Pulp and paper industry
Decarbonization technologies to reach the neutral emissions in 2050

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Abstract
Pulp and paper (P&P) production is among the major industrial sectors in Europe and for that reason one which has to reduce its greenhouse gas (GHG) emissions. 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

1. Introduction
With the European targets on greenhouse gas (GHG) emissions reduction to 2050 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 1,8 Mton of CO_2 emissions per year in Austria. 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.

2. Literature review

2.1. The paper and pulp 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.

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;

Paper has been produced in Austria for many centuries. It is for long established as one of the industrial products of the country. Nowadays, the P&P industry is composed of 23 mills. In 2017, it contributed to 0,89% of Austria's GDP [1, 2]

There are 5 types of pulp produced in Austria: 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. Production of mechanical pulp is decreasing in the past years, whereas the textile and non-deinked pulp productions have 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 pulp produced [3].

Several life cycle assessment (LCA) studies about paper (studies about the impact of paper products "from cradle to grave") conclude that, among the different life stages of paper, the production stage is the one with the highest global warming potential (between 49% and 84% of the total life cycle potential) [4–6]. This is due to the use of fossil fuels as a way of providing the high heat needs to produce pulp and drying of paper. 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.

In 2018, 5,06 Mton of paper products were produced in Austria, with close shares of printing and writing paper and packing paper and board (47,4% and 46,3%, respectively) and a small share of tissue and other products (6,3%) [3].

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 [3], out of 18639 GWh of fuels, the industry was self-sufficient in terms of heat consumption and produced 67% of the electricity consumed. Most of the 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).

There was a general decreasing trend in direct fossil-CO_2 emissions (from fossil fuels used at the mills) from 2000 to 2018. n 2018, the direct emissions were of 1727 kton of CO_2 [3]. Indirect fossil-CO_2 emissions from the consumption of grid electricity were estimated to be 74,7 kton of CO_2.

Biofuels, which are the major source of energy for the P&P industry, are considered to be carbon neutral. It is important to understand what this means exactly. 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. For that reason, biofuels are considered to be "carbon neutral" in the context of the industry.

Bio-CO_2 is a part of a fast carbon cycle, it is emitted after the wood is harvested and re-absorbed when new trees grow. A growing forest is a carbon sink (or carbon pool) whereas deforestation and recently harvested areas represent a carbon source. This means that forest growth (or decrease) is a measure of the carbon absorbed from the atmosphere. The P&P industry is a major consumer of wood, and so it influences directly forests stocks. 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. This is due to good foresting practices regulated by management certificates. The P&P industry uses wood from certified forests. 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%) [7].

2.2. P&P 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 paper can be separated from the production of pulp in non-integrated mills, producing just one or the other. 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;

Wood arrives at the mill in the form of long raw logs (with bark), in the woodyard. The main processes involved in wood preparation are debarking the wood logs (in a drum debarker), wood chipping (which reduces the wood logs to small chips) and screening to ensure the wood chips have the correct size to be digested. These processes are powered by electrical energy and are not very energy-intensive.

The processes involved in the production of pulp change according to the type of pulp produced. Wood is mostly composed of fibers, joined by lignin. The fibers are the main component of paper, whereas high lignin content tends to weaken the paper. The first step of pulp production is always pulping:

- To produce chemical pulp, pulping is made by digesting the wood chips for several hours in pressurized hot water vessels (digester) with the addition of chemical components that dissolve the lignin. There are two types of chemical pulp: kraft, digested in a basic pH solution, which preserves fiber strength, producing strong paper with 45-55% yield, and sulfite, digested in an acid pH solution, producing weaker but whiter pulp, with 40-50% yield. Kraft is the most common pulping process, in Austria and in the World. Due to the need for heating and pressurizing the digester, chemical pulping is an energy-intensive process, consuming both electricity and heat. After the chemical cooking process, the pulp must be separated from the cooking liquor, now called black liquor. The liquor is firstly evaporated and then burned in a recovery boiler, producing high-pressure steam, from which the pulping chemicals are also recovered;
- Mechanical pulping processes separate the fibers from each other by mechanical means, retaining part of the lignin in the paper and increasing the yield to values around 90%. There are several processes. Wood is usually grinded with conditions of pressure and temperature which vary according to the process used. Mechanical pulping processes are energy-intensive, mostly in the form of electricity, but some also consume steam;
- 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. Recycled fiber pulp is also subjected to mechanical removal of impurities;

After pulping, the pulp is washed to remove the impurities. In the case of chemical pulping, this is a step in which the pulp is separated from the cooking liquor. After, the screening step takes place, to remove the remaining wood pieces from the pulp, which were not properly pulped. Washing and screening are electrical processes, not energy-intensive.

The final step of pulp production is bleaching. The purpose of this process is to give white color to the pulp. Iis not fundamental and is only applied to paper grades that require good optical characteristics– graphic paper, tissue, whiteboard, etc. If the pulp is sold to the market, an extra step of drying is required, which is very energy-intensive.

Paper is produced in a continuous Fourdrinier machine, which consists of three main sections: forming, where the pulp is introduced with a fiber content of about 0.5%-1% [8] and the paper sheet is formed; pressing, where the formed paper enters with about 20% fiber content [8] and water is removed by pressure, passing the paper net supported by felts between sets of two rolls and; drying, where paper enters with a fiber content of about 50% [9], which is increased up to 90-95% [9] by running the paper web through several steam-heated cylinders. Drying of paper is the most energy-intensive process in paper production.

2.3. Future scenarios for the P&P industry

It is expected that countries in development will rapidly increase consumption, namely in Asia and South America, whereas developed countries, in Europe and North America, will have a steadier profile. 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 Business as Usual 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% [10]. The increase of 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%).

Technology development is obviously among the most determinant factors when it comes to CO_2 emissions. Without updates in technology, Moya and Pavel [11] 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.

Fleiter et al [12] 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.

The study 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 [13] and investigate the potential to mitigate emissions by the use of selected technologies.

2.4. 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. A total of 37 of the best available technologies and 25 innovation technologies with the potential to reduce energy consumption and/or carbon emissions were identified from the literature. The individual impact of 7 of those technologies was assessed in the thesis. The technologies chosen are not yet used in Austria and are mostly in the R&D phase. They either reduce the energy consumed at pulping or at drying of paper (two of the most energy-consuming steps of P&P production) or decarbonize the steam supply by replacing fossil fuels.

The chosen technologies, organized according to the described categories, were [14–22]:

Pulp production

- Direct green liquor utilization (DGLU)
- Steam cycle washing (SCW)

Paper production

- Impulse drying (ID)
- Condebelt drying (CD)
- Gas-fired dryers (GFD)
- Dry sheet forming (DSF)

Decarbonization of steam supply

- Direct electric heating (DEH)

3. Methodology

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 pulp and paper production.

The model was developed in a linear bottom-up approach. Firstly, literature research was made to understand the steps of the production process in detail and determine the specific energy (electricity and heat) consumption of each step. The specific energy consumption of each step is presented in Table 1 [12, 15, 23–25]. The specific consumptions shown are relative to the output of each process.

Table 1: Specific electricity and heat consumption of the individual processes in pulp and paper production

	Process	Sp. Elect. (kWh/t)	Sp. heat (kWh/t)
Wood prep.	Debarking	8,5	0
	Chipping & conveying	30,3	0
Chemical	Kraft Digester	40	472,2
	Sulfite Digester[1]	572	1166,7
	Washing & Screening	30	0
	Oxygen Delignification[2]	75	138,9

	Bleaching	100	638,9
	Pulp Drying[3]	155	1250,0
Chem. recov.	Liquor evaporators	30	861,1
	Kiln and Recausticizing[4]	50	333/311
	Power plant	60	638,9
	Energy Production	1620	6166,7
Mech. Pulp	Groundwood Pulp	1650	0
	Refiner-Mechanical Pulp	1972	0
	Thermomechanical Pulp	2041	250
	Washing & Screening	50	0
	Bleaching	100	0
RCF pulp	Recycled Fibers pulp	392	0
	Screening	50	0
	De-inking	80	0
	Concentration & dispersion	40	150
	Bleaching	30	0
Newsprint	Forming & Pressing	422,0	0
	Drying	29,31	1192,1
Printing	Forming & Pressing	527,5	0,0
	Drying	29,3	1524,0
Writing	Forming & Pressing	527,5	0
	Drying	29,31	1465,4
Tissu	Forming & Pressing	533,4	0
	Drying	131,88	2198,0
Packing	Forming & Pressing	269,6	0,0
	Drying	14,7	1172,3

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 (integrated or non-integrated production, type of pulp used and RCF content), 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 pulp and paper. 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 pulp and paper separately (instead of pulp produced to sustain the production of paper).

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).

The model was also used to create scenarios for the paper industry in Austria until 2050, based on paper consumption predictions for Europe [13], simulating the introduction of each of these technologies. For each technology, a deployment level was assumed and compared with 100% deployment. More expensive and complex technologies have a lower deployment, whereas technologies with lower costs and simple installation have higher expected deployment. The only technology with 100% expected deployment is direct green liquor utilization.

4. Results

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 CO_2 emitted by 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 innovation technologies chosen is presented.

Figure 1: Specific final energy consumption and CO2 emission of the paper grades studied, including bio-CO2.Figure 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 and bio-CO_2. 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. However, the total emission of CO_2 is much higher when using virgin pulp than RCF pulp, since it depends on the total heat produced.

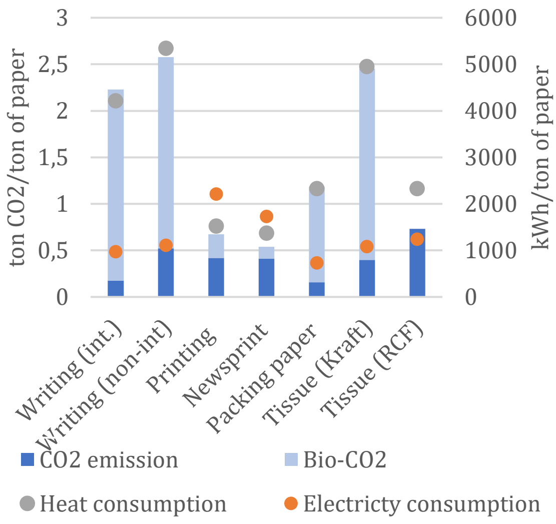

Figure 1: Specific final energy consumption and CO2 emission of the paper grades studied, including bio-CO2.

Figure 2 shows the direct fossil-CO_2 emissions reported by Austropapier [3] and the estimation from the model. The general trend 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, due to underestimation o of the heat used by the industry. After 2009 the results generally overestimate CO_2 emissions. This is due to lower individual process consumption than the values used (that best represent the industry in the years 2008 to 2010). The updates after that point are not accounted for in the model. Nevertheless, the results 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 benefits of implementing future technologies.

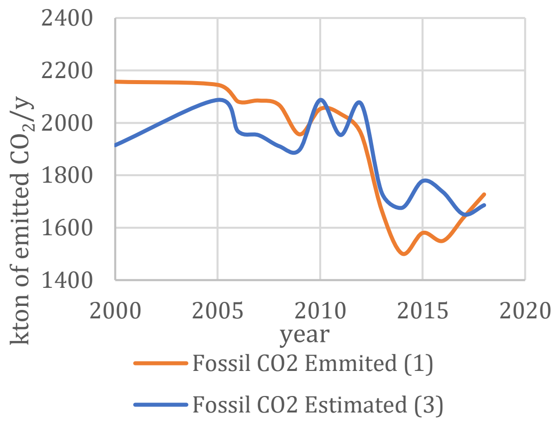

Figure 2: Direct fossil-CO2 emissions from 2000 to 2018

Table 2 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. The chosen technologies have the potential to reduce the specific fossil-CO_2 emissions from 18,5% to 80,7%.

Table 2: Summary of the impacts resulting from the deployment of future technologies to the considered paper grades (W – writing paper, T – tissue)

Tech.	Paper grade	Sp. heat	Sp. elect.	Sp. fossil-CO₂
DGLU	W. (int)	- 2,52%	- 0,92%	- 18,5%
SCW	W. (int)	- 5,21%	- 2,82%	- 38,3%
ID	W. (int)	- 6,29%		- 51,0%
CD	W. (int)	- 6,94%	- 1,51%	- 51,0%
GFD	W.(n-int)	- 4,11%	- 0,4%	- 26,0%
DSF	T.	- 22,2%		- 80,7%
DEH	W.(int)			- 42,9%

Table 3 summarizes the impacts of the deployment of each technology except direct electric heating in the year 2050. The percentages values indicate the change in comparison to the values in the base year (2015). Since direct electric heating does not change the energy consumption but the way steam is produced, its impacts are presented in

Table 4.

Table 3: Summary of the impacts in 2050 resulting from the deployment of future technologies (except direct electric heating) in Austria.

Reference values	Heat (kWh)	Elect. (kWh)	Fossil-CO_2 (kton)
2015	12085	5043	1876
Scenario	**Heat**	**Elect.**	**Fossil- CO_2**
BAU	+18,4%	+9,7%	+0,7%
DGLU(100%)	+17,7%	+9,5%	-0,7%

SCW (40%)	+17,5%	+9,5%	-0,7%
SCW (100%)	+16,3%	+9,1%	-1,0%
ID (75%)	+9,2%	BAU	-6,6%
ID (100%)	+6,1%	BAU	-9,1%
CD (15%)	+16,6%	+9,5%	-0,7%
CD (100%)	+6,1%	+8,1%	-9,1%
GFD (50%)	+13,8%	+9,5%	-2,9%
GFD (100%)	+9,2%	+9,3%	-6,7%
DSF (20%)	+17,8%	BAU	+0,3%
DSF (100%)	+5,3%	BAU	-1,8%

Table 4: Impacts in 2050 resulting from the deployment of direct electric heating in Austria

Reference values	Fuels (kWh)	Grid (kWh)	Fossil-CO_2 (kton)
2015	15478	2090	1876
Scenario	**Fuels**	**Grid**	**Fossil- CO_2**
DEH(50%)	+2,5%	+193,6%	-35,9%
DEH(100%)	-23,8%	+381,7%	-73,5%

5. Discussion of results

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.

The technologies can be divided according to the potential for reduction of CO_2 emissions in 2050:

- 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 [12] 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.

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. Namely the increase of heat recovery and process control, the implementation of gasification together of black liquor together with carbon capture and storage and use of its products as raw materials for biorefinery. Some technologies developed in the context of the Two team project, developed by the Confederation of European paper industries, also promise to drastically decrease CO_2 emissions by the P&P industry in Europe.

6. 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.

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% the global average (respectively). To decrease carbon emissions, efforts to increase efficiency must continue.

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

- Development of new drying methods
- Valorization of waste streams through a fusion with the biorefinery sector;
- Electrification and increase in flexibility;
- Adoption of carbon capture and storage technology.

The next step for the NEFI project is the production of models that 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.

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.

7. References

[1] Statista, *Bruttoinlandsprodukt (BIP) von Österreich von 2008 bis 2018 (in Milliarden Euro).* [Online] Available: https://de.statista.com/statistik/daten/studie/14390/umfrage/bruttoinlandsprodukt-in-oesterreich/. Accessed on: Sep. 12 2019.

[2] Statista, *Umsatz der österreichischen Papierindustrie von 1990 bis 2018 (in Millionen Euro).* [Online] Available: https://de.statista.com/statistik/daten/studie/899174/umfrage/umsatz-der-oesterreichischen-papierindustrie/. Accessed on: Sep. 12 2019.

[3] Austropapier, "Papier aus Österreich 2018/19: Annual Report," Austropapier, 2019. [Online] Available: www.austropapier.at/mediacenter/downloads/.

[4] AF&PA, "Priting and writing papers, Life-cycle assessement summary report," https://www.afandpa.org/docs/default-source/default-document-library/printing-and-writing-lca-report.p, 2010.

[5] A. Dias, L. Arroja, and I. Capela, "Life cycle assessment of printing and writing paper produced in Portugal," *The International Journal of Life Cycle Assessment*, vol. 12, pp. 521–528, 2007.

[6] S. Smith and P.-A. Bontinck, "Streamlined LCA of Paper Supply Systems," DEFRA. [Online] Available: http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=18956. Accessed on: Aug. 21 2019.

[7] E. U. Muller *et al., The state of the world's forests, 2018: Forest pathways to sustainable development*. Rome: Food and Agriculture Organization of the United Nations, 2018.

[8] P. Bajpai, "Basic Overview of Pulp and Paper Manufacturing Process," in *Green Chemistry and Sustainability in Pulp and Paper Industry*, P. Bajpai, Ed., Cham: Springer International Publishing, 2015, pp. 11–39.

[9] M. Suhr *et al., Best Available Techniques (BAT) reference document for the production of pulp, paper and board*. Luxembourg: Publications Office, 2015.

[10] L. Szabó, A. Soria, J. Forsström, J. T. Keränen, and E. Hytönen, "A world model of the pulp and paper industry: Demand, energy consumption and emission scenarios to 2030," *Environmental Science & Policy*, vol. 12, no. 3, pp. 257–269, 2009.

[11] Moya J.A. and Pavel C. C., *Energy efficiency and GHG emissions: Prospective scenarios for the pulp and paper industry*. EUR 29280 EN. Luxembourg: Publications Office of the European Union, 2018.

[12] T. Fleiter, D. Fehrenbach, E. Worrell, and W. Eichhammer, "Energy efficiency in the German pulp and paper industry – A model-based assessment of saving potentials," *Energy*, vol. 40, no. 1, pp. 84–99, 2012.

[13] J.-A. Lamberg, J. Ojala, M. Peltoniemi, and T. Särkkä, *The Evolution of Global Paper Industry 1800–2050*. Dordrecht: Springer Netherlands, 2012.

[14] L. Kong, A. Hasanbeigi, and L. Price, "Emerging Energy-Efficiency and Greenhouse Gas Mitigation Technologies for the Pulp and Paper Industry," 2012.

[15] P. Bajpai, Ed., *Pulp and paper industry: Energy conservation*. Amsterdam, Boston: Elsevier, 2016.

[16] L. A. Lucia, "Novel Pulping Technology: Directed Green Liquor Utilization (D-GLU) Pulping," 2005.

[17] E. Muehlethaler, Y. Starkey, R. Salminen, and D. Harding, "Steam Cycle Washer For Unbleached Pulp (Final Report DE-FC36-04GO14304)," Port Townsend Paper Corporation, 21st Century Pulp and Paper, Idaho National Laboratory, 2008.

[18] D. I. Orloff and J. W. Crouse, "Impulse Drying: Status of the Pilot-Scale Research Program," 1999.

[19] U.S. Dept. of Energy, "Laboratory Development of High-Capacity, Gas-fired Paper Dryer," https://p2infohouse.org/ref/49/48121.pdf, 2006.

[20] H. L. Lee, H. Jung Youn, T. Min Jung, and J. Doo Kim, *Improvement of linerboard properties by Condebelt drying*, 2000.

[21] N. Martin *et al.,* "Emerging energy-efficient industrial technologies," https://escholarship.org/content/qt5jr2m969/qt5jr2m969.pdf, 2000.

[22] Marsidi, M. · Rademaker, R. · Wetzels, W., "Decarbonizing the steam supply of the dutch paper and board industry," Report, ECN part of TNO, Lux Research TNO 2018 P10784, 2018.

[23] D. W. Francis, M. T. Towers, and T. C. Browne, *Energy cost reduction in the pulp and paper industry: An energy benchmarking perspective*. [Ottawa]: Natural Resources Canada, 2004.

[24] P. Lundqvist, "Mass and energy balances over the lime kiln in a kraft pulp mill," Uppsala University, 2009.

[25] DOE, *Energy and Environmental Profile of the U.S. Pulp and Paper Industry*. Washington: Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program, 2005.