LCA Case Studies

Life Cycle Assessment of Printing and Writing Paper Produced in Portugal

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Abstract

Goal, Scope and Background. The environmental sustainability is one of the current priorities of the Portuguese pulp and paper industry. Life Cycle Assessment (LCA) was the methodology chosen to evaluate the sustainability of the printing and writing paper production activity. This paper grade represents about 60% of the total production of paper in Portugal and its production is expected to increase in the near future. The main goal of this study was to assess the potential environmental impacts associated with the entire life cycle of the printing and writing paper produced in Portugal from *Eucalyptus globulus* pulp and consumed in Germany, in order to identify the processes with the largest environmental impacts. Another goal of this study was to evaluate the effect on the potential environmental impacts of changing the market where the Portuguese printing and writing paper is consumed: German market vs. Portuguese market.

Methods. The main stages considered in this study were: forestry, pulp production, paper production, paper distribution, and paper final disposal. Transports and production of chemicals, fuels and energy in the grid were also included in these stages. Whenever possible and feasible, average or typical data from industry were collected. The remaining data were obtained from the literature and specialised databases. A quantitative impact assessment was performed for five impact categories: global warming over 100 years, acidification, eutrophication, non-renewable resource depletion and photochemical oxidant formation.

Results. In the German market scenario, the paper production stage was a remarkable hot spot for air emissions (non-renewable CO_2, NO_x and SO_2) and for non-renewable energy consumption, and, consequently, for the impact categories that consider these parameters: global warming, acidification and non-renewable resource depletion. These important environmental impacts are due to the energy requirements in the printing and writing paper production process, which are fulfilled by on-site fuel oil burning and consumption of electricity from the national grid, which is mostly based on the use of fossil fuels. The pulp production stage was identified as the largest contributor to water emissions (COD and AOX) and to eutrophication. Considering that energy consumed by the pulp production processes comes from renewable fuels, this stage was also the most contributing to renewable energy consumption.

Discussion. The paper distribution stage showed an important contribution to NO_x emissions, which, however, did not result in a major contribution to acidification or eutrophication. The final disposal stage was the main contributor to the photochemical oxidant formation potential due to CH_4 emissions from wastepaper landfilling. On the other hand, paper consumption in Portugal was environmentally more favourable than in Germany for the parameters/impact categories where the paper distribution stage has a significant contribution (non-renewable CO_2, NO_x, non-renewable energy consumption, acidification, eutrophication and non-renewable resource depletion) due to shorter distances needed to deliver paper to the consumers. For the remaining parameters/impact categories, the increase observed in the final disposal stage in the Portuguese market was preponderant, and resulted from the existence of significant differences in the final disposal alternatives in the analysed markets (recycling dominates in Germany, whereas landfilling dominates in Portugal).

Conclusions. The pulp and paper production stages were found to be of significance for almost all of the inventory parameters as well as for the impact assessment categories. The paper distribution and the final disposal stages were only of importance for some of the inventory parameters and some of the impact categories. The forestry stage played a minor role in the environmental impacts generated during the paper life cycle. The consumption of paper in Portugal led to a decrease in the environmental burdens of the paper distribution stage, but to an increase in the environmental burdens of the final disposal stage, when compared with the consumption of paper in Germany.

Recommendations and Perspectives. This study provides useful information that can assist the pulp and paper industry in the planning of future investments leading to an increase in its sustainability.

The results of inventory analysis and impact assessment show the processes that play an important role in each impact category, which allow the industry to improve its environmental performance, making changes not only in the production process itself, but also in the treatment of flue gases and liquid effluents. Besides that concern regarding pollution prevention, other issues with relevance to the context of sustainability, such as the energy consumption, can also be dealt with.

Keywords: *Eucalyptus globulus*; LCA; paper; Portugal; printing paper; pulp; writing paper

Introduction

The environmental sustainability is one of the current priorities in the Portuguese pulp and paper industry. Life cycle assessment (LCA) has been applied to the pulp and paper industry (Ross et al. 2003, Fu et al. 2005) and was the methodology chosen to evaluate the sustainability of the Portuguese printing and writing paper (office paper) production activity, which includes the production of raw materials, the production of the paper itself, the distribution of the paper and the final disposal of the wastepaper. The production of printing and writing paper represents about 60% of the total production of paper in Portugal (CELPA 2002) and is expected to increase in the near future. The main raw material used in the production of this paper is *Eucalyptus globulus* pulp, which is a chemical pulp manufactured by the kraft (or sulphate) process. The production of *E. globulus* printing and writing paper is integrated with the production of pulp. Other minor raw materials consist of pine market kraft pulp (in bales) produced in Scandinavia, and precipitated calcium carbonate (PCC) used as filler.

Nearly 90% of the printing and writing paper produced in Portugal is exported, mainly to European countries (CELPA 2002). The inclusion of all the markets where the Portuguese paper is consumed would require the knowledge on how paper is used and disposed of in all those countries, which is not feasible with a reasonable degree of reliability, due to the lack of accurate, specific information for all the countries. Therefore, the example of the German market was selected to perform this study, because data concerning the distribution and final disposal of paper in Germany were available from IFEU (Institut für Energie und Umweltforschung Heidelberg GmbH). The application of LCA methodology to the Portuguese printing and writing paper consumed in Portugal was earlier analysed by Dias et al. (2002) and Lopes et al. (2003).

1 Methodology

1.1 Goal and scope definition

1.1.1 Goal

The goals of this study were:

- to assess the potential environmental impacts of the printing and writing paper produced in Portugal and consumed in Germany over its entire life cycle, in order to identify the processes with the largest environmental impacts (hot spots);
- to evaluate the effect on the potential environmental impacts of changing the market were the Portuguese printing and writing paper is consumed: German market vs. Portuguese market.

1.1.2 System definition and boundaries

The life cycle stages for printing and writing paper, shown in **Fig. 1**, were grouped into the following categories:

- forestry (includes the production of *E. globulus* wood in Portugal and pine wood in Scandinavia);
- pulp production (refers to *E. globulus* pulp produced in Portugal and pine pulp produced in Scandinavia);
- paper production (includes printing and writing paper production);
- paper distribution (refers to the transport of printing and writing paper from the paper mill to the place of consumption);
- paper final disposal (in Germany, it consists of landfilling, incineration and recycling. The same alternatives, plus composting, are available in Portugal. Several grades of recycled paper are made both in Germany and Portugal, namely tissue, packaging papers and graphic papers. The latter comprises newsprint, magazine paper and printing and writing paper in Germany, while in Portugal only printing and writing paper is produced).

Besides these main sequential processes, each stage also includes additional processes, such as transport, chemical production, energy production in the national grid (electricity and heat), fuel production and processes which were added to the system boundaries to avoid allocation. **Table 1** lists the processes included in each stage considered for both the German and the Portuguese markets.

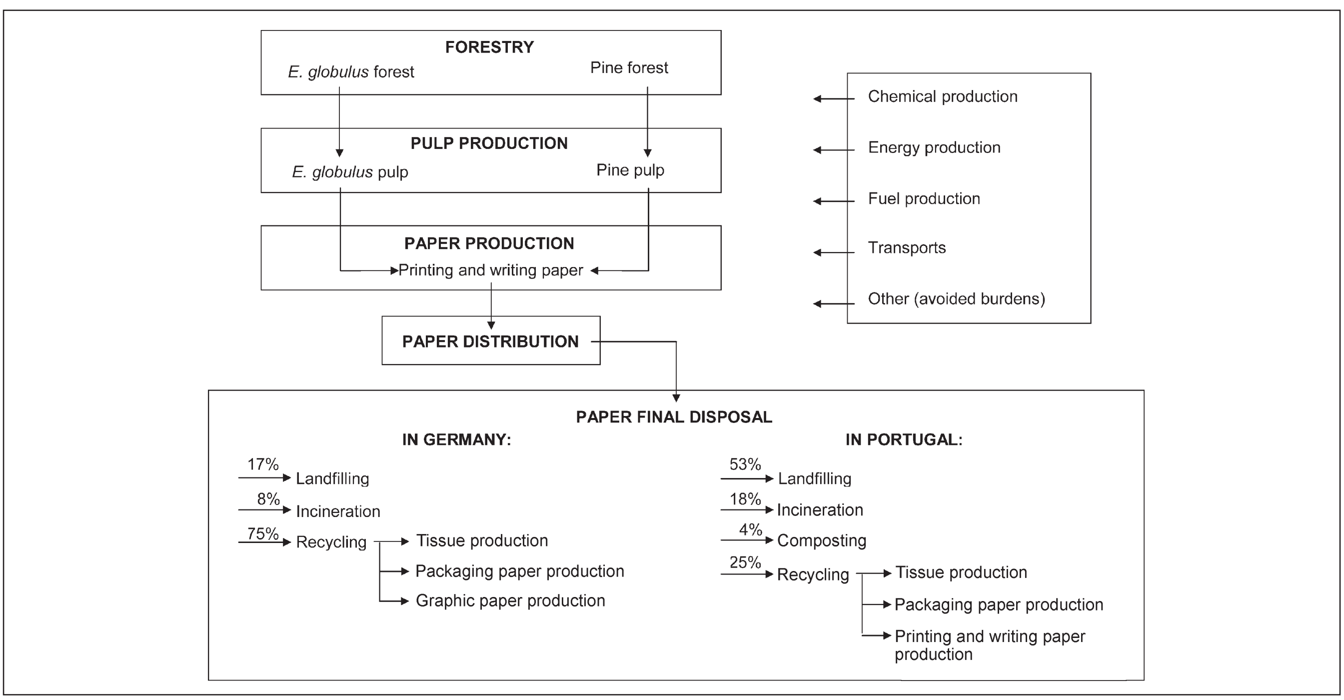

Fig. 1: System boundaries showing the life cycle stages of printing and writing paper

Table 1: Main stages in the printing and writing paper life cycle and corresponding processes

Stages	Processes
Forestry	• *E. globulus* forest • Pine forest
Pulp production	• *E. globulus* pulp production • Pine pulp production • Chemical production (NaOH, $CaCO_3$, H_2SO_4, $NaClO_3$, S_2, NaCl, H_2O_2) • Fuel production (heavy fuel oil) • Energy production in the grid • Transport of wood to the pulp mills • Transport of chemicals
Paper production	• Printing and writing paper production • Chemical production (PCC, CaO, $CaCO_3$, CO_2, optical brightener, starch) • Fuel production (heavy fuel oil) • Energy production in the grid • Transport of pine pulp to the paper mill • Transport of chemicals and fuel
Paper distribution in Germany	• Transport of paper to Germany • Paper distribution in Germany
Paper distribution in Portugal	• Paper distribution in Portugal
Final disposal in Germany	• Landfilling • Incineration • Graphic paper production (from wastepaper) • Packaging paper production (from wastepaper) • Tissue production (from wastepaper) • Packaging paper production (from virgin fibre, to avoid allocation) • Tissue production (from virgin fibre, to avoid allocation) • Chemical production (NaOH, H_2SO_4, $NaClO_3$, H_2O_2) • Fuel production (heavy fuel oil, natural gas, lignite) • Energy production in the grid • Transport of wastepaper from the user to the several disposal alternatives
Final disposal in Portugal	• Landfilling • Incineration • Composting • Printing and writing paper production (from wastepaper) • Packaging paper production (from wastepaper) • Tissue production (from wastepaper) • Printing and writing paper production (from virgin fibre, to avoid allocation) • Packaging paper production (from virgin fibre, to avoid allocation) • Tissue production (from virgin fibre, to avoid allocation) • Chemical production ($NaClO_3$, H_2O_2) • Fuel production (heavy fuel oil, light fuel oil) • Energy production in the grid • Transport of wastepaper from the user to the several disposal alternatives

In order to simplify the study, the materials that represent less than 1% (in mass) of the functional unit were left out. Exceptions to this cut-off criterion are the production of hydrogen peroxide and sodium chlorate used in the pulp production processes because they are energy-intensive processes (Strömberg et al. 1997).

The production and maintenance of capital goods (buildings, machinery, etc.) were excluded from the study, as well as the environmental burdens associated with the production of ink, toner, and other materials used during the utilisation of printing and writing paper.

1.1.3 Functional unit

The functional unit (FU) provides a reference unit to which the inventory data are normalised. In this study, the FU was defined as 1 tonne of white printing and writing paper, with a standard weight of 80 g/m², made in Portugal from *E. globulus* kraft pulp.

1.2 Inventory analysis

1.2.1 Data collection

The inventory data used in this study are representative of the period between 1995 and 2000. Whenever possible and feasible, average (over one year) or typical process-specific data were collected. The remaining data were obtained from the literature and specialised databases.

Data concerning the consumption of fertiliser and fuel during *E. globulus* installation, growth, and harvesting are representative of the typical operations carried out in *E. globulus* plantations in Portugal (Emporsil and Soporcel 1995). Such operations include, among others, path opening, plantation, soil mobilisation and fertilisation, felling, debarking, and off-road hauling. The emissions generated in fuel combustion were estimated using emission factors for diesel and petrol taken from the literature (Habersatter 1998).

Inventory data for the pine forest are average Finnish data taken from KCL-EcoData database (KCL 1999) and comprise pine growth and harvesting, 75% of which is done by regeneration felling and 25% by thinning.

Data on the production of pine pulp were also taken from KCL-EcoData database (KCL 1999) and represent typical Finnish technology for the production of market kraft pulp, bleached in an ECF (elemental chlorine free) process.

Inventory data for the production of *E. globulus* kraft pulp and the production of printing and writing paper are average production data provided by the Portuguese pulp and paper industry. *E. globulus* kraft pulp is bleached with chlorine dioxide (ECF process) and is produced with a consistency of 3.5% dry-solids being directly integrated in paper production. All of the energy required in the pulp production process is generated on-site using renewable fuels, namely, bark and black liquor (wood cooking liquor that contains almost 50% of the incoming wood). In the paper production process, on-site burning of heavy fuel oil plus electricity from the grid fulfils the energy requirements.

In the German market, the Portuguese printing and writing paper was assumed to follow the same final disposal pattern as the totality of printing and writing paper consumed in Germany. In the lack of individual flows for printing and writing paper, the final disposal pattern of graphic paper (which also includes newsprint and magazine paper), or paper in general, was used instead. It was considered that 5.8% of the printing and writing paper remains with the consumer as archives. Of the discarded paper, 75% is submitted to recycling, 17% is landfilled and 8% is burned.

The fluxes of paper going to recycling were allocated to different paper grades. The major part (85%) of the recycled printing and writing wastepaper is used in the production of tissue paper. About 5% is used in the production of graphic paper and 15% was assumed to be integrated in the production of packaging papers.

IFEU provided all data regarding the fluxes of paper in Germany, as well as the inventory data for wastepaper landfilling and incineration in Germany, which are representative of the average German situation. Inventory data for the recycling processes in Germany were derived from several sources. IFEU provided average data for the production of graphic papers, representative of the German technology. KCL-EcoData (KCL 1999) data were employed for the production of high quality tissue. Literature data (FEFCO et al. 1997, Habersatter 1998) were used for the production of packaging papers.

In the Portuguese market, the same percentage of retention of paper in the consumers was adopted as in Germany, and it was considered that 53% of the discarded printing and writing paper is landfilled, 25% is recycled, 18% is incinerated and 4% is composted. Of the paper undergoing recycling, 52% is used to produce tissue, 39% is used to produce packaging papers and 9% is consumed in the production of printing and writing paper. The percentage of paper going to recycling and the fluxes of paper allocated to each paper grade were estimated based on Celpa (Association of the Portuguese Paper Industry) statistics, while the fluxes going to the other alternatives were defined by assuming that printing and writing paper follows the same disposal pattern as the municipal solid waste in Portugal (INR 2000).

The inventory data of the recycling process are typical Portuguese production data. On the other hand, inventory data for landfilling and composting of paper in Portugal were taken from the literature (White et al. 1995). The inventory data of incineration in Germany were adopted for this process in Portugal.

Inventory data for the production of several chemicals, listed in Table 1, were collected from databases and literature (Virtanen and Nilsson 1993, Habersatter 1998, KCL 1999). In the case of PCC, which is produced on-site in the pulp and paper mills, inventory data were provided by the producers.

The transport of wood, pulp, paper, wastepaper, chemicals and fuels was accounted for using average distances mainly provided by the pulp and paper industry and IFEU (for transport in Germany) and emission factors derived from the literature (Habersatter 1998).

The following electricity production models were taken into account: Portugal, Spain, France, Belgium, Finland, Germany, UCPTE (Union for the Connection of Production and Transportation of Electricity) mix, and Nordic mix. The data were retrieved from the literature (Habersatter 1998). The production of heat in the German grid from light fuel oil and natural gas was also characterised (data from IFEU).

Inventory data for the production of fuels (heavy fuel oil, light fuel oil, natural gas and lignite) were taken from the literature (Habersatter 1991).

1.2.2 Allocation procedures

In this study, some allocation procedures (partitioning of the input or output flows of a unit process to the product under study) needed to be applied to deal with multifunctional processes (multi-output and input processes, and open-loop recycling). The allocation procedures were applied following ISO (International Organization for Standardization) recommendations (ISO 1998).

Wherever possible, allocation was avoided by unit process division or system boundaries expansion.

Unit process division was applied to the *E. globulus* pulp production process. The pulp produced in this process is integrated to 100% with the paper production process. However, the available data from the existing mills referred to partially integrated processes, in which there is also the production of surplus market pulp. This pulp is dried to a consistency of 90% dry-solids. Thus, the existing systems were disaggregated and the data from the drying section of the pulp production process were excluded.

System boundaries expansion (avoided burden approach) was adopted to deal with wastepaper recycling and with processes that produce surplus electricity or heat. In the first case, it was assumed that the use of recycled paper displaces the use of equivalent paper grades made from virgin fibre. The environmental burdens of the production of virgin papers were subtracted from the environmental burdens of the recycling processes. Regarding the German market, inventory data for the production of virgin tissue were available from KCL-EcoData (KCL 1999), while, for the production of virgin packaging papers, inventory data were taken from the literature (FEFCO et al. 1997, Habersatter 1998). No credit was given to the production of recycled graphic paper because it represents less than 1% (in mass) of the functional unit. The inventory data concerning the processes of production of tissue, packaging papers and printing and writing paper made from virgin fibre in Portugal are average production data. In the case of processes that produce surplus electricity (*E. globulus* pulp production, pine pulp production, landfilling, incineration and corrugated paper production from wastepaper), the environmental burdens associated with the production of the same amount of electricity in the national grids where the processes take place were subtracted from the inputs and outputs of these processes (avoided burden approach). In the processes that produce surplus heat (incineration and corrugated paper production from virgin paper), the same procedure was applied, considering the alternative production of heat in the grid where the processes take place.

Where allocation could not be avoided, the outputs and inputs of the system were partitioned based on physical relationships. For example, in the incineration process, stoichiometric relations were employed to allocate emissions of carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrogen chloride (HCl) and hydrogen fluoride (HF) to paper, while nitrogen oxides (NO_x) were allocated based on the share of this gas in the flue gas flow. The remaining emissions considered in this study for paper incineration were estimated using an allocation by mass.

1.3 Impact assessment

A quantitative impact assessment was performed for five impact categories: global warming over 100 years (GW), acidification (A), eutrophication (E), non-renewable resource depletion (NRRD) and photochemical oxidant formation (POF). **Table 2** shows the inventory parameters assigned to each impact category, as well as the category indicators and the characterisation factors that allow the aggregation of parameters within the impact categories. These factors were taken from the literature (Heijungs et al. 1992, Lindfors et al. 1995, Hauschild and Wenzel 1998, IPCC 2001). Neither normalisation nor grouping and weighting between categories have been performed, because they were not necessary for the identification of the hot spots throughout the life cycle.

2 Results and Discussion

The analysis of the results at the inventory level is limited to a few key parameters: renewable and non-renewable energy consumption, non-renewable CO_2, NO_x, SO_2, chemical oxygen demand (COD) and adsorbable organic halogens (AOX). Renewable CO_2 emissions (CO_2 released from renewable sources) were excluded from this assessment since they were assumed to be balanced by CO_2 sequestration due to forest growth. This assumption was made according to Eurosac and Eurokraft (1996), because there was a lack of reliable data regarding CO_2 sequestration.

Figs. 2 and **3** show the inventory analysis and the impact assessment results, respectively, highlighting the contribu-

Table 2: Impact categories and corresponding parameters used in this study

Impact category	Indicator [units]	Parameter	Weighting factor	Source
Global warming, 100 years (GW)	Global warming potential [kg CO_2-eq]	Non-renewable CO_2	1	IPCC (2001)
		CH_4	23	
		N_2O	296	
Acidification (A)	Acidification potential [kg SO_2-eq]	SO_2	1	Hauschild and Wenzel (1998)
		NO_x	0.7	
		HCl	0.88	
		NH_3	1.88	
		HF	1.6	
		H_2S	1.88	
Eutrophication (E)	Eutrophication potential (maximum) [kg PO_4^{3-}-eq]	NO_x air	0.13	Lindfors et al. (1995)
		NH_3 air	0.35	
		N water	0.42	
		NO_3^- water	0.1	
		NH_4^+ water	0.33	
		P water	3.06	
		PO_4^{3-} water	1	
		COD water	0.022	
Non-renewable resource depletion (NRRD)	1/Static reserve life [$year^{-1}$]	Crude oil	1/40	Lindfors et al. (1995)
		Natural gas	1/60	
		Coal	1/390	
Photochemical oxidant formation (POF)	Photochemical ozone creation potential [kg ethylene-eq]	CH_4	0.007	Heijungs et al. (1992)
		Halogenated hydrocarbons	0.021	
		Aromatic hydrocarbons	0.761	

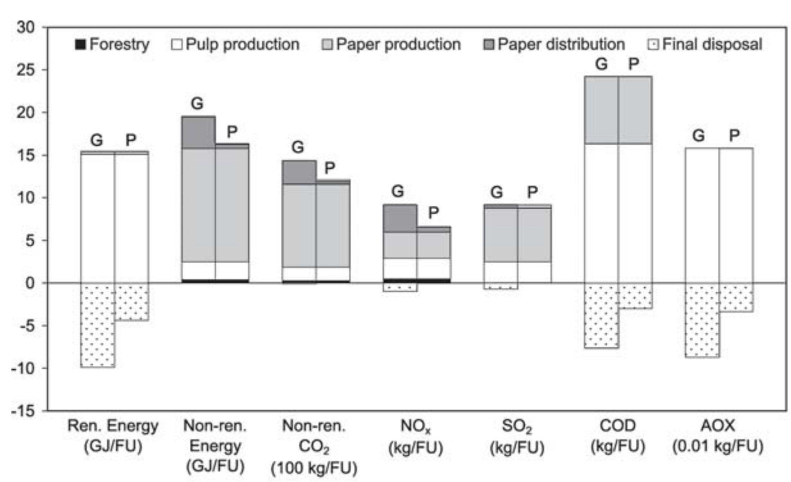

Fig. 2: Inventory analysis results (G = German market, P = Portuguese market)

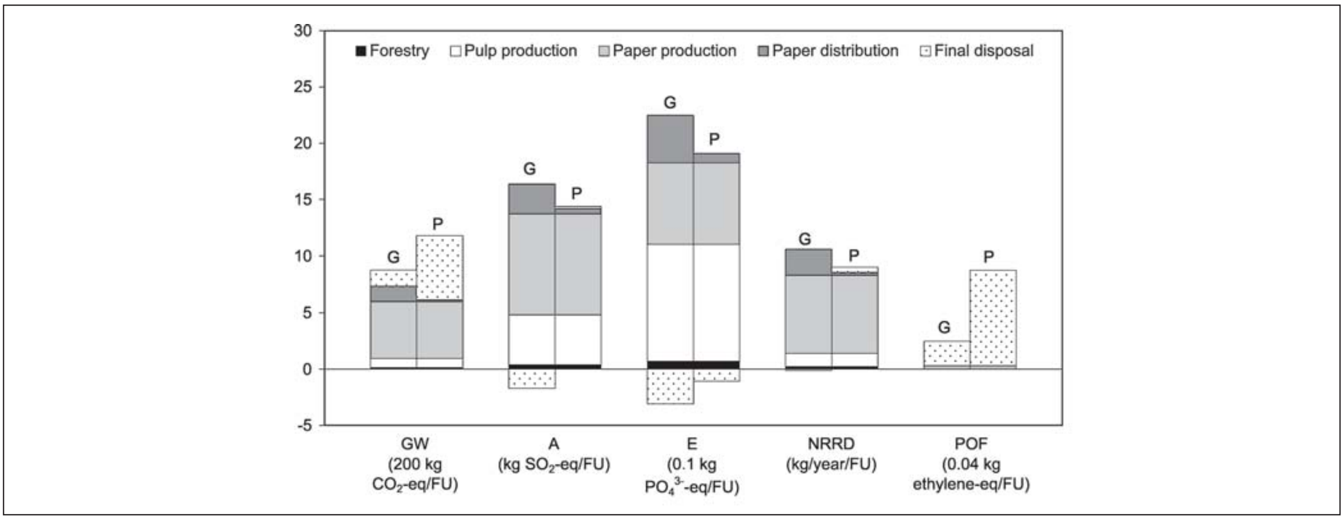

Fig. 3: Impact assessment results (G = German market, P = Portuguese market)

tion of each stage of the life cycle, for both the German (G) and the Portuguese (P) markets. The negative contribution of the final disposal stage reflects the credit given to avoid allocation, meaning that the environmental burdens associated with the processes used to give credit are greater than those from wastepaper final disposal.

2.1 Inventory analysis results

2.1.1 German market

The most important consumer of renewable energy is the pulp production stage since all the energy consumed in the pulp production processes is based on renewable fuels (bark and black liquor). The larger contribution comes from the production of *E. globulus* pulp, which represents about 80% of the pulp consumed in paper production. The negative contribution of the final disposal stage is due to the credit given to the paper recycling processes. This means that the production of paper from recycled fibre consumes remarkably less renewable energy than the production of paper from virgin fibre.

Almost 70% of non-renewable energy consumption occurs in the paper production stage, of which approximately 50% is due to on-site energy generation based on heavy fuel oil and about 30% is related to the production, in the Portuguese grid, of the electricity consumed in the paper production process (which is mostly based on fossil fuels). The consumption of non-renewable energy in the final disposal stage is in balance with the credit given to this stage.

The relative contribution of each stage of the life cycle to non-renewable CO_2 emissions is similar to the result obtained for non-renewable energy consumption. Therefore, the paper production stage is the major source of non-renewable CO_2 emissions due to the production of energy (on-site and in the national grid).

The paper distribution stage and the paper production stage are the most important sources of NO_x emissions. In the paper distribution stage, this contribution is due to the fact that the transportation of paper is mainly done by truck (less than 1% of the distance travelled is made by train). In the paper production stage, the production of energy (on-site and in the national grid) and the transportation of chemicals accounts for 50% and 25% of NO_x emissions, respectively. The pulp production stage has also an important contribution to this inventory parameter, mainly due to fuel combustion in the *E. globulus* pulp production process and transportation of *E. globulus* wood, which account for about 40% and 30% of NO_x emissions in the pulp production stage, respectively.

As for the other air emissions, the paper production stage plays a significant role in SO_2 emissions, as a result of energy production. On-site energy production and production of electricity in the national grid account, respectively, for approximately 40% and 30% of SO_2 emissions in the paper production stage.

The pulp production stage contributes largely to COD emissions, mainly due to *E. globulus* pulp production, which is responsible for about 80% of COD emissions in the pulp production stage. Paper recycling, in the final disposal stage, 'avoids' the emission of a remarkable amount of COD.

AOX emissions are originated mostly in the pulp production stage, as a result of the use of chlorine dioxide as bleaching agent in the pulp production processes. The *E. globulus* pulp production is the main source of AOX emissions, contributing with approximately 80% of the emissions. The credit given to paper recycling results in an important reduction in AOX emissions. The other stages account for negligible AOX emissions.

2.1.2 Portuguese market

When the printing and writing paper is consumed in Portugal, there is a decrease of 20% in the total emissions of NO_x and a decrease of approximately 15% in both the total emissions of non-renewable CO_2 and the total consumption of non-renewable energy, in relation to the results obtained for the German market. This is mainly due to the remarkable decrease (between 80 and 85%) observed in these parameters in the paper distribution stage, as the distances travelled to deliver paper to the consumers are smaller than when paper is consumed in Germany. An average distance of about 200 km was considered for paper distribution in Portugal, against almost 2700 km in Germany.

Paper consumption in Portugal is less favourable than in Germany with respect to the emissions of SO_2, COD and AOX, and the consumption of renewable energy (being the difference specially significant for the last three parameters), since the contribution of the paper distribution stage is not important for these parameters, and the results obtained for the final disposal stage are higher in the Portuguese market.

2.2 Impact assessment results

2.2.1 German market

The most important contributor to the global warming potential is the paper production stage, mainly due to non-renewable CO_2 emitted during energy production. Although the final disposal stage presents a negative emission of non-renewable CO_2, as shown in Fig. 2, this stage contributes to 15% of the total global warming potential. This is due to methane (CH_4) emitted during paper landfilling, which is a much stronger greenhouse gas than CO_2 (IPCC 2001).

The paper production stage has the largest contribution to the acidification potential, which is mainly caused by SO_2 emissions generated during energy production.

The greatest contribution to the eutrophication potential comes from the pulp production stage, mainly as a result of COD and NO_x emissions. The paper production stage has also a remarkable contribution to this impact category, mainly due to NO_x emissions.

The non-renewable resource depletion potential is largely due to the consumption of heavy fuel oil in the paper production stage, of which about 70% is used for on-site energy generation and almost 20% is used to produce the electricity from the grid consumed in the paper production process.

The final disposal of wastepaper is clearly the major contributor to the photochemical oxidant formation potential as a result of CH_4 emissions from wastepaper landfilling.

2.2.2 Portuguese market

The Portuguese market is unfavourable for the global warming and photochemical oxidant formation impact categories, because landfilling is the main final disposal alternative for wastepaper, resulting in important CH_4 emissions, as landfill gas is not burned.

In contrast, the acidification, eutrophication and non-renewable resource depletion potentials are smaller (between 2 and 15%) when the printing and writing paper is consumed in Portugal instead of Germany, since the decrease achieved in the paper distribution stage exceeds the increase observed in the final disposal stage.

3 Conclusions

The hot spots over the whole life cycle of printing and writing paper consumed in the German market were identified from the inventory analysis and impact assessment results. These results suggest that:

- the paper production stage plays an important role in almost all the inventory parameters and impact assessment categories considered. This stage is a remarkable hot spot for air emissions (non-renewable CO_2, NO_x and SO_2) and non-renewable energy consumption, and, consequently, for the impact categories that consider these parameters (global warming, acidification and non-renewable resource depletion). These important environmental impacts are the result of the energy requirements in the paper production process, which are fulfilled by on-site fuel oil burning and consumption of electricity from the national grid, which is mostly based on fossil fuels;
- the pulp production stage was identified as the largest contributor to water emissions (COD and AOX) and to eutrophication, mainly due to *E. globulus* pulp production. As all the energy consumed by the pulp production processes comes from renewable fuels, the pulp production is also the most contributing stage to renewable energy consumption;
- the paper distribution stage shows an important contribution to NO_x emissions. However, the contribution of this stage to acidification and eutrophication (the impact categories that include NO_x) is not very important;
- the final disposal stage is the main contributor to the photochemical oxidant formation potential due to CH_4 emissions from wastepaper landfilling;
- the forestry stage plays a minor role in the environmental impacts generated during the paper life cycle.

Paper consumption in Portugal is environmentally more favourable than in Germany for the parameters/impact categories where the paper distribution stage has a significant contribution: non-renewable CO_2, NO_x, non-renewable energy consumption, acidification, eutrophication and non-renewable resource depletion. For the remaining parameters/impact categories, the increase observed in the final disposal stage in the Portuguese market is preponderant. This increase is particularly remarkable for those parameters associated mainly with virgin pulp production (COD, AOX and renewable energy consumption), as the Portuguese market does not benefit as much as the German market from the credit given to recycling. The increase of the contribution of the final disposal stage in the Portuguese market is also significant for the global warming and photochemical oxidant formation impact categories, due to CH_4 emissions caused by landfilling, the major final disposal alternative for paper in Portugal.

4 Recommendations and Perspectives

This study provides useful information that can assist the pulp and paper industry in the planning of future investments leading to an increase in its sustainability. The results of inventory analysis and impact assessment show the processes that play an important role in each impact category, which allow the industry to improve its environmental performance, making changes not only in the production process itself but also in the treatment of flue gases and liquid effluents. Besides those that concern pollution prevention, other issues with relevance to the context of sustainability, such as the energy consumption, can also be dealt with.

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Preliminary Assessment of the Environmental Benefits of Enzyme Bleaching for Pulp and Paper Making

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Abstract

Goal and Background. The LCA methodology is used to compare the potential environmental benefits of an emerging biotechnology, enzyme-bleaching, with those of elemental chlorine free (ECF) bleaching, an existing technology that is widely used in paper making. Through the use of biodegradable enzymes to supplement, or eventually to replace, chemicals in the bleaching process to extract lignin, enzyme bleaching processes are aimed to reduce the use of chlorine based bleaching chemicals and to achieve cost savings by circumventing investment into oxygen delignification or ozone bleaching technology.

Scope and Method. The assessment is conducted using SimaPro 4.0 and focuses on the processes within the bleach plant stage. For this study, ECF is replaced by enzyme bleaching only in the first stage of the bleaching process. Because this is a comparative study, all upstream and downstream processes are excluded. The impact categories based on Eco-indicator 95 are used to characterize the inventory data in this study. Other methodologies, such as Eco-indicator 99 and CML 2000, have not been chosen as they are more region-specific and are not yet fully applicable to the Canadian environmental condition. A new initiative to develop a Canadian Life Cycle Impact Assessment (LCIA) Method is ongoing at the Interuniversity Reference Center for the Life Cycle Assessment, Interpretation and Management of Products, Processes and Services (CIRAIG), Ecole Polytechnique, Canada.

Results and Conclusion. The analysis shows that the introduction of enzyme bleaching into the ECF process significantly improves the overall environmental performance in the majority of the impact categories. Extending the substitution of enzyme bleaching for chlorine dioxide is warranted. Of the three impact categories where increased impact was noted, two of these which increased emissions of greenhouse gases and increased incidence of summer smog, would be completely eliminated if the enzyme mediator was manufactured at the point of use. There remains a potential for increased impact from eutrophication, which would need to be managed.

Recommendations and Outlook. With the only partial substitution of ECF by enzyme bleaching examined here, chlorine dioxide consumption, energy consumption, NaOH consumption, and transportation remain the key hot spots and warrant further research. Anything that can be done to replace or reduce chlorine dioxide consumption will benefit the environment.

Keywords: Bio-bleaching; cellulose; elemental chlorine free (ECF) bleaching; enzyme bleaching; laccase; pulp and paper making; pulp bleaching; system closure