transport of the raw materials to the mill is often considered separately and pulp production may be investigated separately from paper production.

Like the stages, the impact categories of paper production considered may vary. Among others, the main impact categories of paper production are:

- energy demand – the energy consumption among the different stages of the product's lifecycle;
- non-renewable resource depletion – consumption of non-renewable resources such as fossil fuels, nuclear fuels or minerals (often just mentioning fossil fuels);
- global warming potential (GWP) – a measure of the increase in temperature in the earth surface caused by the emission of GHGs;
- acidification – decrease in the pH of rain, with negative impacts for soils, agriculture, buildings, etc, due to the emission of gases such sulfur dioxide (SO_2) and nitrogen oxides (NO_x);
- eutrophication – decrease in water quality due to the increase in the concentration of nutrients such as phosphorus and nitrogen, disrupting the ecosystem.

The most important category for the focus of this thesis is global warming potential (which is often related to energy use and non-renewable resource depletion), which is caused by the emission of three gases – CO_2, CH_4 (with GWP_{100} of 21 kg CO_2-eq [3]) and NO_2 (with GWP_{100} of 310 kg CO_2-eq [3]).

Table 2.6 shows the GWP of the different stages of paper life-cycle, in the eight scenarios considered.

Table 2.6: GWP of the different stages of paper life-cycle, according to different scenarios.

Scenario	**GWP (ton CO_2 eq/ton paper)**	**Raw material extraction**	**Production**	**Transport & use**	**End-of-life**
Pt	2.4	~0%	50%	~0%	50%
G	1.6	~0%	75%	12.5%	12.5%
UK_BaU	1.2	n.a.	80%	n.a.	8%
UK_CLRec	1.9	n.a.	80%	n.a.	5%
UK_CLRec +Virgin	1.6	n.a.	75%	n.a.	6%
UK_Virgin	0.8	n.a.	49%	n.a.	12%
UK_Rec	1.8	n.a.	84%	n.a.	6%
USA*	2.0	8.3%	55.4%	1.3%	34.9%

*Excluding carbon storage in use and landfill.

The total GWP varies among the different scenarios considered, depending on factors such as the waste management option and the transportation distance. All paper consumed in the UK is considered to be totally recycled, reducing the emissions of GHGs at the end-of-life stage, whereas paper consumed in Portugal or the USA is partially sent to landfill, which leads to the emission of methane. The paper consumed in Portugal and Germany has the same production process, differing only in transportation and end-of-life phases. Even though the paper consumed in Germany travels for long distances, emitting CO_2 due to fuel consumption, the paper consumed in Portugal ends-up in landfills, emitting the same CO_2-eq as the production phase. The high GWP attributed to raw material extraction in the USA may be related to the transportation of raw materials for long distances to reach the production sites.

Transportation and waste management are then both important factors. Nevertheless, in all the scenarios, the life-cycle phase with the highest GWP is the production of paper and pulp, representing a fraction of

GWP between 49% and 84%. This is due to the use of fossil fuels as a way of providing the high heat needs for the production of pulp and drying of paper. In the UK_Virgin scenario, the production is assumed to take place exclusively in integrated P&P mills, increasing the use of bio-fuels and decreasing the need for fossil fuels needed. Still, production accounts for 49% of GWP. For this reason, measures applied to the process which will be studied in this thesis are a priority when tackling the emission of GHG by the P&P industry and are considered fundamental for achieving sustainable production.

2.3 Forest sector and bioenergy carbon emissions

The paper industry is in close relation to the forest sector since wood is the most important raw material for this industry. Wood is primarily used as raw material for paper production, but its waste and by-products are used for energy production and represent considerable fractions of the total energy requirements, being considered sources of bioenergy. In 2017, bioenergy represented about 29.09% of the P&P industry final energy consumption globally [7]. In Europe, the share of bioenergy is even more significant, with 52.8% of the final energy consumption [46]. This section will briefly present the discussion on the impacts of bioenergy and the impacts of the paper industry on the forest.

A forest is constantly exchanging carbon with the atmosphere, absorbing or emitting CO_2. Without disturbances, the forest is constantly absorbing carbon by means of the photosynthesis process, until it eventually reaches a steady-state equilibrium under which new growth and decay from dead trees occur at similar rates. The natural growth rate of a forest has a similar shape as one of an individual tree, presented in Figure 2.10 [47].

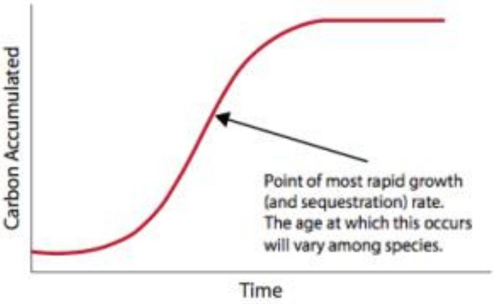

Figure 2.10: Natural growth rate curve of a tree.

This means that young forests are strong carbon absorbers in order to sustain the fast development rates of the new trees, whereas mature sites absorb less CO_2 or can be even neutral. Disturbances are sources of CO_2 emissions (forest fires or recently harvested areas). Wild forests have neutral CO_2 emissions in the long term: carbon is absorbed when each tree grows and is released back to the atmosphere when the biomass naturally decays after the death of the tree (almost completely, since a portion is stored in the soil).

The impacts of the use of the forest as a renewable energy source have been a topic of discussion. The main topic is the influence of the use of wood for energy on the natural cycles of the forest and on its development. Studies with different time or special scales may reach completely different conclusions.

The Intergovernmental Panel on Climate Change (IPCC) stipulates that emissions resulting from the use of bioenergy should be attributed to the Land use, land use change and forestry (LULUCF) sector and not to the consuming sector/industry. Those emissions are accounted for when the trees used are harvested. The national inventory, presented at each year by the member countries of the United Nations, reports these emissions by calculating the total harvested wood and assuming an average emission factor per ton of wood, no matter the use which is given to it. The assumption is that all the wood harvested will result eventually in carbon emissions. Carbon neutrality of bioenergy does not mean that emissions from bioenergy are not considered. Instead, it means that they are attributed to the forest sector [2]. The carbon balance of all wood products is then easily represented by the mass balance of wood in forests: A growing forest is a carbon sink (or carbon pool) whereas deforestation and recently harvested areas represent a carbon source.

The CO_2 emissions from biomass used in the paper industry fit into this category. For that reason, it is common to report separately the CO_2 emissions from fossil fuels. Nevertheless, it is considered a good practice to report biogenic carbon emissions [48].

However, carbon for harvested wood remains temporarily stored in the form of wood products since it was absorbed by the forest but not yet emitted. Each sector that uses wood products reports the carbon which is stored in its products which can last for days, in the case of biomass for energy, but also decades to centuries when the wood is used for more durable uses, such as construction or furniture. This means that paper products are a form of carbon storage and paper recycling is preventing carbon which was once sequestrated from the atmosphere from again emitted. For example, if a wood beam is produced out of a tree using 70% of its wood, the CO_2 emissions to the atmosphere accounted to the forest sector will correspond to the decay of the entire tree, but also 70% of the emissions will be calculated as “captured” from the atmosphere in the way of carbon storage in the wood beam, leaving as “net emission” the remaining 30% of CO_2 for the period in which the wood beam is being used and not converted into energy. If the wood waste (30%) is used to produce energy in the paper industry, no positive or negative emissions will be accounted for it.

The forest carbon stock has increased in Europe since 1990, which by the described methodology of the IPCC means that it is a carbon sink. However, the global forest area has suffered a worrisome loss of 1% of the land area from 1990 up to 2015 (31.6% to 30.6%) [49].

Different views of the use of bioenergy look only to CO_2 emissions to the atmosphere, ignoring the entire cycle and claiming that all CO_2 emissions contribute to the greenhouse effect, no matter what is the source,

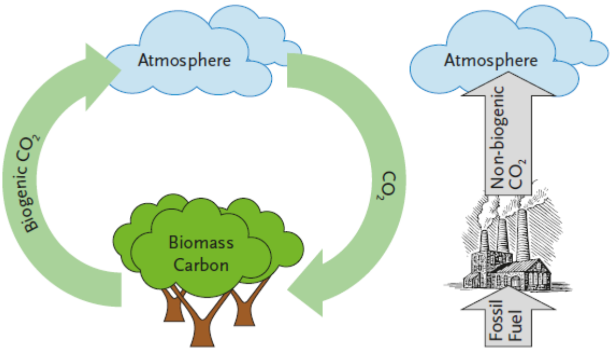

Figure 2.11: Illustration of the important distinction between bioenergy (cyclic carbon flow) and fossil-based energy (linear carbon flow) [1].

and also give emphasis to the fossil CO_2 associated with the harvest, transport and other activities. While those claims present valid arguments, it should not be ignored that bio-CO_2 emissions to the atmosphere are a part of a continuous cycle, whereas fossil-CO_2 is not balanced by any natural sink.

However, forest growth is not enough to conclude about the sustainability of the forest sector. The study of how to explore the forest and its viability must be done locally, attending to the local conditions. For that reason, forest management certificates are essential (by identities such as the Program for the endorsement of forest certification – PEFC or the Forest Stewardship Council – FSC). Such certificates ensure the balance between harvesting and regrowth of the forest and that the harvest rate is not excessive, but also the conservation of native tree species, soil quality, etc.

Forest certification is a pillar for the paper industry – 90.4% of the forests owned by P&P producers in Europe are certified. In Austria and Portugal, 100% of the forests owned by the paper industries of each country are certified.

2.4 European Union emission trading system (EU ETS)

Policies are a powerful tool that governments may use to limit the impact of companies. The European Union emission trading system (EU ETS) is considered to be the "*cornerstone of the European Union's drive to reduce its emissions of manmade greenhouse gases system"* [50], namely CO_2 emissions. This system, created through the EU directive 2003/87/CE and initialized in 2005, is the World's first and biggest carbon market still in place today. In 2013, the EU ETS entered into the 3rd phase, after the 1st and 2nd stages devoted mostly to develop the market in a process of learning by doing.

The goal of the EU ETS system is to establish a cap to greenhouse emissions, which will be gradually lowered to meet the targets defined by the EU for 2050, by means of trading emission allowances ("cap and trade" principle). The system works annually with the following principles:

1. Every year, the EU establishes a total amount of emission allowances. Each allowance allows the emission of 1 ton of CO_2-eq. By annually decreasing the number of total allowances, the EU forces the total annual emissions to gradually decrease;
2. Allowances may be distributed for free at the beginning of the year or sold/bought in an auction market. For that companies are divided into two groups: High risk of carbon leakage – companies facing competition in countries outside the EU without penalties for carbon emissions, which are given 100% free allowances for their average yearly production; Other companies received in 2013 free allowances equivalent to 80% of their average yearly production, but the share of free allowances is decreasing up to 30% in 2020 ;
3. The free allowances are calculated using the average yearly production of the installation by the benchmark specific emission per unit of product output, corresponding to the 10% best-performing installations in Europe (with lower specific emissions). The benchmark is defined per product. If the installations will expect higher specific emissions, they can choose to buy more

allowances or lower its emissions by updating the technology installed, instigating investment in low emission technologies;

4. At the end of the year, each installation must report its emission and present a number of allowances to support its emission. If it does not own enough allowances (installation B, in Figure 2.12), four months are given to buy the allowances deficit or purchase off-set credits, corresponding to emission reductions achieved in other geographic zones or sectors. If the total allowances are not presented, the company will have to pay heavy fines. A company that owns allowances in excess (installation A, in Figure 2.12) may keep them to use in the future or sell them at the market.

The EU ETS system works then to keep global emissions under an established limit, compensating the industries which over-emit with reductions in other projects. It covers 11 000 installations and 45% of EU GHG emissions. The P&P industry is covered by the EU ETS and is included in the list of sectors at high risk of carbon leakage.

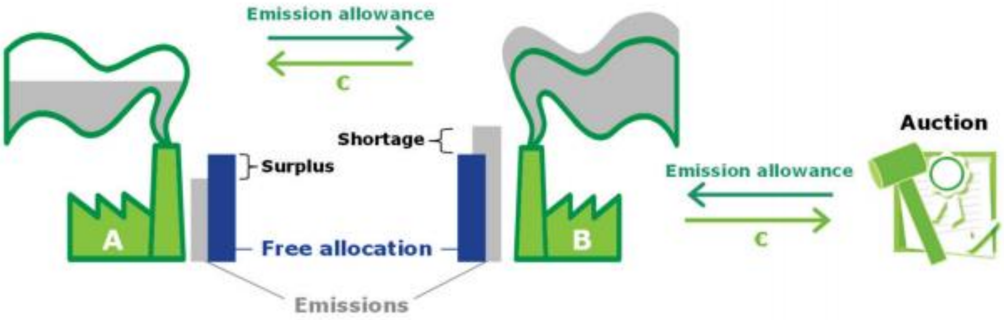

Figure 2.12: Illustration of the EU ETS system [50]

2.5 Paper and pulp production process

The production of virgin paper (produced from wood) consists of three major phases which are wood preparation, production of pulp and finally the production of the paper itself. Often, the production of P&P can be separated in non-integrated mills, producing just pulp (including the wood preparation phase) or just paper. Integrated mills are the ones where the entire process takes place, from wood input to paper output.

In the production of recycled fiber paper, the used paper is firstly blended and then dissolved into pulp. For some applications, an extra step of de-inking the pulp is needed to produce white paper. After the production of the recycled fiber pulp, the third phase is like the production of virgin paper.

The characteristics of the paper produced depend greatly on (among other factors):

- The wood used as raw material. Softwood has longer fibers and so the resulting paper is stronger than hardwood, which has short fibers. Both types of wood are used, for different applications;

- The pulping process – Pulping may be done by either mechanical or chemical means. Mechanical pulps are weaker but have a higher yield (mass of dry pulp produced out of the mass of dry wood). This is the most significant phase in the entire process;
- The paper drying method and finishing processes;

By changing these factors, different paper grades can be obtained.

The following sections will focus on each phase in detail, clarifying the processes and sub-processes. The specific energy consumption of each process is shown in Table 3.1, in the next chapter.

2.5.1 Wood preparation

Wood preparation takes place in the woodyard of the paper mill, where the transformation of the raw wood logs into wood chips (with adequate characteristics to be used for pulp production) takes place.

It is common practice that the wood arrives at the mill in the form of long raw logs (with bark). In some cases, the wood arrives in different conditions, if some of the preparation steps are made previously, at the site. The first process is debarking the wood logs, i.e. to remove the bark (exterior rough surface) of the wood logs. This process takes place in a drum de-barker, in which bark is removed by the impact of rolling several wood logs against each other.

The second step is chipping the wood, which reduces the wood logs to small chips. It is a very important step since the size of the chips affects greatly the pulping process. Common types of wood chippers are disk, drum or screw type.

The final step of wood preparation is screening, to ensure the wood chips have the correct size to be digested (typically 20 mm long and 4 mm thick – [51]). Inadequate size chips can go back in the process or treated as waste, together with sawdust, which is used for energy production (or sometimes sold to a different industry).

The processes involved in wood preparation are powered by electrical energy and are not very energy-intensive. Energy consumption fluctuations are frequent due problems in chipping the wood logs, which require the use of more power, leading to temporary consumption picks. However, wood preparation is typically not the focus of energy measures.

2.5.2 Production of pulp

Wood is mostly composed of fibers, joined together by lignin. The fibers are the main component of paper, whereas high lignin content tends to weaken the paper. During the pulping process, those two components are partially separated, and impurities are extracted. Different pulping processes may be applied to the wood, according to the desired paper specifications. After pulping the fibers are submitted to further treatments (which are common to all types of pulp).

Figure 2.13 illustrates the typical production process of chemical pulp, starting with wood preparation.

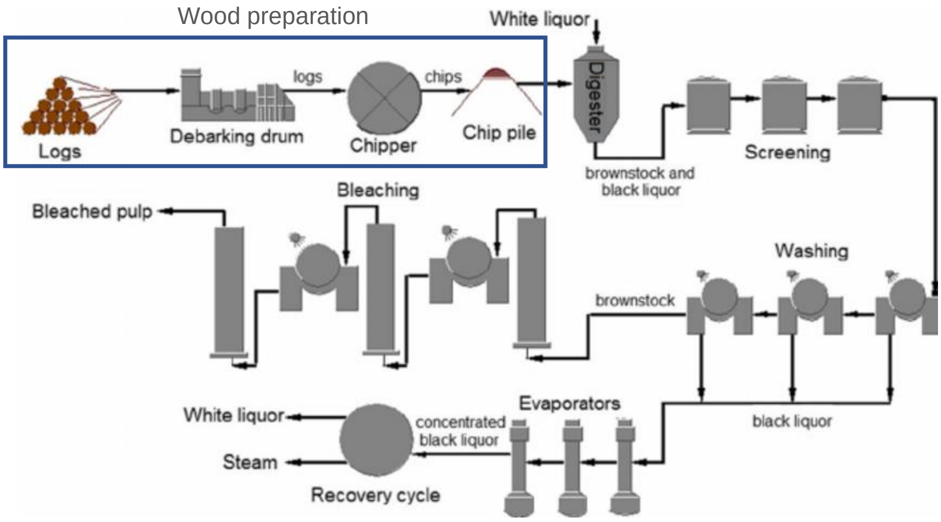

Figure 2.13: Typical kraft pulp production line, including wood preparation [52]

2.5.2.1 Pulping processes

Chemical pulping

In chemical pulping, the wood chips are digested during several hours in pressurized hot water vessels (digester) with the addition of chemical components that dissolve the lignin. The paper resulting exclusively from chemical pulp is called wood-free due to the low lignin content. Chemical pulping can be applied to both hardwood and softwood. There are two different types of chemical pulping processes:

- Kraft (or sulfate) process – the wood is cooked in a water solution of sodium hydroxide (NaOH) and sodium sulfide (Na_2S) known as white liquor, which has basic pH (13-14). This process effectively removes most of the lignin and preserves the fiber strength but reduces the yield to the range of 45-55 % [53]. The resulting paper is strong and has a wide range of applications. However, pulp from this process is darker than in other processes and often needs to be bleached. The kraft process is the most used in the paper industry, representing 80% of world production [54] and about 46% of Austria's pulp production;
- Sulfite process – the wood is cooked in a water solution of sulfuric salts (Sulfites or biSulfites) with acidic pH (1.5-5), producing weaker but whiter pulp (easier to bleach), with a yield of 40-50% [53]. The Sulfite process is more sensitive to wood characteristics than kraft, but it is a more versatile process. The different choices of basis – magnesium, sodium, potassium, ammonia or calcium, provide the process with a wide range of possible pH. The Sulfite process represents 10% of the world pulp [54] and about 36% of Austria's pulp production.

Both processes take place in a wood digester, that may be continuous or batch. Continuous systems are the standard in the industry since for large-scale production, continuous batching has lower capital and operational expenditures (CAPEX and OPEX), high yield and lower energy consumption. However, batch digesters may be suitable for specific applications with smaller production.

Due to the need for heating and pressurizing the digester, chemical pulping is an energy-intensive process, consuming both electricity and heat. It is identified in the literature to be among the main research and development (R&D) energy-saving opportunities [55]. After the pulping process, the cooking liquor is separated from the fibers and the chemicals are almost completely recovered. The lignin removed is usually combusted and used to produce steam, used to provide heat for supplying heat to various processes in the mill.

Mechanical Pulping

Pulp was originally produced exclusively by mechanical processes. Mechanical pulping processes separate the fibers from each other by mechanical means, retaining part of the lignin in the paper and increasing the yield. The paper obtained is soft, with good printing qualities, but is weaker and ages quicker than wood-free paper.

Originally, the pulp was produced by the groundwood process, which has the highest yield. All the subsequent mechanical processes derive from this process and aim mostly to the strength the paper produced but reduce the yield. Each process presents different results depending on the wood used.

- Groundwood Pulp (GW) – This process uses wood logs from softwoods (instead of wood chips), which are grinded in grinding stones. The mechanical energy is mostly converted to heat, softening the lignin, and diluting the free fibers in water (also used to cool-down the grinding stones and to prevent the wood from igniting). The resulting pulp has a yield of 93-95% [53], low strength but good brightness (≥ 85% ISO after bleaching – [51];
- Pressure Groundwood (PGW) – Same process as GW at increased pressure (up to 3 bar), increasing the softening of lignin and therefore increasing the strength of the paper, obtaining a similar yield. This process also uses softwoods;
- Refiner mechanical (RMP) – This process grinds softwood wood chips between two steel discs, with bar patterns, typically a rotating and a static disc. The impact of the bars and the heat generated by friction softens the lignin and breaks the wood into individual fragmented fibers. The energy input is controlled by changing the distance between the discs. This process has similar yield values to the GW process, producing a paper with good optical properties;
- Thermomechanical (TMP) – Modified RPM process. Wood chips (softwood) suffer a high-temperature pretreatment and then are refined in pressurized disc refiners. This increases paper strength, with a low reduction of the yield to values of 80-90% [53]
- Chemimechanical (CMP) - Modified RPM process. Wood chips are impregnated with chemicals and then are refined in disc refiners. Different pulp properties may be obtained by changing the chemicals used. The yield is 80-90% [54] and lower values of energy are required to the grinding process. This process is used to obtain a high yield of pulp with higher strength, in particular for the hardwood;
- Chemithermomechanical (CTMP) – The combination of chemical and thermal pretreatment applied to the RPM process, allowing a higher pulp yield than in CMP (90-94%[54]) with considerable strength, applied to hardwoods.

Mechanical pulping processes are energy-intensive, mostly in the form of electricity, but some also consume steam. In all the processes, energy is recovered in the form of steam and hot water (particularly in TMP and CTMP, due to the high pressure), which is then used for supplying heat to other processes in the mill.

Recycled Fiber Pulping

Pulping of recycled paper is a simpler process than pulping of virgin wood and less energy-intensive. The main step is dissolving the shredded paper in hot water by mechanical means. For paper grades requiring white pulp, an additional step of deinking takes place, by addition of chemicals causing the separation of ink from paper and giving the ink particles hydrophobic characteristics, making them easily separable from the water.

Recycled fiber pulp is also subjected to mechanical removal of impurities. First bigger particles are separated by screening and filtering, and then the pulp is passed through a hydro-cyclone to remove smaller particles through the action of centrifugal forces

2.5.2.2 Washing and screening

Pulp washing aims to remove the impurities from the pulp. In the case of chemical pulping, this is a step in which the pulp is separated from the cooking liquor. In modern pulp mills, the pulping chemicals should be almost entirely recovered, so it is important that the cleaning process is effective. However, washing should consume the least amount of water possible, so the process is a compromised solution to obtain the maximum quality possible with the minimum amount of water possible. Effective cleaning also facilitates bleaching of pulp.

Screening aims to remove the remaining wood pieces from the pulp, which were not properly pulped. The screened parts can go back in the process to the pulping phase or be rejected and used to produce energy in the recovery boiler. In the case of recycled paper pulp, screening aims to remove undesired components such as plastic

Washing and screening are electrical processes, not energy-intensive.

2.5.2.3 Bleaching

The final step of pulp production is bleaching. The purpose of this process is to give white color to the pulp. This process is not fundamental, it is only applied to paper grades that require quality optical characteristics– graphic paper, tissue, whiteboard, etc. The unbleached pulp is typically used for applications such as boxboard or paper bags. Bleaching is done by chemically treating the pulp. After mixing of the chemicals, the pulp passes through a bleaching tower in which the reactions take place. After that, the pulp is washed for removal of chemicals.

The bleaching process is different according to the pulping process. For chemical pulp, the bleaching process aims to further remove the residual lignin, whereas, in the mechanical pulp, the bleaching process is completely different, with the goal of whitening the lignin. However, this effect is not permanent, and with time mechanical pulp paper tends to yellow.

2.5.3 Chemical recovery and energy production

After the chemical cooking process, the pulp must be separated from the cooking liquor, now called black liquor. Since the kraft process is much more frequent in industry, the recovery process will be described specifically for kraft pulping.

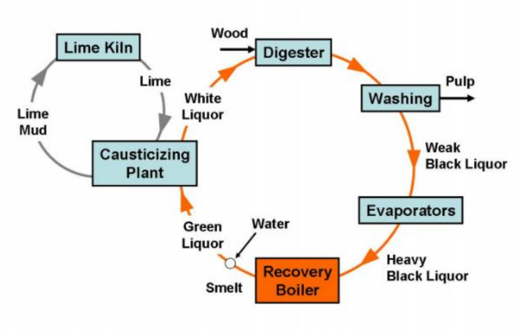

Figure 2.14: Chemical recovery cycle [56]

The first step is to evaporate the black liquor, to decrease water content (increase of dry concentration from 14-18% to 70-85% [54]) and increase the boiler efficiency and liquor heating value. This step is among the most energy-intensive of chemical pulping, consuming large amounts of heat. It is identified in the literature to be among the main R&D energy-saving opportunities [55]. Afterward, the liquor is burned in a recovery boiler, producing high-pressure steam. The common practice is to use this steam to power a CHP unit composed of a steam turbine, using the medium or low-pressure steam from the turbine for process heat, as described in Figure 2.15. The overall energy efficiency of the cycle is 85-90% and the power to heat ratio is approximately 0.3 [54]. The cycle produces more heat than electricity since chemical pulp production consumes more heat than electricity.

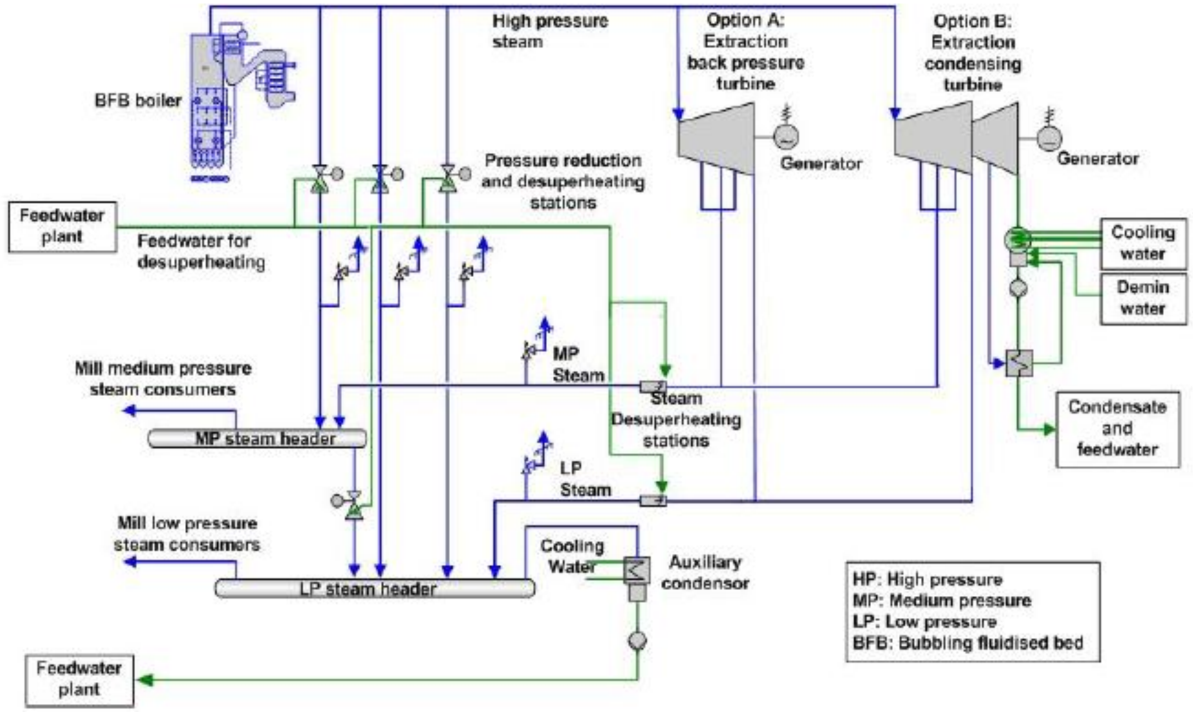

Figure 2.15: Typical CHP plant in a pulp/paper mill [54]

From the boiler, the pulping chemicals are also recovered in the form of smelt (Sodium sulfide - Na_2S - and Sodium Carbonate - Na_2CO_3), which after the addition of water is called green liquor. The green liquor is then causticized – it reacts with lime (CaO) to convert the Sodium carbonate into Sodium hydroxide (NaOH) used in the pulping process. This way the white liquor is produced and ready for the digester.

After causticizing the lime used is recovered in the form of limestone ($CaCO_3$) and must be restored into lime in a lime kiln (Figure 2.16). This step is also very energy-intensive. Usually, lime kilns are powered by fossil fuels, as black liquor is used in the recovery boiler. Natural gas or oil are the most common fuels used.

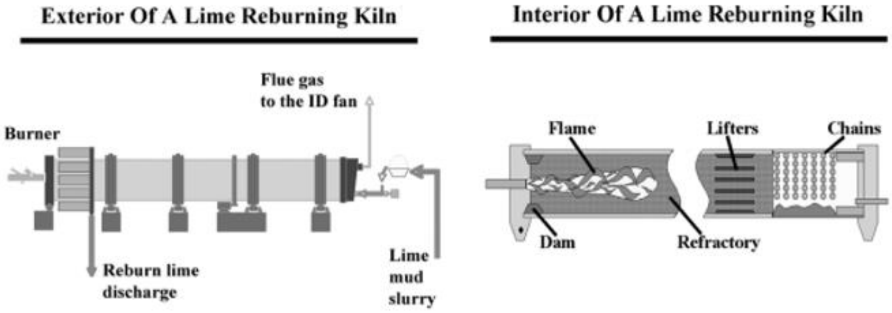

Figure 2.16: Lime kiln configuration [57]

2.5.4 Paper production

In most paper mills, more than one type of pulp is used, to obtain a paper with the desired specifications. The pulp is pumped in the form of a fibrous suspension, in integrated mills, or is delivered in dry form (10% moisture content), in non-integrated mills. Firstly, it is submitted to preparation steps that ensure it is in the best condition to enter the paper machine, such as fiber slushing (dissolution into a suspension), mixing of different pulps or refining (to modify the morphology of the fibers to obtain better quality paper). Other processes can be applied such as cleaning or screening, depending on the conditions of the pulp. Paper fillers may be added to the pulp – mineral fillers which reduce the consumption of pulp and change the characteristics of the paper produced.

Figure 2.17 illustrates the typical Fourdrinier paper machine.

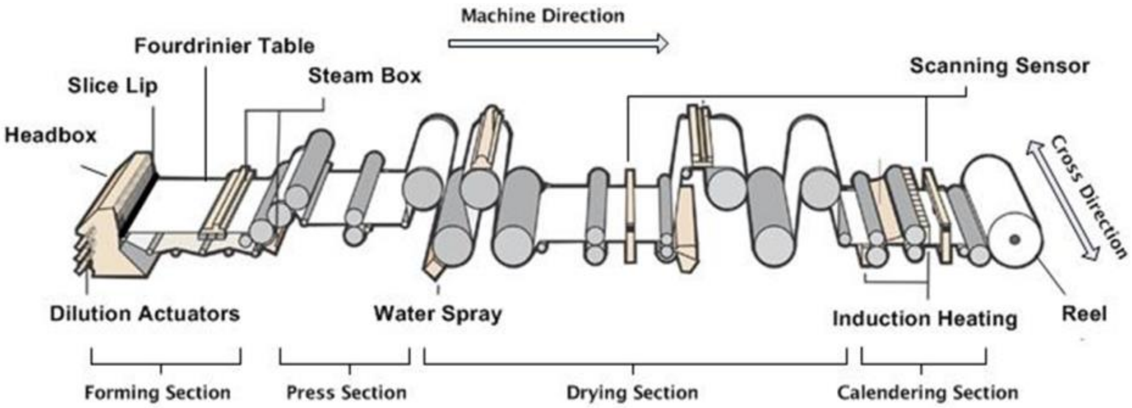

Figure 2.17: Typical paper machine, with a final calendering process to increase surface quality [58].

After the stock preparation steps, the pulp is introduced into the paper machine, through the headbox. The main purpose of this element is to feed pulp at a constant rate to the forming section, creating a uniform dispersion of fibers across the total with of the machine, without gaps. The headbox can work by gravity or by pressure (which increases the production speed). The paper machine consists of three main sections:

- Forming/Wire section – pulp is introduced in this section with a fiber content of about 0.5%-1% [59], where the paper sheet is formed. The pulp may be supported by a single wire and water is drained from the bottom side by gravity (slower machine) or other elements. Better results are obtained by using a twin-wire design, in which the pulp is feed in between two wires, allowing the water to be extracted through the two sides. Other elements used in modern forming sections are foils combined with vacuum boxes. Foils are blades that are placed under the wire, which introduce a pressure variation, by adding a vacuum on the drainage of the foil. It is in this section that most of the water is removed;
- Press section – the formed paper enters this section with about 20% fiber content [59] and still very weak. Here water is removed by passing the paper net supported by felts between sets of two rolls (two or three sets in series). A final set of rolls may be added to increase the smoothness of the paper;
- Drying section – In this section, the remaining water from the paper is removed. Paper enters this section with a fiber content of about 50% [54], which is increased up to 90-95% [54]. The most common process is to run the paper web through several steam-heated cylinders, organized in a superior and inferior row, displaced from each other. However, some grades of paper are dried with different systems. Tissues, due to the smoothness required, are dried in a Yankee drier, with a large, single hot cylinder. The drying process is the most intense process in the entire line. It is identified in the literature to be among the main R&D energy-saving opportunities [55].

After drying, the paper may be submitted to finishing processes, namely coating and calendaring. Coating is the application of chemicals to the paper to give it superior surface characteristics, it is only applied to some paper grades. The drying process may be separated into pre-coating-drying and after-coating-drying if coating is used. Calendering consists of running the paper through a set of rolls, increasing the surface smoothness and improving its appearance. Finally, the paper is rolled and stored.

2.6 Future scenarios for the P&P industry

One important question is which factors will influence CO_2 emissions and to what extent they can be predicted and altered. The basis of any prediction is the consumption patterns that can be expected. In the past, paper consumption patterns seem to follow the trends of GDP *per capita*, but in recent years (1990-2000) a breaking point occurred in most of the developed countries. Some authors have explained the breaking point as a consequence of digitalization. This is the case for some of the paper grades, such as newspaper, but other grades are not affected, such as tissue or board. Other authors defend that the origin of this separation is the increase of wealth of the population up to a saturation point, after which the individual needs for paper are fully satisfied and constant. In that case, the indicator should be the population growth and not GDP *per capita* [60, 61]. This theory covers most paper grades, which consumption depends on individual consumption habits. As a consequence, countries in development will rapidly increase consumption, namely in Asia and South America, whereas developed countries, in Europe and North America, will have a more steady profile, which corresponds to the predictions of several authors [60, 62, 63].

In that case, it is expected that CO_2 emissions related to the paper industry will raise more dramatically in developing countries. A bottom-up study about the global paper industry estimated that, in a BaU scenario, the CO_2 emissions will experience an increase in all regions of the globe. Emissions in Europe will increase by 25.8% up to 2030 in relation to 2000 and in North America by 74.8%, while the increase in Asia should be 243.8% [61]. Increasing carbon taxing and reduction in resource availability may restrain the increase of emissions in Europe to 18.0%, 161.3% in Asia and cause a slight reduction in North America (-0.2%).

Future carbon emissions by the paper industry depend on many other factors other than consumption. Besides the policies applied, factors such as international trading, economy and research are considered crucial and cause considerable differences among the results of different authors.

Technology development is obviously among the most determinant factors. Without updates in technology, Moya and Pavel [62] predict an increase in energy consumption by the European P&P industry of 1.1% and in CO_2 emissions of 4.8% in 2050, relatively to 2015. The application of the best available technologies in paper production may lead the energy consumption in Europe to decrease by 14.4%, causing a reduction of CO_2 emissions of 62.2%. According to this bottom-up study, the increase in carbon taxing allied to a reward for the capture of bio-CO_2 may actually turn the paper industry into a carbon sink, by application of CCS technology. This is not a likely possibility, but it shows that positive policies allied to research and technology development have the potential to cause a positive impact. But, not only the technology potential to decarbonize the paper industry should be taken into consideration. Also, investment cycles, technology costs and overall cost-effectiveness should be considered. Moya and Pavel have simulated the adoption of new technologies in the European paper mills by applying a criterion of machinery retrofitting by stipulating the maximum age reachable by any machine as 30 years. BATs are adopted according to a cost-effectiveness criterion, with a maximum of 20 cost-effective investments per year.

Fleiter et al [64] also consider the diffusion of 17 process technologies and the consequent CO_2 mitigation. In this study, it is possible to compare a cost-effective diffusion scenario (similar to the one considered by Moja and Pavel for Europe) to a technical diffusion scenario (excluding cost considerations, ie maximum diffusion possible). In the technical diffusion scenario, electricity and fuel consumption in 2030 would be reduced by 16% and 21%, respectively, in reference to 2007 (resulting in 19% mitigation of CO_2 emissions), while in the cost-effective scenario, the reductions are 13% and 15%. The reality is not likely to correspond to the technical diffusion scenario, but it shows that the German government may push companies to make bigger efforts to reduce emissions to lower values than by cost-effective updates. The same can be said about the entire paper industry in Europe. Many other technologies are not considered in the study, and so the reduction values only represent a fraction of the real potential.

These and other scenarios for the P&P industry were considered for the research in this thesis (the complete list can be found in the appendix C). The model in this thesis will also be done in a bottom-up methodology. It will consider paper consumption trends for Europe reported by Lamberg et al [60] and investigate the potential to mitigate emissions of the P&P industry in Austria until 2050 by the application of selected technologies.

2.7 Innovative technologies to reduce CO_2 emissions

The technologies with the potential to decarbonize the P&P industry were obtained by a study of different authors, reporting technologies applied to different steps of the production process. Kong et al [65], Fleiter et al [64] and Bajpai [66] identified emerging state-of-the-art and emerging technologies in all the stages of the production process, whereas Marsidi et al [6] focus on a technical and economic analysis of the technologies related exclusively with the decarbonization of the steam supply in the paper industry of the future. Rogers [67] and Parsons Brinckerhoff [68] identify best available technologies (BAT) and innovation technologies (IT) that have the highest potential to decarbonize the industry and apply them in scenario development for this industry, in Europe and the U.K. (respectively). CEPI [69] has suggested a set of technologies as a result of the Two team project with the potential to radically decrease the energy consumption and CO_2 emissions which are still in the research phase (namely the winning technology – Deep Eutectic Solvents, applied to pulp production, has great potential).

A total of 37 BAT and 25 IT with the potential to reduce energy consumption and/or carbon emissions were identified from the literature (the complete list may be found in the appendix B) The impact of 7 of those technologies, which were chosen according to criteria presented in the methodology section, was assessed in the thesis.

The chosen technologies, according to categories, were:

1 Future technologies in pulp production [65, 66, 70, 71]

1.1 Direct green liquor utilization (DGLU) – This technology consists in a modification in the chemical pulping process which consists in redirecting a part of the green liquor from the recovery boiler to use in the pulping process, since it has the potential to accelerate the pulping process. The direct use of green liquor is also an opportunity to reduce the fuels used in the lime kiln. This process is in the demonstration phase and it is expected to have low CAPEX and simple installation.

1.2 Steam cycle washing (SCW) – This is a new washing technology which uses steam to wash the pulp after chemical pulping, instead of water. As a result, it is possible to produce higher consistency pulp and reduce energy for pumping and heating in the thickening, screening, and evaporation operations. The global effect is a reduction of 30-40% of the energy for kraft pulping (overall, not just digesting). This process is close to the commercialization phase.

2 Future technologies in paper production [65, 66, 72–75]

2.1 Impulse drying (ID) – This technology is not a replacement for the current drying section. It is a modification in the press section which consists of pressing the paper against a high-temperature element. This way, dry content in paper may go as high as 65%, decreasing the energy need for drying by 10 – 25%. This technology is in the demonstration phase.

2.2 Condebelt drying (CD) – This is a replacement to the current drying section, in which the paper web is dried in a drying chamber between two steel belts, achieving higher dryer rates and efficiency. The drying heat energy is this way reduced by 10 – 20 % and electricity consumption decreased by 20 kWh. This technology is in the demonstration phase.

2.3 Gas-fired dryers (GFD)– Gas-fired dryers are an alternative to the current drying drums heating by steam in which the same method is applied but the drums are heated by combustion inside the drum. This process has much higher efficiency and higher temperatures are achieved, resulting in higher drying rates and a faster process. Drying energy reduction in the order of 15 % is obtained. The technology is still in the pilot stage and has low CAPEX since it is an adaptation of the technology used nowadays. The implementation of this technology in the model accounted simply with the change in heat use and the change in fuel consumption was not considered.

2.4 Dry sheet forming (DSF) – A new method of forming which results in great reductions of drying energy. In this method, the paper is formed without the addition of water to the pulp. The sheet is supported by an air jet and a solution of resigns is sprayed on the surface to help to form the paper sheet. This forming method is only suitable for tissue or hygienic paper since the surface smoothness decreases and the thickness has higher variations but the resulting paper is soft. The decrease in drying energy is of 50%. This is the technology with higher energy reduction potential but its applicability is low. It is already in the commercial stage.

3 Decarbonization of steam supply [6, 76–78]

3.1 Direct electric heating (DEH) – This option consists simply of replacing the fossil fuel boilers with commercial electric boilers which generate steam at 90% efficiency. The feasibility of this option depends strongly on the electrical grid capacity to take such a high load increase without increasing the use of fossil fuels. This technology would be more suitable if allied with direct access to a renewable energy source, such as a solar park or a hydroelectric power station, with the installation of an energy storage system, allowing the storage of renewable energy in periods of abundance. Another possible option would be to install an electric boiler as an alternative to the fossil fuel boiler (and not as a replacement), allowing the use of electricity only when there is an abundance of renewable energy, increasing the flexible use of grid electricity.

3 Methodology

3.1 Model definition and objectives

As discussed in section 02.2 of the literature review, different studies conclude that the phase of the life cycle of paper products with the biggest GWP is the production phase, due to the emissions of CO_2 during energy production. For that reason, it is important for the Austrian and Portuguese P&P industries to consider strategies to reduce those emissions. According to the regulations defined in the EU ETS, which go along with the guidelines of the IPCC, the CO_2 emissions from bioenergy do not need any licenses (by other words, they are free of charge), so the industry is focused on reducing fossil CO_2 emissions only. The model developed focuses on fossil CO_2 emissions during the production process. The implications of that methodology will be discussed in the section on results discussion.

The first step to calculate the annual emissions in Austria was to properly understand what the sources of CO2 along the process are and what should be the focus of the decarbonization measures. A model was created using excel. It calculates energy consumption and CO_2 emissions as a direct result of P&P production.

The model was developed in a linear bottom-up approach. Firstly, extensive literature research was made to understand the main steps of the production process in detail and determine the specific energy (electricity and heat) consumption of each step, by comparing the values calculated by several authors for different technologies. This task was not simple since the specific energy consumption of the processes changes with several factors, so it was necessary to find the values which better represent the entire P&P industry. The compilation of the values which were found to be more representative of the industry is presented in Table 3.1. The boundaries of the model include the processes from raw material entering the production facility to the point of production of paper sheets. The process of production of paper products such as books or magazines is excluded for simplicity reasons.

The model was developed using a bottom-up methodology. This procedure was adopted to satisfy the two main goals of the model:

1. To provide a clear indication of which processes are more energy-intensive and which type of energy (heat or electricity are they consuming) is consumed and;
2. To calculate the impact of replacing a technology used nowadays by innovative technology in heat and electricity consumption of the entire process and the consequent CO_2 emissions. For example, if the pulping technology A would be replaced by the pulping technology B, which consumes 20% less heat, the model would describe how that replacement would impact the overall energy consumption and CO_2 emissions.

The model was used for two different purposes. First, calculations were made for five paper products individually (printing and writing paper, tissue, newsprint and packing paper) considering different production conditions, in order to obtain the specific energy consumption and CO_2 emission of each of those products, as well as the changes due to the introduction of the innovative technologies chosen.

The model was also used to calculate the energy consumption and CO_2 emissions of the entire paper industry in Austria, using as input the annual production of P&P. Since pulp is sold separately as market pulp, the total production of pulp is not directly related to paper production so the calculation methodology for the entire industry considered the production of P&P separately (instead of pulp produced to sustain the production of paper).

The quality of results is then determined by how exhaustive the process is described and the degree of accuracy of the specific heat and electricity consumption of each process. Some important side processes were not considered because the energy consumption was neglectable when considering the entire production (like water circulation and treatment) or because of a lack of precise information (like transportation inside the paper and pulp mills). Calculations at a national level are not simple since it is not possible to get accurate information about all processes used and some assumptions are required.

By using data of the annual production of the different paper grades and types of pulp in Austria, the total emissions from the industry were estimated, in the time frame of 2000 up to 2018 (skipping the years 2001-2005, for which there is no information available). The results of the model are then compared to the data available.

After the verification of the model, it was used to calculate the energy consumption and fossil-CO_2 emissions for the specific grades previously studied if the innovative technologies chosen are applied to the process (individually). It was also used to create scenarios for the P&P industry in Austria until 2050, simulating the introduction of each of these technologies.

3.2 Specific energy consumption of each process

The specific heat and electricity consumption of the major processes of P&P production are summarized in Table 3.1.

Table 3.1: Specific electricity and heat consumption of the individual processes in P&P production

Process	Specific electricity consumption (kWh/t)	Specific heat consumption (kWh/t)	Reference
	Wood preparation (kWh/t_{wood})		
Debarking	8.5	0.0	[66]
Chipping and conveying	30.3	0.0	[66]
	Chemical pulp (kWh/$t_{AD\ pulp}$)		
Kraft Digester	40.0	472.2	[79]
Sulfite Digester[1]	572.0	1166.7	[66]
Washing & Screening	30.0	0.0	[79]
Oxygen Delignification[2]	75.0	138.9	[79]
Bleaching	100.0	638.9	[79]
Pulp Drying[3]	155.0	1250.0	[66]

Process	Specific electricity consumption (kWh/t)	Specific heat consumption (kWh/t)	Reference
Chemical recovery process (kWh/$t_{AD\ pulp}$)			
Liquor evaporators	30.0	861.1	[79]
Kiln and Recausticizing[4]	50.0	333.3/311.4	[79, 80]
Power plant	60.0	638.9	[79]
Energy Production	1620.0	6166.7	[66]
Mechanical Pulp (kWh/$t_{AD\ pulp}$)			
Groundwood Pulp	1650.0	0.0	[66]
Refiner-Mechanical Pulp	1972.0	0.0	[66]
Thermomechanical Pulp	2041.0	250.0	[66]
Washing & Screening	50.0	0.0	[64]
Bleaching	100.0	0.0	[64]
Recycled fibers pulp (kWh/$t_{AD\ pulp}$)			
Recycled Fibers pulp	392.0	0.0	[66]
Screening	50.0	0.0	[64]
De-inking	80.0	0.0	[64]
Concentration and dispersion	40.0	150.0	[64]
Bleaching	30.0	0.0	[64]
Newsprint (kWh/t_{paper})			
Forming & Pressing	422.0	0.0	[81]
Drying	29.31	1192.1	[81]
Printing Paper (kWh/t_{paper})			
Forming & Pressing	527.5	0.0	[81]
Drying	29.3	1524.0	[81]
Writing Paper (kWh/t_{paper})			
Forming & Pressing	527,5	0.0	[81]
Drying	29,31	1465,4	[81]
Tissue (kWh/t_{paper})			
Forming & Pressing	533.4	0.0	[81]
Drying	131.88	2198.0	[81]
Packing paper (kWh/t_{paper})			
Forming & Pressing	269.6	0,0	[81]
Drying	14.7	1172.3	[81]

[1] The production of Sulfite pulp besides wood digestion is considered to consume the same energy as in the kraft process due to missing information in the literature.

[2] Oxygen delignification is applied only to kraft pulp, not Sulfite pulp.

[3] The values of energy consumption for drying of pulp are assumed to be the same for all types of pulp, due to missing information in the literature.

[4] Two values of heat consumption are used for the lime kiln, for the estimations at the National level and for each grade individually.

It is important to notice that the specific consumptions shown are relative to the output of each process. So, the units of specific electricity consumption of debarking are kilowatt-hour of per ton of debarked wood, whereas the units of specific heat consumption of the kraft digester are kilowatt-hour of heat per ton of digested pulp.

The values change according to the production line circumstances, the technologies applied, the raw materials used, etc. Some important factors which may lead to lower energy consumption were not considered, namely the use of heat recovery in several processes such as pulping or drying. However, these values were considered to be representative of the industry in Austria.

It is clear that even though heat is not used in all the processes, the industry is very heat intensive. The processes of pulping, liquor evaporation and drying of both P&P are very demanding. Naturally, many decarbonization measures focus on decreasing heat consumption and reducing carbon emissions.

3.3 Mathematical formulation – calculations for specific grades

The energy consumption for the production of each paper grade depends on the characteristics of paper produced, which were defined in the model by the following variables:

- Grade produced (printing and writing paper, tissue, newsprint or packing paper);
- Mineral filler content in paper (mf);
- Integrated or non-integrated production
- Type of virgin pulp used;
- Recycled fibers (RCF) content in pulp (r);

Seven different cases were studied (filler content was always considered 10%), shown in Table 3.2

Table 3.2: Production specifications of the cases studied.

	Writing (int.)	**Writing (n. int.)**	**Printing**	**News**	**Packing**	**Tissue (kraft)**	**Tissue (RCF)**
Grade	Writing	Writing	Printing	Newsprint	Packing	Tissue	Tissue
Pulp Mill	Integrated	Non-integrated	Integrated	Integrated	Integrated	Integrated	Integrated
Virgin Pulp	Kraft	Kraft	GW	TMP	Kraft	Kraft	RCF
r	0%	0%	0%	50%	50%	0%	100%

The production scheme of each of the cases studied is shown in appendix A.

For each case, the impacts of producing 1 ton of paper were calculated ($M_{paper} = 1\ ton$). The dry masses of fillers and pulp necessary for the production were calculated according to equations (3.1) and (3.2), respectively. mf represents the mass percentage of paper fillers in paper.

$$M_{filler} = M_{paper} \times mf \tag{3.1}$$

$$M_{pulp} = M_{paper} - M_{filler} \tag{3.2}$$

The pulp used was considered to be a mixture between one type of virgin pulp and RCF pulp, and the masses of each type of pulp were calculated based on r, which represents the mass percentage of RCF in pulp.

$$M_{RCF} = M_{pulp} \times r \tag{3.3}$$

$$M_{virgin\ pulp} = M_{pulp} - M_{RCF} \tag{3.4}$$

The wood used to produce the virgin pulp (chemical and mechanical) was calculated by using the yield (dry mass of pulp over the dry mass of wood – equation (3.5)) of each pulping process (Table 3.3).

$$Yield = \frac{M_{virgin\ pulp}}{M_{wood}} \tag{3.5}$$

Table 3.3: Pulp yield of the different types of pulp considered.

Pulping process	**Pulp yield [53]**
Kraft	50%
Sulfite	45%
Groundwood	94%
Refiner Mechanical	94%
Thermomechanical	85%

The heat consumption for each process p used to produce product x is then the product of the specific heat consumption of the process ($h_{p,x}$) by the mass output of the process(M_p). The total specific heat consumption per ton of pulp or paper (h_x) corresponds to the sum of all processes used for production (found in Table 3.1) divided by the pulp or paper produced (M_x) – equation (3.6). The same calculation is made for electricity – equation (3.7).

$$h_x = {\sum M_p \times h_{p,x}}\Big/{M_x} \tag{3.6}$$

$$e_x = {\sum M_p \times e_{p,x}}\Big/{M_x} \tag{3.7}$$

The production processes of each of the cases studied may found in appendix A.

The required energy was considered to be produced by the use of CHP units, which is the common practice in Europe [54]. The fuels used considered were black liquor (in case of chemical pulping) and waste biomass (with an efficiency of 80%) or natural gas (with an efficiency of 85%). The power to heat ratio was considered to be 30%. The energy production is adjusted to produce the heat needed by the processes. Natural gas cycles are used when the biofuels are not enough to produce all the heat needed (excluding the heat needed by the lime kiln, which is produced by the combustion of natural gas, with 72% efficiency [80], since that is the most common case) or when the paper mill uses market pulp (in which case, the paper mill is equipped with a natural gas CHP plant).

The electricity grid is used to balance the electricity needs with production. Insufficient production leads to consumption from the grid whereas excessive production is sold to the grid.

The CO_2 emitted due to the consumption of fossil fuels ($CO_{2\ direct}$) is calculated as the product of the summation of the product of the fossil fuels consumed (F_i), in this case only natural gas, by the emission factor of each fossil fuel (ef_i), reported at Austria's National Inventory Report [82] – equation (3.8).

$$CO_{2\ direct} = \sum_i F_i \times ef_i \tag{3.8}$$

The CO_2 emitted due to the consumption of grid electricity ($CO_{2,indirect}$) is calculated as the product of the grid electricity consumed ($E_{purchased}$) by the respective emission factor (ef_{grid}). To calculate ef_{grid} (equation (3.10)), the total emissions from energy production to the electricity grid ($CO_{2\ grid,y}$) were estimated as the summation of the product of the consumption of each fuel used to power the grid ($F_{grid,i,y}$) [83] and the respective emission factors (equation (3.9)). The grid emission factor is then calculated as the division between $CO_{2\ grid,y}$ and the total grid electricity in year y ($E_{grid,y}$). The value used in this section corresponds to the most recent data available – 2014.

$$CO_{2\ grid,y} = \sum_i F_{grid,i,y} \times ef_i \tag{3.9}$$

$$ef_{grid} = {CO_{2,grid,y}}\Big/{E_{grid,y}} \tag{3.10}$$

The CO_2 emission due to the purchase of grid electricity is then calculated (equation (3.11)).

$$CO_{2\ indirect} = E_{purchased} \times ef_{grid} \tag{3.11}$$

3.4 Production data of P&P in Austria

For calculating the total consumption of the industry, the annual production in Austria of each product was required in a discriminated manner. Table 3.4 shows the example for the year 2015, the base year for the model (the values for the year of 2018 are presented in Appendix B).

Table 3.4: Production of P&P in Austria in the base year - 2015, discriminated [22].

Pulp Production (Mtons, AD)	
Chemical pulp	1,004
Textile pulp	0,559
Mechanical pulp	0,358
Recycled fiber pulp – deinked	0,745
Recycled fiber pulp -non deinked	1,291
Total	3,955
Paper Production (Mtons)	

Graphic paper	2,732
Packing paper	1,950
Special paper	0,283
Total	4,965

Some values were not provided with enough detail to fit the model, and so the following assumptions were made:

- For energy calculation purposes, the textile pulp was assumed to be composed entirely of bleached Sulfite pulp, since that is the process reported by most companies in Austria;
- After 2013, the production of Sulfite and kraft pulp are reported together as "Chemical pulp". For that time period, for energy calculation purposes, the chemical pulp was assumed to composed of 25% Sulfite pulp and 75% kraft pulp, following the values reported in the previous years;
- After 2016, there is no distinction between bleached and not bleached chemical pulp. For the years of 2017 and 2018, for energy calculation purposes, the chemical pulp (both Sulfite and kraft) was assumed to be 50 % bleached and 50% not bleached, following the values reported in the previous years;
- Since there is no distinction in the reports about the different types of mechanical pulp, the different fractions were estimated based on the values reported by Moja and Pavel [62] for Austria in 2016 (figure 12 of the reference). For energy calculation purposes, the mechanical pulp is assumed to be produced according to the following fractions: 1/3 by thermo-mechanical pulping, 1/3 by refiner-mechanical pulping, 1/6 by stone-groundwood pulping and the remaining by pressured-stone-groundwood pulping. However, due to the similarity between the two last processes and missing data on the literature, the energy consumption of these two processes was assumed to be the same;
- Coated and uncoated papers are reported together under the category of graphic paper. The productions of coated and uncoated paper were considered to be the same based on the values reported by Moja and Pavel [62] for the paper production in Austria in 2016 (figure 14 of the reference). After 2013, newspaper is reported under the same category (before it was reported separately). The fractions are then considered to be 10% newspaper, 45% coated paper and 45% uncoated paper, following the same reference as before;
- For energy calculation purposes, special paper was considered to consume the same energy as tissue since that is the main grade which is not included in graphic or packing paper;
- For energy calculation purposes, all packing papers, kraft papers and board are assumed to have similar consumption values as packing paper, due to missing information and the similar properties of those grades.

3.5 Mathematical formulation – expansion to the entire Austrian P&P industry

The consumption of heat needed for the total annual production of P&P in Austria of each product (x – pulp or paper) was calculated as the multiplication of the specific heat need (h_x – equation (3.6)) for the production of product x by the annual production of product p ($P_{x,y}$). The total heat consumption by the industry (H_y, equation (3.12)) corresponds then to the sum of the heat needed for the production of all products. The same methods are used for electricity consumption (E_y, equation (3.13)(3.12)), using the specific electricity needs to produce each product p (e_x–equation (3.7)).

$$H_y = \sum_x h_x \times P_{x,y} \tag{3.12}$$

$$E_y = \sum_x e_x \times P_{x,y} \tag{3.13}$$

Following, the values of fuel consumption were estimated, distinguishing between fossil fuels and biofuels. The fuel consumption by the P&P industry was estimated using the ratio between the values of total heat consumption and total fuel consumption (α_y, equation (3.14)) reported each year by Austropapier ($H_{y,data}$ and $F_{y,data}$, respectively) [14–24]. Similarly, the ratio between the values of electricity consumption ($E_{y,data}$) and fuel consumption were calculated (β_y, equation (3.15)) . The time evolution of the α and β from 2009 to 2018 is presented in Figure 3.1

$$\alpha_y = {H_{y,data}}/{F_{y,data}} \tag{3.14}$$

$$\beta_y = {E_{y,data}}/{F_{y,data}} \tag{3.15}$$

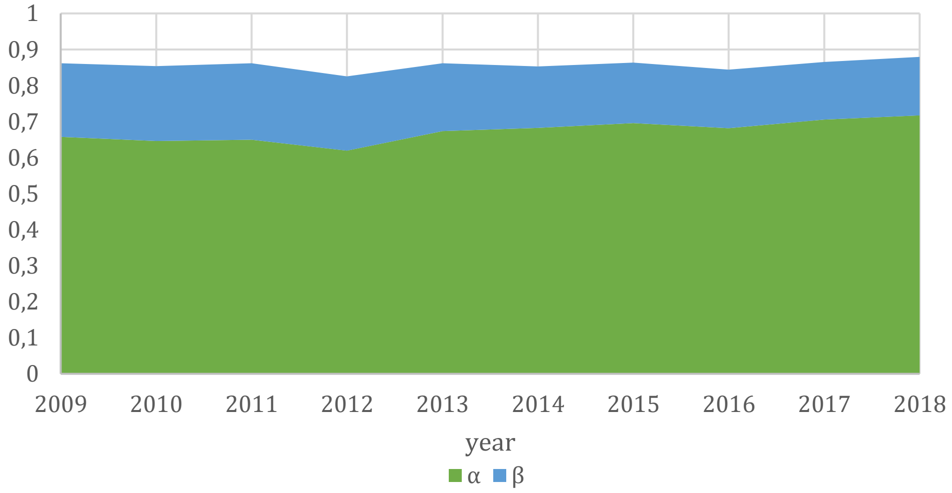

Figure 3.1: Evolution of α and β from 2009 to 2018

The total fuels used (F_y) are then estimated based on α_y (equation (3.16)).

$$F_y = H_y \times \alpha_y \tag{3.16}$$

The fractions of fossil fuels (coal, oil and natural gas) and biofuels used every year in the P&P industry were also obtained from the same source ($f_{i,y}$). The evolution of the fuel mix used by the paper industry in Austria is presented in Figure 3.2. Equation (3.17) represents the consumption of each fuel in year y.

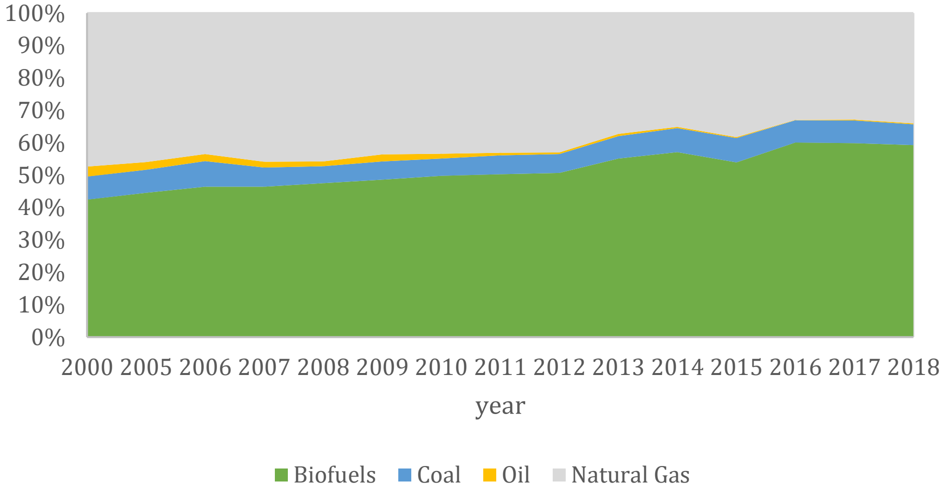

Figure 3.2: Evolution of the fuel mix used by the P&P industry in Austria.

$$F_{i,y} = H_y \times \alpha_y \times f_{i,y} \tag{3.17}$$

The total direct CO_2 emissions are then calculated according to equation (3.8).

To calculate the indirect emissions from electricity usage, another method was used. The estimation of purchased electricity was done by calculating the ratio between the electricity consumed from the grid and the total electricity consumption (g_y– equation (3.18)), also reported by Austropapier ($E_{y,grid,data}$ and $E_{y,data}$, respectively) [14–24].

$$g_y = {}^{E_{purchased,data,y}}\!\big/_{E_{y,data}} \tag{3.18}$$

The total electricity purchased from the grid each year ($E_{grid,y}$) is then estimated based on g_y (equation (3.19)).

$$E_{purchased,y} = g_y \times E_y \tag{3.19}$$

The indirect CO_2 emissions are then calculated according to equation (3.11).

3.6 Calculation of future scenarios

To obtain the energy consumption and CO_2 emission scenarios, assumptions were made relative to the paper and pulp production growth rate or to the technologies used in the process, based on different assumptions for the future. Taking those into consideration, the electricity and heat consumption and CO_2 emissions were calculated by using the same methods explained in the previous sections.

The results of such simplified analysis do not provide an exact prediction for the paper and pulp industry, but they allow some valuable conclusions to be made about the influence of the considered factors.

Different scenarios were calculated. First, a scenario assuming no technology improvements was calculated, after which the effect of the implementation of each technology is calculated individually.

All scenarios have as a start point the evolution of consumption of paper products as predicted by Lamberg et al [60] to Europe, presented in Table 3.5. It is assumed that paper and pulp production will follow the same trend as paper consumption in Europe.

Table 3.5: Predictions for paper consumption used in the model.

	Newsprint	**Printing and writing**	**Packing materials**	**Household and sanitary**	**Other paper and board**	**Total demand**
AAGR (%)	0.2	0.2	0.2	0.3	0,0	0.2

A total of 37 BAT and 25 IT with the potential to reduce energy consumption and/or carbon emissions were identified from the literature. Of those, only the ones filling the following criteria were considered when calculating future scenarios:

- Criterion 1 – The chosen technologies provide a fossil carbon-free alternative to energy/steam production or cause, directly or indirectly, a reduction in energy consumption of the most energy-intensive and most used of the processes in paper production (production of chemical pulp, black liquor evaporation and paper drying);
- Criterion 2 – The values of energy/carbon reduction when applying the technology must be estimated in the literature so to provide a basis for the calculations;
- Criterion 3 – The technology is currently not employed in Austria.

Estimations relatively to the commercial status and the period in which the technology will be in the commercial state were collected, as well as the available information about the cost of implementation (CAPEX). For each technology, the deployment year was assigned based on the commercial status (see Table 3.6).

Table 3.6: Assumptions of deployment year in Austria depending on commercial status.

Commercial Status	Deployment year
Research & Development	2035
Pilot or scaling	2030
Demonstration or Semi-Commercial	2025

For each technology, maximum relative deployment (share of production that will apply this technology) in the industry by 2050 was estimated considering two factors (Table 3.7): CAPEX, evaluated as small, medium or high, and the need to modify the production process to fit the new technology, evaluated in a scale of 1-3. That way, a technology with high CAPEX and causing a big change in the industry will have the lowest deployment (10%), whereas low CAPEX and small change allow full (100%) implementation.

Table 3.7: Assumptions of relative deployment in Austria depending on CAPEX and the need to modify the production process.

	Low CAPEX	Medium CAPEX	High CAPEX
Level of change 1	100 %	75 %	50 %
Level of change 2	50 %	40 %	30 %
Level of change 3	20 %	15 %	10 %

The deployment of each technology is relative to its applicability in the industry. 100% deployment of a technology that is applied only to the production of one paper grade means that it is assumed that all production lines of the paper grade in question will apply this technology, but not lines producing other grades.

The summary of the technological options explored can be found in Table 3.8.

Table 3.8: Summary of the information about the selected future technology

Technology	Impact	CAPEX	Change	Implem. after	Deployment in 2050 (%)
DGLU	25% reduction of energy for kraft pulping	Low	1	2025	100
SCW	30-40% reduction of the energy for kraft pulping (overall)	Medium	2	2025	40

ID	10-25% reduction of the drying energy	Medium	1	2025	75
CD	10-20% reduction of heat consumption for drying and 20 kWh/t electricity reduction	Medium	3	2025	15
GFD	10-20% drying energy reduction	Low	2	2030	50
DSF	50% drying energy reduction	Medium	3	2025	20
DEH	Replacement of fossil fuels. Production of heat from electricity with 90% efficiency.	Low	2	2025	50

For each of the selected technologies, the impact of its implementation was calculated using the model. For this calculation, the production of paper was considered to evolve according to the European trend of consumption. The evolution of the other variables in the model depends on the impacts of each technology.

For calculating the scenarios, the variables were separated into two groups – dynamic variables, which evolve according to the specific assumptions of each trend (in at least one of the scenarios, maybe constant in some cases), and constant variables.

The constant variables are :

- The ratio between the values of heat consumption and fuel consumption (α_y), with the value of 0.72 corresponding to the year of 2018;
- The avarage emission factor associated to the consumption of grid electricity corresponding to the values declared by the IEA in 2014 ($ef_{grid,2014}$),;
- The emission factors of each fuel used (e_i), corresponding to the year 2018;

All other variables are dynamic.

4 Results and discussion

This section presents the results of the model developed. Two introductory results are presented – the final energy consumption and CO_2 emissions of the paper grades studied and the comparison of the results for the P&P industry in Austria until 2018 with available data, used to validate the model.

Then, the evaluation of the impact of the different technologies is presented in two ways: the impact of the application of each technology to the production of a single grade and the impact for the entire industry in Austria until 2050.

4.1 Current impacts of the different paper grades

To calculate the impacts of the industry, it is helpful to understand the impacts of producing different grades of paper. Figure 4.1 shows the final energy consumption (heat and electricity) per ton of paper produced for the different grades studied, along with the specific emission of fossil CO_2.

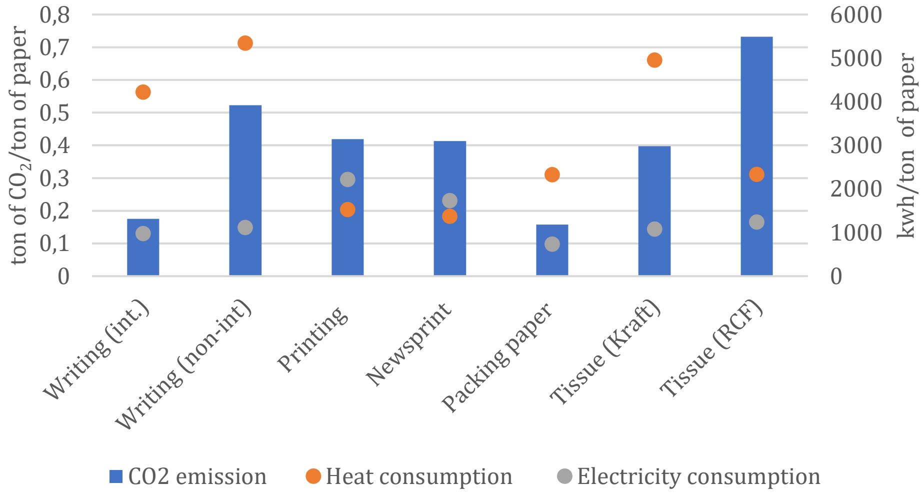

Figure 4.1: Specific final energy consumption and CO_2 emission of the paper grades studied.

When writing paper is produced with non-integrated pulp, the heat consumption increases substantially due to the extra heat needed to dry the pulp. The fossil CO_2 emission is almost three times higher because the extra heat was considered to be obtained from fossil fuels. The production of tissue with RCF instead of virgin pulp results in a reduction of specific heat consumption of about 50% but the fossil CO_2 emissions suffer an increase of more than 75% because, without virgin pulp production, there are no biofuels available, all the energy production comes then from fossil fuels.

The total CO_2 emissions (including bio-CO_2), shown in Figure 4.2, have a closer relationship with final energy consumption.

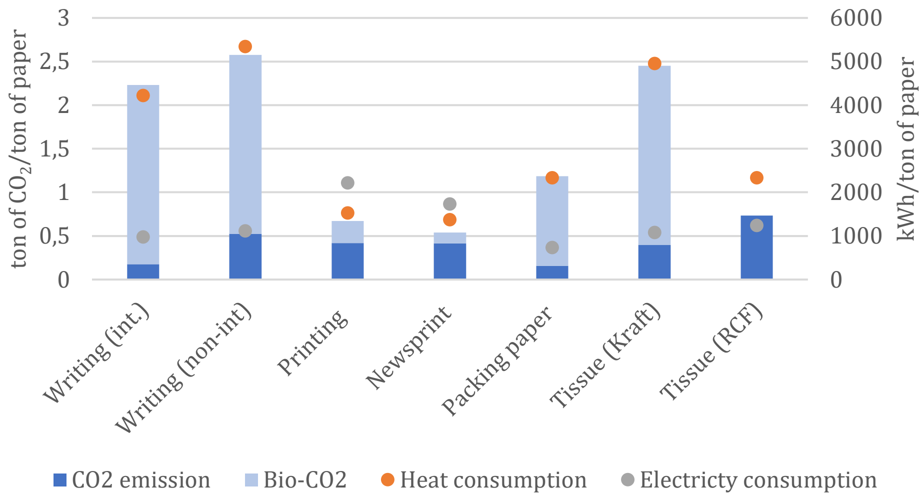

Figure 4.2 Specific final energy consumption and CO_2 emission of the paper grades studied, including bio-CO_2.

4.2 Emissions from 2000 to 2018

The emissions from 2000 to 2018 were estimated as a way of testing the model created. The results of total electricity (grid electricity and produced) and heat consumption are shown in Figure 4.3 and Figure 4.4, respectively, and compared with the values declared by Austropapier.

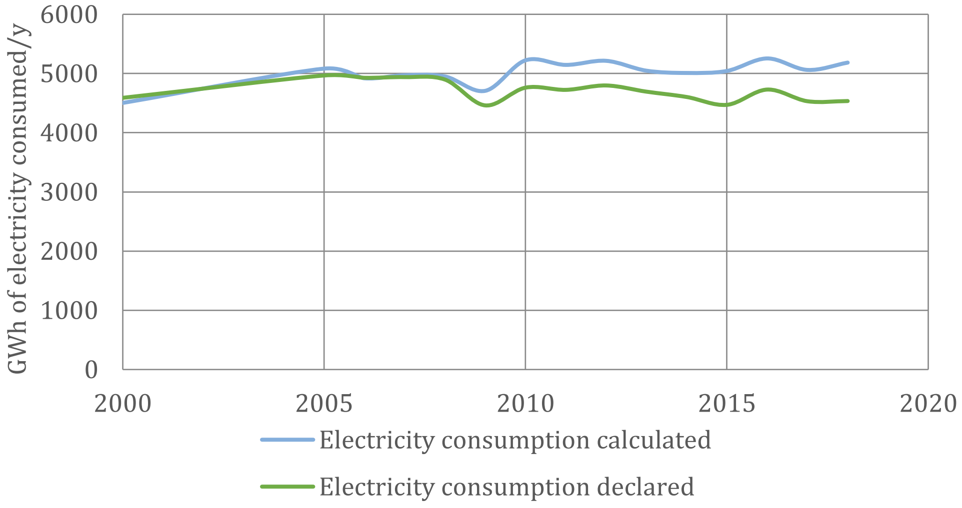

Figure 4.3: Electricity consumption (total) – calculated vs declared, from 2000 to 2018

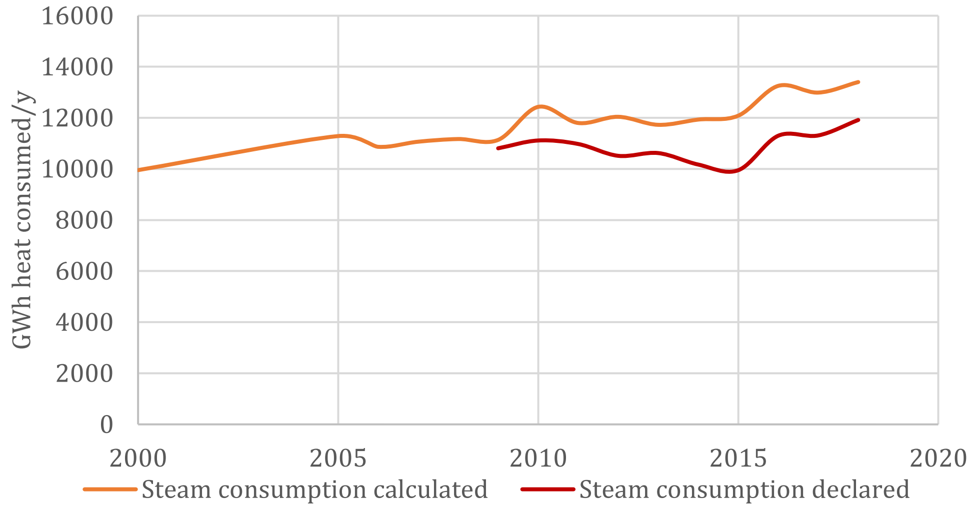

Figure 4.4: Heat consumption – calculated vs declared, from 2000 to 2018

The results obtained follow the same trends as the real values, with reasonable accuracy. The estimation of electricity consumption is more accurate than the heat consumption since the average electricity consumption estimation error is 7% (maximum of 15%) whereas the average heat consumption estimation error is 13%(maximum of 20%). For electricity, it is clear that the error increases after 2008. This suggests that the reason for the increase of error is significant technological development, to the point of consumption levels lower than the ones used for the calculation, since the developed model is a static one. The higher error in the estimation of heat consumption is most probably due to the common measures of heat recovery in many processes in this industry, which are not taken into account in the model.

Figure 4.5 and Figure 4.6 show the estimations of CO_2 emissions, direct (from fossil fuel use) and total (with the addition of indirect emissions from the use of grid electricity), respectively. Since only the fossil fuel emissions were available, the results of the total estimated emissions were compared to the results obtained by estimating emissions from the declared fossil fuel consumption and electricity consumed, using equations (3.8) to (3.11) of the mathematical model.

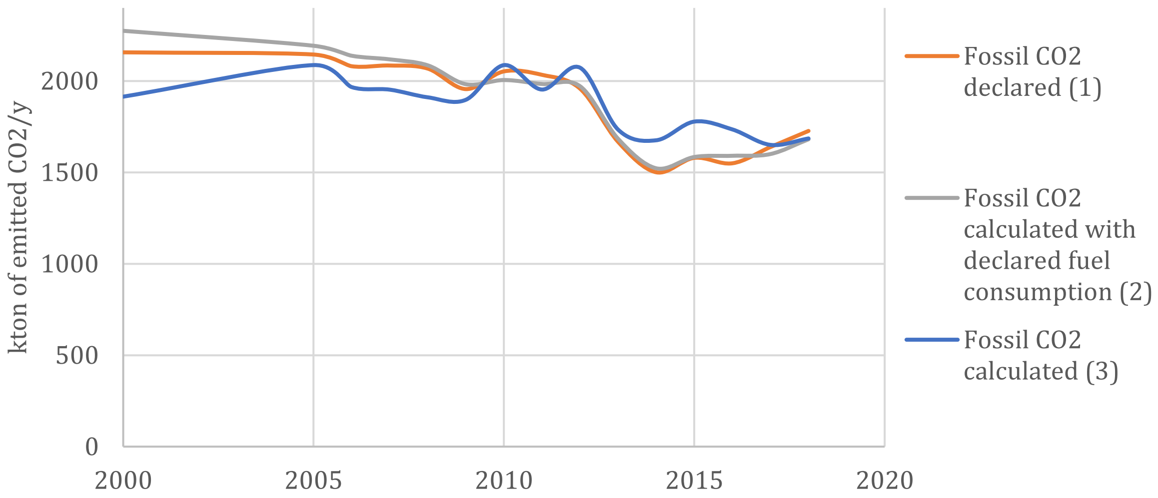

Figure 4.5: Direct fossil-CO2 emissions from 2000 to 2018

Figure 4.5 represents the emissions declared by Austropapier (1) and two different estimations – using the declared fuel consumption (2) and the fuel consumption calculated (3). Curves 1 and 2 present a very similar pattern, with decreasing error. This is an indication that the emission factors considered, referring to the year 2017, are accurate.

The general trend of the three curves in the past 18 years is to decrease CO_2 emissions. Up to the year 2009, there is an underestimation of the CO_2 emissions. Given that the emission factors are not the source of error, then it could be due to an underestimation of the heat used by the industry. On that year there is a decrease in CO_2 emissions (verified in all the curves) due to the serious impact of the economic crisis [22] in the production of paper and pulp (Figure 2.1 and Figure 2.2).

After 2009 the results generally overestimate CO_2 emissions (and heat consumption – Figure 4.4). This may be simply due to lower individual process consumption than the values used (that best represent the industry in the years 2008 to 2010). The technological updates after that point are not accounted for in the model. For example, since 2010, Zellstoff Pöls integrated P&P mill installed two new paper machines, whereas the Sappi Gratkorn mill in Graz has refurbished its paper machine in 2014 and the black liquor boiler and power plant in 2015. The industry in Austria is constantly investing in increasing its efficiency and decreasing energy consumption.

However, other factors could also be the cause of the error in estimation. The paper industry also sells its excess energy in the energy market, making it susceptible to energy market variations. It is reported by Austropapier [20] that the decrease in fossil fuel emissions from 2012 to 2014 was due to favorable prices in the foreign electricity markets, which decreased the electricity produced by the P&P industry since it was not profitable to sell it to external customers. After 2015, the trend changes again and the emissions increased due to the influence of other factors not considered in a simplistic model, such as variations in the amount of electricity which is bought and produced due to fluctuations in the electricity and fuel markets.

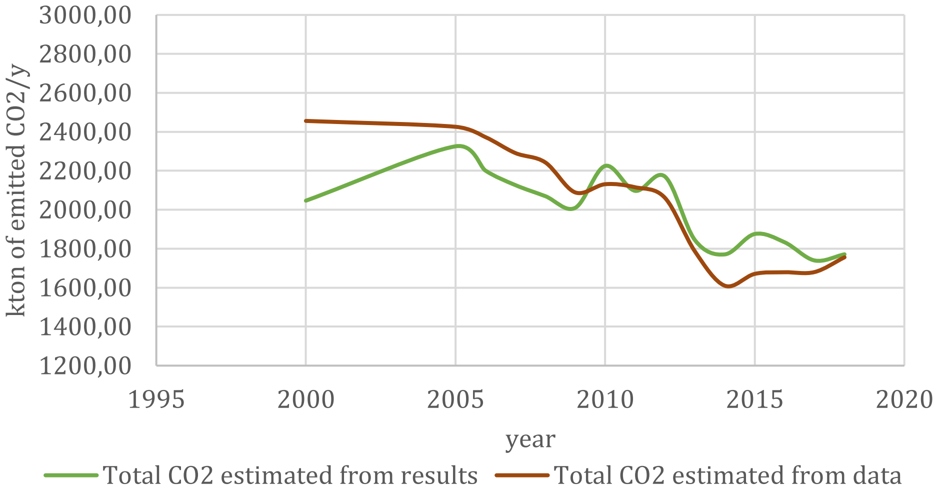

Figure 4.6: Total CO2 emissions from 2000 to 2018

The curves of total CO_2 emissions follow similar trends as the curves of direct emissions since the overwhelming majority of emissions come from the use of fossil fuels. In 2018, only about 5% of total emissions are from the electricity grid, while 95% is due to the use of fossil fuels.

The results of energy consumption and CO_2 emissions up to 2018 show that the model is accurate enough for the purpose of estimation of trends in the industry since the objective is not to have an exact calculation of emissions but to understand the possible benefits of implementing future technologies.

4.3 Scenarios for the Austrian P&P industry until 2050

This section presents the innovating technologies selected and scenarios for final energy consumption and fossil CO_2 emissions for the entire P&P industry in Austria. First, a business as usual scenario (BaU) is presented, considering only the increase of P&P production according to Table 3.5, without any technology improvement. Next, for each of the technologies selected, the application to one of the grades presented in Figure 4.1 is presented along with the impacts for the entire P&P sector in Austria, considering the total amounts of each grade of P&P produced in the country until 2050.

4.3.1 Business as usual (BaU) scenario

The BaU scenario assumes that the production trends for P&P in Austria are the ones presented in Table 3.5 and that no innovation technologies are installed in Austria.

The electricity and heat consumption resulting from the BaU scenario are shown in Figure 4.7.

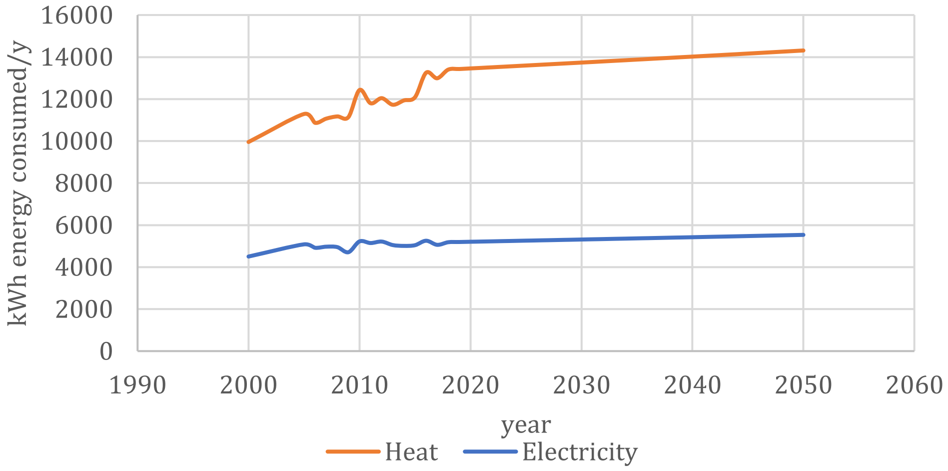

Figure 4.7: Electricity and heat consumption resulting from the BaU scenario.

The production of all products in this trend has low growth. However, the combined heat and electricity consumption of all the industry will significantly increase if there are no changes in the production process. In 2050, heat consumption will increase by 18.4% (2226 kWh) and electricity consumption will increase by 9.7% (491 kWh) compared to 2015.

The resulting total CO_2 emissions are shown in Figure 4.8.

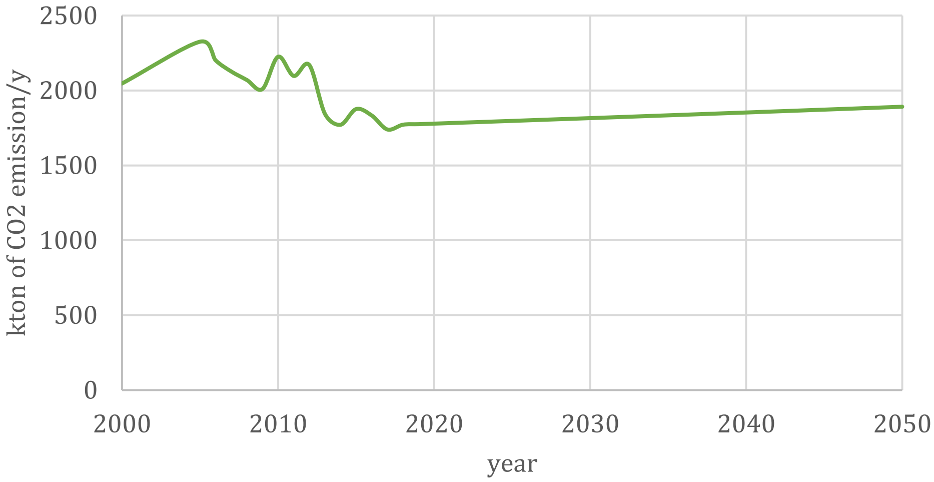

Figure 4.8: Fossil- CO2 emissions resulting from the BaU scenario.

Figure 4.8 shows that, without changing the production process, fossil-CO_2 emissions are expected to experience an increase of about 0.7% (16 kton) relative to the base year (2015).

4.3.2 Technology development scenarios

In this section, the impact of 7 future technologies (Table 3.8) will be shown separately. First, the effects of the application to a specific grade are presented. Then, the impacts on the entire P&P sector in Austria are presented, comparing the results of deployment from the assumptions in Table 3.7 with 100% deployment. The impacts will be calculated in reference to the base year (2015).

The future technologies applied to pulp production or drying of paper impact the emissions by reducing the final heat consumption, with small or no reduction in electricity consumption. They have no direct impact to grid electricity consumption or fuel consumption and low impact on the process electricity consumption so, for each of these technologies, only the change in heat consumption of the industry and the resulting total CO_2 emissions are presented. Electric heating, on the other hand, has no impact on final energy consumption. Its impact is a change in the consumption of fuels and grid electricity by the industry and so, for this technology, the evolution of consumption of fuels and grid electricity and the resulting fossil CO_2 emissions are shown.

4.3.2.1 Future technologies in pulp production

Direct green liquor utilization

Direct green liquor utilization is applied in the production of kraft pulp. The impact of the application of this technology in the production of writing paper in an integrated mill was calculated. Figure 4.9 shows the comparison between writing paper produced with the current liquor cycle with direct green liquor utilization.

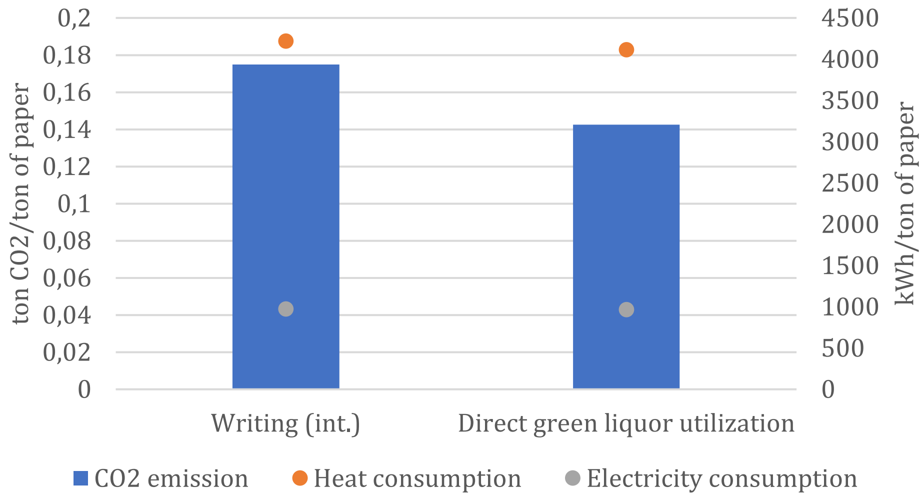

Figure 4.9: Application of Direct green liquor utilization in writing paper production.

The application of this technology has the potential to decrease specific heat consumption by 2.52% and specific electricity consumption by 0.92%. The resulting specific fossil CO_2 reduction is 18.49%.

The heat consumption resulting from the employment of Direct green liquor utilization in Austria is shown in Figure 4.10.

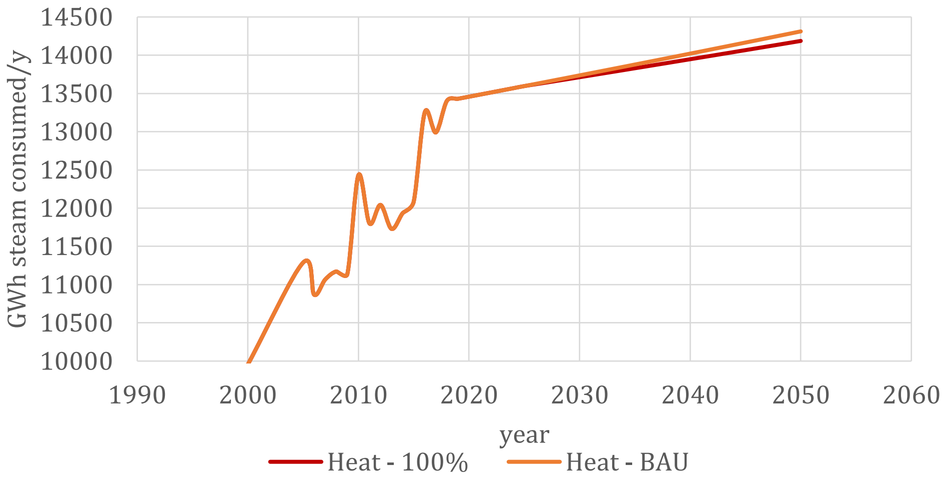

Figure 4.10: Heat consumption resulting from the employment of Direct green liquor utilization.

This technology is the only one for which 100% deployment is expected. There is an increase in heat consumption of 17.4% (2101 kWh) and an increase in electricity consumption of 9.5% (480kWh). The implementation of this technology leads to a slight reduction of consumption that is not sufficient to reduce the overall heat consumption of the industry to 2015 levels.

Figure 4.11 shows the resulting fossil-CO_2 emissions.

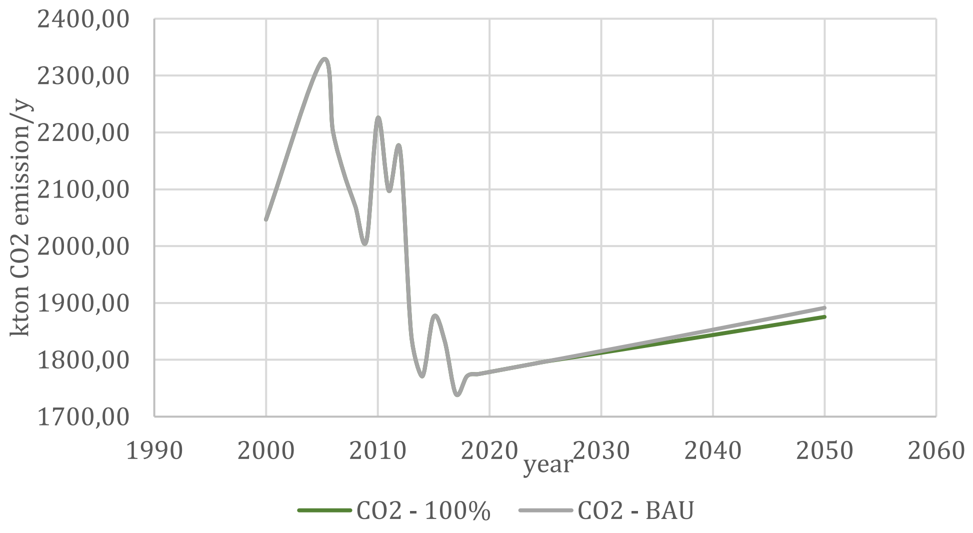

Figure 4.11: Fossil-CO_2 emission resulting from the implementation of Direct green liquor utilization.

With the application of Direct green liquor utilization, fossil-CO_2 emissions have approximately the same value in 2050 as in 2015.

Steam cycle washing

Steam cycle washing is applied in the production of kraft pulp. The impact of the application of this technology in the production of writing paper in an integrated mill was calculated. Figure 4.12 shows the comparison between writing paper produced with the current washing technology and using steam cycle washing.

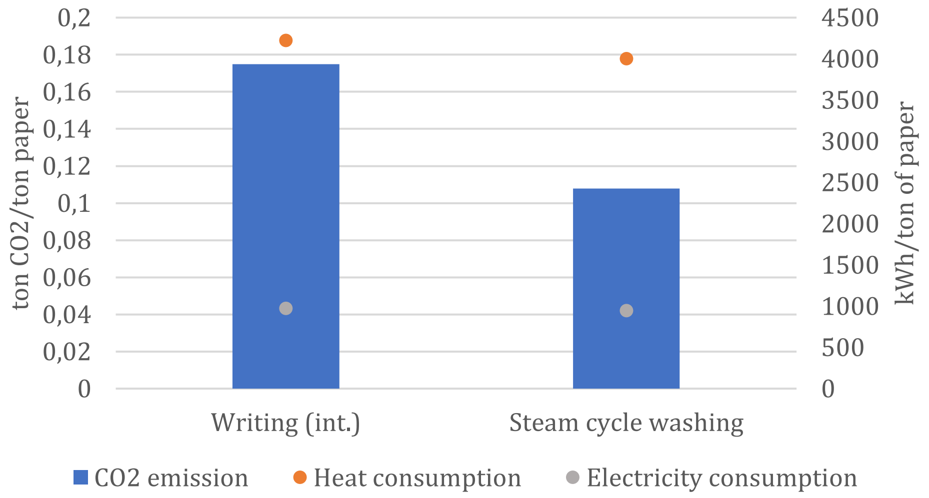

Figure 4.12: Application of Steam cycle washing to writing paper production.

The application of this technology has the potential to decrease specific heat consumption by 5.21% and specific electricity consumption by 2.82%. The resulting specific fossil CO_2 reduction is 38.29%.

The heat consumption resulting from the employment of Steam cycle washing in Austria is shown in Figure 4.13.

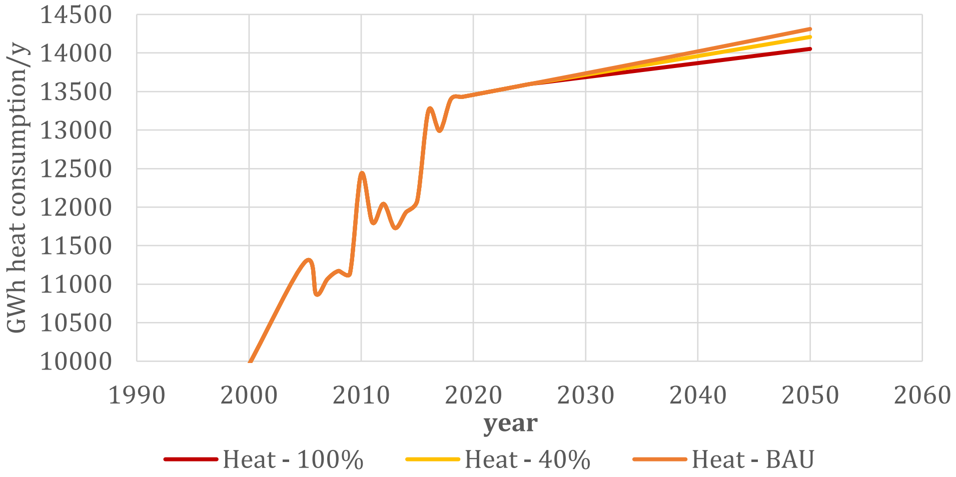

Figure 4.13: Heat consumption resulting from the employment of Steam cycle washing.

This technology has an expected deployment of 40%. Such deployment would lead to an increase in heat consumption of 17.5% (2122 kWh) and an increase in electricity consumption of 9.5% (478 kWh). If deployed by 100%, heat increase would be reduced to 16.3 % (1968 kWh) and electricity increase would be of 9.1% (459 kWh). The implementation of this technology leads to a slight reduction of consumption that is not sufficient to reduce the overall heat consumption of the industry to 2015 levels.

Figure 4.14 shows the resulting fossil-CO_2 emissions.

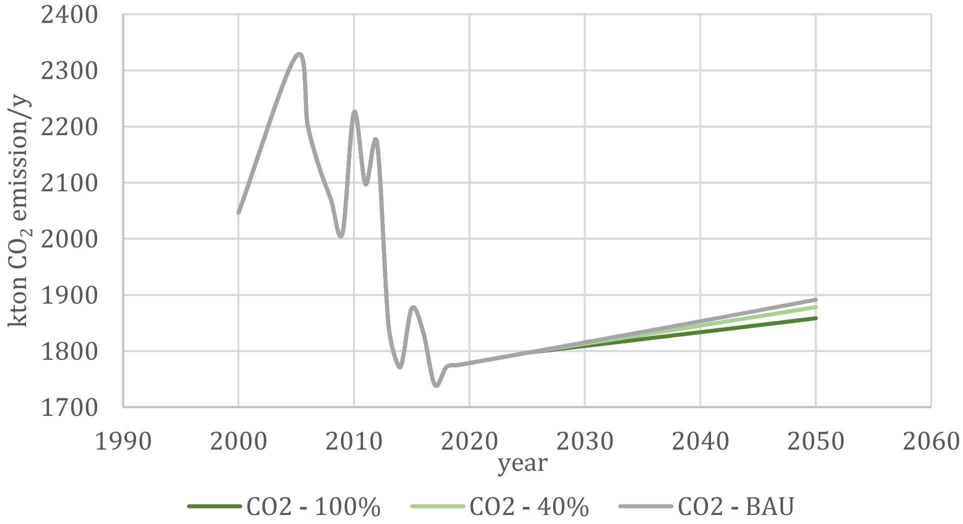

Figure 4.14: Fossil-CO_2 emission resulting from the employment of Steam cycle washing.

With the expected deployment, fossil-CO_2 emissions have approximately the same value in 2050 as in 2015. The maximum decrease in fossil-CO_2 emissions, if 100% of chemical pulp producers use this technology, is 0.9% (17 kton).

4.3.2.2 Future technologies in paper production

Impulse drying

Impulse drying is applied to the press section in paper production. The impact of the application of this technology in the production of writing paper in an integrated mill was calculated. Figure 4.15 shows the comparison between writing paper produced with the current pressing technology and impulse drying.

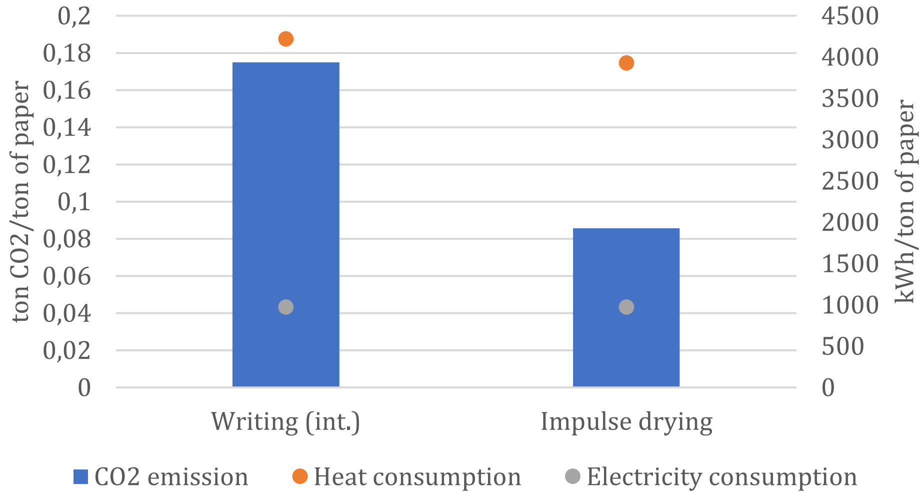

Figure 4.15: Application of Impulse drying to writing paper production.

The application of this technology has the potential to decrease specific heat consumption by 6.29% (electricity consumption remains the same). The resulting specific fossil CO_2 reduction is 51.02%.

The heat consumption resulting from the employment of Impulse drying in Austria is shown in Figure 4.16.

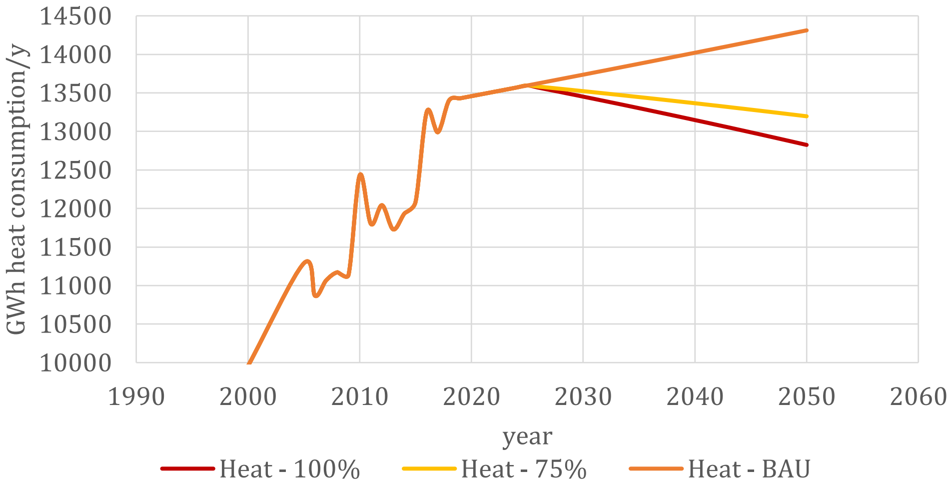

Figure 4.16: Heat consumption resulting from the employment of Impulse drying.

This technology has an expected deployment of 75%. Such deployment would lead to an increase in heat consumption of 9.2% (1111 kWh) and electricity consumption would remain as in the BaU scenario. 100% deployment would reduce the heat increase to about 6.1 % (739 kWh). The implementation of this technology results in a considerable reduction of consumption, but still would not be enough to decrease the total heat consumption of the industry to 2015 levels.

Figure 4.17 shows the resulting fossil-CO_2 emissions.

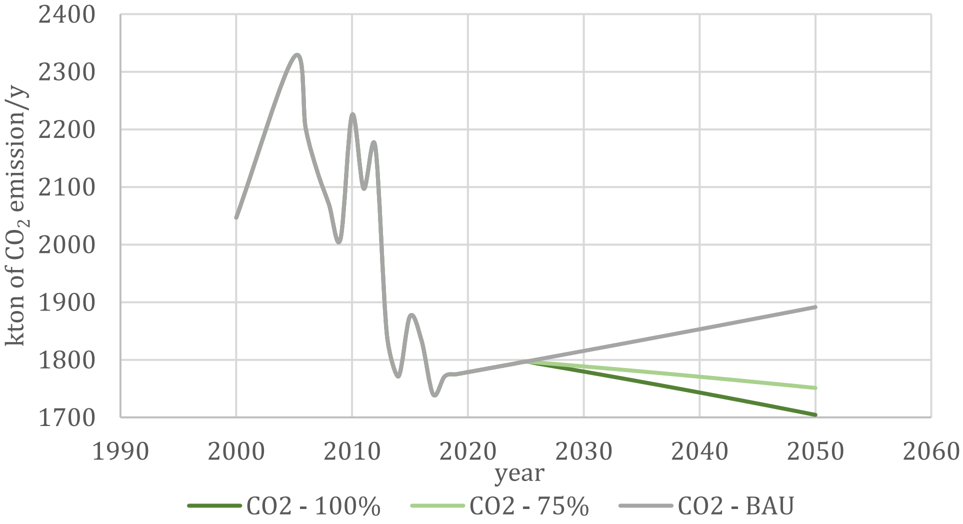

Figure 4.17: Fossil-CO2 emission resulting from the employment of Impulse drying.

With the expected deployment, fossil-CO_2 emissions fall by 6.6% (125 kton) compared to 2015. The maximum decrease obtained by 100% deployment of this technology is 9.1% (171 kton).

Condebelt drying

Condibelt drying is applied to the drying section in paper production. The impact of the application of this technology in the production of writing paper in an integrated mill was calculated. Figure 4.18 shows the comparison between writing paper produced with the current drying technology and condebelt drying.

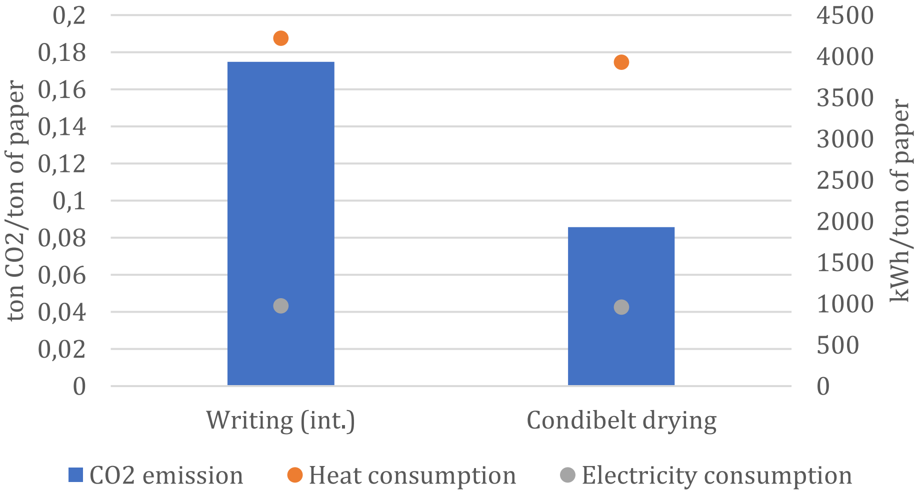

Figure 4.18: Application of Condibelt drying to writing paper production.

The application of this technology has the potential to decrease specific heat consumption by 6.94% and specific electricity consumption by 1.51%. The resulting specific fossil CO_2 reduction is 51.02%.

The heat consumption resulting from the employment of condebelt drying in Austria is shown in Figure 4.19.

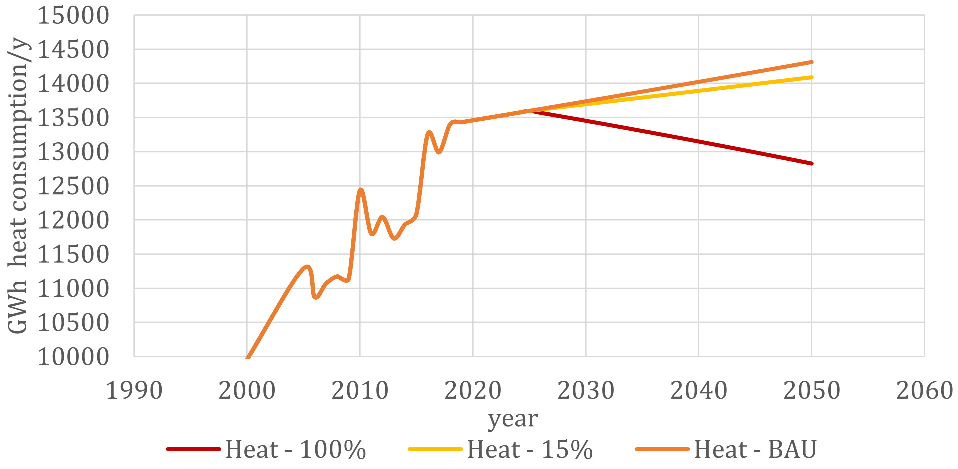

Figure 4.19: Heat consumption resulting from the employment of Condebelt drying.

This technology has an expected deployment of 15%. Such deployment would lead to an increase in heat consumption of 16.6% (2003 kWh) and an increase in electricity consumption of 9.5% (479 kWh). If deployed by 100%, heat increase would be reduced to about 6.1% (731 kWh) and electricity increase would be of 8.1% (412 kWh). The implementation of this technology results in a small reduction of consumption (due to the low implementation rate), not enough to decrease the overall heat consumption of the industry to the values of 2015.

Figure 4.20 shows the resulting fossil-CO_2 emissions.

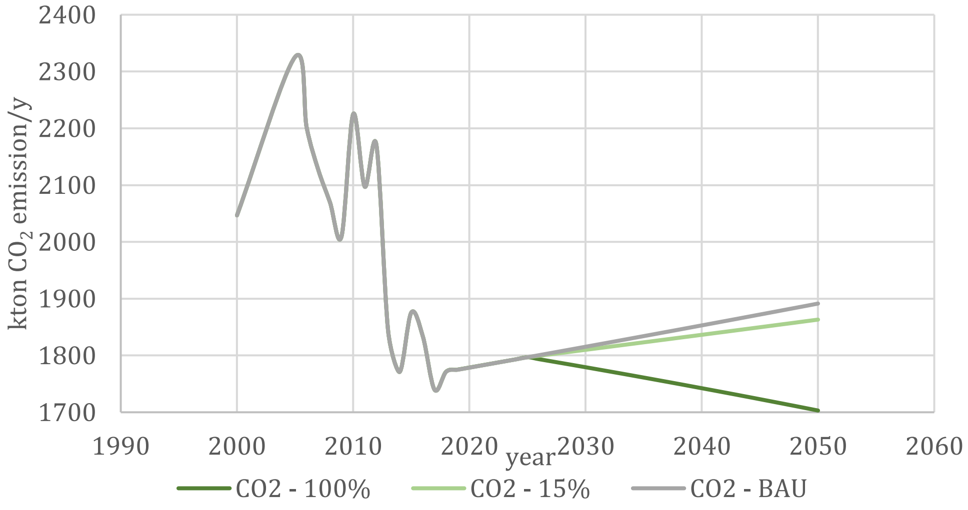

Figure 4.20: Fossil-CO2 emission resulting from the employment of Condebelt drying.

With the expected deployment, fossil-CO_2 emissions fall by 0.7% (13 kton) compared to 2015. The maximum decrease obtained by 100% deployment of this technology is 9.2% (173 kton).

Gas-fired dryers

Gas-fired dryers are applied to the drying section in paper production. The impact of the application of this technology in the production of writing paper in a non-integrated mill was calculated. Figure 4.21 shows the comparison between writing paper produced with the current drying technology and gas-fired dryers.

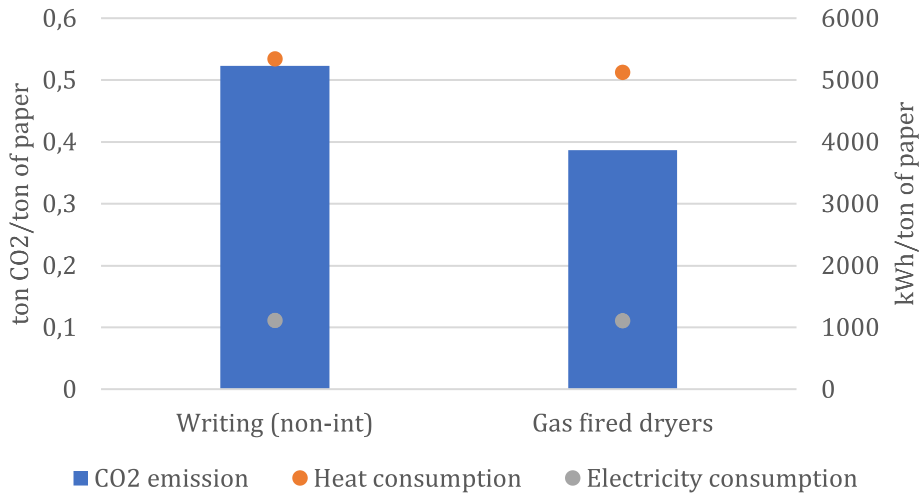

Figure 4.21: Application of Gas-fired dryers to writing paper production (non-integrated).

The application of this technology has the potential to decrease specific heat consumption by 4,11% and specific electricity consumption by 0,40%. The resulting specific fossil CO_2 reduction is 26.04%.

The heat consumption resulting from the employment of gas-fired dryers in Austria is shown Figure 4.22.

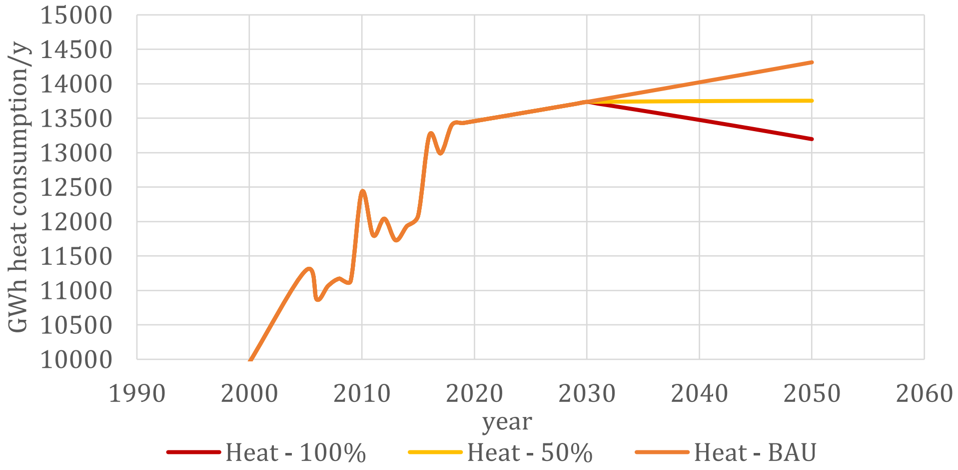

Figure 4.22: Heat consumption resulting from the employment of Gas-fired dryers.

This technology has an expected deployment of 50%. Such deployment would lead to an increase in heat consumption of 13.8% (1669 kWh) and an increase in electricity consumption of 9.5% (479k Wh). 100% deployment would reduce heat increase to 9.2 % (1111 kWh) and electricity increase to 9.3% (467 kWh).

The implementation of this technology results in a low reduction of consumption (due to the low implementation rate), not sufficient to reduce the overall heat consumption of the industry to 2015 values.

Figure 4.23 shows the resulting fossil-CO_2 emissions.

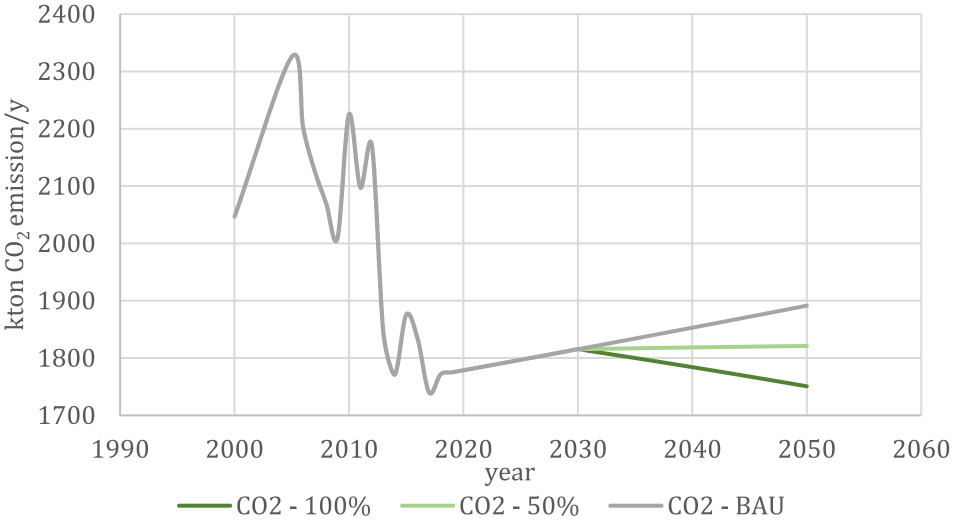

Figure 4.23: Fossil-CO_2 emission resulting from the employment of Gas-fired dryers.

With the expected deployment, fossil-CO_2 emissions fall by 2.9% (55 kton) compared to 2015. The maximum decrease obtained by 100% deployment of this technology is 6.7% (125 kton).

Dry sheet forming

Dry sheet forming is applied to the forming section in tissue paper production. The impact of the application of this technology in the production of tissue paper in an integrated mill was calculated. Figure 4.24 shows the comparison between tissue produced with the current forming technology and dry sheet forming.

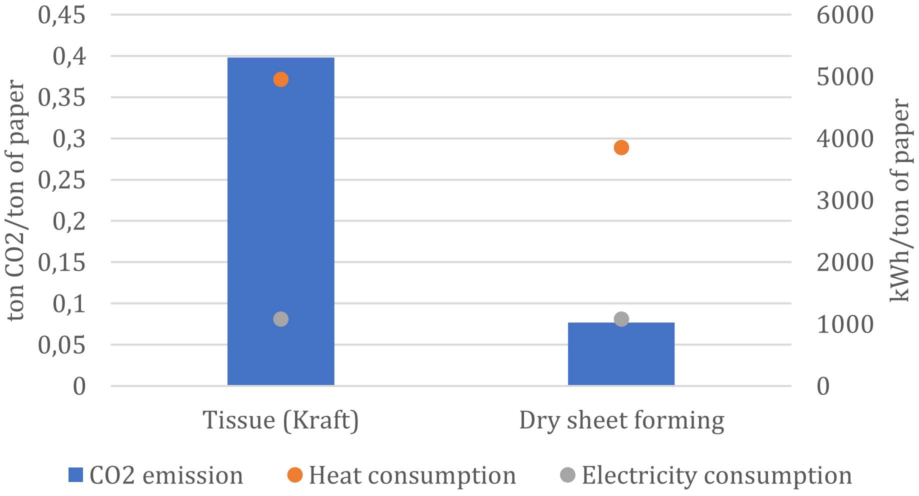

Figure 4.24: Application of Dry sheet forming to tissue production.

The application of this technology has the potential to decrease specific heat consumption by 22.19% (electricity consumption remains the same). The resulting specific fossil-CO_2 reduction is 80.69%.

The heat consumption resulting from the employment of dry sheet forming in Austria is shown in Figure 4.25.

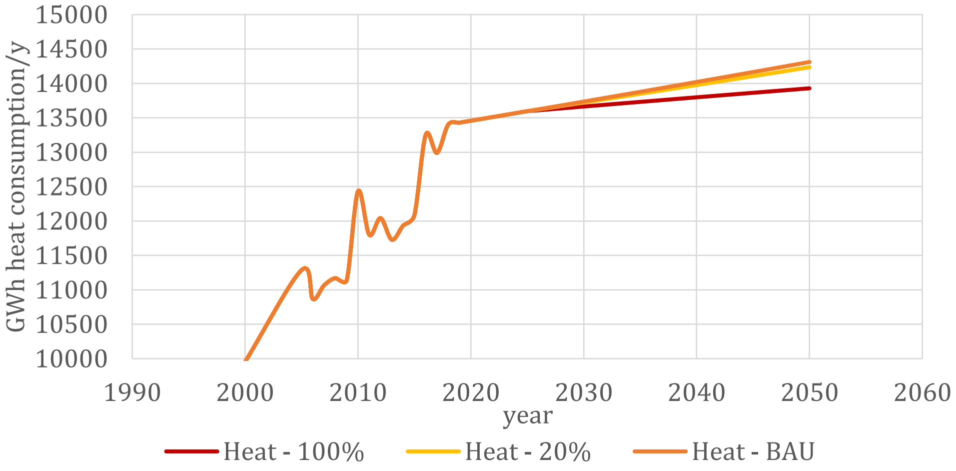

Figure 4.25: Heat consumption resulting from the employment of Dry sheet forming.

This technology has an expected deployment of 20%. Such deployment would lead to an increase in heat consumption of 17.8% (2150 kWh) and no change in electricity consumption. If deployed by 100%, heat increase would be reduced to about 15.3 % (1844 kWh). The implementation of this technology results in a low reduction of consumption (due to the low implementation rate and application only to tissue and soft paper), not enough to decrease the overall heat consumption of the industry to the values of 2015.

Figure 4.23 shows the resulting fossil-CO_2 emissions.

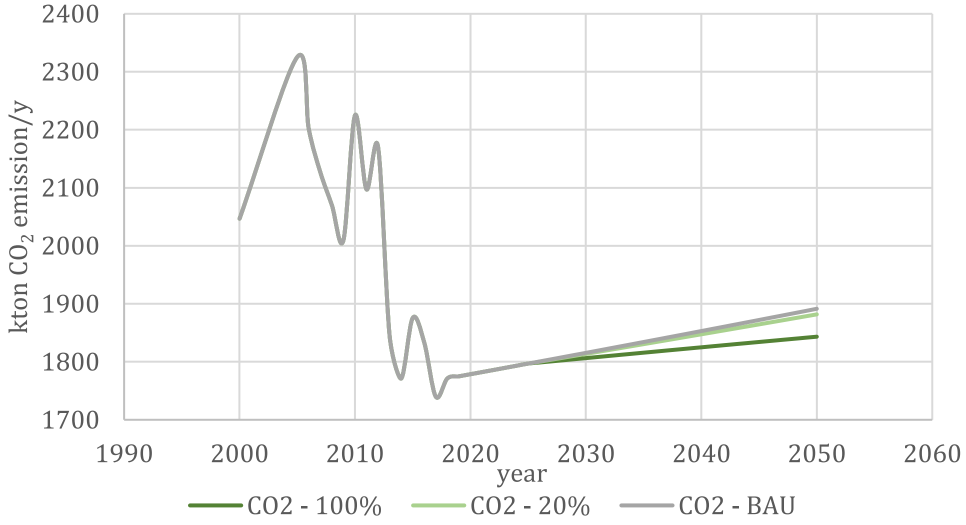

Figure 4.26: Fossil-CO2 emission resulting from the employment of Dry sheet forming.

With the expected deployment, fossil-CO_2 emissions are still higher than the 2015 level, with an increase of 0.3% (5 kton). The maximum reduction obtained by 100% deployment of this technology is 1.8% (32 kton).

4.3.2.3 Decarbonization of steam supply

Electric heating

Electric heating is a possible replacement for fossil-fueled CHP. The impact of the application of this technology in the production of writing paper in an integrated mill was calculated. Figure 4.24 shows the comparison between writing paper produced with heat produced by the use of fossil-fueled CHP and by the use of electric heating.

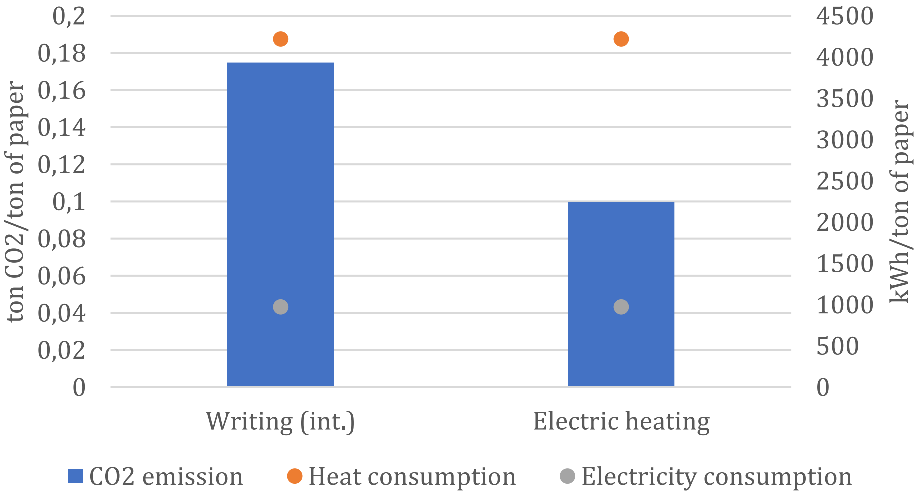

Figure 4.27: Application of Electric heating to writing paper production.

The application of this technology has the potential to decrease specific fossil-CO_2 emission by 42.89%.

The replacement of the fossil fuel boilers by this technology results in a shift from fossil fuels use to grid electricity. In this case, a deployment of 100% means the total replacement of fossil fuels used. The fuels consumption resulting from the employment of Direct electric heating in Austria is shown in Figure 4.28

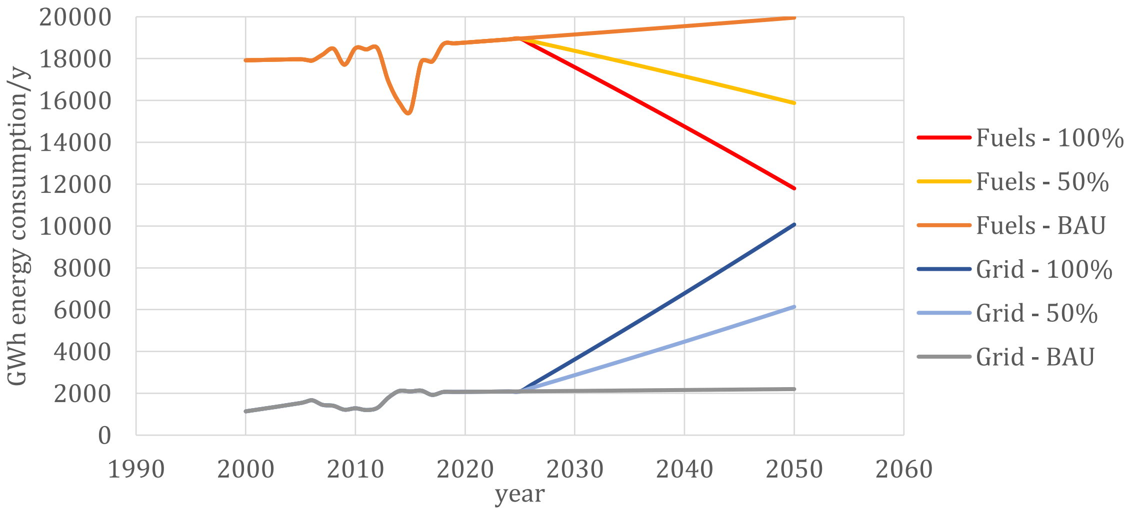

Figure 4.28: Energy consumption resulting from the employment of Direct electric heating.

This technology has an expected deployment of 50%. Such deployment would lead to a reduction of the increase in fuel consumption to 2.5% (398 kWh), with a share of biofuels of 74.0% in 2050, but the use of grid electricity would triple (increase by 193.6% – 4046 kWh). If it would be totally deployed, fuel consumption would decrease 23.8% (3683 kWh, 100% biofuels), and electricity consumption would increase by 381.7% (7979 kWh)

Figure 4.29 shows the resulting fossil-CO_2 emissions.

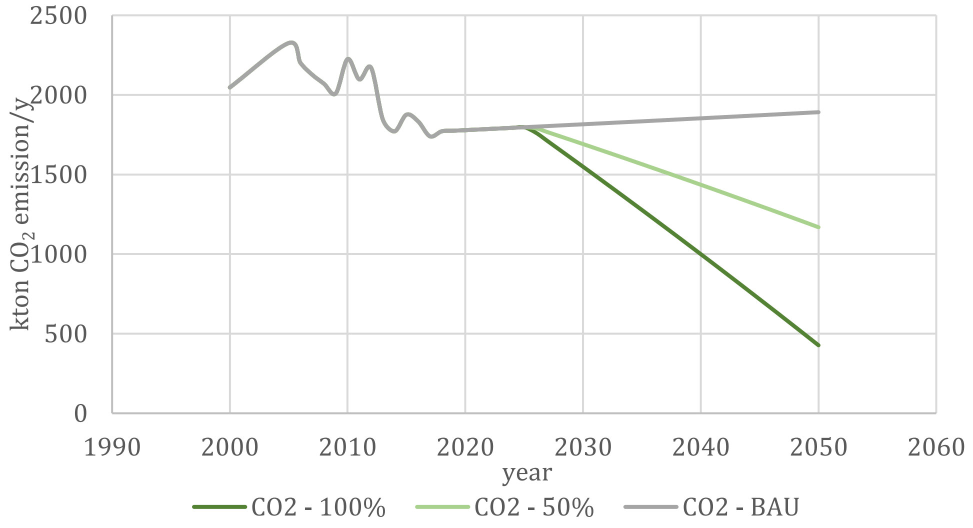

Figure 4.29: Fossil-CO2 emission resulting from the employment of Direct electric heating.

With the expected deployment, fossil-CO_2 emissions would fall by 37.7% (707 kton). The maximum reduction obtained by 100% deployment of this technology is 77.2% (1449 kton).

4.3.2.4 Summary of the impact of future technologies

Table 4.1 summarizes the impacts of the deployment of each technology in the production of a specific paper grade. The fields in white indicate that there is no change.

Table 4.1: Summary of the impacts resulting from the deployment of future technologies to the considered paper grades (in – integrated, n-int – non-integrated)

Technology	Paper grade	Specific heat	Specific electricity	Specific fossil-CO_2
DGLU	Writing (int)	- 2.52%	- 0.92%	- 18.49%
SCW	Writing (int)	- 5.21%	- 2.82%	- 38.29%
ID	Writing (int)	- 6.29%		- 51.02%
CD	Writing (int)	- 6.94%	- 1.51%	- 51.02%
GFD	Writing (n-int)	- 4.11%	- 0.4%	- 26.04%
DSF	Tissue	- 22.19%		- 80.69%
DEH	Writing (int)			- 42.89%

Table 4.2 summarizes the impacts of the deployment of each technology, in the year 2050. The percentages values indicate the change in comparison to the values in the base year (2015). The "Biofuels %" column refers to the share of biofuels in the total fuels used in the industry. The isolated "+" indicates that an increase is expected but it was not calculated directly. For process technologies, the increase in heat consumption was taken as the main indicator, fuel consumption is expected to increase because of the increase in heat consumption. "BAU" indicates that the value is the same as in the "Business as usual" scenario, which is described in the first row of the table.

Table 4.2: Summary of the impacts in 2050 resulting from the deployment of future technologies in Austria.

Reference values	**Heat (kWh)**	**Elect. (kWh)**	**Fuels (kWh)**	**Biofuels %**	**Grid (kWh)**	**Fossil-CO_2 (kton)**
2015	12085	5043	15478	5.,9	2090	1876
Scenario	**Heat**	**Elect.**	**Fuels**	**Biofuels %**	**Grid**	**Fossil- CO_2**
BAU	+18.4%	+9.7%	+28.9%	59,1	+5.4%	+0.7%
DGLU (100%)	+17.7%	+9.5%	+	BAU	+	-0.7%
SCW (40%)	+17.5%	+9.5%	+	BAU	+	-0.7%
SCW (100%)	+16.3%	+9.1%	+	BAU	+	-1.0%
ID (75%)	+9.2%	BAU	+	BAU	BAU	-6.6%
ID (100%)	+6.1%	BAU	+	BAU	BAU	-9.1%
CD (15%)	+16.6%	+9.5%	+	BAU	+	-0.7%
CD (100%)	+6.1%	+8.1%	+	BAU	+	-9.1%
GFD (50%)	+13.8%	+9.5%	+	BAU	+	-2.9%
GFD (100%)	+9.2%	+9.3%	+	BAU	+	-6.7%
DSF (20%)	+17.8%	BAU	+	BAU	BAU	+0.3%
DSF (100%)	+5.3%	BAU	+	BAU	BAU	-1.8%
DEH (50%)	BAU	BAU	+2.5%	74,0	+193.6%	-35.9%
DEH (100%)	BAU	BAU	-23.8%	100,0	+381.7%	-73.5%

4.4 Results Discussion

4.4.1 Comments on the model developed: strengths and limitations

The model developed for this master thesis was developed in a bottom-up methodology. The challenge, in this case, was characterizing the entire P&P industry of Austria using a simplified model, for two motives: 1) the paper industry produces many different products, and the Austrian paper industry is composed by a wide range of different production facilities with different specifications and; 2) the information about the production details was often scarce.

To overcome this challenge, some simplifications had to be made. First of all, side processes were not included, some of which may have some impact, like the transportation of materials inside the P&P mill using fossil fuel moved vehicles. The description of the main processes is simplified as they are represented by their heat and electricity consumption. It was not possible to calculate the energetic load at a time frame smaller than one year since the production data are reported annually.

Since energy production facilities are not necessarily similar in every mill, it was not possible to calculate the necessary fuel consumption to supply the final energy needed based on technical data, as was made for the production process. To calculate fuel consumption, it was necessary to use a ratio between total heat and fuel consumption data (α). A similar ratio, β, was calculated, between the total electricity and fuel consumption, but not used in calculations. Both α and β are determined by the energy systems used to produce energy at the facilities, mainly by three specifications: 1) The efficiency of the energy conversion system; 2) The power-to-heat ratio and 3) the energy losses from the energy system to the point of consumption by the different production machinery. In Figure 3.1 it is possible to understand how these coefficients have been evolving for Austria in the past. Whereas the summation is approximately constant, α follows a slightly growing trend and β a slightly decreasing trend. This is possibly explained by the decrease in the production of mechanical pulp (which consumes mostly electricity) along with the increase of chemical pulp (which consumes mostly heat). Because of this behavior, when estimating the effect of the installation of innovative technologies, the value of α was considered to be constant with the value of 2018.

The lack of information regarding the energy systems is also an issue for the calculation of the type of fuels used. For that reason, the fuel mix used by the industry was taken from data (and not calculated). That means that processes consuming fuel directly (such as the lime kiln) are not considered in that way, but instead, they are treated as heat consumers. This simplification is acceptable for the large scale considered, but on a smaller scale a more detailed approach would provide more interesting results. The fuel mix is considered static in the future because its evolution was linear in the past years (Figure 3.2), except for the case of the technologies of energy production (each technology has a different impact). This means that when considering the installation of new process technologies, the change in fuel mix is ignored, which probably induces an overestimation of fossil-CO_2.

By doing the assumptions explained, it was possible to calculate the energy consumption and CO_2 emissions of the industry in Austria with an acceptable degree of accuracy. The model allows some important conclusions to be made about the production methods used today. Furthermore, the model allows the impact of the application of the innovative technologies to be escalated from the impact relative to a process (for example, saying that technology XPTO allows the energy consumption in chemical pulping to decrease by 50%) to the impact on the entire production process of paper (the reduction in specific energy consumption of producing the paper grade Y caused by the application of technology XPTO) and the impact to the entire paper and pulp sector in Austria (the reduction in energy consumption that technology XPTO causes in the entire sector). Since all the studied technologies are still in early development stages, the model may be used to indicate to policymakers and industry professionals which technologies present the best perspectives to decarbonize the industry and are then worth researching and investing.

4.4.2 Technological pathways for the decarbonization of the P&P industry in Austria

The result of the BAU scenario indicates that without any technology development, the carbon emissions of the Austrian paper industry in 2050 will be almost 1% higher than in 2015, with almost 30% higher consumption of fuels and 5% higher consumption of grid electricity. For the EU, a scenario without technological improvement would lead to an increase in energy consumption of 1% and an increase in GHG emissions of 5% in comparison to 2015 [62].

By analyzing Table 4.2 it is possible to compare the impacts of the application of the technologies studied in the production of the grades they were applied to. The minimum specific fossil CO_2 reduction is 18% and it goes as high as 80%, considering the application to the paper grades considered. When studying the total P&P industry in Austria, emissions cannot be completely allocated only to paper, since pulp is also exported and used to produce textile products as well.

Figure 4.30 presents the emission obtained by 100% deployment of all technologies in Austria.

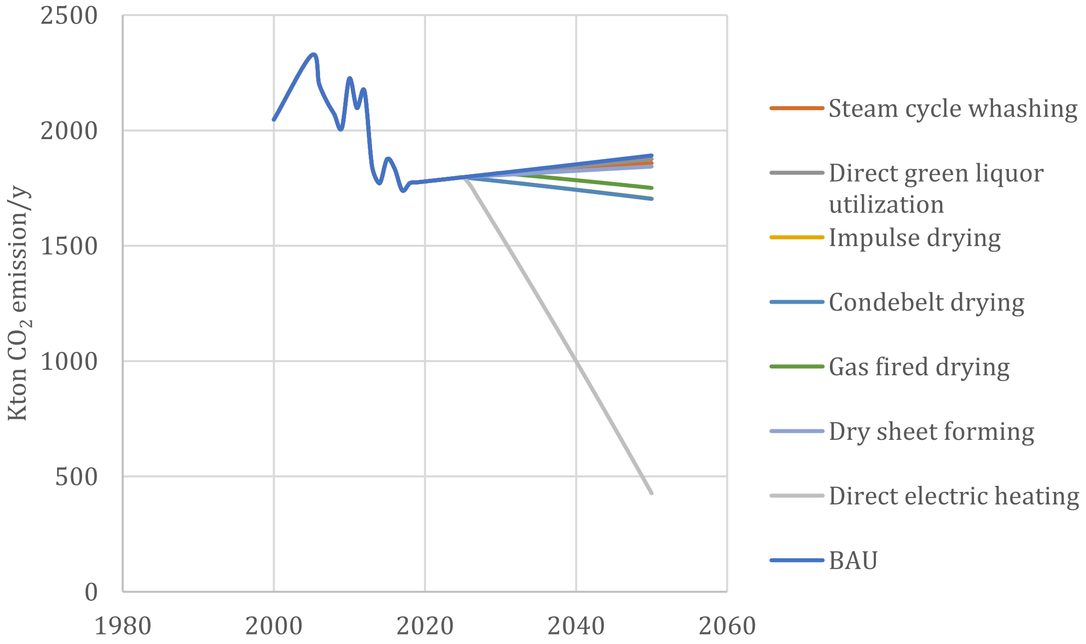

Figure 4.30: Comparison between the CO_2 emissions of 100% deployment scenario of each of the technologies.

The technologies can be divided according to the potential for reduction of CO_2 emissions in 2050, as shown in Figure 4.30:

- High CO_2 emissions (> 1800 kton/y) – in this group figure the technologies applied to chemical pulp production, for which the maximum carbon reduction is about 1%, and also drying technologies that are applied to too small segments of the production, such as dry sheet forming (which reduces specific emissions of tissue paper by 80%, but results in a reduction of less than 2% of the total emissions in Austria). The individual impact of these technologies is reduced. However, the simultaneous application of technologies with reduced impact will be essential to improve the efficiency of the industry, since most of the BAT or IT have a low impact on the global level. By applying 17 process technologies such as these (some of which are out of the scope of this study, since they are not applied to the most energy-intense processes), Fleiter et al [64] estimated that it would be possible to achieve a 19% CO_2 reduction relatively to a frozen-efficiency scenario in Germany;
- Medium CO_2 emissions (≤1800 kton/y) – this is the category of drying technologies, with a maximum carbon reduction of 10%. Energy reduction for paper drying is a priority for the sector. The most promising technologies in this group are Condebelt drying and Gas-fired dryers. Even though the first promises more significant heat reduction, the later one would require a less radical change in the production line and a lower investment, which could mean higher deployment in the future. Gas-fired dryers increase the efficiency of heat supply to the drying process but still depends on the combustion of methane and so CO_2 emissions are unavoidable. However, methane can be obtained from biogas or biomass gasification. Another option would be to adapt the system to use hydrogen instead/along with methane, which may be obtained from CO_2 neutral electricity;
- Low CO_2 emissions (<800 kton/y) – This category includes the installation of electric boilers as a way of replacing fossil fuels for steam supply, with the potential to eliminate up to 70% of CO_2 emissions. The installation of electric boilers seems to be an easy solution, requiring a lower investment than a new biomass boiler. However, the impact on the grid is very intense (with the expected deployment of 50%, the load on the grid doubles). In that case, the CO_2 emissions may be substantially higher than the estimation shown since higher shares of fossil fuels to sustain the extra load on the grid would probably be required. The installation of a hybrid solution would be a more interesting solution, using electric boilers to balance the electric grid in periods with excessive renewable energy production, and keeping the traditional boilers for other periods.

The present thesis focuses only on some of the promising technologies which were found in the literature. More efficiency measures such as these will have to be taken in every step of the production process (namely in the pulp production and paper drying) in order to reduce energy consumption to the minimum value possible. The decarbonization of the steam supply at the mill will also play an important role. Besides the use of electric boilers, the replacement of fossil fuels by biofuels could also be an important measure. Since the production is a continuous process, the potential to increase the flexibility of grid electricity use of the paper industry resides in the energy production technologies.

The deployment level of each technology will have a significant impact on CO_2 reduction. Although the assumptions of deployment in the model are only indicative, we can see that most of the technologies will have a deployment level lower than 50%. In this study, the economic situation of Austria and the Austrian paper and pulp industry were not considered, but this will have a significant impact on the deployment of the technologies and therefore on the reduction of CO_2 emissions.

Other technologies besides the ones considered will have an important role in the future of the paper industry. Among those, the most important are:

- Heat recovery – In an industry with such intensive heat use, heat recovery processes are crucial to improve energy efficiency. Even though it is already used in the industry, heat recovery is expected to increase in the future, applied to the paper machine line. It is identified by Parsons Brinckerhoff as one of the key technological groups for the future [68];
- Process control – The constant analysis and optimization of all the parameters of paper production will have a serious impact on the efficiency of the process, process speed and material efficiency. Process control is already used in the paper industry, but some other industries are far more developed. The tendency nowadays is to improve data collection and evolve towards the concepts of industry 4.0. The adoption of these practices will have a significant impact on energy consumption [68];
- Gasification and biorefinery – Gasification of waste biomass and black liquor is still in the development stage, but it promises great potential in the paper industry [84, 85]. Gasification converts biomass to combustible gas (syngas) which can be used for energy recovery, with lower emission values than the original biomass. Syngas obtained from gasification has great potential to be used or sold as a raw material to the biorefinery, replacing fossil fuels in this industry and increasing the value of the waste of pulp production. The loss of the black liquor as fuel may result in an increase in emissions by the paper industry, but the joined environmental impact of the paper and refinery industries would be reduced [62];
- Carbon capture and storage (CCS) – This technology has a high potential for the paper industry. Post-combustion CCS may be applied to the recovery or fossil fuel boilers, or precombustion CCS may be used together with gasification. Nowadays, CCS systems consume high amounts of heat and electricity, decreasing the energy efficiency of the process. If energy consumption decreases, CCS could be used to turn the P&P industry in a carbon sink, since most of the fuels used are biofuels;
- Two team project technologies – The two team project carried out by the Confederation of Paper Industries (CEPI) in 2013 resulted in new concepts to the paper industry, with great potential to reduce energy intensity and CO_2 emissions. All these technologies are still in the research phase and there is not enough information to include them in a mathematical model. Nevertheless, there are great expectations about them, namely about the winning project: Deep Eutectic Solvents. It will be used to develop a new pulping method, which requires a fraction of the water use of the chemical process used nowadays and allows a separation of the pure lignin without the application of extra technologies. It is expected that the overall fossil CO_2 emissions of the paper and pulp industry in Europe may reduce by 20% and primary energy savings of 40% [69].

4.4.3 Sustainable decarbonization policies

The work developed focuses exclusively on CO_2 emissions from the combustion of fossil fuels, as P&P mills are allocated only for those emissions and not for the emissions of CO_2 from the combustion of biomass. As was explained the section 2.3, in the national inventory reports of the member countries of the IPCC, the carbon emission from bioenergy are accounted to the forest sector. Following this line, the EU ETS requires countries to pay only for fossil CO_2.

These policies are efficient in their main objective: decreasing fossil carbon emissions. However, some of the side effects may be less positive, which should be prevented:

- The disregarding for CO_2 emissions from bioenergy may lead to an unsustainable increase in the use of biomass for energy, as a fast way of decreasing fossil CO_2 emissions. There are many risks associated with this, such as loss of natural forests to forest crops or the excessive growth of fast cultures such as the Eucalyptus, which have intense growth rates, damaging the soil and the biodiversity. Another option may be the importation of wood from large distances (such as the wood imported from Canada and the U.S. to Europe), leading to carbon emissions from transportation. Also, the exporting country may not have forest certification, leading to forest reduction elsewhere in the globe (even though the forest area is growing in Europe, it is decreasing globally in comparison to 1990);
- The EU ETS allocates responsibility for fossil CO_2 emissions to producers individually. As free allowances are reduced and the prices in the allowances market increase, companies will be pressed to reduce their individual emissions. As that strategy may lead to a fast reduction at the company level, it may not be the most efficient at a national or even European level. As an example, the partial use of lignin from black liquor for the chemical industry may be a good strategy to reduce carbon emissions of both industries in total, but it also means loss of bioenergy available for the paper industry, and possibly need to buy more carbon allowances. In this sense, the EU ETS may be an obstacle to industrial clustering.

Sustainable decarbonization policies must then have as prime objective the decrease of carbon emissions through a decrease in energy and raw material use. For that reason, it is essential that the process technologies that lead to small decreases in energy consumption such as direct green liquor utilization, dry sheet forming, etc, are implemented, to decrease energy use. Other technologies with more radical carbon decrease, such as the electrification of the heat supply, may result in increased emission at some other level, not considered in the current thesis.

It should be a priority of the national governments to have strategies to ensure that the reduction in carbon emissions is made in the most efficient way at the national level.

5 Conclusions and future work

The P&P industry is a dynamic sector that will keep its role as an industrial product of Austria and an important sector for its economy. The products of this industry, once limited to the production of graphic paper, are evolving into new essential and highly specialized products and taking increasingly important roles in areas such as hygiene, packing or food wrapping, as a more sustainable alternative to the products used up to now.

The P&P has a strong impact on the forest sector. The sustainable use of forest wood has many benefits, fastening the carbon cycle, preventing wildfires, providing incentives for forest owners to maintain healthy forests and increasing forest growth, which works as an important carbon sink. Paper production in Europe is typically based on wood from certified forests and is seen as an incentive to sustainable foresting. It is crucial that the efforts to achieve carbon neutrality do not compromise the management of forests, overproducing too intensive cultures that may exhaust the forests ecosystems and pressuring natural forests. On the other hand, policies should promote the use of bioenergy and decrease of fossil fuels at a macro level and not simply pressuring companies at an individual level, which may lead to inefficient uses of bioenergy.

In order to decrease carbon emissions, the production process will be the target of deep modifications. The basic step is to adopt efficiency measures, which increase the energy efficiency of the current production process, consuming the smallest amount of energy possible. The Austrian paper industry is nowadays a reference on the global scale, having a specific energy consumption and carbon emissions of 75% and 60% of the global average (respectively). To decrease carbon emissions, efforts to increase efficiency must continue.

Two basic sustainability measures have been successfully introduced in Europe up to now: increasing the rate of paper recycling and the use of recycled fibers to produce new paper (decreasing the energy needs drastically) and increasing the share of biofuels used in the industry (shifting emissions from fossil-CO_2 to bio-CO_2). It is important that these strategies remain as a pillar for the industry, particularly the increase of the recycling rate in countries where the paper is currently ending-up on landfills.

Some important trends that may mark a deep change in the industry in the next few years:

- Development of new drying methods – as seen before, the replacement of the current drying section based on steam drums could lead to a drastic increase in efficiency and production speed;
- Valorization of waste streams through a fusion with the biorefinery sector – The chemical pulping results in high amounts of waste lignin, which is currently used for energy production. Lignin is a valuable product for many other industries, particularly for biorefinery, and so many authors argue that lignin use would much more efficient if it would be sold as a side product. This would mean that the industry would be letting go of its main source of clean energy and other technologies will have to replace this gap. Gasification may fill the gap, using the syngas for biorefinery. Also, this

may implicate the use of new pulping technologies which allow easier extraction of lignin such as Deep Eutectic Solvents;

- Electrification and increase in flexibility – Steam production is the biggest source of CO_2 emissions in this industry and so the electrification of steam production is expected to occur in the future. The use of a hybrid system, capable of producing steam by electricity or fuels, would turn the paper industry into a flexible electricity consumer
- Adoption of carbon capture and storage technology – this technology is still in development, and its implementation has high cost and energy consumption. However, the CO_2 intensive industries are hoping for the development of a more efficient solution in the future. For the paper industry, this could mean the transformation into a carbon sink instead of a carbon source. In the future, new technologies allowing the utilization of stored carbon (carbon capture and utilization) may be the most interesting option due to the lack of storage alternatives in Austria.

This thesis focused on the impacts of the individual adoption of some technologies which will contribute to the trends described above, regarding technical possibilities of these technologies, The next step for the NEFI project is the production of models which consider the adoption of more than one of the considered technologies and others not considered. This study should account for other factors besides technical possibilities which are equally decisive, such as energy markets, economy, the specific interests of Austrian companies and European and Austrian policies.

The P&P industry is also a strong sector in Portugal but with a very different structure. Whereas in Austria, the P&P industry produces a wide variety of products with different types of P&P being produced, imported and exported, in Portugal most of the pulp is produced through the kraft process (all mechanical pulp consumed is imported) and the majority of paper produced is office paper (with low shares of production of toilet paper and carton). The Portuguese P&P may face the need to diversify to different grades since the consumption of office paper is expected to face a slight growth, whereas other grades such as packing paper are expected to grow much more and adapt to new market needs.

A future study could explore how the technologies studied would preform in Portugal and which other technologies would have better performance given a different reality. The industry in Portugal uses very low shares of recycled pulp comparing to the industry in Austria. It could be interesting to explore strategies to increase the share of recycled pulp since the consumption of energy is significantly lower.

The achievement of a carbon-neutral P&P industry by 2050 is possible, but depends strongly on the investment in research, on the industries' willingness to deploy new technologies and on the government's incentives to do so. Nevertheless, paper production in Austria is a mature practice and is long-established as innovative and sustainable. Considering expertise and experience obtained by centuries of paper production, the Austrian industry is in a privileged position to become an earlier adopter of future technologies and a leader in the decarbonization of the paper industry.

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Appendices

A. Paper grades production schemes

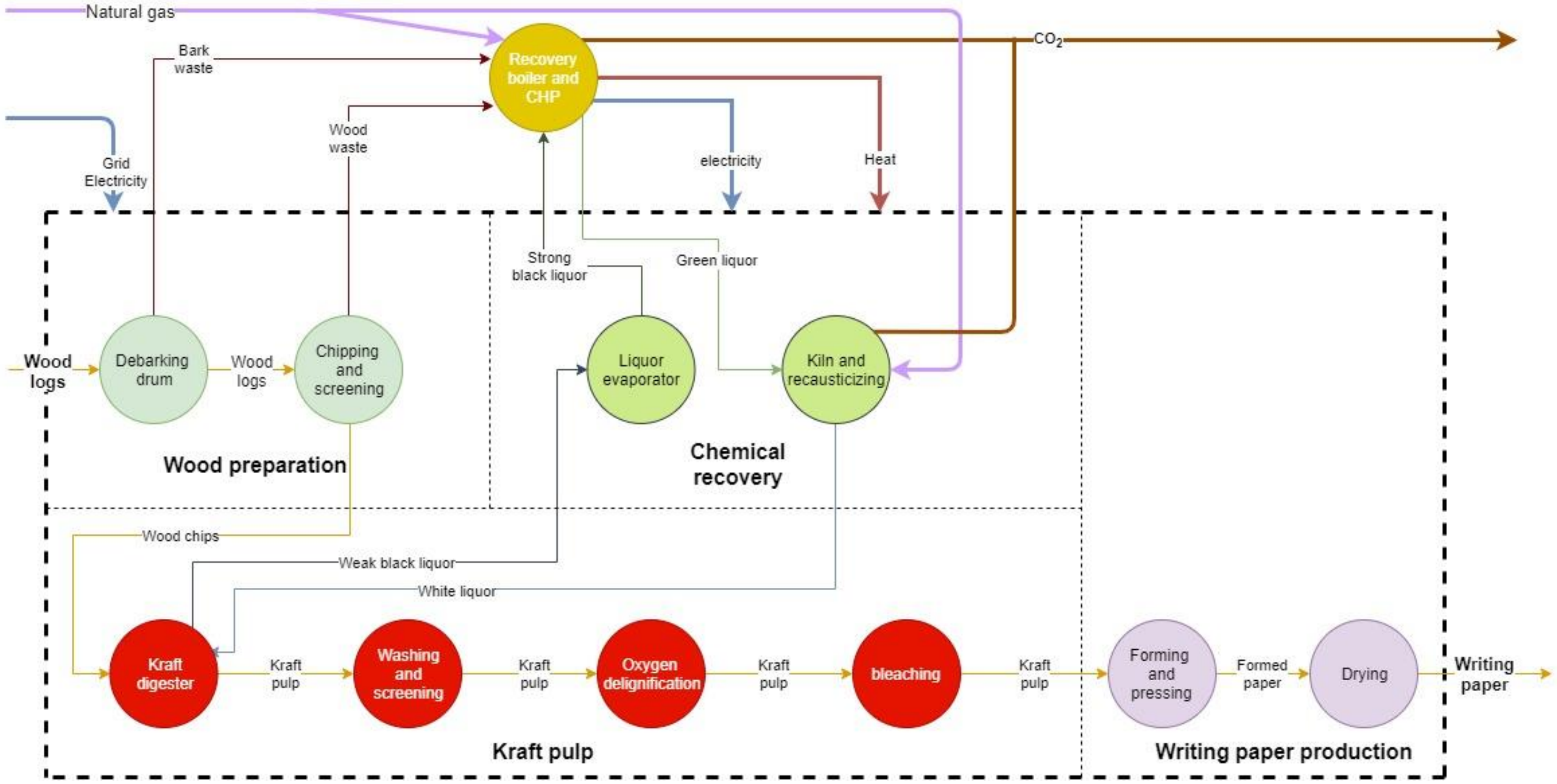

Figure A.1: Production scheme of writing paper (integrated).

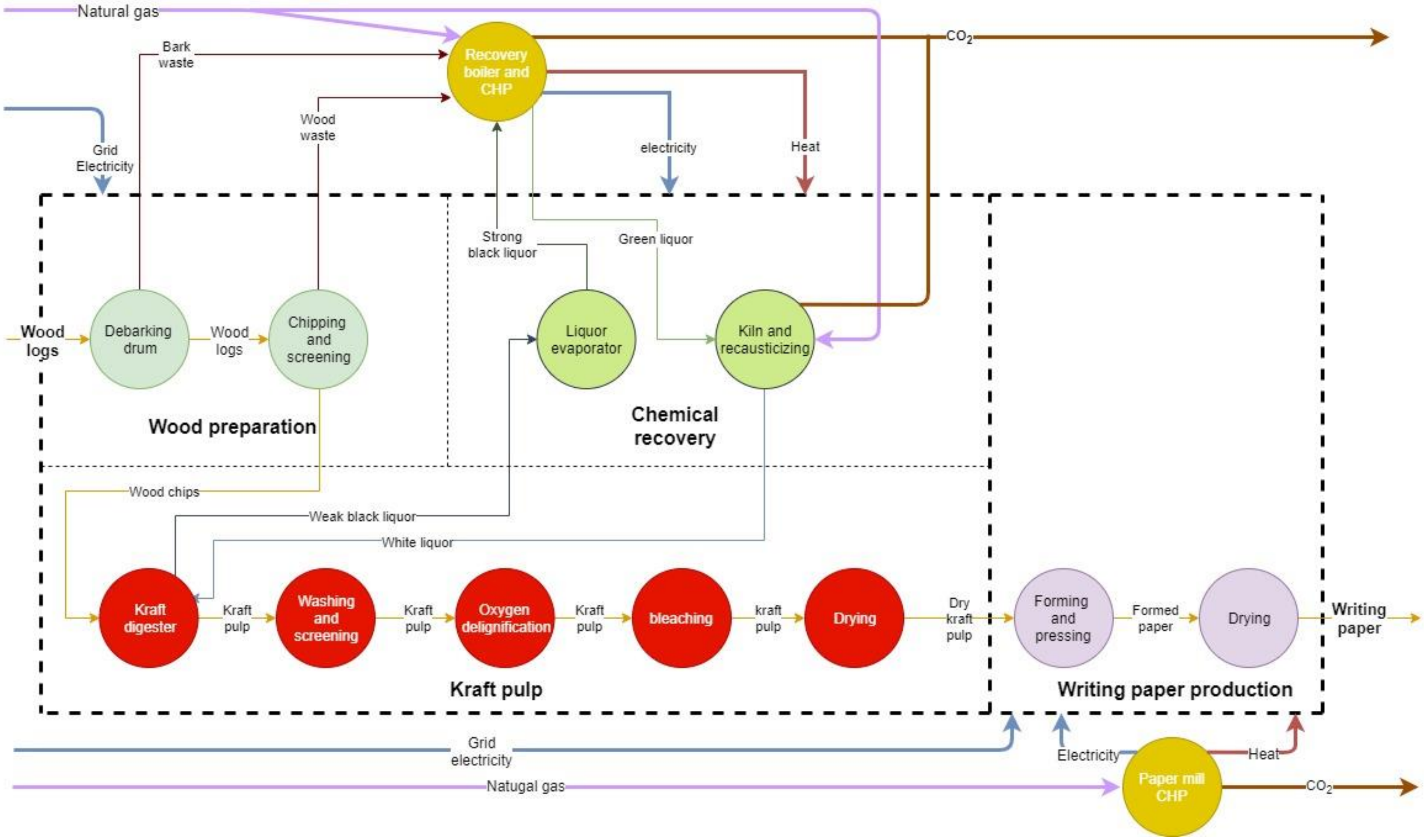

Figure A.2: Production scheme of writing paper (non-integrated).

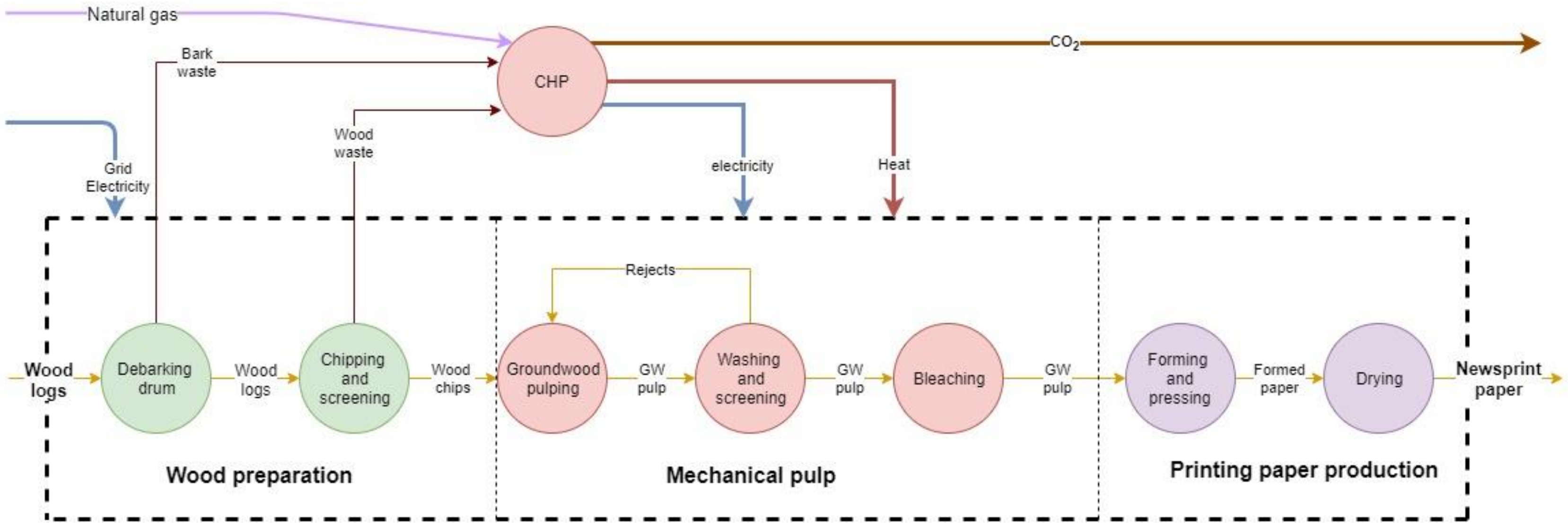

Figure A.3: Production scheme of printing paper.

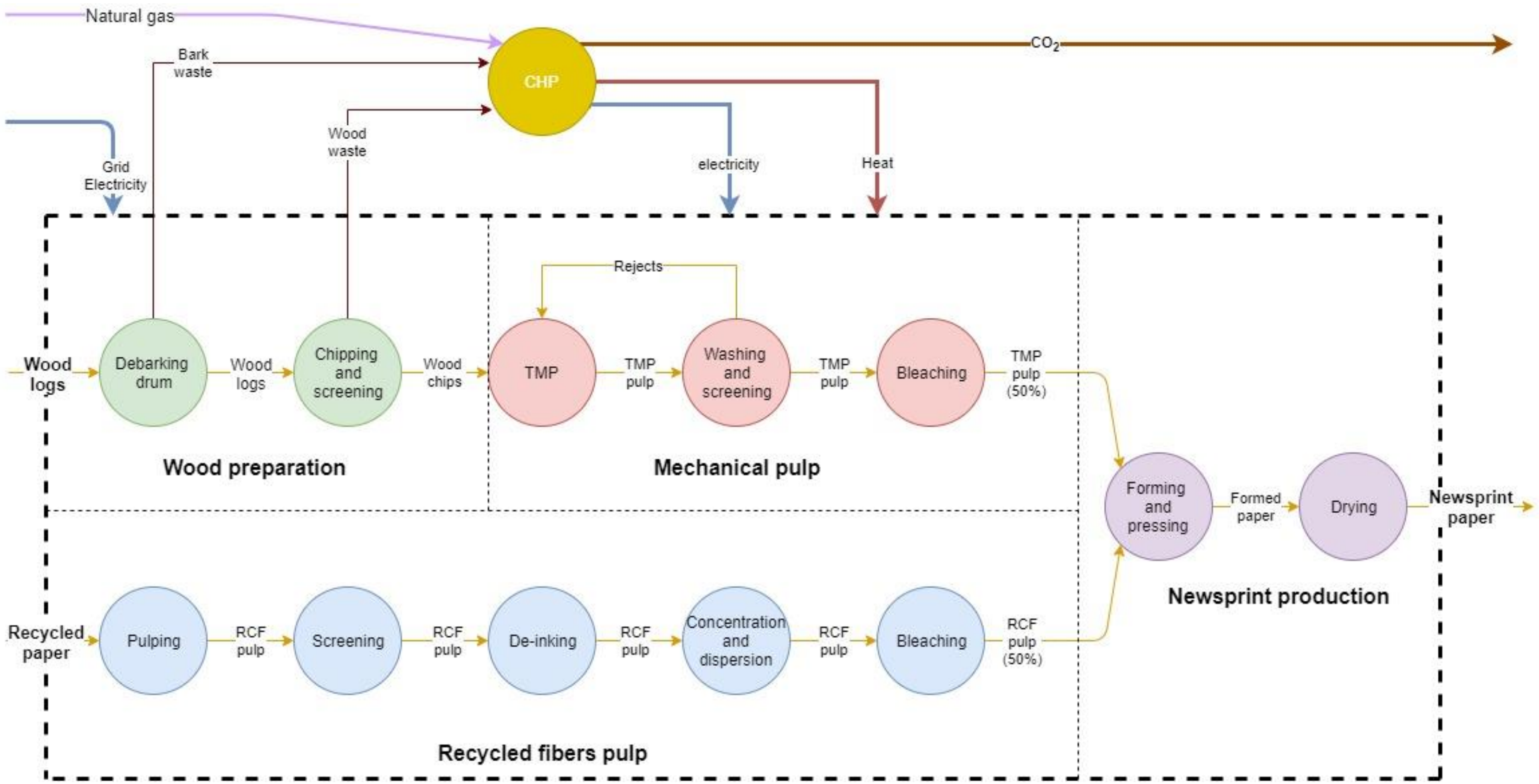

Figure A.4: Production scheme of newspaper.

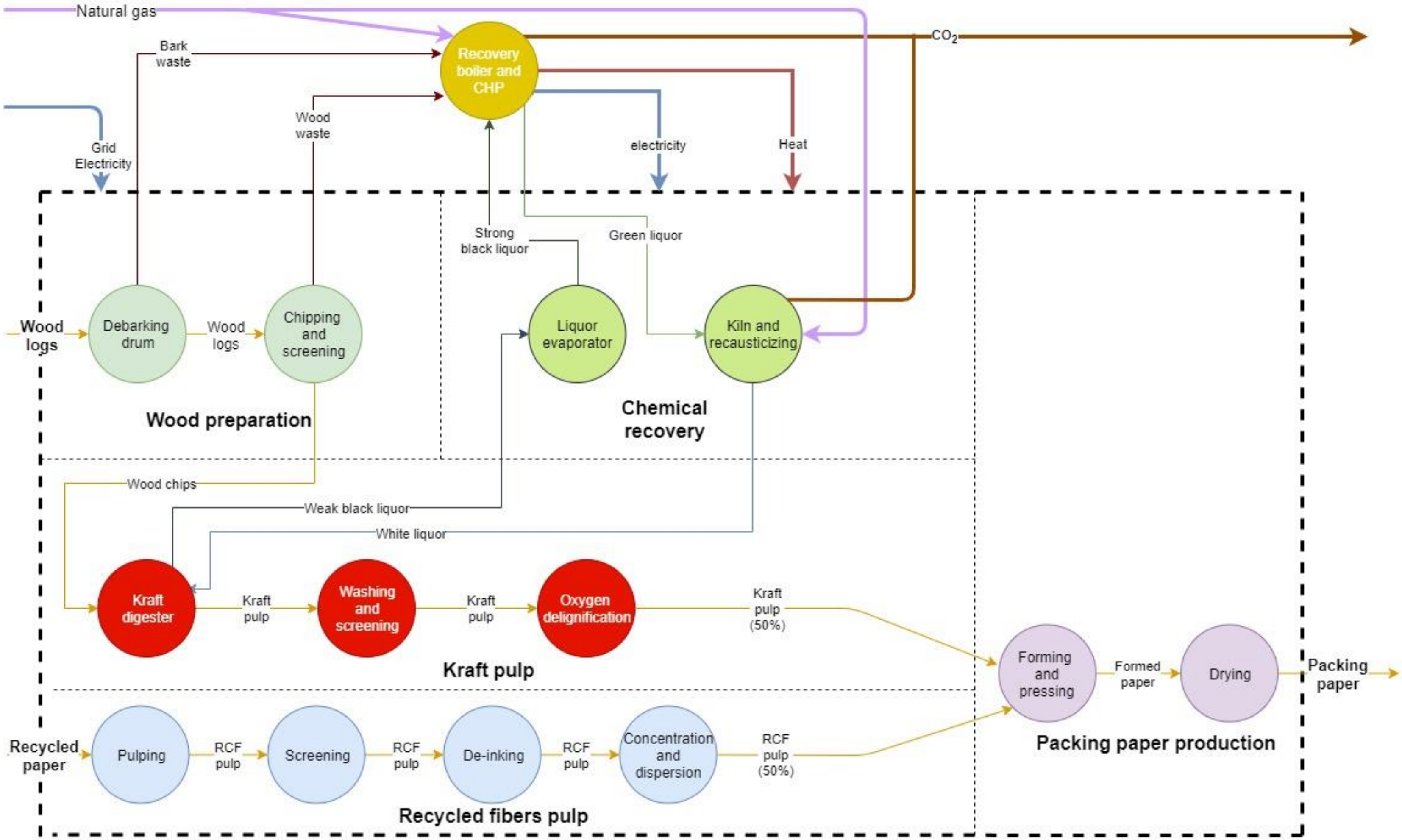

Figure A.5: Production scheme of packing paper.

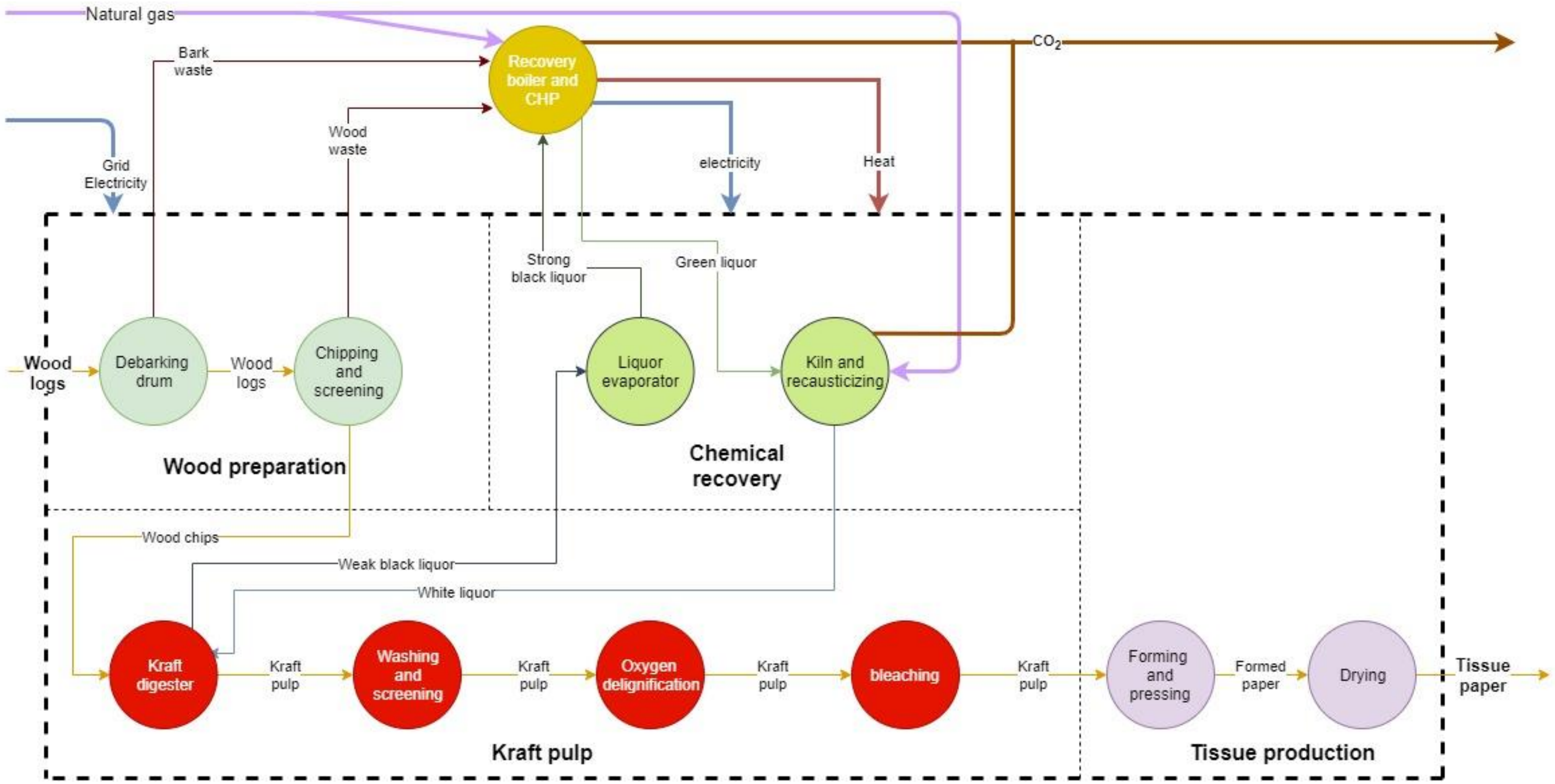

Figure A.6: Production scheme of tissue paper(kraft pulp).

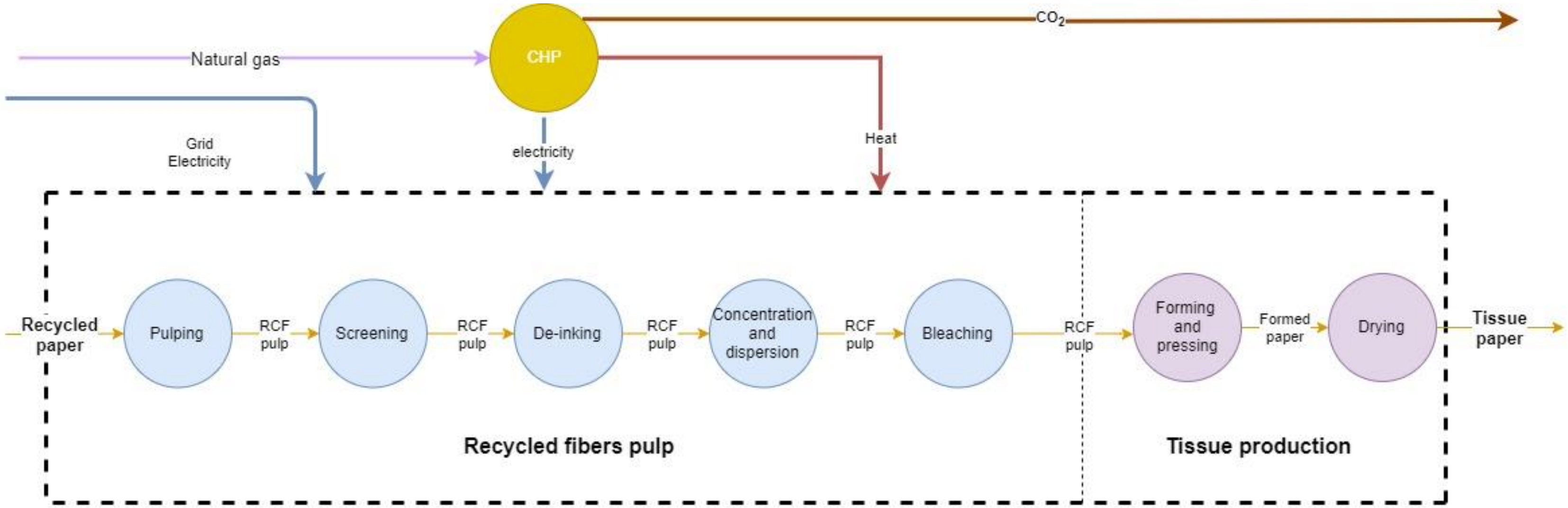

Figure A.7: Production scheme of tissue paper(RCF pulp).

B. Technology tables

Table B.1: Review of the state-of-the-art technologies studied

Process	Type of technology	Description	reference
Energy Production	biomass gasification	Wood waste used for gasification instead of combustion. The syngas is used for in a combined cycle gas turbine (CCGT)	[6, 67, 70, 86, 87]
	Biomass CHP	Energy revovery of waste biomass through a combined heat-and-power (CHP) cycle	[68]
	Economizers on steam boilers	Installing economisers on steam boilers can improve efficiency with 3-4%.	[68]
	black liquor gasification	Recovery of cooking chemicals made through black liquor gasification instead of combustion. The syngas is used for in a CCGT	[67, 86, 87]
	Biogas production from sludge	Use of the sludge from the water cycle to produce biogas, which can replace fossil fuels	[6]
Pretreatment Technologies	Biological pre-treatment	Biological pre-treatment is developed to decrease the energy consumption for mechanical pulping through modifying the cell wall of fibers and changing its external environment to enhance refining without jeopardizing pulp quality. The two common biological pre-treatment technologies used on wood chips in mechanical pulping are fungal and enzymatic.	[65, 67, 86]
Kraft Pulping	Modified cooking	The major principles of modified kraft cooking that distinguish it from conventional kraft cooking are: the split white liquor charge, prolonged delignification by using the washing zone for delignification and the use of counter-current cooking at the later part of the cook because it was thought at that time that the concentration of dissolved lignin and sodium ions in the liquor should be as low as possible, particularly in the final phase of the kraft cook. 6 different configurations: Modified continuous cooking (MCC), by Kamyr, Extended modified continuous cooking (EMCC) by Ahlstrom,, Isothermal modified continuous cooking (IMCC) and Black liquor impregnation (BLI), both by Kvaerner pulping, Lo solids by Ahlstrom/Andritz and Compact cooking (CC)	[66, 67]
	dry kraft pulping	chip pre-soaked then digested without further liquid being added	[67]
	Borate auto causticizing	sodium borate added to pulping liquor this takes part in a recausticizing reaction in the recovery boiler reducing the need for lime	[67]
	Steam cycle washing	steam is used rather than water to wash out the pulping chemicals from digestant	[67, 86]

Process	Type of technology	Description	reference
	LignoBoost	Part of the lignin (25-50%) is extracted from the black liquor by solving CO2 in it, lowering the pH which causes lignin to precipitate. Lignin is then purified. It can be after used as quality fuel or a useful product for other industries. (already installed in the US and Finland, not in Austria)	[65, 86]
RCF pulping	recycle paper fractionation	long and short fibres are separated before deinking allows removal of ink particles earlier in process (tested in the Andritz mill)	[67]
	Efficient screening	Improvements were made in the field of screening and filtering. Further optimization of the screening process shows energy savings, depending on the plant characteristics.	[64, 68]
	High consistency pulping	Pulping with lower water content, reducing energy consumption to circulation and pumping of pulp	[64, 68]
	Sludge dryer	Use waste heat to pre-dry sludge before burning to increase the calorific value of the sludge, thus replacing more fossil fuel.	[68]
	Surfactant spray deinking	surfactant spray added to deinking tower improves yield	[67]
	Pulsed Power Technology for Decontamination of Recycled Paper	A shock wave is propagated through the pulp, causing sticky contaminants to oxidize and become benign.	[86]
Paper Machine	Closed hood	A closed hood (instead of an open or semi-open one) over the paper machine allows more efficient heat use	[68]
	Heat recovery on close hoods	Heat recovery applied in a paper machine with a closed hood	[68]
	Transport membrane Condenser	Energy recovery system for the low temperature heat from the exhaust of the paper machine	[86]
	Increase dew point in hood from 55°C to 70°C	Increase of due point means lower energy for drying needed. It is made by increasing the air temperature while keeping no more than 40 % relative humidity.	[68, 88]
	State-of-the-art steam system:	Includes condensate system with stationary syphons and spoiler bars, with optimized differential pressures for condensate evacuation	[64, 68]
	Laser Ultrasonic Stiffness Sensor	Sensor to measure stiffness, allowing real-time control of production and more efficient use of materials	[86]
Forming	Infrared profiling	Moisture profiling of the paper before forming, in the headbox	[68]
	Steam box to increase sheet temperature and dryness	Steam box preheat the water used for forming the paper , improving dewatering efficiency and allowing higher dry contents to be attained in the press section	[64, 68]
	High consistency forming	Pulp enters the forming section with smaller water content (3% fibres). Suitable to low weight grades such as tissue.	[67, 68, 86]

Process	Type of technology	Description	reference
	dry sheet forming	use turbulent air in place of water as paper carrier, meaning that there is no water addition to the dry pulp, reducing energy for drying	[67, 68]
Press section	Extended nip press: tissue		[68]
	Hot pressing	Hot pressing increases water removal in the press section, reducing the heat needs in the drying section	[68]
	Improved dewatering in press section beyond shoe press		[68]
	Displacement Pressing	Combination of mechanical and air pressure, increasing solids content up to 60%	[86]
Drying	impulse drying of paper	blast paper with hot air during final press	[67]
	condebelt dryers	the paper is dried in a drying chamber by contact with a continuous hot steel band, heated by either steam or hot gas. Not suitable for high basis weight papers	[65, 67, 86]
	Infrared drying	The paper is pre-dried using infrared radiation, produced electrically or by burning NG. Is suitable for drying coated grades	[66]
	Air impingement drying	Effective drying is achieved by blowing hot, high-velocity air onto the sheet and circulating the air back to the dryer.	[66]
	Waste heat recovery and heat integration		[64, 68]

Table B.2: Review of the future technologies studied

Process	Type of technology	Description	reference
Pretreatment Technologies	Microwave pre-treatment	Microwave pre-treatment technology alters the cellular microstructures that control permeability in wood so that the pulping chemicals can pass more easily to the centre of the chips, which reduces both the amount of energy and chemicals needed for the pulping process	[65, 67, 86]
	Chemical pre-treatment with oxalic acid	Chemical pre-treatment mainly uses oxalic acid (OA), acid leaching, and electrochemically treated salt solutions to enhance the refining efficiency in mechanical pulping. Improves paper strength and reduces resign content.	[65, 67, 86]
	Hemicellulose extraction before chemical pulping	Extraction of hemicellulose before pulping increases the heating value of the black liquor, decreases alkali consumption and improves the efficiency of the mill. It can be done by simply solve the hemicellulose in water	[86]

Process	Type of technology	Description	reference
P&P Production	100% electricity	Evolution towards green electricity will reduce fossil fuels consumption; reduction of energy cost in the total cost by 12%.	[69]
	Toolbox	Combination of innovations, e.g. enzymatic pulp treatment, shear compression, energy efficient thermo-mechanical pulping, sophisticated biomass fractionation into lignin, cellulose and hemicellulose, biomass separation into molecules	[69]
Steam Production	Direct electric heating	Steam can also be raised using direct electric heating. This is not much different from an electric kettle, just operating on a much larger scale and at higher temperatures and pressures	[6]
	Hydrogen Combustion	The industry could buy hydrogen and burn that instead of gas. Currently most hydrogen is produced from methane, so in the short term it is likely more expensive and not reducing CO2 emissions. It just shifts the problem to the hydrogen supplier. If there is a possible in place to create sustainable hydrogen, this is a viable alternative	[6]
	Electrolysis	Rather than buying hydrogen, companies could generate hydrogen on-site using electrolysis and then burn the hydrogen to generate the desired temperature	[6]
	Heat pump recovering waste heat	Heat from the environment or a reservoir is raised to a higher temperature level using electricity.	[6]
	Dual-pressure Reheat Recovery Boiler	Dual pressure recovery boiler is designed as a combination of a classic recovery boiler and a classic subcritical utility. It allows pulp mills to take advantage of the power generation potential of the high pressure reheat cycle on a recovery boiler.	[65, 86]
	Carbon capture and storage	Maybe applied through pre-combustion (associated with Black liquor gasification), post-combustion (which is the easier technology) or oxy-combustion technologies	[62, 76, 87]
Pulp Production	Deep eutectic solvents (DES)	DES opens the way to produce pulp at low temperatures and at atmospheric pressure. Any type of biomass could be dissolved into lignin, cellulose and hemicellulose with minimal energy and emissions	[69]
	Utilization of green liquor	Pre- Cooking of wood in green liquor (20-30% of the green liquor), without the reaction with lime, reducing energy consumption, lime kiln load, increasing pulp yield and bleachability.	[67, 86]
	membrane concentration of black liquor	Partial replacement of the evaporation of black liquor by membrane concentration, reducing the thermal energy needed	[67, 86]
Paper Production	Functional surface	Shift to producing more lightweight products; selling surface instead of weight (up to 30% material reduction per surface unit).	[69]

Process	Type of technology	Description	reference
	New fibrous fillers	Wood fibres are partially replaced by the fibrous fillers (based on calcium and silica). improve pressing reduces dryer load. limited by strength issue	[67, 68]
Forming	Flash Condensing with Steam	Process: largely dry fibers are blasted into a forming zone with agitated steam and condensed into a web using one-thousandth the volume of water used today.	[69]
	Aq-vane	Used in the formation of multi-layer paper and paperboard, to separate the different layers, usually separated by vanes or lamellas. This technology entails injecting a thin passive liquid layer (a liquid vane or Aq-vane) in the headbox through a narrow hollow channel between neighboring pulp streams, which prevents mixing between the layers	[65]
	Dry pulp for cure-formed paper	Waterless paper production by means of two techniques: dry pulp and cure-forming.	[69]
Press Section	Displacement pressing	This technology combines mechanical and air pressure, pressing web lightly while forcing air through it and using special pressing fabrics with a special four-roll Beck cluster press (BCP). BCP provides a pressurized atmosphere that acts on the moving web and fabric. Maximum dry content of 60%	[65]
Drying	Supercritical CO2	To dry P&P without the need for heat or steam and even dye paper or remove contaminants	[69]
	Superheated steam drying	Use superheated steam for drying and use it afterwards as fiber carrier and for forming paper.	[69]
	gas-fired dryers	Dryers are heated with hot gases from gas combustion (that may happen inside the drum) instead of steam. 75% energy efficiency compared to 65% of the usual system	[65, 66, 86]
	Boost dryer	Dryers cylinder at 6 to 12 bars above atmospheric pressure. After leaving the pressurized hood, the water condenses One boost dryer can replace several conventional dryers. Suitable for board and packing paper. Reduces space need	[65, 67, 86]
	Microwave Dying	Paper is dried by exposure to microwave radiation. Suitable for high basis weight paper	[65, 67, 86]

C. Review of previous scenarios

Table C.1: Review of scenarios for individual countries or Europe identified from the literature.

Name of Scenario	CO2 emission and price and energy consumption in base year	CO2 emission and price and energy consumption in 2030	CO2 emission and price and energy consumption in 2050	Technology assumption	AGR PP To 2050	Region and Reference
Business as usual diffusion	n.a.	2020 2% Elec savings 4% fuel savings 2030 4% elec savings 8% fuel savings	n.a	The BAU scenario assumes that barriers to technology diffusion remain high in the future and represents an extrapolation of past trends. The exogenous technology diffusion rates are based on the past development as well as on discussions with paper industry representatives. These diffusion rates are typically lower than they would be in case firms decided purely on the basis of cost-effectiveness Techonologies applied**: Black liquor gasification**, Heat recovery (TMP, GW), High efficiency GW, Enzymatic pretreatment of MP, Efficient refiner and pretreatment of MP, high consistency pulping, efficient screening, heat recovery from bleaching, De-inking flotation optimization, efficient dispersers, **Efficient refiners (paper**), optimization of refining**, chemical modification of fibers**, steam box, **shoe press**, **new drying techniques**, **heat recovery from paper machine**		Germany [64]

Cost-effective diffusion			2020 4% Elec savings 11% fuel savings 2030 13% elec savings 15% fuel savings	n.a	The cost-effective diffusion scenario assumes homo economicus behavior and the implementation of all cost-effective technologies. Cost-effectiveness is assessed on the basis of the investments annuity, using a discount rate of 15%. It implies the removal of all non-financial barriers. If the technology is calculated to be cost-effective, the exogenous diffusion path from the technical scenario is considered. In case it is not cost-effective, the diffusion path from the BAU scenario is assumed.		
Technical diffusion			2020 6% Elec savings 12% fuel savings 2030 16% elec savings 21% fuel savings	n.a	It does not include cost considerations for the diffusion of technologies. No premature stock replacement is allowed and thus the diffusion can still be considered "realistic", although ambitious. Given the long lifetime of certain processes, it can take a long time for the full saving potential to be realized, even in the technical scenario. The scenario may therefore be termed a "realistic" technical diffusion scenario as it does not include completely unrealistic technology options and diffusion paths.		
Current trends Scenario Gridd: 2030 - 100g CO2/kWh 2050 – 26g CO2/kWh	BAU pathway	Base year: 2012 CO2: 3,3 Mt CO2: 0,72 t/t paper	About 38 % CO_2 reduction CO2: 0,4464 t/t of paper	34% CO_2 reduction CO2: 0,4752 t/t paper	Current SAT were the only technologies deployed starting in 2015 with most of them deployed to 100% by 2030 (8% Energy management, 20% improved process control, 9% waste heat recovery and heat integration, 6% SAT steam system for PM, 12 % extended nip press, 6% Focus on maintenance)	1%	United Kingdom [62]
	20-40% Pathway		n.a.	n.a.	(Not developed since BAU achieves a reduction of over 20%)	1%	

	40-60% Pathway	n.a.	74 % CO$_2$ reduction	SAT have been deployed in the same way as in the BAU pathway, starting in 2015 with most of them deployed to 100% by 2030. 75% deployment off major investment tech. Biomass CHP is applied to 25% of the sector by 2025 (24% Heat recovery on hoods future, 23% Biomass-based CHP or boiler, 10% Improved process control, 5% Impulse drying, 4% waste heat recovery an 4% energy management)	1%
	Max Tech Pathway 1	About 60% CO$_2$ reduction	97,5% CO$_2$ reduction	Scenario of electrification of the industry. Same as 40-60%, with 100 % electricity applied to 25% of the sector by 2050, starting in 2045. Industrial clustering and heat network applied to 75% of the sector by 2050 and start in 2020. (26% Industrial clustering and heat networking, 20% 100% electricity, 15% heat recovery from hoods future, 7% Improved process control, 3% Impulse drying, 3% Waste heat recovery integration)	1%
	Max Tech Pathway 2	About 65% CO$_2$ reduction	98% CO$_2$ reduction	Scenario based on the replacement of fossil fuels with biomass-based CHP, begging in 2020 and reaching 100% in 2050. Remaining technologies have the same pattern as in 40-60% reduction. (54% Biomass-based CHP or boiler, 13% Heat recovery on hoods future, 6% Improved process control,3% impulse drying and 3% waste heat recovery and heat integration)	1%
Challeging World Scenario Gridd:	BAU pathway	About 38% CO$_2$ reduction CO2: 0,4464 t/t of paper	56% CO$_2$ reduction CO2: 0,3168 t/t of paper	Same technologies as in Current trends, with lower adoption rate. The options reach full deployment between 2040 and 2050	-0,5%

2030 - 200g CO2/kWh 2050 – 150g CO2/kWh	20-40% Pathway	n.a.	n.a	(Not developed since BAU achieves a reduction of over 20%)	-0,5%
	40-60% Pathway	n.a.	n.a.	(Not developed since BAU achieves a reduction of over 40%)	-0,5%
	Max Tech Pathway 1	About 40 % CO_2 reduction	69% CO_2 reduction	Similar to current trends scenario, but 100% electrification is not deployed, industrial clustering and heat networking is only deployed to 25% of the industry and future process of heat recovery from hoods to 50% of the industry in 2050. Improved process control and waste heat recovery are only fully deployed after 2040 and impulse drying only after -2050.	-0,5%
	Max Tech Pathway 2	About 55% CO_2 reduction	85% CO_2 reduction	Similair to current trends, but most technologies deployment starts in 2020 and is completed between 2040 and 2050. Biomass availability reduces biomass CHP deployment to 50% in 2050	-0,5%
Collaborative Growth Scenario Gridd:	BAU pathway	About 32% CO_2 reduction	5% CO_2 increase	Same technologies as in Current trends, with the same adoption rate.	2%
2030 - 50g CO2/kWh 2050 – 25g CO2/kWh	20-40% Pathway	n.a.	18% CO_2 reduction	Higher rate of investment in SAT.	2%

40-60% Pathway		n.a.	41% CO_2 reduction	all options included under the current trends scenario were deployed at the same rate as in the current trends scenario, except biomass CHP. Biomass CHP is assumed to reach a 50% deployment by 2050 compared to 25% for the current trends scenario.	2%	
Max Tech Pathway 1		About 60% CO_2 reduction	96% CO_2 reduction	Similar to current trends scenario	2%	
Max Tech Pathway 2		About 65% CO_2 reduction	97% CO_2 reduction	Similar to current trends Scenario	2%	
IMAGE: 2 Degrees	Base year: 2010	n.a.	~5 MT CO2/y emissions	Climate targets are achieved by exponentially increasing carbon taxing. Fossil fuels are phased-out by 2030 (except natural gas, with a fixed share of about 10% after 2035). In Europe, Electrification starts after 2040 and has over 25% of the energy share in 2050 (assuming use of heat pumps and electric steam boilers). Modern Biofuels under 75%	Mechanical and chemical pulp: 0.75%. Constant paper production up to 2040, after which decrease (except printing and writing)	European Union [89]
IMAGE: 1.5 Degrees		n.a.	Carbon sink: ~ -280 MT CO2/y	Climate targets are achieved by exponentially increasing carbon taxing. Fossil fuels are phased-out by 2030. In Europe, Electrification starts after 2040 and has slightly less than 25% of the energy share in 2050 2050 (assuming use of heat pumps and electric steam		

				boilers). Modern Biofuels above 75%. Strong Implementation of CCS after 2020		
WISEE: CCS		n.a.	Carbon sink: ~ -25 MT CO2/y	Existing assets, largely equipped with carbon capture technology - black liquor gasification and electricity and steam generation through a syngas combined cycle with CCS, implemented after 2030. Biomass replaces fossil fuels CCS not applied in all sites as it may not be economically feasible.		
WISEE: Circular Scenario		n.a.	0 emissions	Circularity is the core strategy, implemented by electrification. Strong relation with other sectors. Steam generated through electricity from renewable sources with application of electric boilers and heat pumps. Black liquor used in biorefinerie on-site (chemicals recovered to the process)		
Baseline Scenario	Base year: 2015 Energy consumed: ~1630 PJ CO_2 emissions: ~37 Mt	Without technological improvements Energy consumed: ~1550 PJ (4,9 % reduction) CO2 emissions:~34 Mt (8% reduction) With technological improvements	Without technological improvements 1,1% energy increase 4,8% CO_2 increase With technological improvements 14,4% energy reduction	The baseline scenario uses the trends of energy, resources and demand up to 2050. CO_2 prices change from 7,2 EUR/t to 87,6 EUR/t Technology is applied according to cost-effectiveness criteria. CCS and new drying technologies are not applied because they are not cost-effective.	0,21% (7,6% in total)	European Union [62]

	Energy consumed: ~1420 PJ (12,9 % reduction) CO2 emissions:~17 Mt (54% reduction) With tech improvements and biorefineries Energy consumed: ~1640 (1,1% increase) CO2 emissions:~18 Mt (47% reduction)	62,6% CO_2 decrease With tech improvements and biorefineries 3,3% energy increase 59,5% CO_2 reduction	
CO2x2	Energy consumption ~1420 PJ (12,8% reduction) CO_2 emissions ~17 Mt (54% reduction)	Energy consumption ~1400 PJ (14,1% reduction) CO_2 emissions ~15 Mt (60% reduction)	Same assumptions as baseline, but with the additional assumption of double CO_2 allowance price. Technology is applied according to cost-effectiveness criteria. CCS not applied because it is not cost-effective.
MWhx2	Energy consumption ~1420 PJ (12,8% reduction) CO_2 emissions ~17 Mt (54% reduction)	Energy consumption ~1440 PJ (12% reduction) CO_2 emissions ~15 Mt (60% reduction)	Same assumptions as baseline, but with the additional assumption of double electricity price. Technology is applied according to cost-effectiveness criteria. CCS not applied because it is not cost-effective. Black liquor gasification implementation rate doubles compared with baseline.

FuelsX2	Energy consumption ~1420 PJ (12,8% reduction) CO_2 emissions ~17 Mt (54% reduction)	Energy consumption ~1440 PJ (12% reduction) CO_2 emissions ~15 Mt (60% reduction)	Same assumptions as baseline, but with the additional assumption of double fuels price. Technology is applied according to cost-effectiveness criteria. CCS and new drying technologies are not applied because they are not cost-effective, except drying infrared moisture profile, which is adopted even so in 12 mills.
CO_2x2 with CCSneg	Energy consumption ~1420 PJ (12,8% reduction) CO_2 emissions ~17 Mt (54% reduction)	Energy consumption ~1600 PJ (no reduction) CO_2 absortion ~4Mt (111% reduction)	Same assumptions as CO_2x2, but with the additional assumption of rewarding the bio-CO2 captured on the deployment of CCS. Technology is applied according to cost-effectiveness criteria. CCS is cost-effective after 2035, and applied to the recovery boiler and power boiler (not contemplated in the usual CCS). New drying technologies are not applied because they are not cost-effective, except drying infrared moisture profile, which is adopted even so in 2 mills.