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A comparative LCA study of various concepts for shopping bags and cement sacks

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Summary

On commission of BillerudKorsnäs AB, IVL Swedish Environmental Research Institute (IVL) has performed an LCA on two products, D-sack (a cement sack which dissolves in the cement mixture) and a shopping bag (for clothes) based on paper produced by BillerudKornäs at Karlsborg and Skärblacka mill. These products have been compared to competing paper concepts and plastic materials. As base case, a cut-off was made at the customer gate. A system expansion was made by including end-of-life, with and without avoided emissions (credits). The study has considered the environmental impact categories; Global warming potential (GWP), Acidification potential (AP), Eutrophication potential (EP), Photochemical ozone creation potential (POCP) and Primary energy demand.

The study has taken place during 2015/2016 using primarily data for 2014 for the BillerudKorsnäs pulp and paper sites in Karlsborg and Skärblacka. The study has been performed in accordance with ISO 14044:2006 and reviewed by a third party reviewer.

D-sack has been developed by BillerudKorsnäs and the cement/concrete manufacturer LafargeHolcim. The D-sack packaging dissolves in the cement paste at the concrete mix, leaving no paper waste. Based on a more comprehensive study performed on the degradation of fibres in concrete, two time scenarios have been considered regarding the end-of-life for the D-sack;

- 100 years perspective
- Infinite time perspective

For the infinite perspective, it is assumed that the concrete structure is demolished and therefore CO_2 will be released into the atmosphere, whereas for the 100-year perspective, it is assumed that no CO_2 emissions are released from the concrete. Therefore, in the 100-year perspective, the D-sack is considered to be a CO_2 capture, since the carbon dioxide, which was once captured during tree growth and incorporated in paper fibres of the D-sack, are considered to still be retained in the concrete structure.

The main conclusions of the study for the packaging products are:

Cement sack

In the base case, D-sack has an advantage over the generic cement sack regarding global warming potential, with 29 % lower impact. This is because of the higher impact from “material production” and the “packaging production” for the generic cement sack. Since the D-sack doesn’t require any waste management and therefore the system expansion increases the impact for the generic cement sack somewhat further compared to D-sack. Although, there are some gained credits for the generic sack, due to avoided virgin material production from material recycling, the environmental performance of the D-sack is still better. This is true in both time scenarios but especially in the 100-year scenario, when the D-sack is considered as a carbon capture.

For acidification and photochemical oxidation potential, the base case shows a lower impact from the D-sack than the generic cement sack. The outcome is the same when also including end-of-life for the generic cement sack. However, when the avoided emissions are accounted for, the credits decreases the acidification potential for the generic cement sack so in total the generic cement sack has a lower impact than the D-sack.

Looking at the eutrophication potential for the base case (Figure 11), the generic cement sack has a slight advantage over the D-sack, this is because of the higher impact from the material production at Karlsborg. The outcome is the same when also including end-of-life, although, when the avoided emissions are accounted for, the eutrophication for the generic cement sack becomes almost half compared to D-sack.

The relatively low environmental impact from the D-sack is because of the manufacturing process at Karlsborg mill utilizes a high amount of biofuels, whereas European mills more often run on fossil fuels. Also Karlsborg mill utilizes excess energy from the mill both for heat and electricity generation which is used internally at the mill. However, important parameters to address at Karlsborg mill besides the direct emissions from the mill, are the chemicals used for coating.

Shopping bag

For the base case, without including end-of-life, and regarding the climate impact the BillerudKorsnäs bag has a remarkably low impact compared to the other bags in the study, it has for instance, a 59 % lower global warming potential than the recycled LDPE bag. The recycled paper bag has the second lowest impact and the renewable LDPE bag has the highest impact.

Skärblacka mill has a relatively low climate impact during the material production. This is because the mill utilizes a high amount of biofuels, whereas for instance European recycling mills are more often run on fossil fuels. Also Skärblacka mill utilizes excess energy from the mill both for heat and electricity generation which is used internally at the mill.

However, in the base case for acidification, eutrophication and ground level ozone formation, the recycled LDPE bag shows the best performance. This is because of the higher impact from the material production at Skärblacka where the direct emissions from the mill and to some extent the upstream emissions from production of the chemicals (especially flocculation/thickening agents and starch) are important parameters to address.

The system expansion (end-of-life included), shows the same relative outcome for all impact categories as for the base case, this is also the case when avoided emissions also are accounted for, except for ground level ozone, where the effect of including avoided emissions heavily reduces the impact for the paper bags and especially for the recycled paper bag.

1 Introduction

Life cycle assessment (LCA) can work as a tool for measuring the environmental performance of different products and processes. This report presents an LCA performed for BillerudKorsnäs based on data from 2014 for two products; the D-sack for cement and a shopping bag, using material from BillerudKorsnäs. These products are also compared with corresponding products of other materials.

Environmental LCA is the calculation and evaluation of the environmentally relevant inputs and outputs and the potential environmental impacts of the life cycle of a product, material or service (ISO 14044:2006).

Environmental inputs and outputs refer to demand for natural resources and to emissions and solid waste. The life cycle consists of the technical system of processes and transports used at/needed for raw materials extraction, production, use and after use (waste management or recycling). LCA is sometimes called a "cradle-to-grave" assessment (Figure 1). In this study a cradle-to-customer assessment was made as base case and as a second step, end-of-life was also included for the products. The LCA calculations are based on a functional unit, meaning the function, which is provided by the product system, for instance 1 kg material or 1 type of product/service.

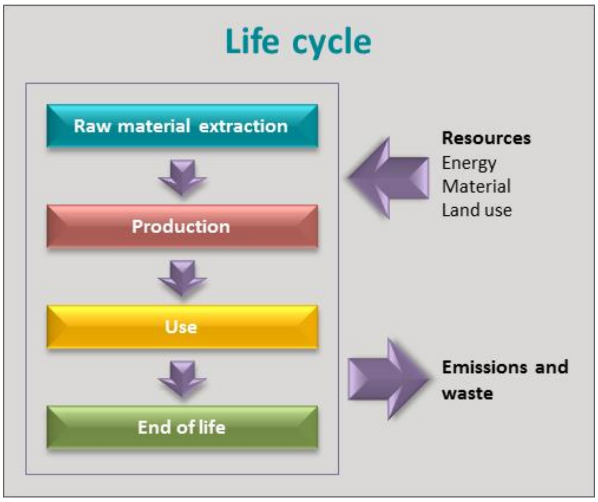

Figure 1. Illustration of the LCA-framework

This LCA has been carried out by IVL Swedish Environmental Research Institute, to which BillerudKorsnäs have delivered information regarding their products and processes, which have, when necessary, been supplemented by data from IVL. This life cycle assessment has been carried out in accordance with the ISO Standard (ISO 14044:2006). The study has been critically reviewed and approved by third-party; Göran Brohammer, Bureau Veritas, Sweden.

The project group has consisted of the following members:

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2 Goal and scope definition

2.1 Objective and system boundaries

The objective of the study was to perform a LCA of two specific products based on BillerudKorsnäs paper; D-sack (cement sack) and a shopping bag, on regard to the four environmental impact categories; Global Warming Potential (GWP), Acidification potential (AP), Eutrophication potential (EP), Photochemical ozone creation potential (Ground level ozone) (POCP) as well as primary energy and material resources. The objective was also to perform a LCA on the same type of products produced from different competing materials.

In the base case, the system boundaries cover the entire production of raw materials to the customer gate, excluding the use-phase, in order to make it as relevant as possible to the company's customers. Then a cut-off was made by excluding end-of-life for the products. This phase was however regarded in the system expansion scenario, which is further described in section 3.4. In the end-of-life scenarios, avoided emissions have been considered. Avoided emissions are those emissions, which are avoided when for instance excess heat or generated electricity in a process can be used in the society instead of alternative fuel sources, hence, the emissions from the alternative source are considered to be avoided.

The analysed products are distributed in many different ways to the customers. It can therefore be difficult to specify the distribution packaging for the analysed products. Thus, in this study only the primary products have been considered and not the secondary packaging materials.

Single use shopping bags can eventually be used several times (reuse) in so called product recycling. The reuse of shopping bag products are difficult to estimate and depends very much on customer behaviour. The second use of shopping bag products has therefore not been taken into account in this study. It is therefore also likely to assume that the secondary use of the shopping bag products are approximately equal for all type of bags in this category. A common type of use is as garbage bags, which normally prevent multiple use.

In this study, only normal end-of-life (recycling, incineration and landfill) for the shopping bags have been assumed. However, shopping bags can also spread in the environment as litter. Here, the bags are broken down by microorganisms, sunlight and mechanical stress. Paper bags break down easily in nature by natural processes. For plastics, the situation is more problematic. The plastic breaks down into smaller plastic fragments that then spread to land and water recipients. Especially in water recipients, plastic fragments found to be harmful to many species. For this reason, it has also sought to limit the use of this type of plastic products. These environmental effects, however, have been difficult to quantify in an LCA study. These effects have therefore not been included in this LCA study and are only commented here qualitatively.

2.1.1 Functional unit

A functional unit is the function provided by the product system in such a way that it becomes comparable between different systems. In this study, the functional unit is the specific product fulfilling a defined function, e.g. a sack that should be able to carry 25 kg cement. Due to material properties, the weight of a product in paper or for instance plastic is not necessarily the same. The products and their functional units are further described in the inventory analysis in section 3.

2.1.2 Characterization factors

Characterization factors are used in order to quantify and analyse the potential environmental impact of a product or process. They are based on chemical and biological reactions in air, water and soil to which all emissions have been normalized to a reference unit, using different factors (characterization factors). These factors are different for different chemical substances. Below follows a short description of the different impacts categories used in this study.

2.1.3 Global warming potential (GWP)

When speaking of global warming today, one usually refers to those emissions released from human activities, which enhance the natural occurring global warming, which in the end raises the global average temperature. GWP is a measure of how much a unit mass of gas contributes to global warming, measured in kg CO_2 equivalents. Other important gases besides CO_2 are methane (CH_4) and nitrous oxide (N2O). In this study GWP has been calculated from a 100 years perspective.

2.1.4 Eutrophication potential (EP)

Eutrophication occurs due to excess nutrients in water and soils. Nitrogen and phosphorous are the most important compounds associated with eutrophication. If seas and lakes becomes rich is nutrients, this can lead to increased algae growth, which during degradation, consumes oxygen at the bottoms, forms hydrogen sulphide and as a consequence, leads to dead bottoms of lakes and seas (SMHI, 2014).

EP is a measure of the potential effect something has on eutrophication of waters and soils. The higher the EP value, the higher the risk of associated environmental damage. The reference unit is kg phosphate (PO_4^{3-}) equivalents.

2.1.5 Acidification potential (AP)

Acidification means that substances with low pH are emitted to water and soils to such degree that they don’t have any chance to become naturally neutralized. Sulphur dioxide (SO_2) and nitrogen oxides (NO_X) are important contributors, which form sulphuric and nitric acid in contact with water in the atmosphere, called acid rain. This causes corrosion damages on buildings etc. that result in high costs for the society. Also, acidification of lakes can lead to death of certain species living there and acidification of soil can lead to nutrient leaching and decreased vegetation growth.

AP is a measure for the potential effect something has on acidification of soils and waters. The higher the AP value, the higher the risk of acid rain and associated environmental damage. The reference unit is kg sulphur dioxide (SO_2) equivalents.

2.1.6 Photochemical ozone creation potential (POCP)

POCP is a measure for estimating airborne substances potential to form ground-level ozone. In the presence of sunlight and compounds such as nitrogen oxides, carbon monoxide (CO) and volatile organic compounds (VOC) react with oxygen in the air and sunlight and form ground level ozone. Engine exhaust gases are common source of these emissions.

Ground level ozone irritate eyes and lungs for humans, they also inhibits the photosynthesis and damages the water balance for plants and vegetation.

2.1.7 CML2001

In this study, characterization factors from CML2001 (Centre of Environmental Science of Leiden University) were used, seen in Table 1. These are frequently used within LCA and are sometimes referred to as KPIs (Key Performance Indicators).

Table 1. Used characterization factors, implemented from Gabi 7.3

Characterization factors (KPIs)		
Short name	**Name**	**Unit**
GWP	CML2001 – Apr. 2015, Global Warming Potential, excl. biogenic carbon (GWP 100 years)	kg CO_2-eq.
EP	CML2001 – Apr. 2015, Eutrophication Potential	kg PO_4-eq.
AP	CML2001 – Apr. 2015, Acidification Potential	kg SO_2-eq.
POCP	CML2001 - Apr. 2015, Photochem. Ozone Creation Potential (POCP)	kg ethene-eq.

3 Inventory analysis

The inventory analysis presents the products, modelling and assumptions.

3.1 Description of the products

The study has been performed on two types of products; a cement sack (D-sack) and a shopping bag. D-sack stands for "Dissolvable sack" and is a 25 kg cement sack made from bleached, virgin Kraft paper. The D-sack package dissolves in the cement paste at the concrete mix, leaving no paper waste. The product has been developed by BillerudKorsnäs and the cement/concrete manufacturer LafargeHolcim. In this study, D-sack is compared with a generic cement sack in unbleached/bleached Kraft paper, manufactured somewhere in Europe. The generic cement sack also has a plastic film, which is glued inside the sack, in order to receive the right tightness against powder. The D-sack has instead a coating layer, which is applied directly at the Karlsborg mill during the material production. The coating layer consists of an inorganic filler and synthetic rubber. The D-sack is compared with a conventional cement sack manufactured in Europe and is represented by data which is an average of bleached and unbleached sack Kraft paper manufacturing in Europe.

The second BillerudKorsnäs product analysed is a shopping bag made from virgin Kraft paper. This bag is compared to shopping bags made in the materials; recycled paper, recycled polyethylene (LDPE) and renewable low-density polyethylene (LDPE). The bags are assumed to be shopping bags for clothes providing the same function. The paper bags have a volume of 31 litres, while the plastic bags are 26 litres. Even though the recycled paper and plastic bags are made from recycled materials, they still require an amount of virgin material in the final product. This is because recycled material alone cannot provide the same quality and strength as virgin material can. The virgin content for each product is given in Table 3.

The studied material's product weights, place of conversion, and end-of-life are listed in Table 2 (cement sack) and Table 3 (shopping bag). The products in paper and plastic respectively are considered to represent the same function i.e. carry at least the same volume. The specific places for conversion and country for the end-of-life scenario were received from BillerudKorsnäs (BillerudKorsnäs 2015a).

Table 2. Material, product weight, and place of conversion (packaging manufacturing), as well as place of end-of-life for the system expansion for the cement sack (25 kg cement).

Material	Weight of the product (g)	Paper material origin	Place of conversion	Place for End-of-life (System expansion)
Bleached Sack Kraft paper (D-sack)	101	BillerudKorsnäs (Karlsborg)	Düsseldorf, Germany	France
Sack Kraft paper	85	European average	Central Germany	France

Table 3. Material, product weight, and place of conversion (packaging manufacturing), as well as place of end-of-life for the system expansion for the shopping bag.

Material	Weight of the product (g)	Amount of virgin material	Material origin (paper and plastics)	Place of conversion	Place for End-of-life (System expansion)
Kraft paper	74	100%	BillerudKorsnäs (Skärblacka)	Frankfurt, Germany	England
Recycled paper	74	15%	European average	Frankfurt, Germany	England
Recycled LDPE	42	50%	European average	Frankfurt, Germany	England
Renewable LDPE	42	100%	Brazil	Frankfurt, Germany	England

The following chapters contain more detailed information regarding the different materials.

3.2 Data collection and modelling

The life cycle of the products were modelled in LCA-software Gabi 7.3 (thinkstep 2016). For modelling of the pulp and paper production at BillerudKorsnäs sites, data for 2014 have been used. Data for the upstream commodities (electricity, chemicals etc.) have, as far as possible, been chosen to fit the actual substance, but in some cases, analogues or approximations have been made. Primarily, data for 2014 have been used for the upstream commodities but when difficult to find data for 2014, older data have been used supplementary or as approximations.

3.2.1 Manufacturing at BillerudKorsnäs

Raw material for the paper products are manufactured by BillerudKorsnäs at two different sites in Sweden; Karlsborg and Skärblacka, see Table 4.

Table 4. Production site and final product for BillerudKorsnäs materials.

Production site BillerudKorsnäs	Material	Product
Karlsborg	Bleached Sack Kraft paper	D-sack
Skärblacka	Unbleached Kraft paper	Shopping bag

Site-specific data were received by BillerudKorsnäs. These data cover data of raw materials, purchased chemicals and fuels, net electricity consumption, emissions to air and water, and generated waste.

The emissions associated with the manufacturing process at each mill were calculated by BillerudKorsnäs based on energy balances over the mills. Several products are produced at each paper mill. The emissions and resource uses were all allocated, based on mass and function, to each specific product used for the applications analysed in this study. The main emissions to air and water measured at each paper mill were obtained from Karlsborg (BillerudKorsnäs 2014a) and Skärblacka (BillerudKorsnäs 2014b) for year 2014. Carbon dioxide (fossil) was calculated by IVL based on data received from the energy balances. Biogenic-based carbon dioxide has been considered as neutral i.e. the emissions and uptake have been considered equal in most cases. The biogenic carbon dioxide is only shown when the biogenic uptake and emissions are not balanced. Other emissions associated with the manufacturing of paper, but which are rarely measured at the sites, are nitrous oxide (N_2O), methane (CH_4), ammonia (NH_3), non-methane volatile organic compounds (NMVOC), and polycyclic aromatic hydrocarbons (PAH). These emissions were calculated by IVL based on standard emissions factors developed by the Swedish Forest Industries Federation for general paper production (Kindbom et.al. 2006). The covered emissions for the LCA are summarized in Table 5.

Table 5. Emissions from the manufacturing process at BillerudKorsnäs included in the LCA.

Emissions to water	Emissions to air	By IVL calculated emissions
COD	Nitrogen oxides (NO_X as NO_2)	CO_2 fossil
Nitrogen	Sulphur oxides (as SO_2)	N_2O
Phosphorous		CH_4
Suspended solids		NH_3
		NMVOC
		PAH

Forestry

Forestry was modelled based on (Berg et. al. 2005) and covers the production of timber from cultivated forests. The data cover the entire process from plant nursery, plantation, silviculture, forest thinning and forest felling. According to (Berg et. al. 2005), a total energy use for the above processes was calculated to 82 MJ/m^3 sub (solid under bark) which represents a Swedish average. The energy use is mainly diesel consumption for different machines. All energy use has been allocated to the main product i.e. the logs calculated as solid wood under bark. Branches, treetops etc. are by-products, which can be used e.g. as fuels or in other applications. These by-products are considered to be outside the system boundary. Data for the emissions from diesel engines in construction machines were taken from (UNFCCC 2012). The diesel has been modelled as 100% fossil diesel, hence no biodiesel has been assumed in the fuel blend.

Chemicals, electricity and fuels

For the production of chemicals and fuels, database data from thinkstep 2016 and Ecoinvent 3.1 were used. BillerudKorsnäs purchases chemicals for the manufacturing process from retailers in different countries. Therefore, modifications of the database data for the chemicals were made when necessary, by substituting European average electricity mix, for country specific electricity, also from database (Ecoinvent 3.1). For hydrogen peroxide and sodium chlorate, EPD data from the manufacturer Eka chemicals (Eka 2009a and Eka 2009b) were used. Chemicals that were less than 5 kg/ton paper has been excluded.

Information about total purchased fuel (diesel) for internal transports at the mills were received from BillerudKorsnäs. The fuel use was allocated by mass based on yearly total production of the used paper grades at each mill. Emissions from the internal transports were based on database data (Ecoinvent 3.1).

For transportation of heavy and light fuel oil used in the manufacturing process, and fuel for internal transports, a distance of 200 km by truck was assumed. The impact of using ship was also investigated and the results shown very little impact on the overall results for the mills (less than 0.05 %).

BillerudKorsnäs purchase residual electricity from Vattenfall (BillerudKorsnäs 2016a). The mix for 2014 (Vattenfall 2016) as well as g CO_2-eq./kWh, can be seen in Table 6. Upstream data for nuclear and hydro power was based on Vattenfalls EPDs (EPD 2013; EPD 2015).

Skärblacka has an excess of energy, which is used in a district heating system for the close-by society. The excess energy generated from the mill is actually quite large, however, since the society, which utilizes district heating is relatively small, only a small amount of the excess heat can be recovered in the close-by district heating system. However, this energy utilization has a positive effect on the energy system for the local society in question.

Table 6. Vattenfall´s residual mix for 2014 and CO_2-eq./kWh.

Energy type	Vattenfall mix 2014
Nuclear power	50.5 %
Hydro power	48.7 %
Wind power	0.8 %
g CO_2-eq. per kWh	7.3 g

3.2.2 Kraft paper (European average)

The comparative cement sack is based on 100 % virgin fibre, this is the usual case for cement sacks in Europe since the virgin fibre offer the strength and quality which is necessary for cement sacks (BillerudKorsnäs 2016b). For modelling the European generic cement sack, a model (dataset) was built in Gabi based the gate-to-gate data presented in (FEFCO 2015) for Kraftliner. Since this data did not include NMVOC, CH4, N2O and NH3, these emissions were, as for BillerudKorsnäs mills, added by calculations based on standard emissions factors developed by the Swedish Forest Industries Federation for general paper production (Kindbom et.al. 2006). However, this data includes 36 % input of waste paper in the production, therefore recalculations were made in order to receive 100 % virgin. This was done by substituting 360 kg/tonne of the recycling process (described in 3.2.3) from this dataset. Then 640 kg virgin is left, hence the results are then multiplied by 1.5625 in order to scale to 1000 kg 100 % virgin Kraft paper.

To the generic cement sack, a plastic film (HDPE) is glued inside the bag, this is done during the conversion step. This is not done for the D-sack, which instead has a coating, which is applied directly after the paper production at Karlsborg mill.

No data has been included neither for filling the generic cement sack nor for the D-sack, since this operation is considered to be equal for both sacks. Likewise, has not the transportation of the actual cement been accounted for, only transportation of the sacks themselves.

3.2.3 Recycled paper (European average)

For modelling of the paper recycling process, data was based on (BREF 2015), which is a reference document for the best available technology within the EU for different industrial areas. The used energy data are shown in Table 7. Data for the recycling process for "packaging paper" described in BREF in table 6.1 was used with European average electricity mix.

According to the BREF 2015, 1100 kg waste paper is required to make 1 tonne recycled paper. Therefore, it was assumed that 100 kg paper is left in a slurry which is used as internal fuel (thermal energy) at the mill. The heat value of the slurry is assumed to be 8 MJ/kg[1], and with an assumed thermal efficiency of 80 %, the thermal energy from the slurry is 640 MJ/tonne paper. Hence, this amount was withdrawn from the total thermal energy required for the paper machine (4020 MJ) = 3380 MJ/tonne paper.

After the paper is recycled into pulp, it passes the paper machine, which produces the paper. The data for the paper machine were taken from table 7.3 (thermal energy) and 7.11 (electricity) in (BREF 2015). For electricity European average mix was used and for heat generation, this was modelled based on the same distribution reported for Testliner (Fefco 2015) (natural gas: 88 %, HFO: 0.06 %, light fuel oil: 0.02 %, Hard coal: 3 %, lignite: 4 %, biofuel: 1 %, waste: 3 %). Natural gas is the most common fuel and a combined heat and power production (CHP) is also common. However, due to the large impact, this mix was changed to 50 % natural gas and 50 % biomass in the sensitivity analysis in section 4.2.3.

Table 7 summarizes the values used for energy consumption of the paper recycling process as for the paper machine.

Table 7. Energy consumption for the paper recycling process and paper machine (BREF 2015).

Energy consumption	Paper recycling process	Paper machine
Electricity [kWh/ton]	250	550
Thermal energy [MJ/ton]	-	3380 (4020)

The mill is assumed to have its own biological treatment plant and hence, the emissions from the recycling mill were taken from table 6.10 in (BREF 2015) (after biological treatment).

In order to ensure the strength and quality of the recycled paper, a certain amount of primary fibres has to be added during the fibre cycle (BREF 2015). In this study, 15 % virgin fibres were assumed to be added to the recycled paper bag, this was based on expertise at BillerudKorsnäs (BillerudKorsnäs 2016b). For this database data was used, which represents European average.

[1] *A net calorific value of 8 MJ/kg represents a moisture content of approximately 50 % in the reject fibre sludge. No filler is used in this type of paper, therefore no filler is assumed to be present in the reject fibre sludge.*

3.2.4 Recycled LDPE

Data for the recycling of polyethylene was based on data from a recycler in Sweden (Miljösäck 2014). Collected municipal plastic waste is delivered to Swerec. Here, soft and hard plastic are separated by air, into respectively polymer type. These are then crushed to flakes, which are washed, and then melted into pellets; these are then sold to other companies that manufacture different plastic products (Swerec 2014). One such manufacturer is Miljösäck, at which the different plastic fractions are used as raw material for the plastic bag manufacturing, including printing.

For collection and transport to the recycling facility, 500 km truck with trailer with the following driving conditions has been assumed:

- Driving share motorway: 10 %
- Driving share rural: 30 %
- Driving share urban: 60 %

Since the data for the plastic recycling, film blowing, converting and printing was given in aggregated form, the results cannot be presented as the different processes "raw material production" and "packaging production", as it can for the other products in this study. Therefore, the material production (recycling process) as well as the conversion to bags, is both covered in the "material production" bar. Most plastic bags consist of a mix of post- and preconsumer waste, in order to receive the right strength and quality. Hence, the recycled bag was modelled with 50 % postconsumer and 50 % preconsumer plastic (H&M 2016), where Miljösäck data was used for the postconsumer share and the preconsumer share was approximated with virgin material. A sensitivity analysis with 100 % postconsumer was also performed.

3.2.5 Renewable LDPE

The PE is assumed to be produced from ethanol based on sugar cane. The cultivation of sugar cane as well as the conversion into PE is assumed to take place in Brazil. This is because Brazil is the world's largest sugar cane ethanol producer (sugarecane.org). For the ethanol production, the Ecoinvent dataset "BR: ethanol production from sugar cane" (Ecoinvent 3.1) was used. In order to receive the LDPE, the ethanol then goes through different chemical process steps. The first step is a catalytic dehydration from ethanol to ethylene. This was modelled based on (Cameron et.al 2012) and stoichiometric calculations. Secondly, the ethylene is polymerized into polyethylene. This was modelled by substracting "DE: Polyethylene Low Density Granulate (LDPE/PE-LD)" from the dataset "DE: Ethene (ethylene)" from thinkstep 2016.

3.3 Modelling of the packaging products

The paper, which is produced at the BillerudKorsnäs sites, is transported to a converter, which manufactures the actual product, including printing. This chapter presents the data used for the different packaging products. There is also a description of the upstream electricity used in the conversion processes as well as the transports.

Electricity and energy

The conversion and printing (manufacturing of the packaging product) takes place in Germany, both for the cement sack and the shopping bag. Therefore, German average electricity mix (thinkstep 2016) was used. For thermal energy used in the conversion/printing of the product, natural gas has been assumed. For this, database data from thinkstep 2016 ("DE: Thermal energy from natural gas") has been used.

Transports

For trucks, trains, and ships, database data from thinkstep 2016 were used. Transports by truck within Europe were modelled with a diesel driven truck (euro 4) 34-40 tonne gross weight, and 6 ppm sulphur content in the diesel. Ship transports were modelled with an ocean going ship running on heavy fuel oil with a sulphur content of 2.7 wt %. Train transports were assumed to be electricity driven. For the fuels, the study covers all upstream activities from raw material extraction to emissions occurring during combustion (well-to-wheel).

Many transports are limited by the maximum load weight of the vehicle while some transports of bulky loads are limited by the truck's volume capacity and these goods will thus not reach up to the maximum load weight of the truck. This effect needs to be taken into account in the transport calculations. In many cases, the transport of plastic bags and plastic sacks are weight limited while the corresponding transport of paper products is limited by volume.

A normal trailer loads about 31 tonnes and can carry 66 pallets. A pallet of paper products weighs about 300 kg and a corresponding pallet with plastic products weight about 500 kg. This means that a trailer with 66 pallets of paper products of 300 kg each weight in total 66*300=19.8 metric tonnes. This reaches therefore not up to the truck's maximum load of 31 tonnes. The corresponding pallet with plastic products weight 66*500=33 tonnes. This is more than the maximum load weight. The transportation is here limited by weight.

To compensate for the paper product's volume limitation, it can be expected that paper goods can only load 19.8/31=0.6387 i.e. approximately 64 % of maximum load. To compensate for the volume restriction, one thus has to divide the transport data of the weight-limited transport with this figure. This means for example that for a transport, the NOX emission is 1/0.64=1.5625 times higher per tonne*km when carrying paper bags than when carrying plastic bags. In addition, the paper bag weight 74 g and the plastic bag weight 42 g. This means that the mass of paper bags to be transported is 74/42=1.762 times larger than the plastic bags. The total transport work thus becomes 1.5625*1.762=2.753 times larger for the paper bag compared to the plastic bag. The transport distances and type of vehicles for the plastic and paper transport solutions are summarized in Table 8.

Table 8. Modelled transport systems for the studied products.

Product	Product	Material transport	Packaging transport (to final customer)
Cement sack	D-sack	Karlsborg – Düsseldorf (2350 km): • 80 % by train • 20 % Truck with trailer	To filling (La Couronne): Truck with trailer (950 km) To final customer (France): Truck with trailer 500 km
	Cement sack	Transport central Germany: Truck with trailer (500 km)	To filling (La Couronne): Truck with trailer (950 km) To final customer (France): Truck with trailer 500 km

Product	Product	Material transport	Packaging transport (to final customer)
Shopping bag	BillerudKorsnäs bag	• Skärblacka – Trelleborg: Train (500 km) • Trelleborg – Frankfurt: Truck with trailer (870 km)	To final customer (London): Truck with trailer (765 km)
	Recycled paper bag	• Transport to Frankfurt: Truck with trailer (500 km)	To final customer (London): Truck with trailer (765 km)
	Recycled plastic bag	Collection of waste and transport to recycling plant: Truck with trailer (500km): • Motorway driving: 60 % • Rural driving 10 % • Urban driving: 30 %	To final customer (London): Truck with trailer (765 km)
	Renewable plastic bag	• Transport to Rio de Janeiro harbor: Truck with trailer (1000 km) • Rio de Janeiro - Hamburg: Ship (10 200 km) • Hamburg - Frankfurt: Truck with trailer (490 km)	To final customer (London): Truck with trailer (765 km)

3.4 System expansion

System expansion means that the stated system boundaries are modified. This is performed to show the effect the processes in a system can have on the surrounding society and to include these effects in the study and in the results. It should be mentioned that the system expansion of this assessment is not part of the directly related impact of the product. However, the effects are real but are shown separately by convention in the LCA methodology. A typical example of system expansion is to include the positive effects of the use of the heat from waste incineration or process surplus heat in the surrounding society. The use of surplus heat is an important method for saving energy resources and reducing emissions. In this study, system expansion was made by also including end-of-life (waste management) for the packaging products; with and without avoided emissions (from generated electricity and heat as well as virgin material production).

The end-of-life was modelled based on statistics from Eurostat for year 2014 for the fractions; paper and cardboard packaging and plastic packaging (Eurostat 2014) for France and the UK specifically. As can be seen in Table 9, the recovery rate for packaging is not 100 %. Therefore, the remaining part is assumed to end up in the municipal solid waste stream (MSW), of which is assumed to go to either incineration or landfill. Therefore, statistics for the distribution between landfill and incineration for MSW was also extracted from the Eurostat database and the final percentages were recalculated and can be seen in Table 9. The generic cement sack also consists of a polyethylene film; however, this has also been accounted for in the model.

Table 9. Statistical data for waste management for packaging waste (Eurostat 2014). Incineration includes energy recovery at waste incinerators.

Waste management for packaging waste	France	The UK
Paper and cardboard packaging:		
Recovery rate	*97%*	*80%*
Recycling	94%	73%
Incineration	4%	17%
Landfill (MSW)	2%	10%
Plastic packaging:		
Recovery rate	64%	48%
Recycling	25%	38%
Incineration	60%	35%
Landfill (MSW)	15%	27%

Usually, one can recycle the paper fibres and the polymer chains more than once. It has been reported that paper fibres can go through 6-7 cycles before it becomes too weak and cannot be used anymore. The same number of cycles is valid for the polymer chains (Fti Förpacknings- och tidningsinsamlingen, Packaging and Newspaper Collection Service in Sweden). Usually after recycling, the materials are of inferior quality and can only be used for products with lower quality demands, called "down cycling". Recycling of that product will in turn become another product with lower quality. In this study, only the first recycling cycle is accounted for. Hence, no effects from possible future recycling processes have been taken into account in this study, since they can be considered belonging to the next product system.

For the paper recycling process, the same model was used as for the studied product "recycled paper bag". Likewise, for the recycling process of polyethylene, this was based on the same model as the studied product "recycled LDPE bag".

Since the generic cement sack also contains a plastic film, the recycling of this has been approximated with the recycling process from Fiskeby board. Fiskeby is a Swedish paper fibre recycling company producing paper board from recycled fibres (from cartons, used beverage cartons etc.). They separate the fibres from the plastic fraction, which is utilised internally and covers a part of their energy demand. Data for the Fiskeby process was received from (Fiskeby 2015) to IVL within another project, but can be used in other projects as well. The data was adjusted in order to fit the actual amount of plastic film in the generic cement sack in this study.

Avoided emissions

When the material, plastic or paper, is recycled, the material is assumed to replace other virgin material production. Hence, emissions from other virgin material production are considered to be avoided, and this is called “avoided emissions or credits”. The avoided emissions from virgin material production have been subtracted. No effects from possible future recycling processes have been taken into account in this study.

For the paper products (the generic cement sack as well as the paper shopping bags), it has been assumed to replace virgin Kraft paper, for which data for Kraftliner (Fefco 2015) has been used, as described in section 3.2.2.

Recycled polyethylene granulates was assumed to replace average virgin polyethylene PE, for which database data was used (“DE: Polyethylene Low Density Granulate (LDPE/PE-LD)”)

Incineration was assumed to be performed with energy recovery, both electrical and thermal. It was assumed that the generated electricity from incineration replaces European average electricity from grid, and that the generated thermal energy replaces process steam from natural gas. Database data (thinkstep 2016) was used for emissions associated with incineration of paper and plastic, which also included energy recovery.

Emissions associated with landfill of paper and plastic was modelled with database data (thinkstep 2016). The landfill scenario for paper was modelled under the assumption that 28% of the generated landfill gas (methane) was recovered and used for electricity production, this is according to the database data (thinkstep 2016). The produced electricity from the landfill gas has been assumed to replace European average electricity from grid.

4 Results

Below are the results for the cement sacks and the shopping bags presented for each impact category respectively. The numeric values for the results diagrams can be found in Appendix I. The system expansion with and without avoided emissions is shown separately. The results for the paper mills are given per metric tonne.

4.1 Cement sack

Global Warming Potential

Figure 2 shows the climate impact for the cement sacks. In total D-sack has about 30% lower impact than the generic cement sack.

The “packaging production” meaning the conversion and printing has the largest climate impact over the life cycle for both sacks and contributes to about 58 % and 50 % of the total climate impact of the D-sack and generic cement sack respectively. This is due to the electricity used for making the sacks (conversion). The packaging production is performed in Germany and the German electricity mix has a climate impact of around 600 g CO_2-eq./kWh. For the generic cement sack, the packaging production step also includes the plastic (HDPE) film, which is glued inside the bag and thus increases the impact somewhat more than for D-sack.

The transports (packaging and material) are of less importance, this is because both the converter and the customers are located in Europe and hence the transport distances become relatively short. Although, the material from Karlsborg mill is transported a longer distance than for the generic sack, most of the transport is done by electricity powered trains, which have a lower impact than transports with trucks, which is the case for the generic sack. The impact of the packaging transport (to customer) is almost the same for the compared sacks, the difference is due to the difference in weight of the sacks.

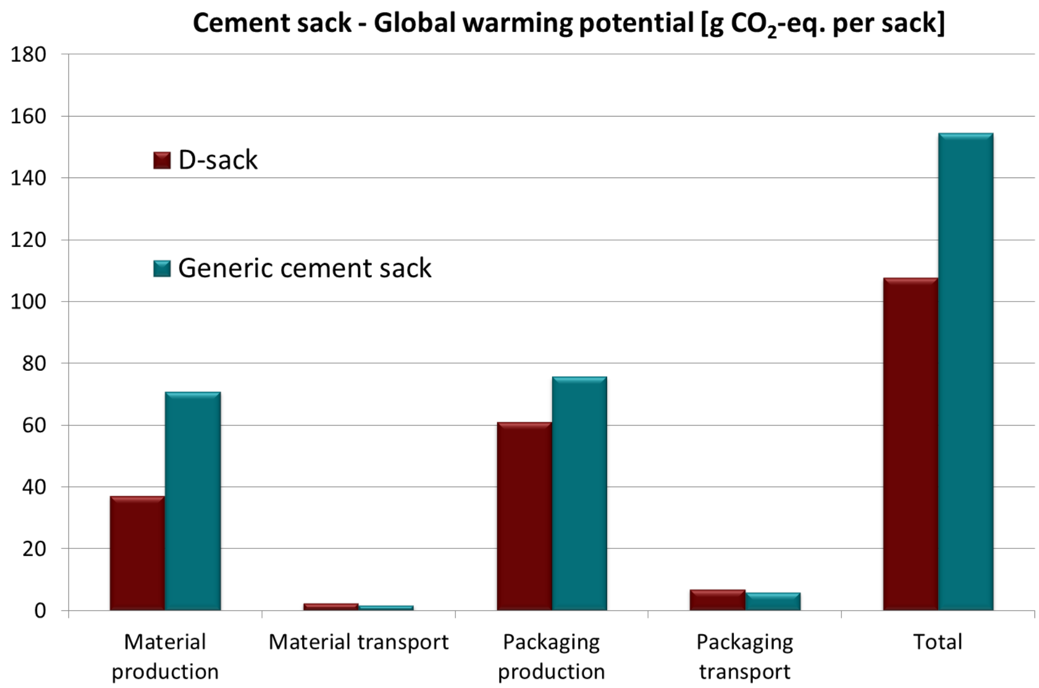

Figure 2. Global warming potential for the cement sacks, from raw material production to final product at customer

The global warming potential also per tonne produced paper ("Material production") is higher for the generic European mill than for Karlsborg mill. This is mainly because Karlsborg mill has a high amount of biofuels, whereas European mills more often run on fossil fuels. Also Karlsborg mill utilizes excess energy from the mill both for heat and electricity generation which is used internally at the mill, meanwhile the electricity which is bought from grid has a relatively low impact (Vattenfall 2016).

The paper used for the generic cement sack (without the HDPE-film) has an impact of around 400 kg CO_2-eq./tonne paper. This is dominated almost equally by the electricity usage (European average mix), as by the direct CO_2 emissions from the European mill, which originates from fossil fuel sources such as natural gas, hard coal, heavy fuel etc. Since Karlsborg buys electricity from Vattenfall, with low fossil sources in their supply mix, the impact from electricity becomes low.

The climate impact from Karlsborg mill, per tonne paper, is presented in more detail in Figure 3. Since the fossil energy usage and, as a consequence, the direct CO_2 emissions from the mill is low, other parameters becomes more important such as chemical usage. Figure 4 shows the distribution of climate impact of the chemicals used at Karlsborg mill. The paper used for the D-sack is coated which is performed directly at the mill. These have a large influence on the papers total climate impact.

In Figure 5, the contribution of the direct emissions from the mill is shown. Even though methane is a very strong greenhouse gas, the emissions are of less importance at Karlsborg mill, since these are kept at a low level.

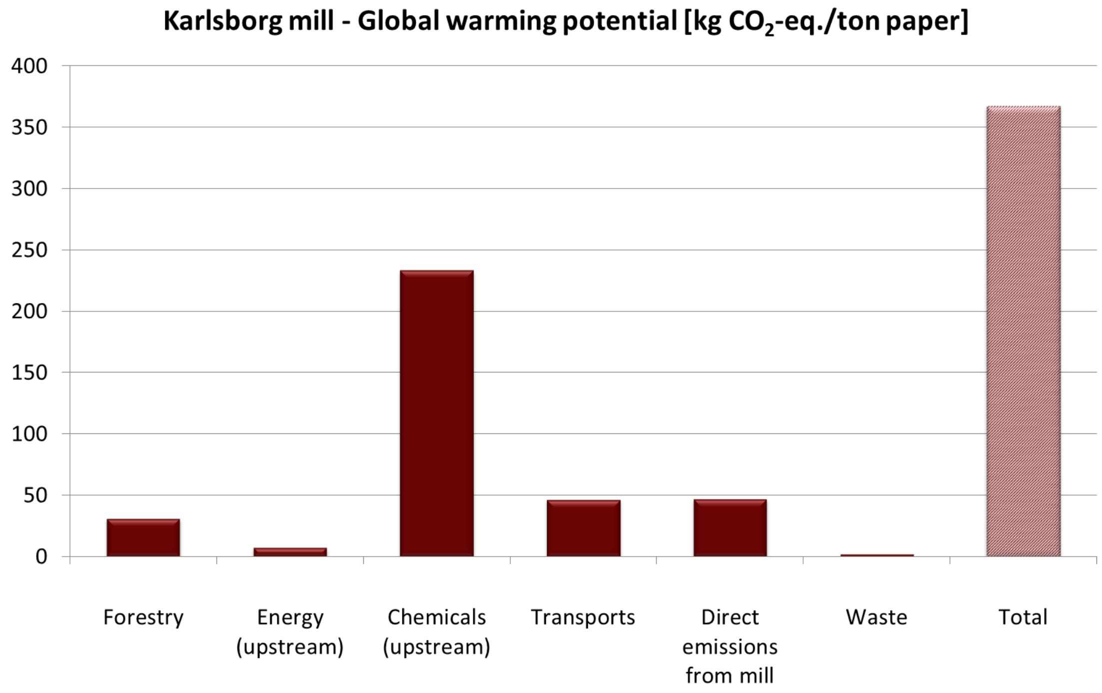

Figure 3. Global warming potential for the production of 1 tonne paper at Karlsborg mill

In Figure 3, "*Forestry*" refers to those emissions, which are generated during activities in the forest, which are required for generating wood such as production of seedlings, silviculture, logging and forwarding.

"Energy (upstream)" refers to those emissions generated during production (upstream) of external energy (production of electricity and fuel oil) that is used in the manufacturing process. Note that the emissions released during combustion of the fuel oil are included in "*Direct emissions from mill*".

"Chemicals (upstream)" refer to those emissions generated during production of the chemicals used in the production of paper. Hence, these emissions are not emitted at the mill, but where the production of the chemical takes place.

"Transports" refer to transports of all commodities (forest, chemicals and fuels (oil, diesel, gasoline)) to the mill, as well as emissions from internal transports at the mill that have a very small impact.

"Direct emissions from mill" refers to those emissions that are emitted from the mill because of paper manufacturing.

"Waste" refers to the waste, which is generated during production of the paper and also transportation of the waste to waste management facility.

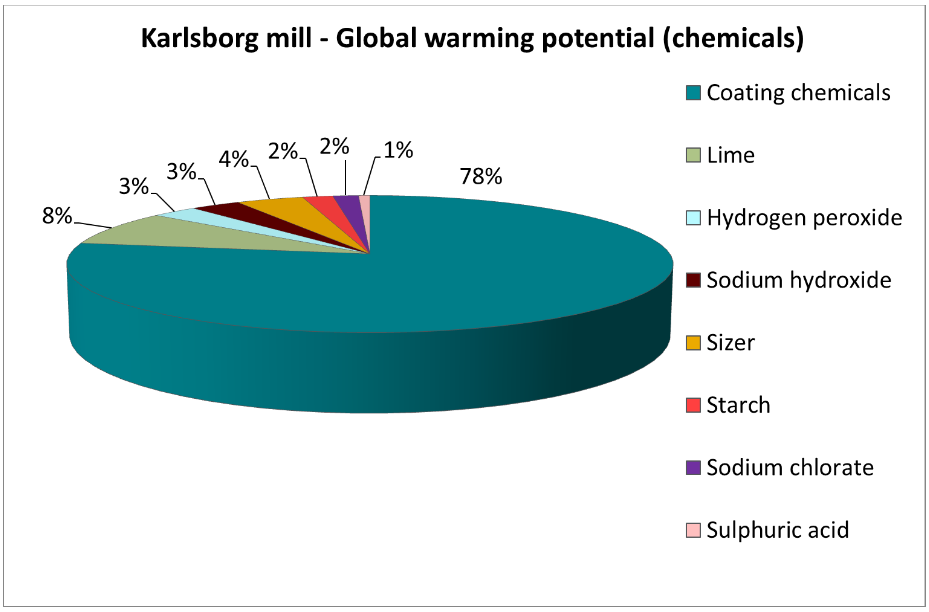

Figure 4. The distribution of the global warming potential from the chemicals used at Karlsborg mill

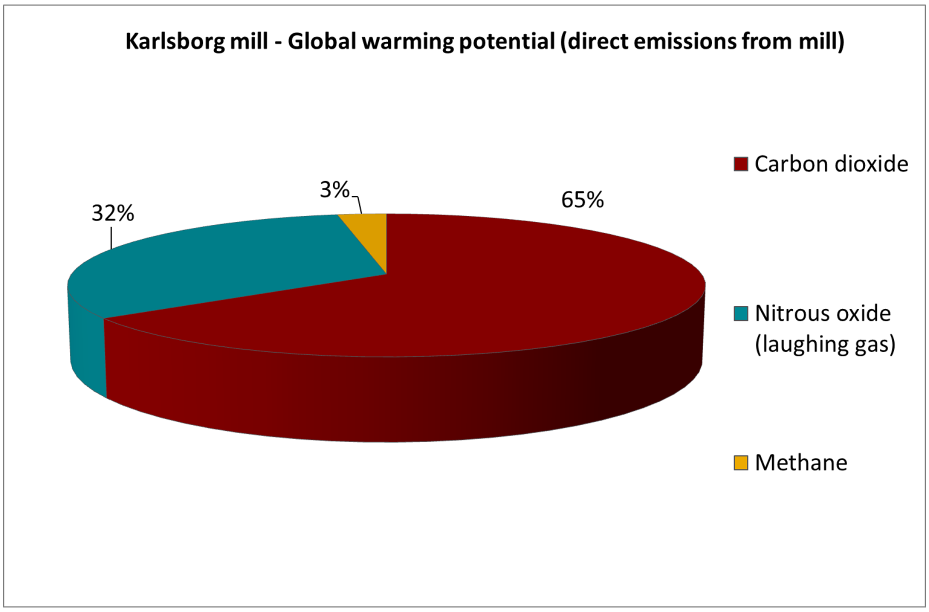

Figure 5. The distribution of the global warming potential from the direct emissions from Karlsborg mill

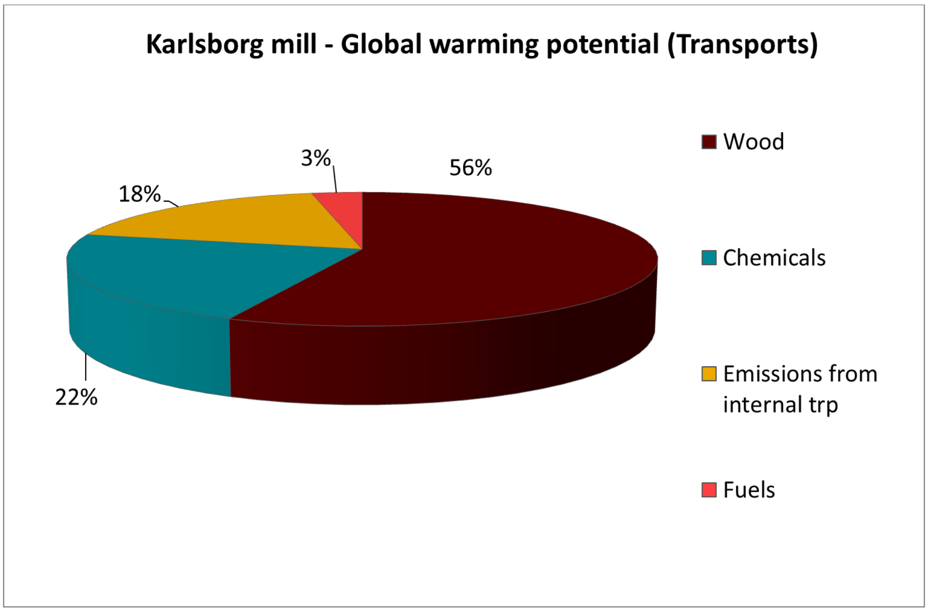

Figure 6. The distribution of the global warming potential from the transports to and at Karlsborg mill.

Acidification Potential

The acidification potential from the two cement sacks is shown in Figure 7. While the transport is of minor significance, the material production is the dominating contributor. For the generic paper, the electricity usage at the mill and the direct emissions from the mill are the most significant parameters for the acidification potential. The production at Karlsborg mill has a somewhat lower acidification potential than paper production at the average European mill and since the packaging production for the generic cement sack has a higher impact due to the addition of the HDPE film, the total acidification potential becomes higher for the generic cement sack.

The acidification potential per tonne paper at Karlsborg mill can be seen in Figure 8. Direct emissions due to the biomass fuel, such as nitrogen oxide, sulphur dioxide and ammonia (Figure 10) together with the chemicals (Figure 9), is the major contributors to the impact from the mill.

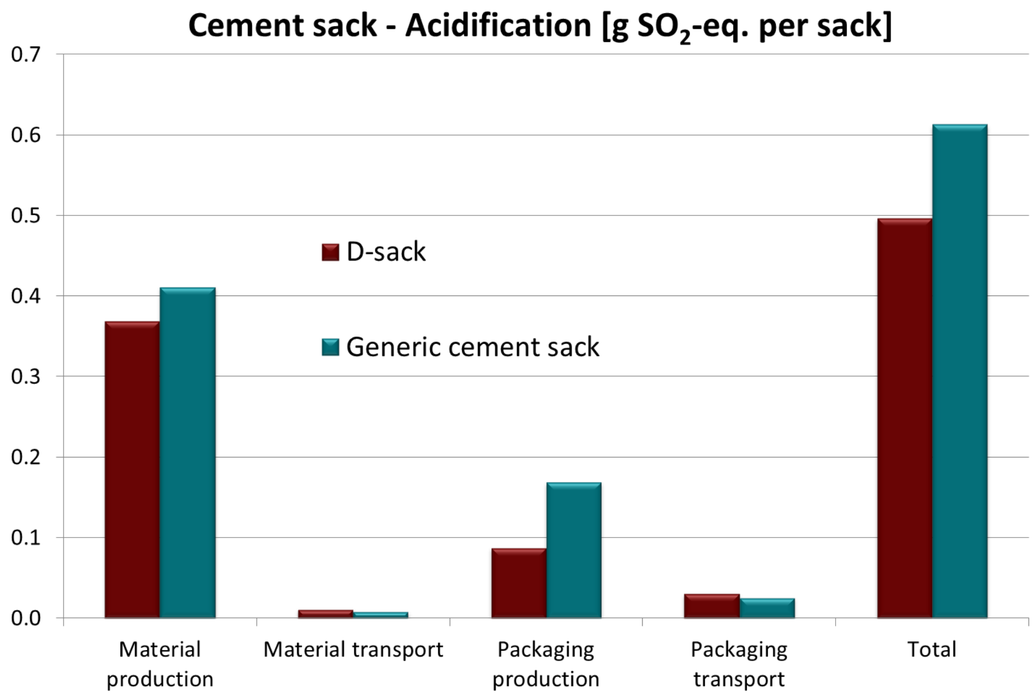

Figure 7. Acidification potential for the cement sacks, from raw material production to final product at customer

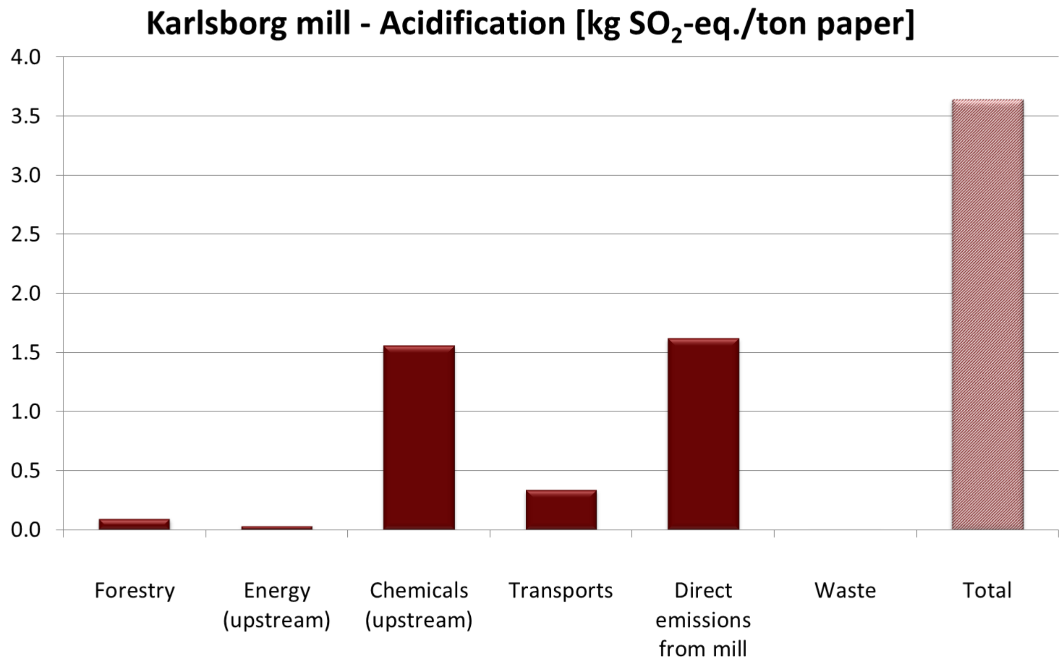

Figure 8. Acidification potential for the production of 1 tonne paper at Karlsborg mill

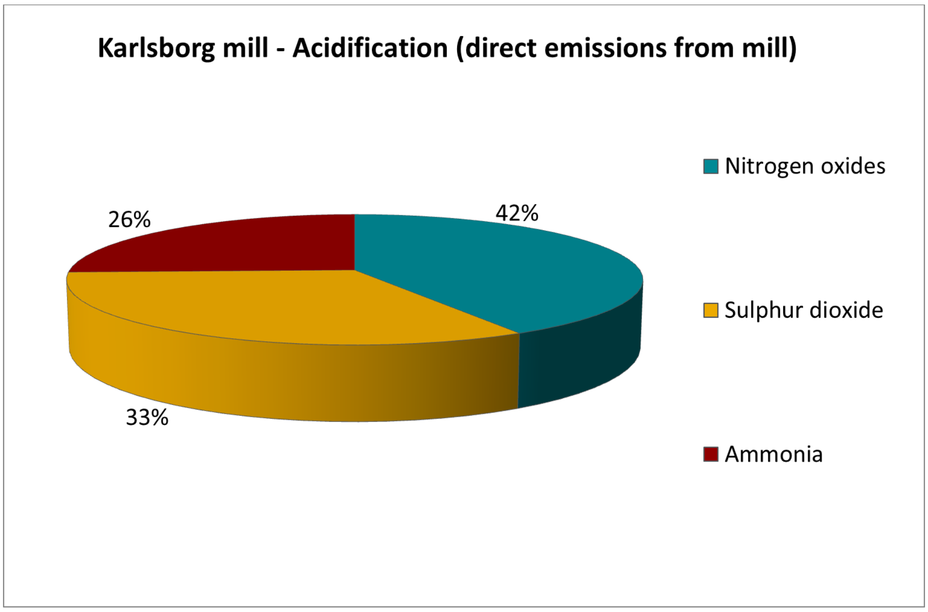

Figure 9. The distribution of the acidification potential from the direct emissions from Karlsborg mill

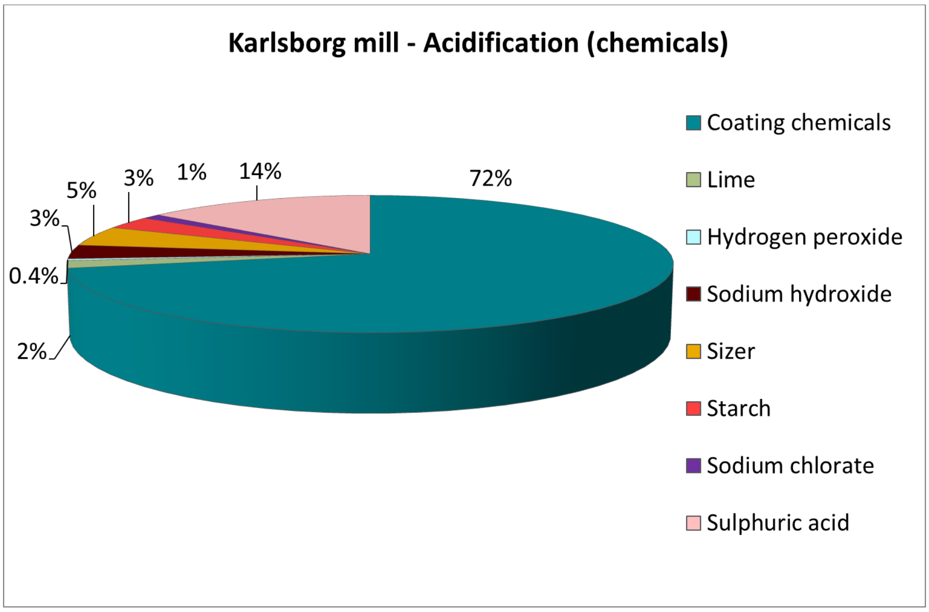

Figure 10. The distribution of the acidification potential from the chemicals used at Karlsborg mill

Eutrophication Potential

The impact on eutrophication is presented in Figure 11. The "Material production" clearly dominates the life cycle for both sacks. This is mainly because of direct emissions from the mills, such as, COD and phosphorous to water, but also nitrogen oxides to air. For Karlsborg mill, the COD is higher per tonne paper than for the generic cement sack. However, it should be mentioned that because Karlsborg is situated by the coast in the north of Sweden and although the recipient is the Baltic Sea, the eutrophication is not as a comprehensive problem as in the southern parts of the Baltic Sea. Hence, the regulations are not as strict for Karlsborg mill as for mills down on the continent, where the recipients are lakes or rivers, therefore allowing for a higher release of COD at Karlsborg than for the European mills. Since no geographical aspect has been considered quantitatively in this study these kinds of differences is neither reflected in the results.

As for the acidification, eutrophication is also effected when biomass is used as fuel in the paper manufacturing process. Biomass contains nitrogen, which is released as nitrogen oxides to air.

For the generic cement sack, the HDPE film and the glue, which is added in the "packaging production" step raises the impact compared to D-sack, which doesn't require this plastic film since it is coated instead.

As for the other impact categories, the transports are of minor significance for the eutrophication potential.

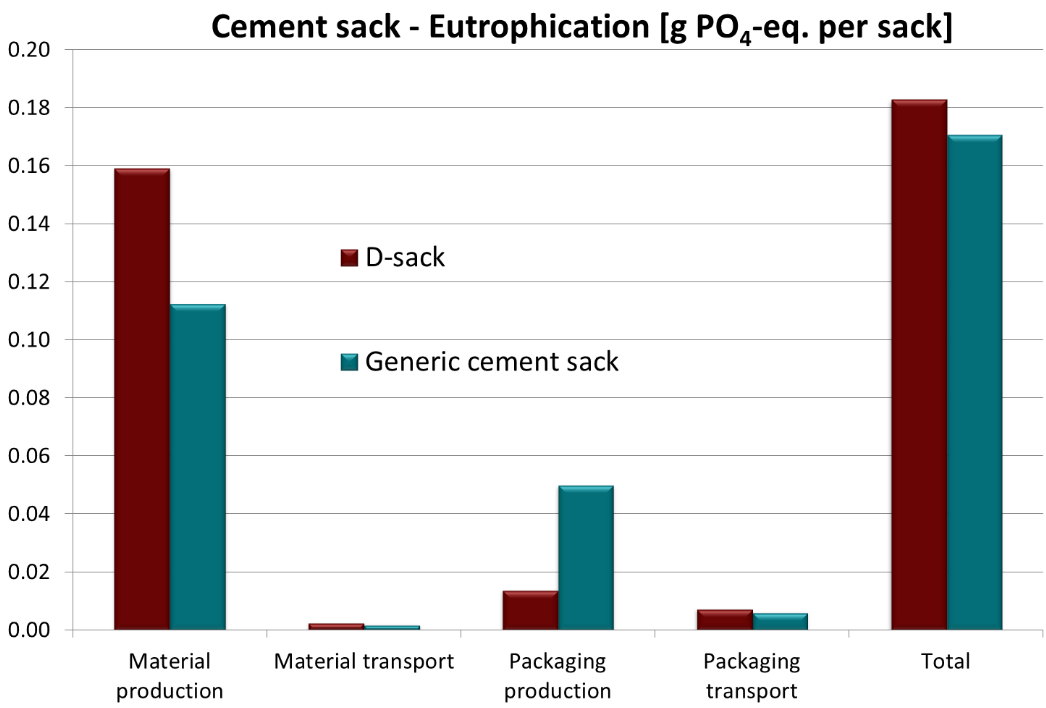

Figure 11. Eutrophication potential for the cement sacks, from raw material production to final product at customer

Figure 12 presents the eutrophication potential from Karlsborg mill, per tonne paper. The impact from the direct emissions from the mill dominates the eutrophication potential and their contribution can be seen in Figure 13, where COD released to water is of significant importance.

Figure 14 shows the relative impact from the chemicals. The manufacturing of the chemicals used the coating is the single most important chemical considering eutrophication.

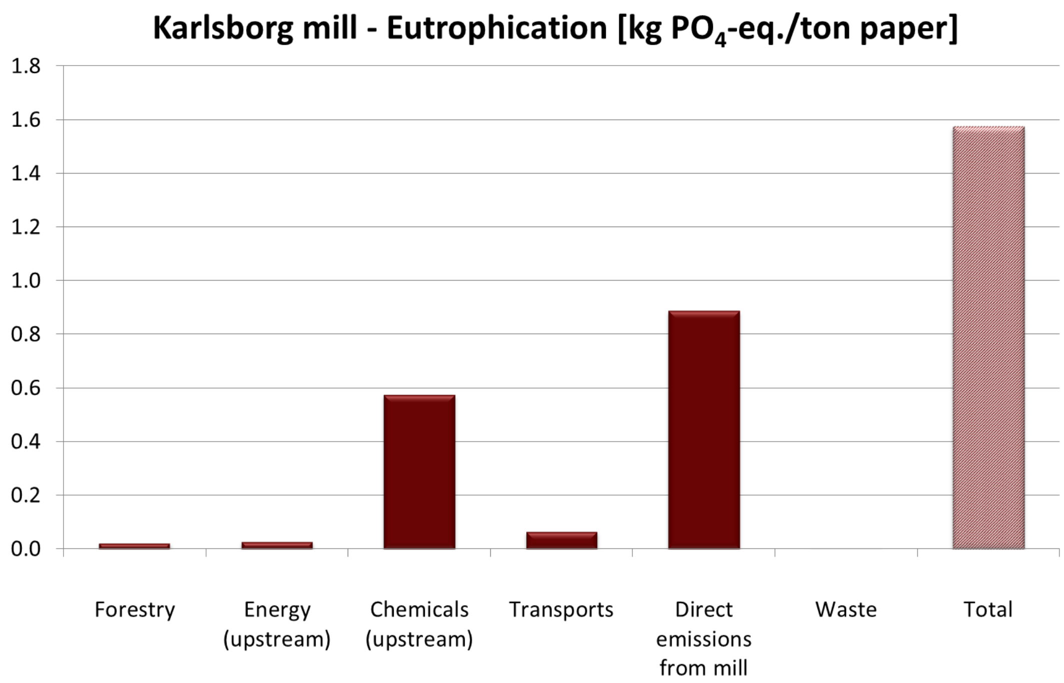

Figure 12. Eutrophication potential for the production of 1 tonne paper at Karlsborg mill

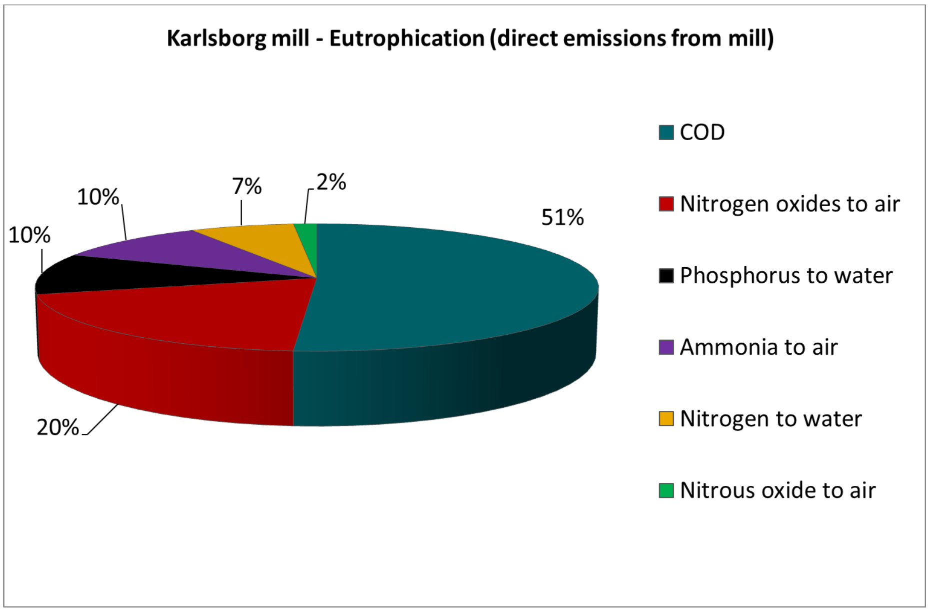

Figure 13. The distribution of the eutrophication potential from the direct emissions from Karlsborg mill

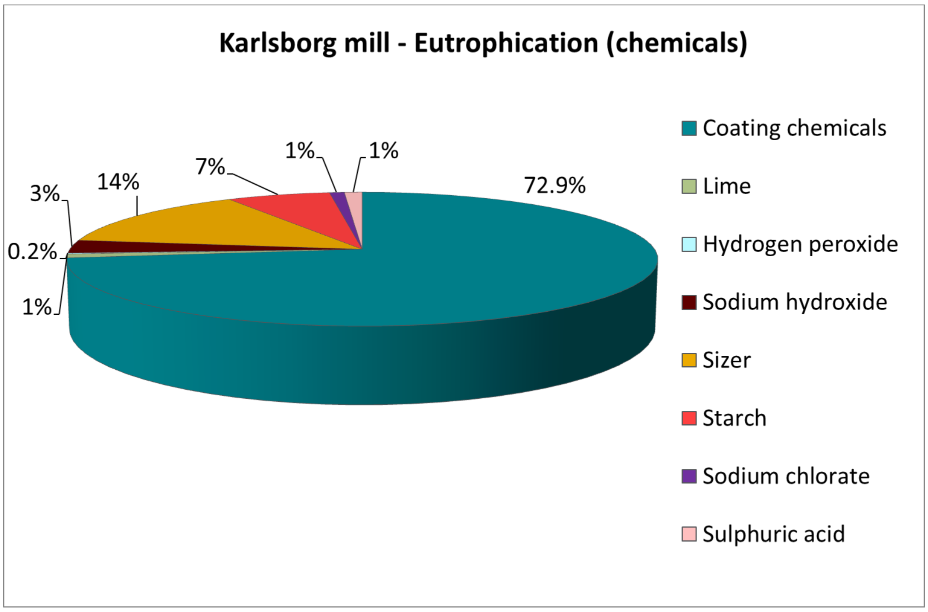

Figure 14. The distribution of the eutrophication potential from the chemicals used at Karlsborg mill

Ground level ozone formation potential

The impact on ground level ozone for the cement sacks is shown in Figure 15. Direct emissions, which are released from the mills during the material production, have most significance on the ground level ozone formation potential, see also Figure 16. For both mills, NMVOC is the single most significant emission, see also Figure 17. The NMVOC emissions originates mainly from terpene emissions, which are released during production and handling of wood chips. The relatively high emissions from the generic European mill results in a higher total impact on ground level ozone than from the D-sack.

The impact from the packaging production is mainly due to electricity during conversion. For the generic cement sack, around 12 % of the total impact is due to upstream manufacturing of the HDPE film, which is glued inside the sack.

Figure 18 shows the chemicals used at Karlsborg mill and their relative impact on ground level ozone formation potential. Again, the chemicals used in the coating process are most important.

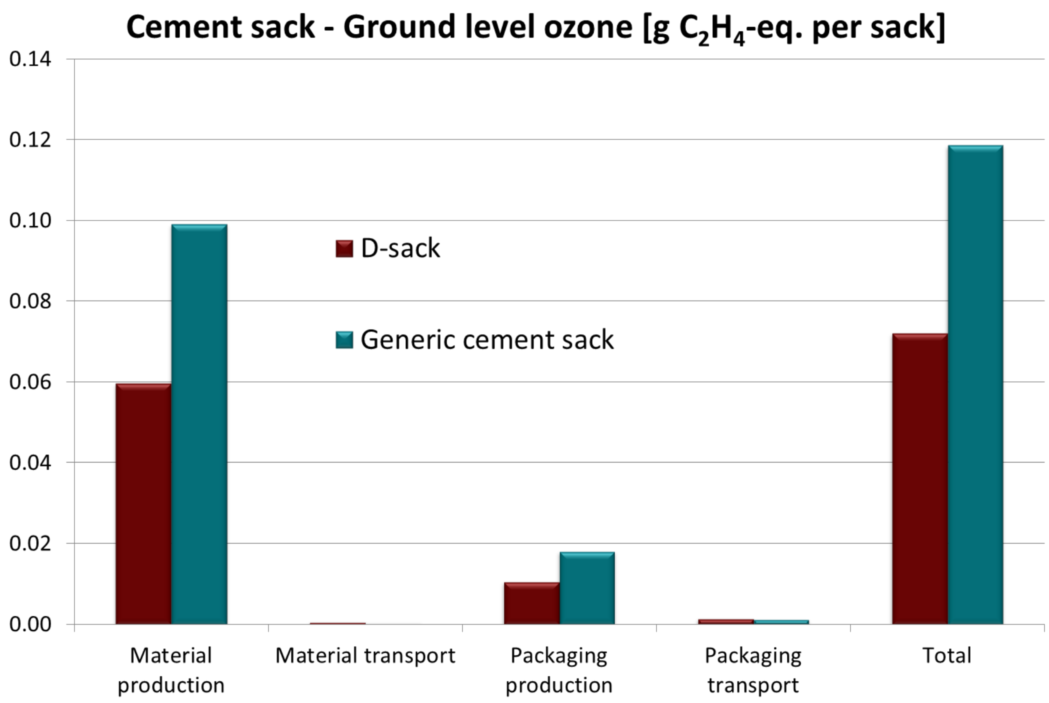

Figure 15. The impact on ground level ozone formation potential for the cement sack, from raw material production to final product at customer

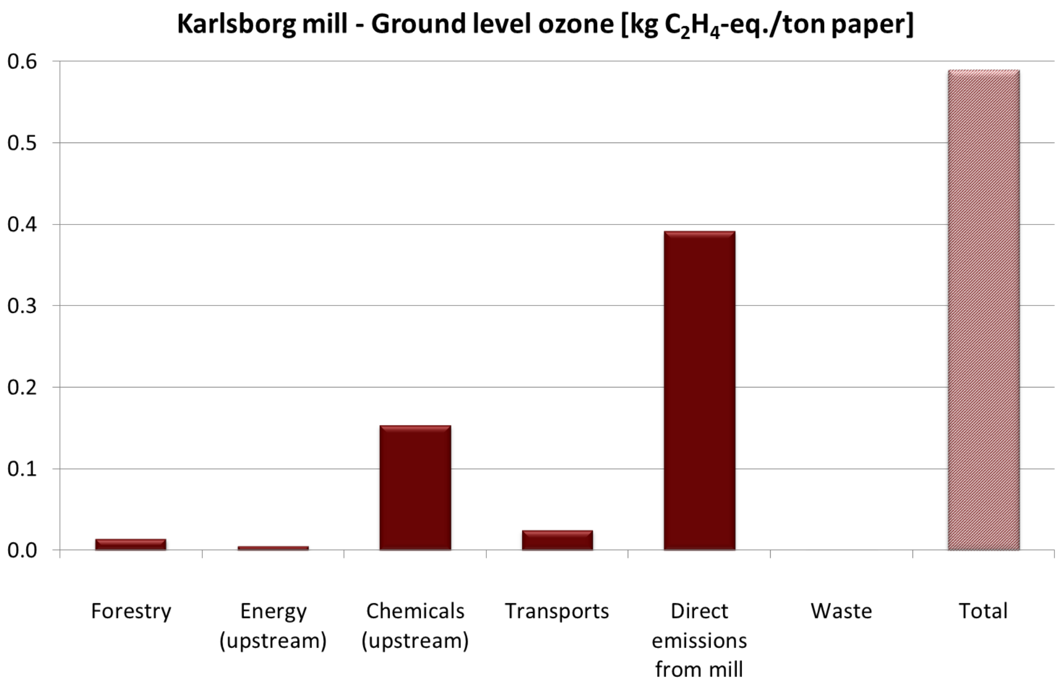

Figure 16. The impact on ground level ozone formation potential for the production of 1 tonne paper at Karlsborg mill

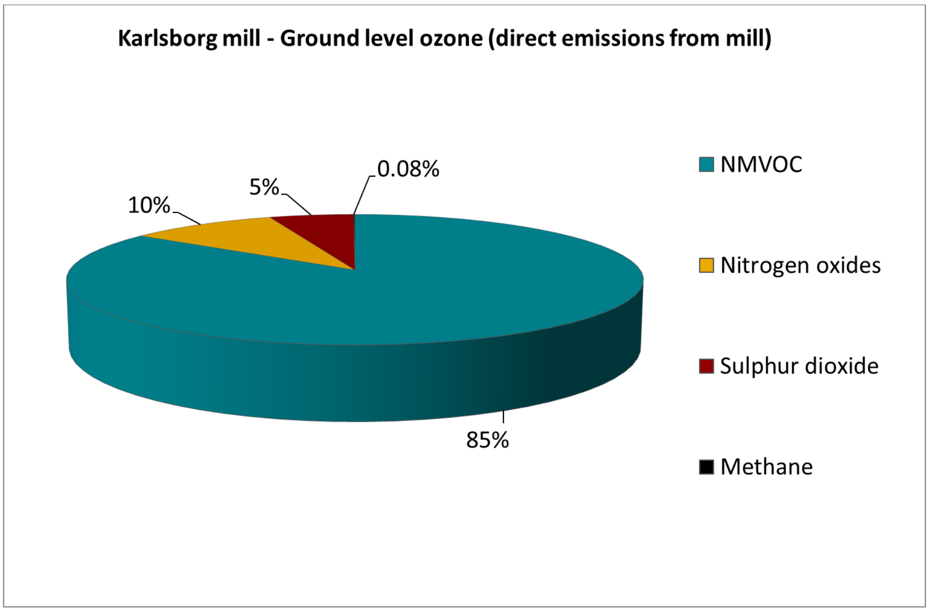

Figure 17. The distribution of the impact on ground level ozone formation potential from the direct emissions from Karlsborg mill

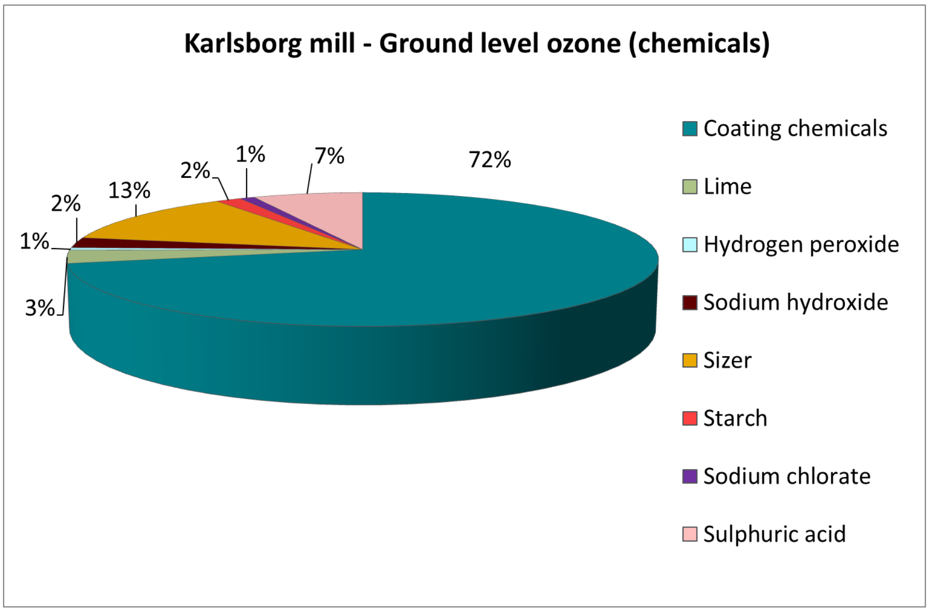

Figure 18. The distribution of the impact on ground level ozone formation potential from the chemicals used at Karlsborg mill

Primary energy demand

Primary energy is the energy contained in crude fuels (original energy resource) received as input to a system. Primary energy has not been subjected to any conversion or transformation. Figure 19 shows the primary energy required for the cement sacks during their life cycle from crude material to a final product at the customer (cradle-to-customer).

The share of renewable energy totally used for the sacks during their lifecycle is also shown in the Figure 19 (60%, and 53%). Renewable energy resources such as hydro, wind and solar energy, comes from electricity production. The high amount of biomass comes from the utilisation of biomass as energy during paper production. All integrated Kraft paper mills recover the lignin in the wood as black liquor in the recovery boiler, which then can be used as energy internally in the mill. This energy could not be used elsewhere except at the mill in contrast to purchased fuels such as fuel oil or coal. For making bleached Kraft paper, around 57 % of all the wood coming into the mill, is utilised as energy, the remaining 43 % ends up as fibres in the paper product.

Uranium comes mainly from the electricity mix used during conversion (German mix). D-sack uses somewhat more uranium due to the high amount of nuclear power in the Swedish electricity mix, used at the mill. The uranium resource has been based on the released heat in the nuclear reactor. Most of the natural gas originates from the German electricity mix during conversion for both sacks, but also from the upstream production of chemicals (D-sack) and HDPE (generic cement sack). Crude oil is used for both sacks for transportation, upstream manufacturing of chemicals and HDPE, as well as energy input at the paper mills.

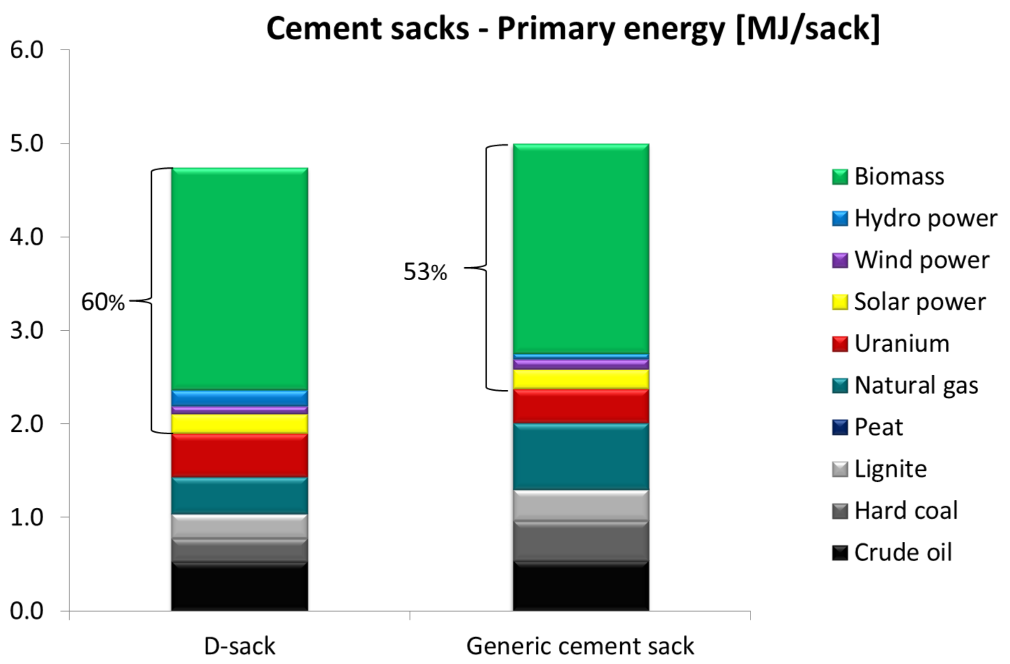

Figure 19. Primary energy demand, including all upstream activities such as energy, transports, chemicals etc. required for the sacks.

4.1.1 System expansion

Since the D-sack is dissolved in the cement mixture and therefore ends up in the concrete, no waste management has to be considered for the D-sack. However, there are some important aspects to consider.

Well inside the concrete, it is possible that the fibres undergoes alkaline hydrolysis and that the degradation products remains in the concrete unless they are volatile or transported out of the concrete by air or water flowing through the permeable concrete. For degradation of the fibres or their degradation products to carbon dioxide and water, a final microbial decomposition of the materials is required. The microbial activity in the concrete is very low due to the high pH value in the concrete. The direct oxidation with air of the materials is also very slow. Any direct decomposition to CO_2 in the concrete is therefore not expected to occur.

After the lifetime of the concrete product, which can be assumed to be approximately 100 years, the concrete structure is demolished. Large concrete blocks from the demolition can be used as backfill in underground structures or landfilled. The concrete can also be crushed to secondary materials and recycled as ballast or used as filler in new concrete. At landfill or aggregate applications, the concrete will be exposed to water where there is a possibility for the degradation products to leach out from the concrete to the environment. A more comprehensive study regarding the chemical effects of the degradation of fibres in concrete was conducted by IVL on commission by BillerudKorsnäs. Based on this, two time scenarios have been considered regarding the end-of-life for the D-sack;

- 100 years perspective
- Infinite time perspective

For the infinite perspective, it is assumed that the concrete structure is demolished and therefore CO_2 will be released into the atmosphere, whereas for the 100-year perspective, it is assumed that no CO_2 emissions are released from the concrete. Therefore, in the 100-year perspective, the D-sack is considered to be a CO_2 capture, since the carbon dioxide, which was once captured during tree growth and incorporated in paper fibres of the D-sack, are considered to still be retained in the concrete structure. This has been taken into account when calculating the "Total" and has been calculated as follows:

Dry paper consists of approximately 50 % carbon. The paper used in the D-sack has 90 % dryness, hence, 1 tonne paper equals 900 kg dry fibres, and of which 50 % is carbon, therefore 450 kg carbon/tonne paper. This means 450 kg carbon must have been captured during the forest growth, assumed taken from the CO_2 in the air:

C [12g/mol]+ O_2 [16 g/mol] --> CO_2 [44 g/mol]

450 kg x (44/12) = 1650 kg CO_2 uptake/tonne paper

No similar investigations have been made regarding emissions, which affects the other impact categories; acidification, eutrophication, and ground level ozone e.g. in landfills. Therefore, only the standard time scenario (100 years) is presented for these impact categories.

Global warming potential

Figure 20 and Figure 21 shows the global warming potential of the cement sack for the two time scenarios and when the end-of-life treatment (in France) has been included for the generic cement sack according to the statistics in Table 9. In the following figures, no avoided emissions (credits) due to virgin material or energy substitution during end-of-life has been accounted for, and therefore only the "burden", from the treatment processes; recycling, incineration and landfill, as well as transports is taken into consideration.

Landfill of paper has a higher climate impact per kg paper than the recycling process, however considering the high recycling rate of paper and cardboard in France (94 %), according to Eurostat, the impact from the recycling stands for around 90 % of the total impact from end-of-life. The climate impact from recycling is mainly because of the energy, which is required in the process (mostly natural gas). Incineration and landfill have a small impact because of the small share, which is treated accordingly in France. The impact from end-of-life has a small effect on the overall acidification potential. Landfill stands for around 3 %, while incineration only contributes with around 1 %.

For the D-sack, the negative bar in the end-of-life stage should be seen as an illustration of the carbon dioxide uptake. In the 100 years scenario, this carbon dioxide is assumed to be retained in the concrete structure, and therefore regarded as a carbon capture hence the total impact becomes negative. In the infinite time scenario however, in Figure 21, the CO_2 is assumed to be released in the atmosphere at some point, however since the same amount of CO_2 once was captured, the net equals zero, and it is therefore not illustrated in the figure.

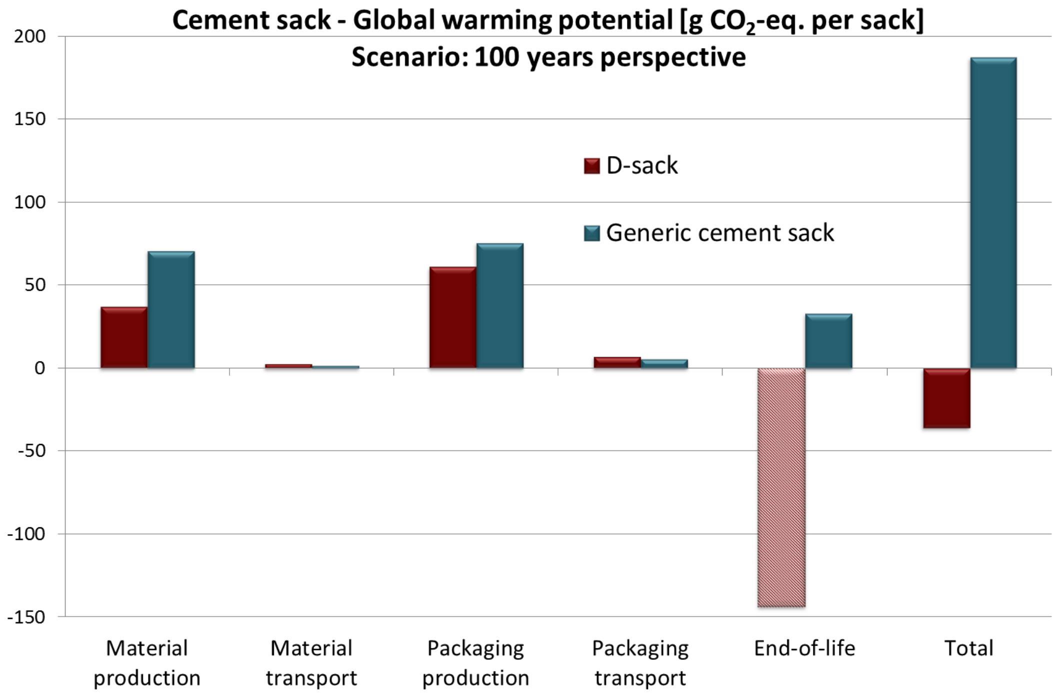

Figure 20. Global warming potential for the cement sacks, when also end-of-life for the generic cement sack has been included, for the 100 years scenario

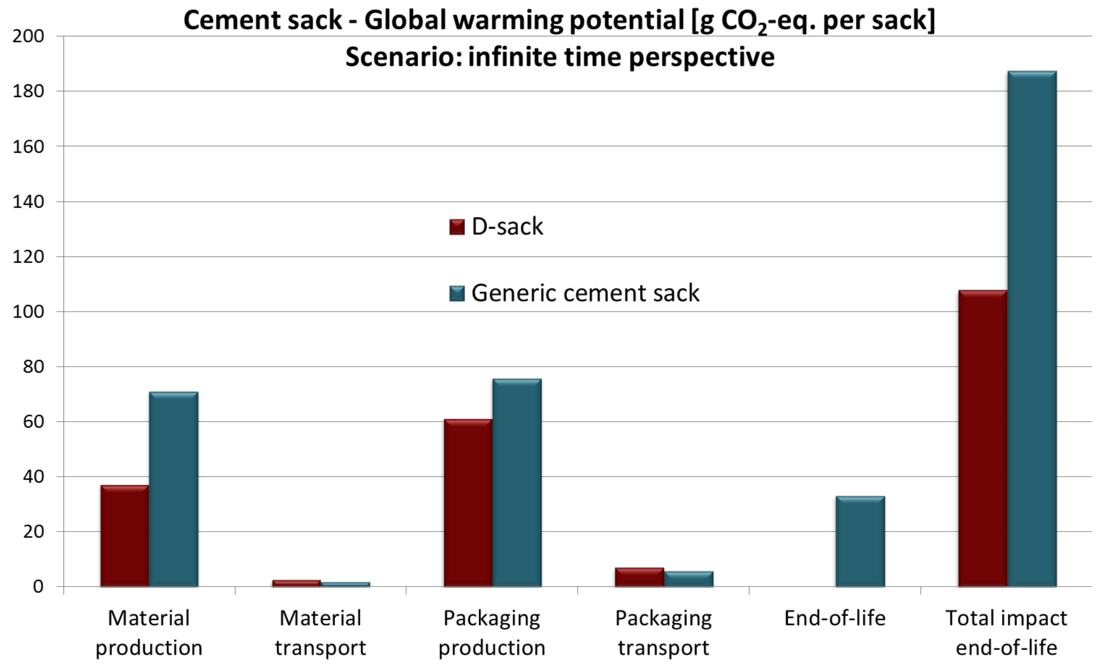

Figure 21. Global warming potential for the cement sacks, when also end-of-life has been included, for the infinite time scenario.

Figure 22 and Figure 23 shows the results when also avoided emissions have been accounted for (for the generic cement sack), and for the two time scenarios. Avoided emissions means that when the sack is recycled, the materials is assumed to replace virgin Kraft paper production, and the generated electricity and heat during incineration is assumed to replace European electricity and thermal energy from natural gas. The credits are always negative, since it is assumed that something with a high environmental impact can be avoided. This is also based on the statistical data for waste management in France (see Table 9) and since according to this the largest part of paper products are recycled, the credits from recycling will also have the largest effect.

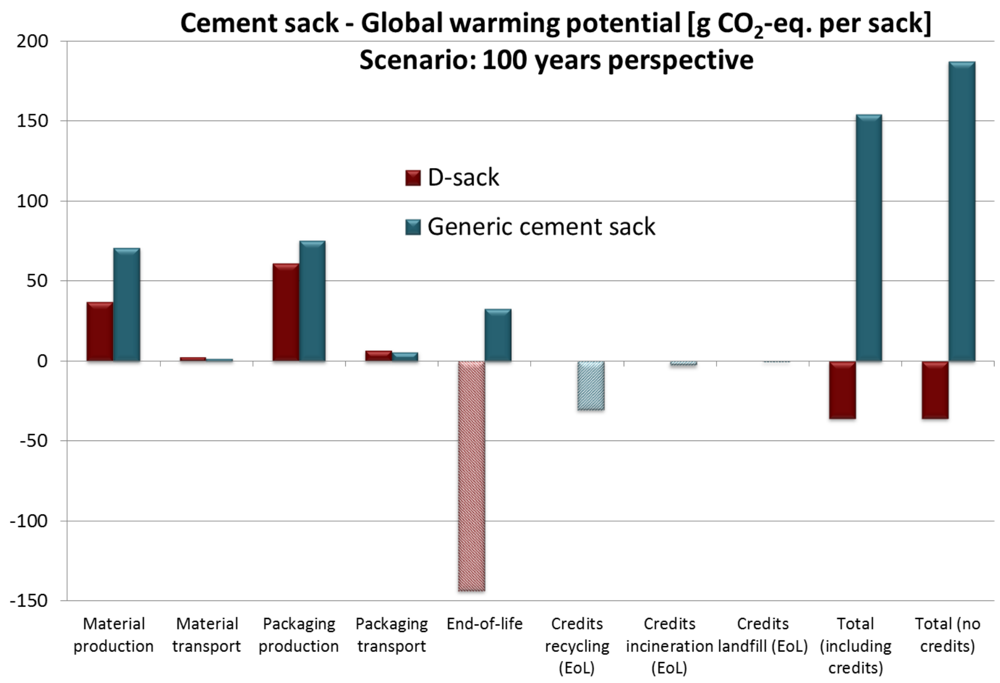

Figure 22. Global warming potential for the cement sack and 100-year time scenario. End-of-life as well as credits from avoided emissions from generated energy and virgin material production has been included

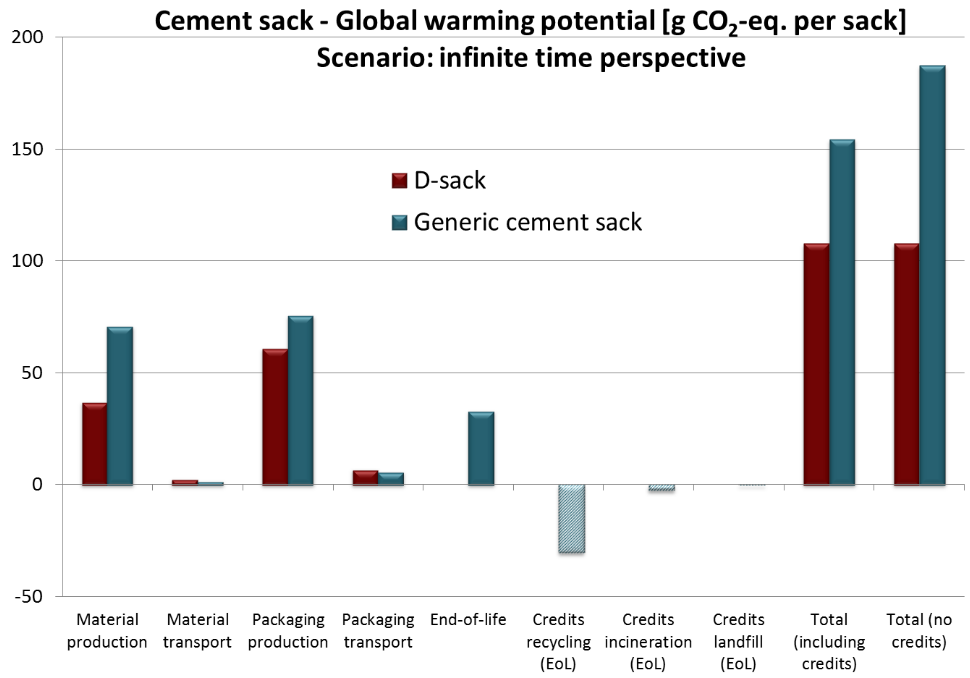

Figure 23. Global warming potential for the cement sack and the infinite time scenario. End-of-life as well as credits from avoided emissions from generated energy and virgin material production has been included

Acidification Potential

The impact on acidification potential from the entire life cycle is presented in Figure 24. For the generic cement sack, around 65 % of the impact from end-of-life is due to the recycling process, and this is mainly because of the upstream production of the energy required in the recycling process. Secondly are the emissions from transport, which accounts for around 30 % of the total acidification impact from end-of-life, due to nitrogen monoxide emissions to air. Incineration and landfill have a small impact because of the small share, which is treated accordingly in France. The impact from end-of-life has a small effect on the overall acidification potential.

Figure 25 shows the results when also the avoided emissions are accounted for. When doing so, the total acidification potential for the generic cement sack is decreased so that it becomes slightly less than for the D-sack.

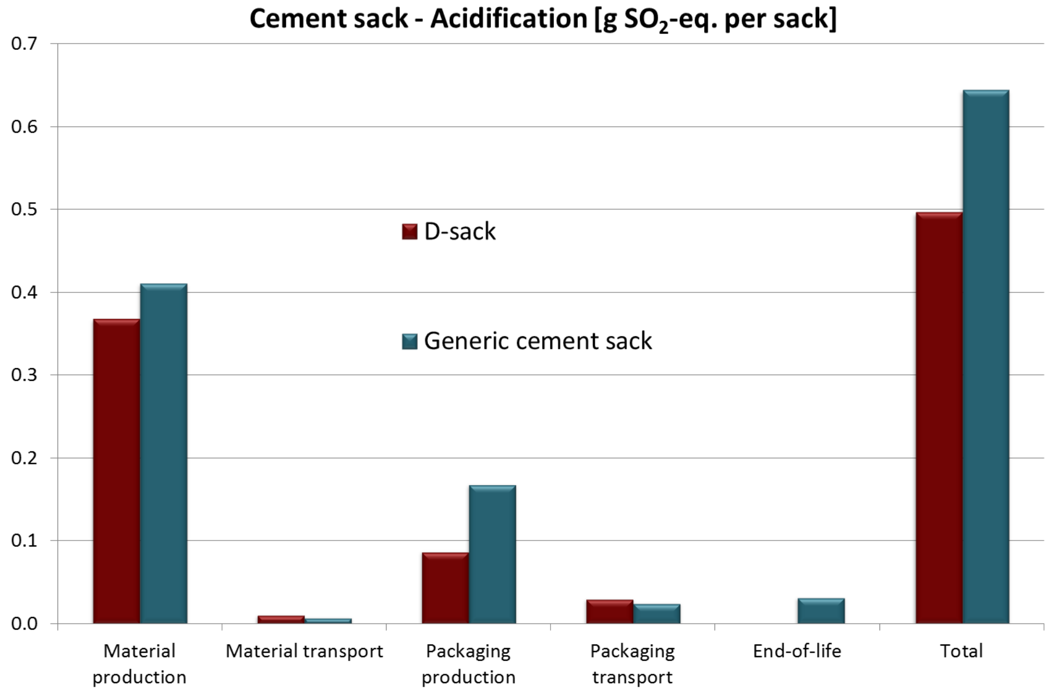

Figure 24. Acidification potential for the cement sacks, when also end-of-life for the generic cement sack has been included

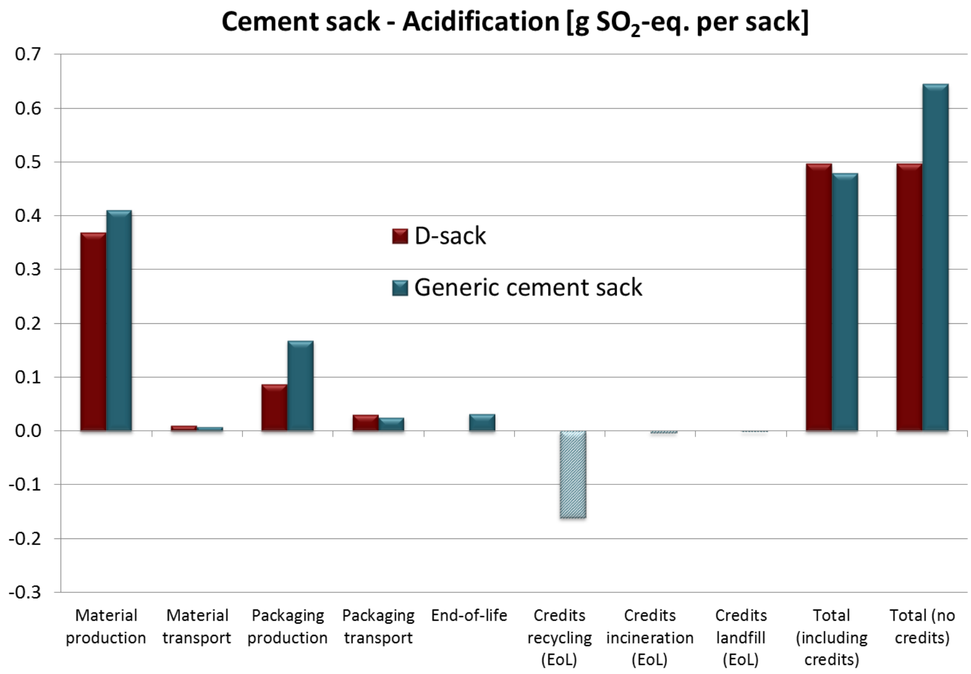

Figure 25. Acidification potential for the cement sacks. End-of-life as well as credits from avoided emissions from generated energy and virgin material production (for the generic cement sack) has been included

Eutrophication Potential

The impact on eutrophication is shown in Figure 26. Around 50 % of the impact on eutrophication from end-of-life is due to the recycling process, mainly due to the upstream production of energy, which is used in the process. The transports accounts for almost 30 % of the total impact from end-of-life, due to emissions such as nitrogen monoxide to air. Landfill and incineration have a small impact because of the small share treated in France. The impact from end-of-life has however a small effect on the overall eutrophication potential.

Figure 27 shows the results when also the avoided emissions are accounted for, which in total further decreases the eutrophication potential for the generic cement sack.

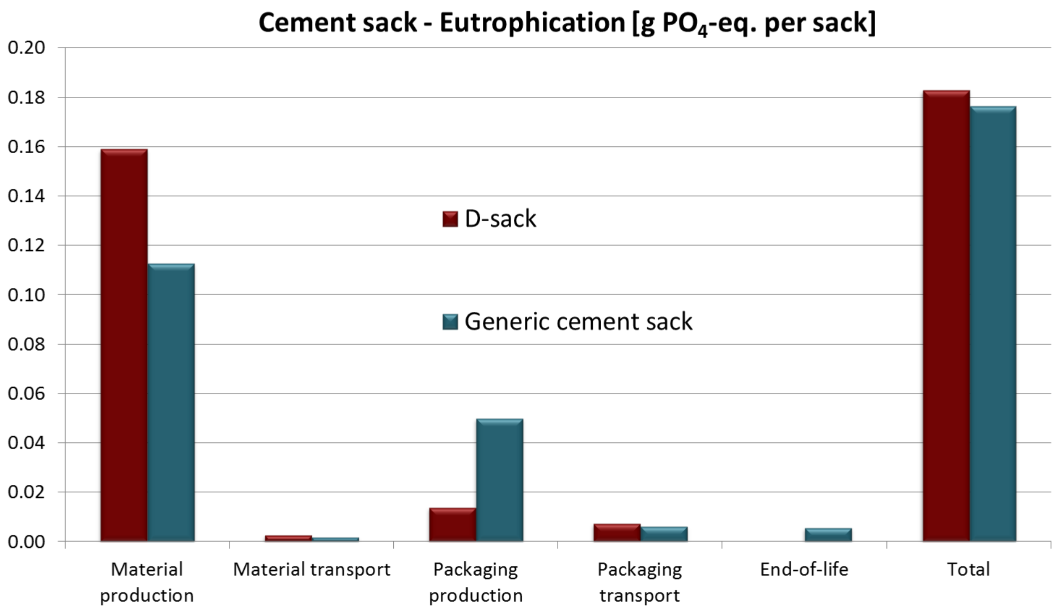

Figure 26. Eutrophication potential for the cement sacks, when also end-of-life for the generic cement sack has been included

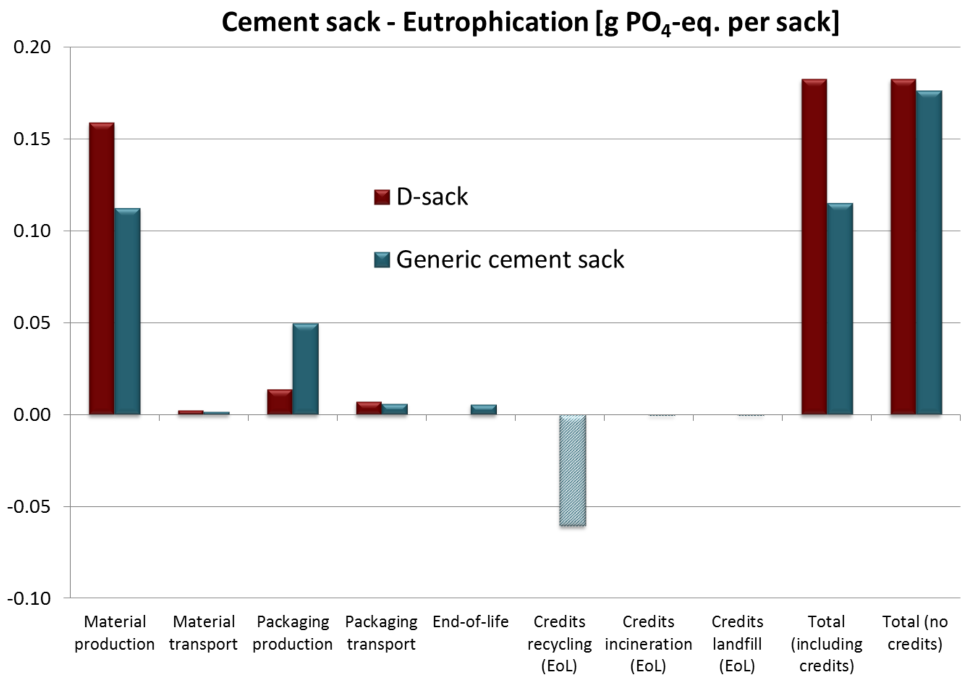

Figure 27. Eutrophication potential for the cement sack. End-of-life as well as credits from avoided emissions from generated energy and virgin material production (for the generic cement sack) has been included

Ground level ozone formation potential

The impact on ground level ozone is shown in Figure 28. More than 70 % of the end-of-life is due to the recycling process, mainly due to the upstream production of energy. Transports for collection accounts for around 10 % while landfill stand for around 8 % and incineration for 3 %. The impact from end-of-life has however a small effect on the overall ground level ozone potential.

Figure 29 shows the effect due to the avoided emissions, which slightly decreases the overall impact from the generic cement sack.

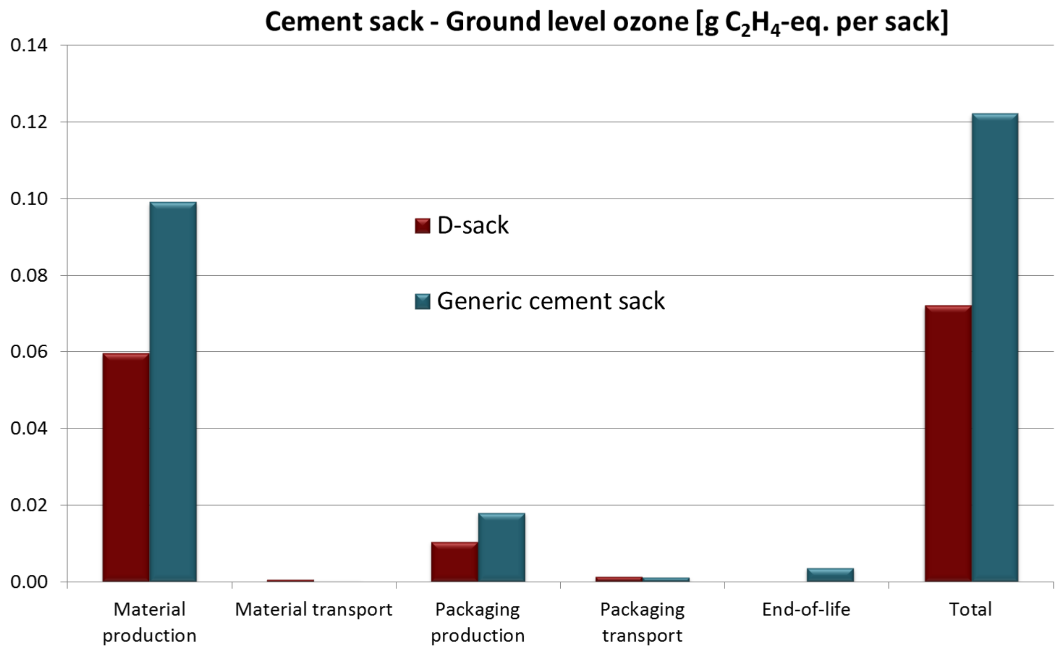

Figure 28. Impact on ground level ozone formation potential for the cement sack, when also end-of-life for the generic cement sack has been included

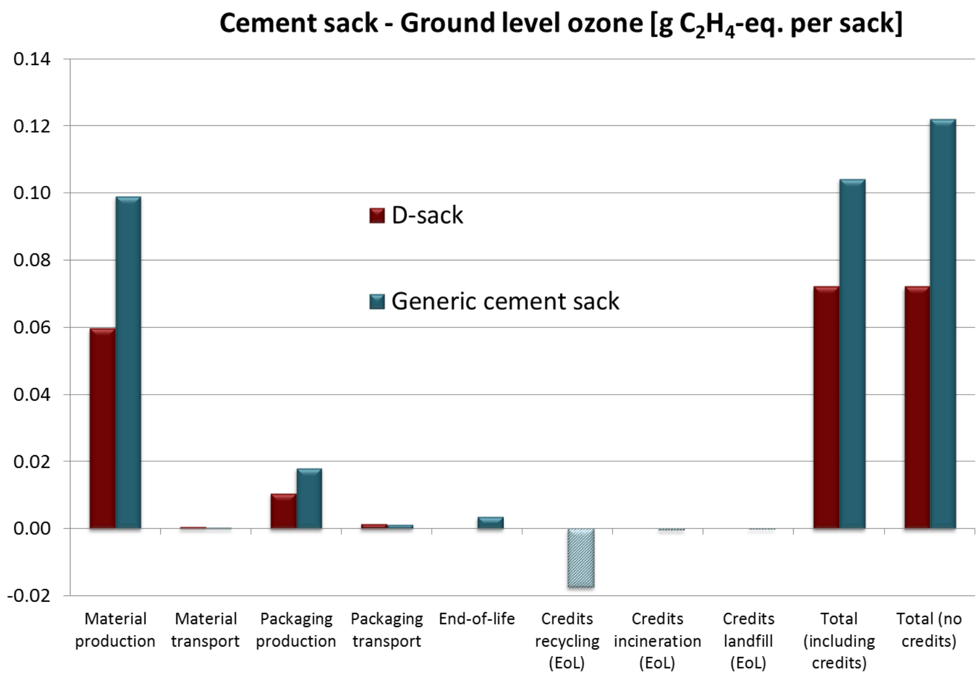

Figure 29. Impact on ground level ozone formation potential for the cement sack. End-of-life as well as credits from avoided emissions from generated energy and virgin material production (for the generic cement sack) has been included

4.1.2 Conclusions

In the base case, without including end-of-life (Figure 2), the D-sack has in total a lower climate impact than the generic cement sack. This is because of the higher impact from “material production” and the “packaging production” for the generic sack. The D-sack has an advantage of not requiring any waste management after its use phase, therefore, in the system expansion the impact from the generic cement sack is increased somewhat further compared to D-sack, due to the waste handling. Although, there are some gained credits for the generic sack, due avoided virgin material production from material recycling, the environmental performance of the D-sack is still better. This is true in both the infinite time scenario but especially in the 100-year scenario, since the D-sack then is considered as a carbon capture.

Regarding acidification and ground level ozone (Figure 7 and Figure 15), the base case shows a lower impact from the D-sack than the generic cement sack. The outcome is the same when also including end-of-life for the generic cement sack. However, when the avoided emissions are accounted for, the generic cement sack has a somewhat lower acidification potential than the D-sack in total. Meanwhile the outcome of ground level ozone remains unchanged, with a higher impact for the generic cement sack than the D-sack.

Looking at the eutrophication potential for the base case (Figure 11), the generic cement sack has a slight advantage over the D-sack, this is because of the higher impact from the material production at Karlsborg. Here, the impacts from upstream production of the chemicals for coating as well as the direct emissions from the mill are important parameters to address. The outcome is the same when also including end-of-life, although, when the avoided emissions (credits) are accounted for, the eutrophication for the generic cement sack becomes almost half compared to D-sack.

However, it should be mentioned that D-sack has other advantages, which have not been addressed quantitatively in this study. When conventional cement sacks are handled at the constructions sites, cement powder (dust) is released when the bags are opened and mixed with water to concrete. The cement dust can irritate the lungs of the workers and hence becoming an environmental health issue. However, since the D-sack sack is thrown directly into the concrete mixer, where the sack dissolves during mixing; therefore the workers will have a reduced exposure to cement particles and the health effects will be reduced.

4.2 Shopping bag

Global warming potential

Figure 30 presents the global warming potential of the shopping bags. As can be seen, the “material production” for the BillerudKorsnäs shopping bag has an advantage over the other bags when it comes to the climate aspect. This is because the Skärblacka mill, like the Karlsborg mill, uses a great share of biofuels in its production, the mill also utilise excess energy from the mill both for heat and electricity generation which is used internally, meanwhile the electricity which is bought from grid has a relatively low impact (Vattenfall 2016).

The other materials have a considerably higher impact and renewable LDPE bag (from sugar cane ethanol) has the highest impact of the studied bags.

Since the renewable LDPE is produced in Brazil and then shipped to Europe, the impact from transportation is larger than for the other materials. The climate impact from material transportation per kg material, is actually about twice as high from the renewable LDPE bag as for the BillerudKorsnäs bag, however, since the weight of the BillerudKorsnäs bag is about the double, the impact per bag becomes almost equal. The material transport for the recycled paper and plastic bags are less, since they are assumed to be transported a shorter distance.

Figure 31 gives a more detailed picture of the climate impact from the recycled paper bag. From that, it can be seen that the energy required for the paper machine is the most significant parameter. This is because of the large fossil sources in the electricity mix as well as for the thermal energy. Today, natural gas is commonly used as energy source at most of the recycling mills (ACE 2016).The source used for thermal energy was studied more in the sensitivity analysis in section 4.2.3.

Since the recycled LDPE bag actually consists of 50 % virgin material, in order to receive the right quality and strength of the bag, Figure 32 shows the contribution of the virgin and the recycled part, clearly the virgin part is of significant importance. The effect by alternating the recycled share to 100 % is treated separately in the sensitivity analysis in section 4.2.3.

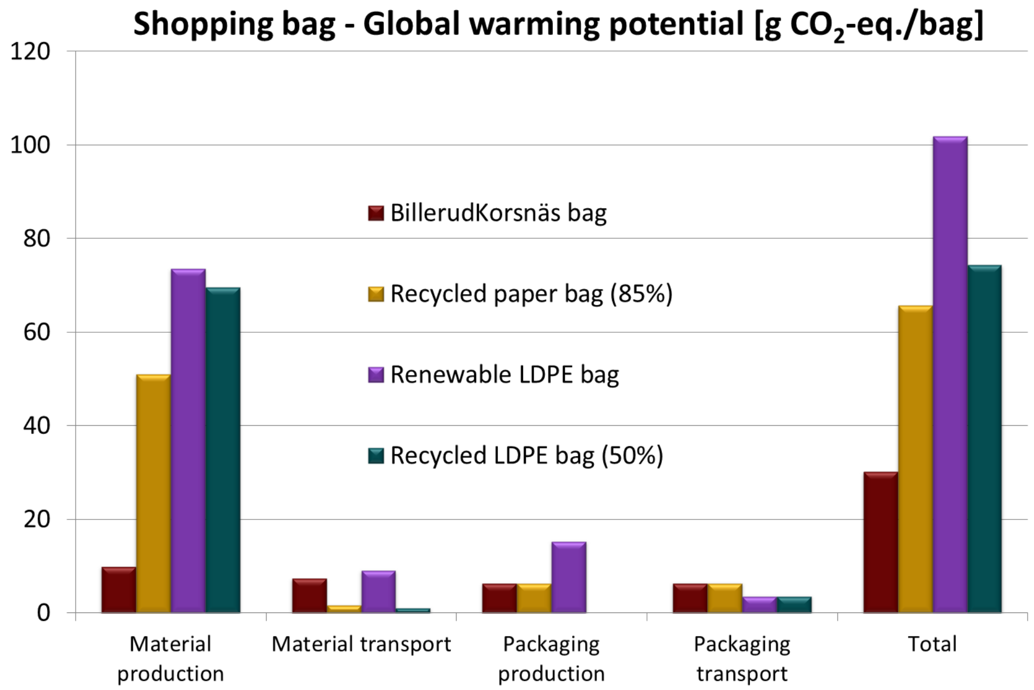

Figure 30. Global warming potential for the shopping bags, from raw material production to final product at customer. For the recycled LDPE bag, the emissions from the Packaging production are included in the Material production part.

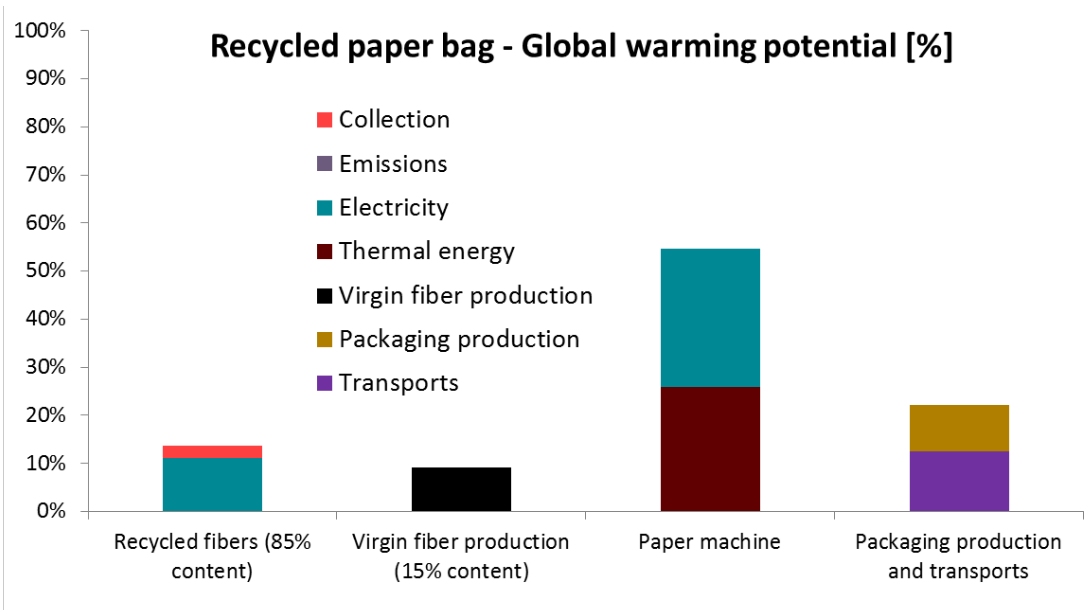

Figure 31. The distribution of the global warming potential for the recycled paper bag

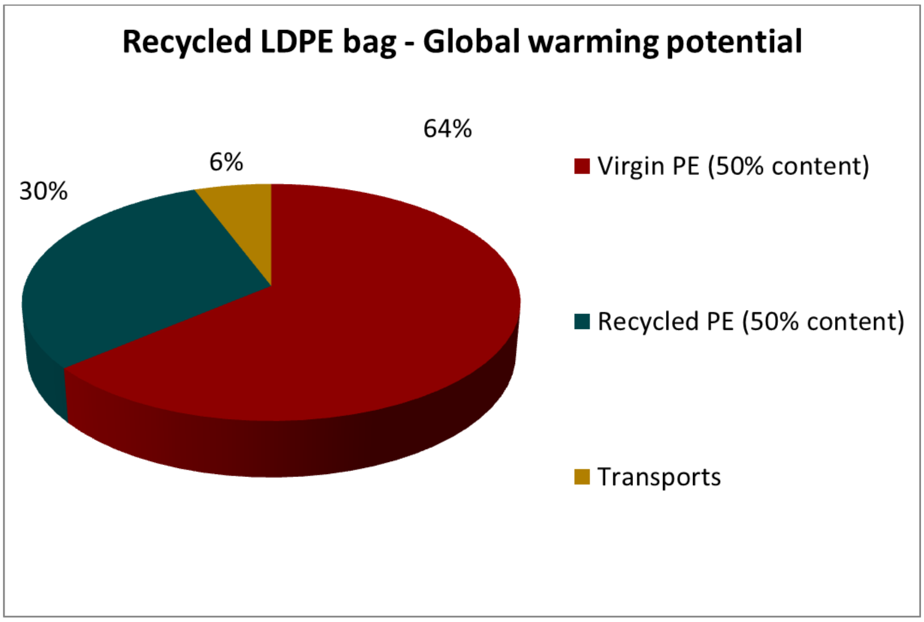

Figure 32. The contribution of virgin and recycled LDPE to the global warming potential

The global warming potential from Skärblacka mill, per tonne paper, is presented in more detail in Figure 33. Manufacturing of the chemicals used at the mill, is the most significant parameter for the climate impact, and Figure 34 shows their contribution and from which can be seen that the flocculation/thickening agents and sodium hydroxide are important chemicals to address. Interesting is that the emissions from the mill has relatively low impact. This is because Skärblacka has over the last years, made their process more energy efficient, which has decreased the need for fossil energy and hence, lowered the carbon dioxide emissions considerably. The distribution between CO_2, N_2O and methane is shown in Figure 35. The fact that Skärblacka has relatively low CO_2 emissions from their production and nitrous oxide is a very strong greenhouse gas (298 times more than CO_2), the contribution from nitrous oxide compared to carbon dioxide becomes very dominant.

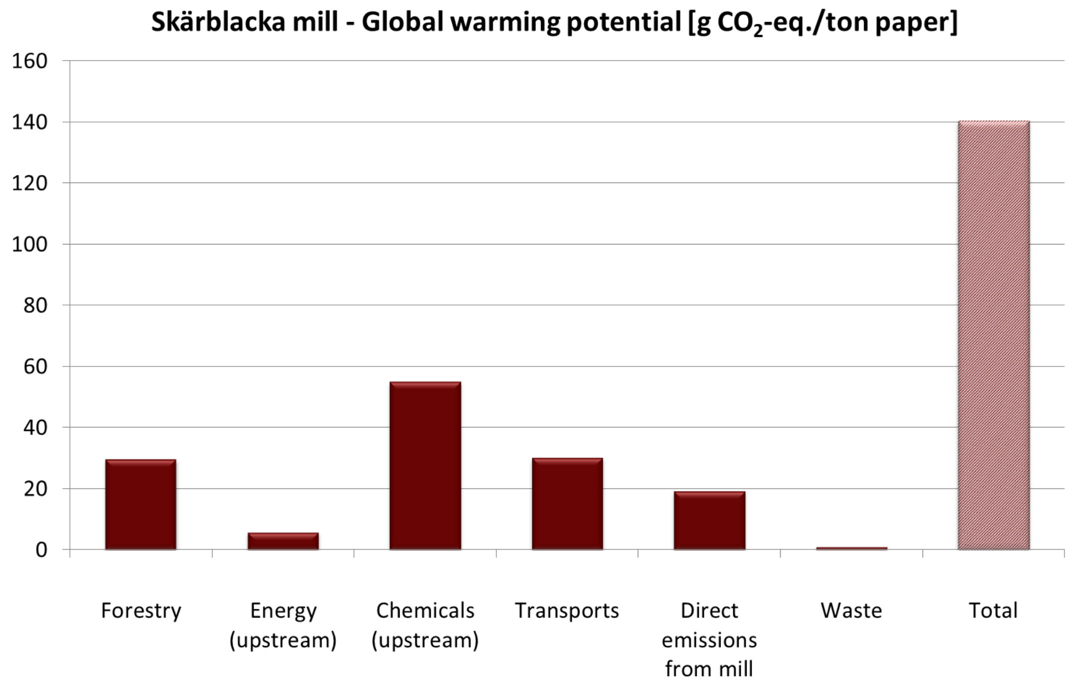

Figure 33. Global warming potential for the production of 1 tonne paper at Skärblacka mill

In Figure 33, "Forestry" refers to those emissions, which are generated during activities in the forest which are required for generating wood such as production of seedlings, silviculture, logging and forwarding.

"Energy (upstream)" refers to those emissions generated during production (upstream) of external energy (production of electricity and fuel oil) that is used in the manufacturing process. Note that the emissions released during combustion of the fuel oil are included in "*Direct emissions from mill*".

"Chemicals (upstream)" refer to those emissions generated during production of the chemicals used in the production of paper. Hence, these emissions are not emitted at the mill, but where the production of the chemical takes place.

"Transports" refer to transports of all commodities (forest, chemicals and fuels (oil, diesel, gasoline)) to the mill, as well as emissions from internal transports at the mill, which have a very small impact.

"Direct emissions from mill" refers to those emissions, which are emitted from the mill as a consequence of pulp and paper manufacturing.

"Waste" refers to the waste, which is generated during production of the paper and also transportation of the waste to waste management facility.

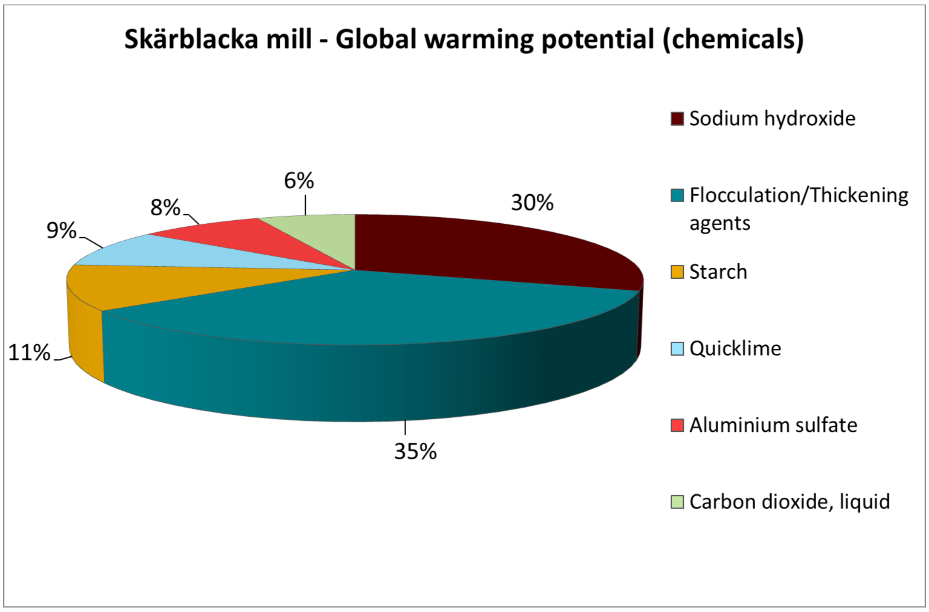

Figure 34. The distribution of the global warming potential from the chemicals used at Skärblacka mill

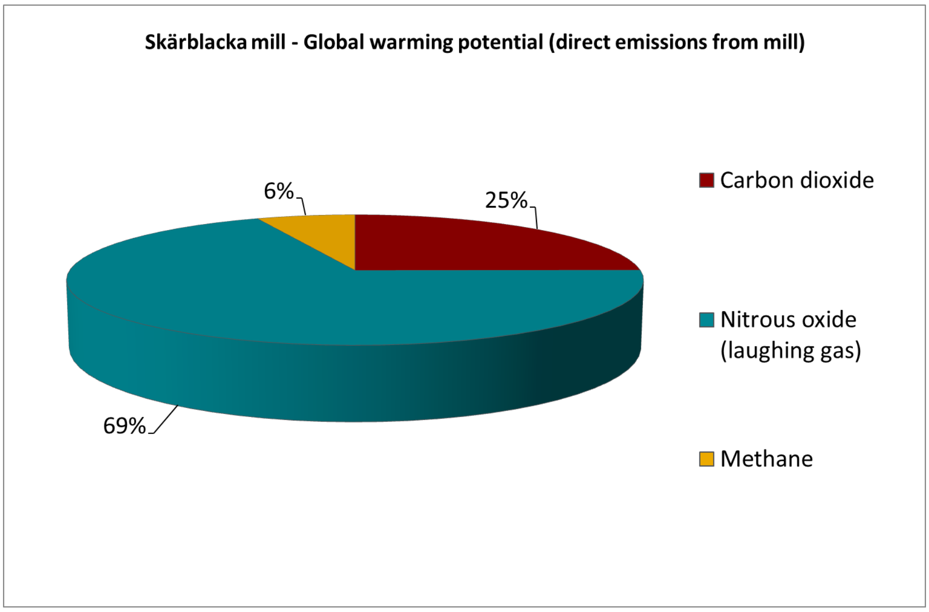

Figure 35. The distribution of the global warming potential from the direct emissions from Skärblacka mill

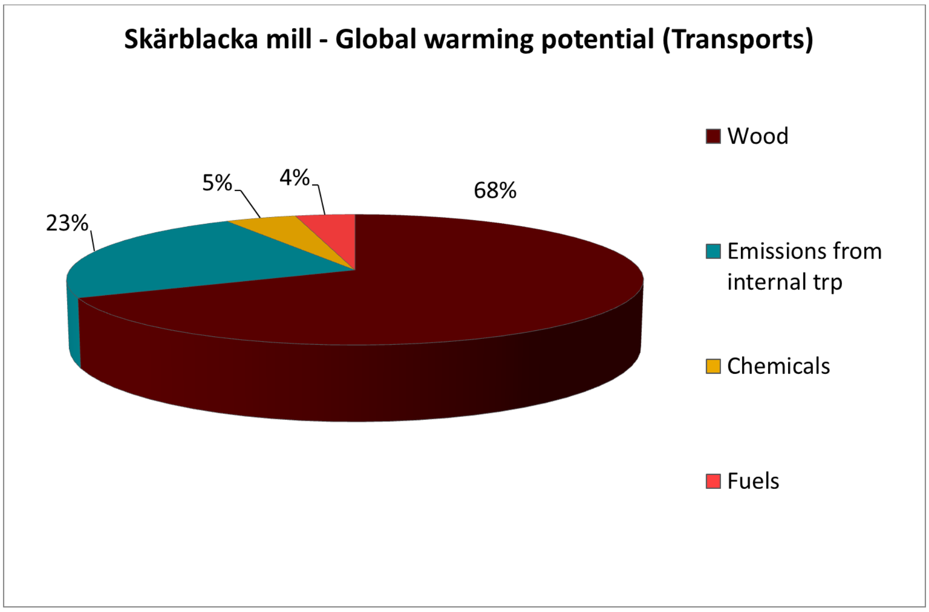

Figure 36. The distribution of the global warming potential from the transports to and at Skärblacka mill.

Acidification Potential

The impact on acidification for the different bags is shown in Figure 37. The material production dominates the total impact for all bags. The recycled LDPE bag has the lowest impact while the renewable LDPE bag has the highest. This is mainly due to ammonia emissions originating from the dataset for ethanol production from sugar cane, which alone stands for 58 % of the total impact from the renewable LDPE bag.

For the recycled paper bag, the 15 % virgin fibres, which are added contribute with 24 % on the total acidification impact.

Although Skärblacka uses a great amount of biofuel for their energy supply, still, burning of biomass causes direct emissions such as nitrogen oxide, sulphur dioxide, and ammonia; see Figure 38 and Figure 39 for the impact from Skärblacka mill. These emissions affect the acidification potential and the impact of the BillerudKorsnäs bag and the recycled paper bag becomes almost the same.

The impact from the upstream manufacturing of chemicals is relatively low for Skärblacka mill. The distribution can be seen in Figure 40, where starch and the flocculation/thickening agents have most significance.

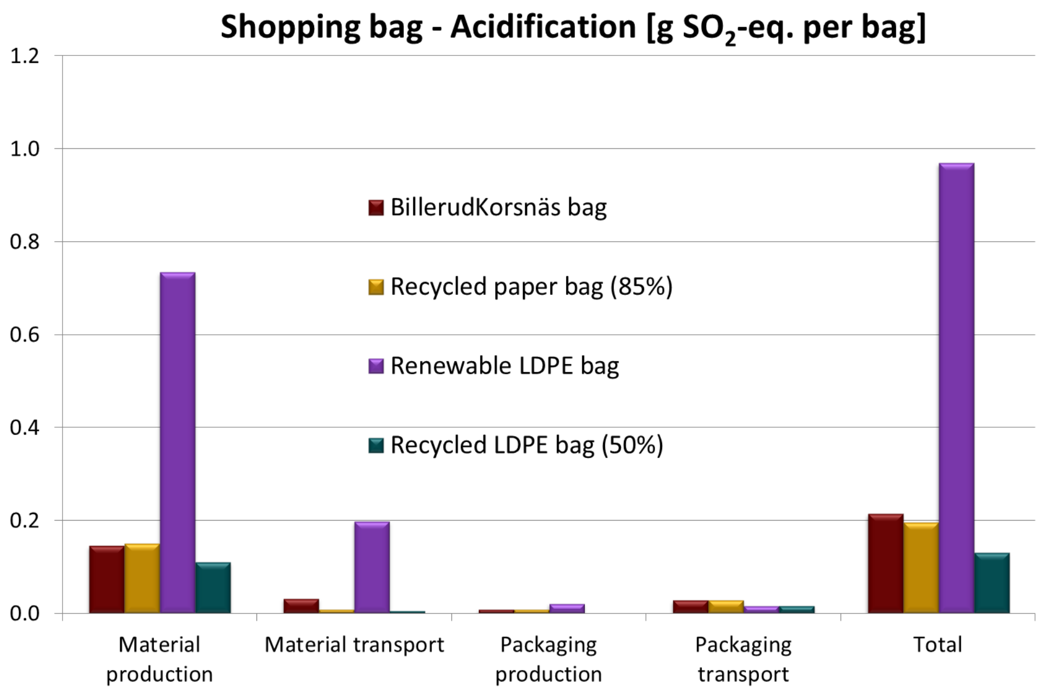

Figure 37. Acidification potential for the shopping bags, from raw material production to final product at customer

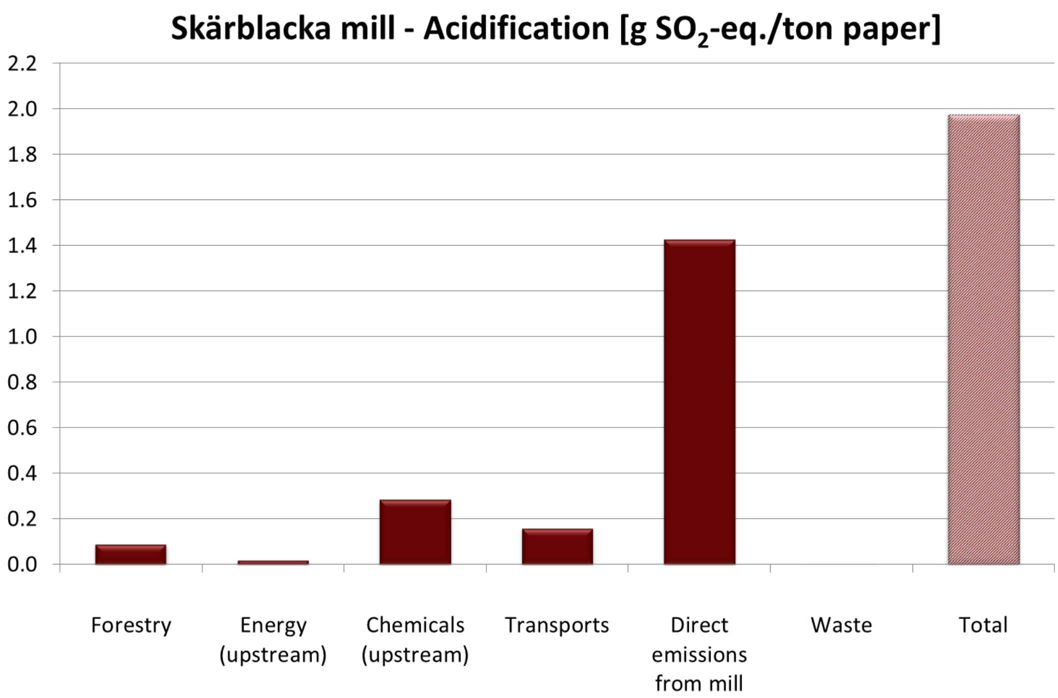

Figure 38. Acidification potential for the production of 1 tonne paper at Skärblacka mill

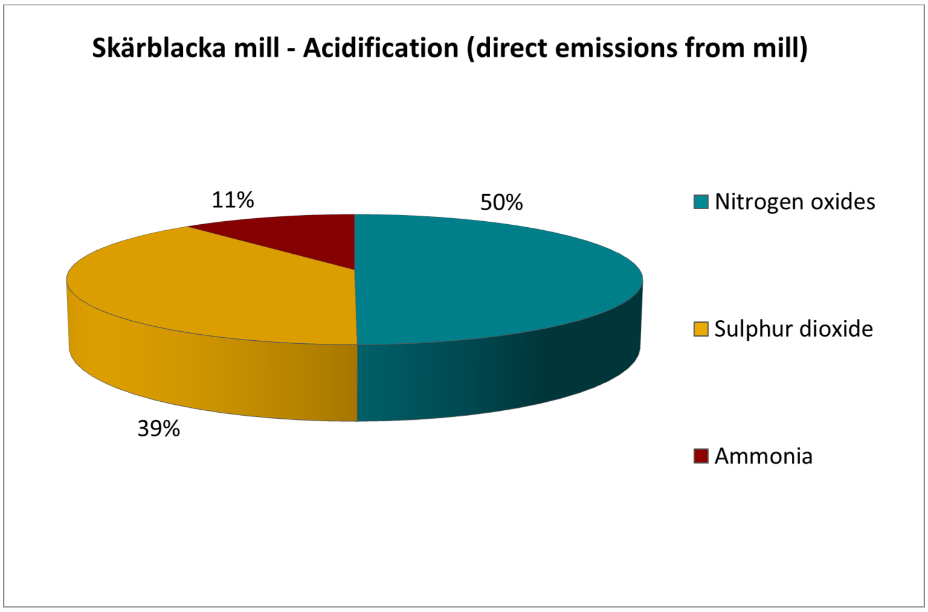

Figure 39. The distribution of the acidification potential from the direct emissions from Skärblacka mill

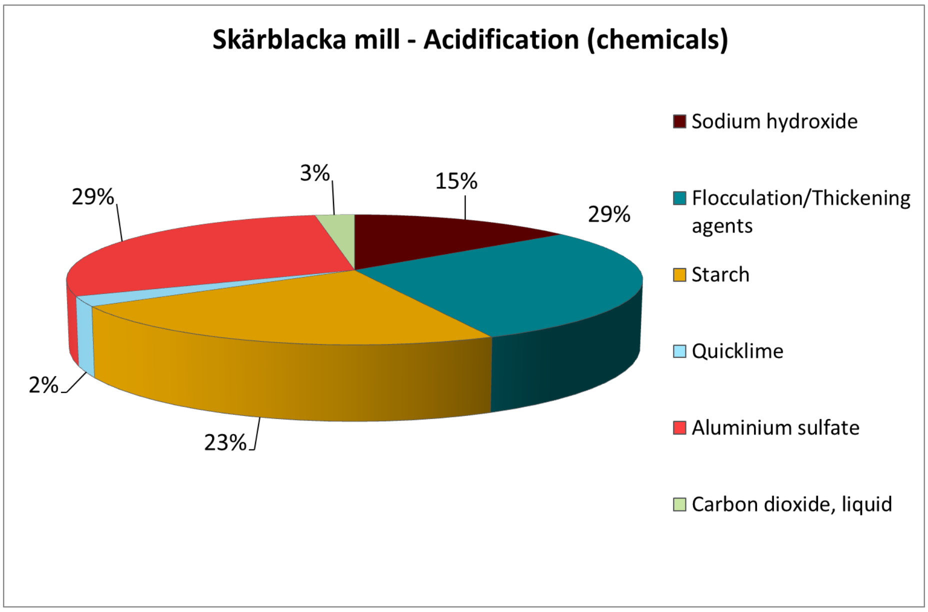

Figure 40. The distribution of the acidification potential from the chemicals used at Skärblacka mill

Eutrophication Potential

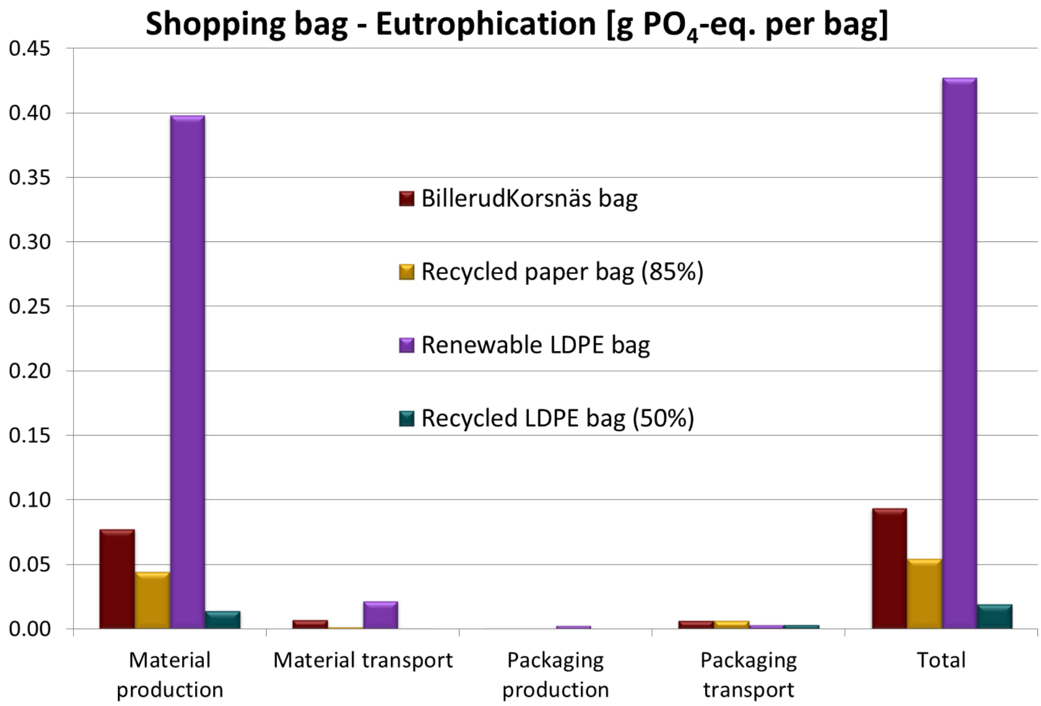

Figure 41 shows the eutrophication potential from the different shopping bags. The material production is the most contributing parameter, for all bags. Again, the renewable LDPE bag has the highest impact, and this is due to relative high emissions of ammonia to air and nitrate to water from the Ecoinvent dataset used for ethanol production from sugar cane (“BR: ethanol production from sugar cane”). Since aggregated database data is used, it is difficult to know if the sugar cane is actually cultivated in such a way, which gives rise to these high emissions. However, according to Ecoinvent (Ecoinvent report 2007), fertilizers are used in Brazil during cultivation of sugar cane and therefore one can suspect that this is the reason for the high emissions of ammonia and nitrate to water, which is seen for the renewable LDPE bag, but not for the other bags. In Sweden for instance, there is almost no fertilization during forestry cultivation.

Both paper bags have higher impact on the eutrophication than the recycled plastic bag, and this is somewhat expected since paper manufacturing is associated with emissions to water, such as nitrogen, phosphate, BOD and COD, which affects the eutrophication. For the recycled paper bag, 48 % of the total impact is due to the 15 % virgin fibre content, which is added to achieve the right quality of the paper bag. Meanwhile, 23 % is due to the recycling process.

The impact from the material production for the BillerudKornäs bag is shown in more detail in Figure 42. The direct emissions from the mill as well as the chemicals are important contributors. As can be seen in Figure 43 and Figure 44, COD and emissions such as NO_X and nitrogen to water, and manufacturing of the flocculation/thickening agents dominates the impact of Skärblacka mill. The high impact from the upstream production of the flocculation/thickening agents is due to high emissions of ammonia to water.

Figure 41. Eutrophication potential for the shopping bags, from raw material production to final product at customer

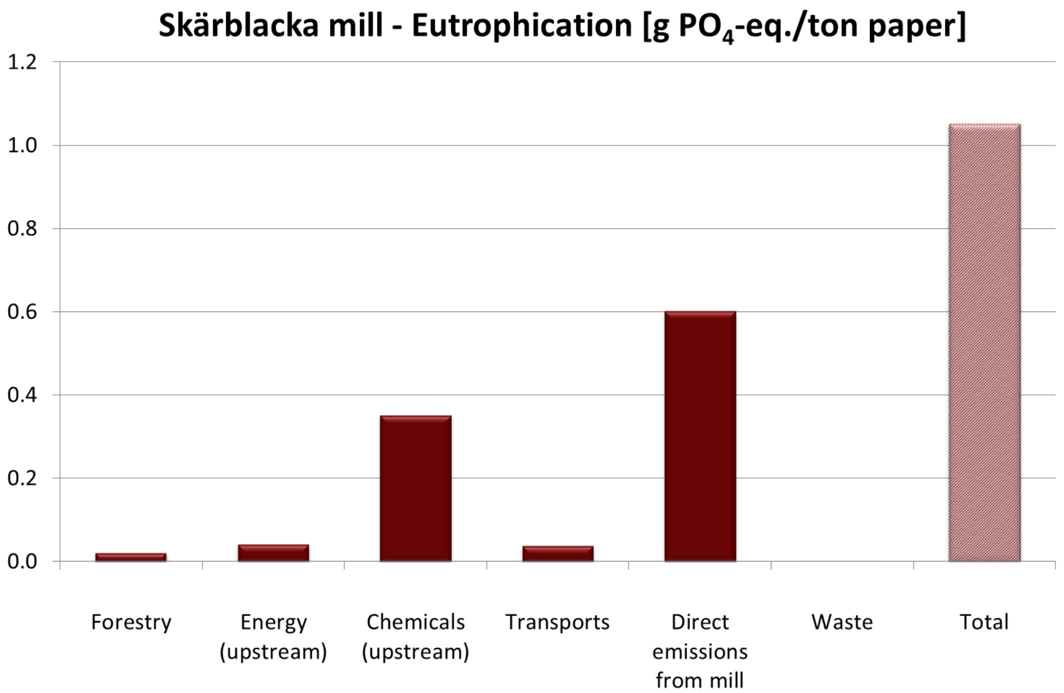

Figure 42. Eutrophication potential for the production of 1 tonne paper at Skärblacka mill

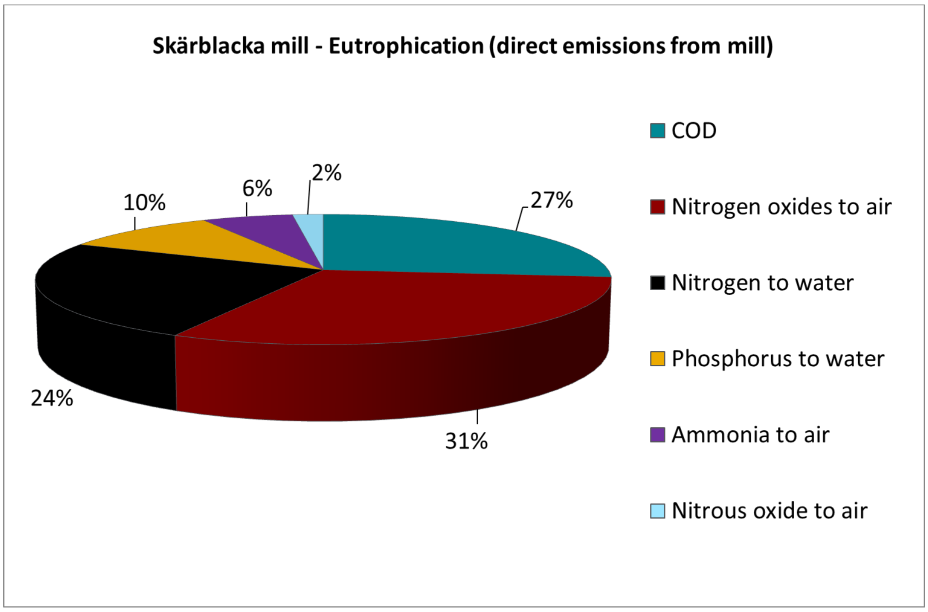

Figure 43. The distribution of the eutrophication potential from the direct emissions from Skärblacka mill

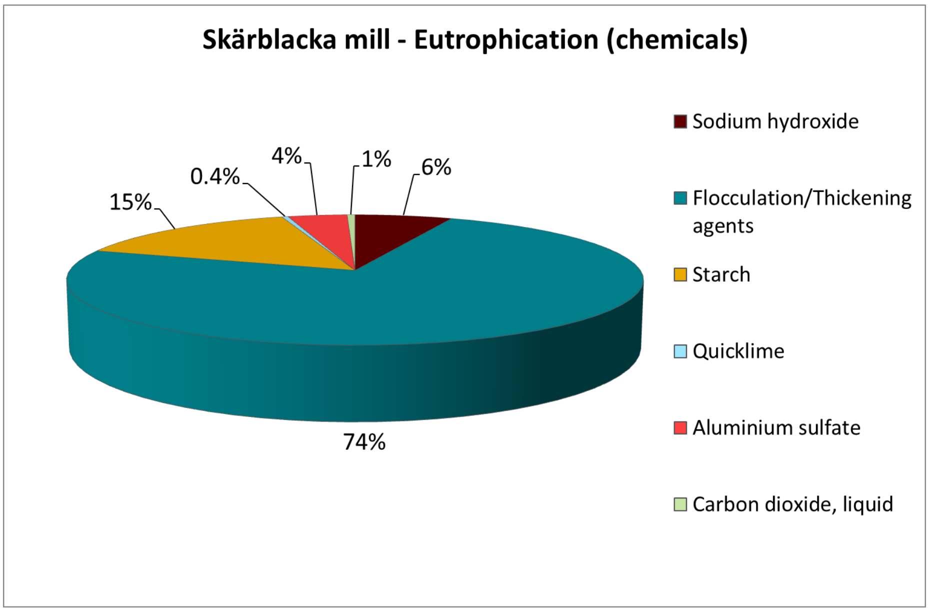

Figure 44. The distribution of the eutrophication potential from the chemicals used at Skärblacka mill

Ground level ozone formation potential

Figure 45 shows the impact on ground level ozone formation potential. Clearly, the renewable LDPE bag has a large impact compared to the other bags. Looking closer, one find that 94 % of the total impact from the renewable LDPE is due to one single emission (carbon monoxide (CO)) originating from the Ecoinvent dataset for production of ethanol from sugarcane in Brazil ("BR: ethanol production from sugar cane"). Since aggregated database data is used, it is difficult to know if the sugar cane is actually cultivated in such a way, which gives rise to these high emissions. However, according to Ecoinvent (Ecoinvent report 2007), burning of the sugar cane fields before harvesting is the most important source for emissions such as carbon monoxide, therefore it is not unlikely that the LDPE from sugar cane ethanol is associated with the relatively high impact which is shown in Figure 45. The results indicate that sugar cane harvesting for ethanol production may be an issue of concern. Similar operation (burning of fields before harvesting) does not occur during forestry cultivation in Sweden, hence these high CO emissions are not to be found for the BillerudKorsnäs bag, neither for the recycled paper and plastic bags.

Due to the high impact from the renewable LDPE bag, it is difficult to see the relative impact from the other bags; therefore, Figure 46 shows the impact of these three bags only (renewable LDPE excluded).

For the recycled paper bag, 22 % of the total impact is due to the 15 % virgin fibre content, compared to the 20 % of the total impact, which comes from the recycling process (85 % recycled fibre content).

The impact from the manufacturing at Skärblacka mill is shown in Figure 47. The direct emissions from the mill and especially NMVOC, is an important contributor to the impact on ground level ozone, see Figure 48. These come mainly from terpene emissions, which are released during production and handling of wood chips.

Even though the chemicals used at Skärblacka are of less importance to the total impact, Figure 49 shows their relative effect.

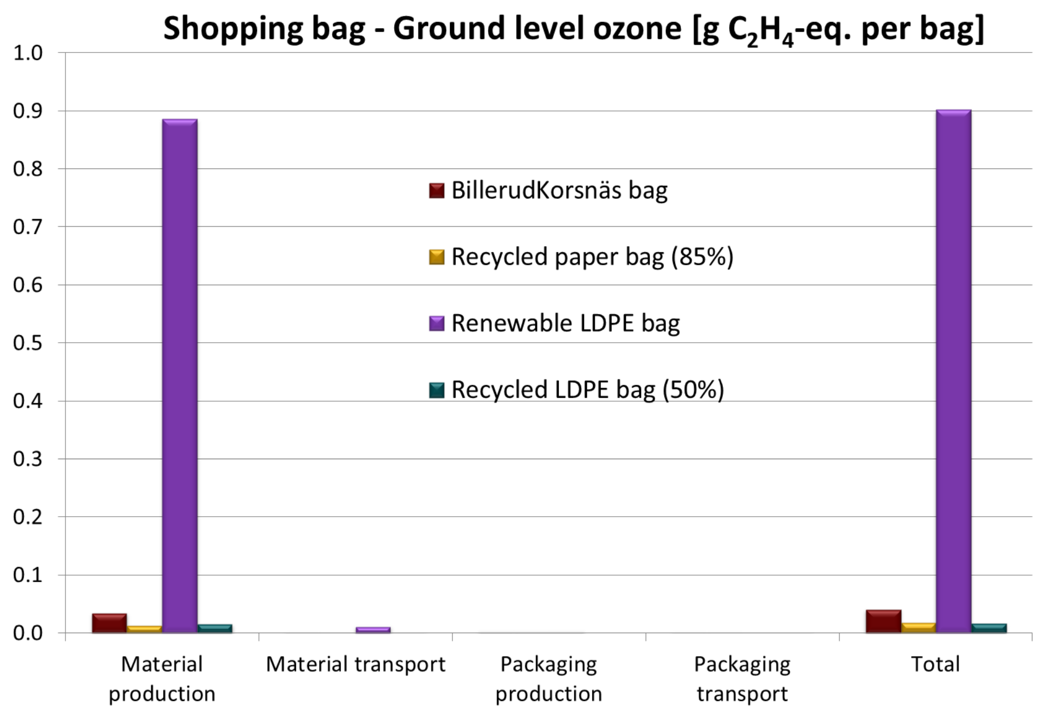

Figure 45. The impact on ground level ozone formation potential for the shopping bags, from raw material production to final product at customer

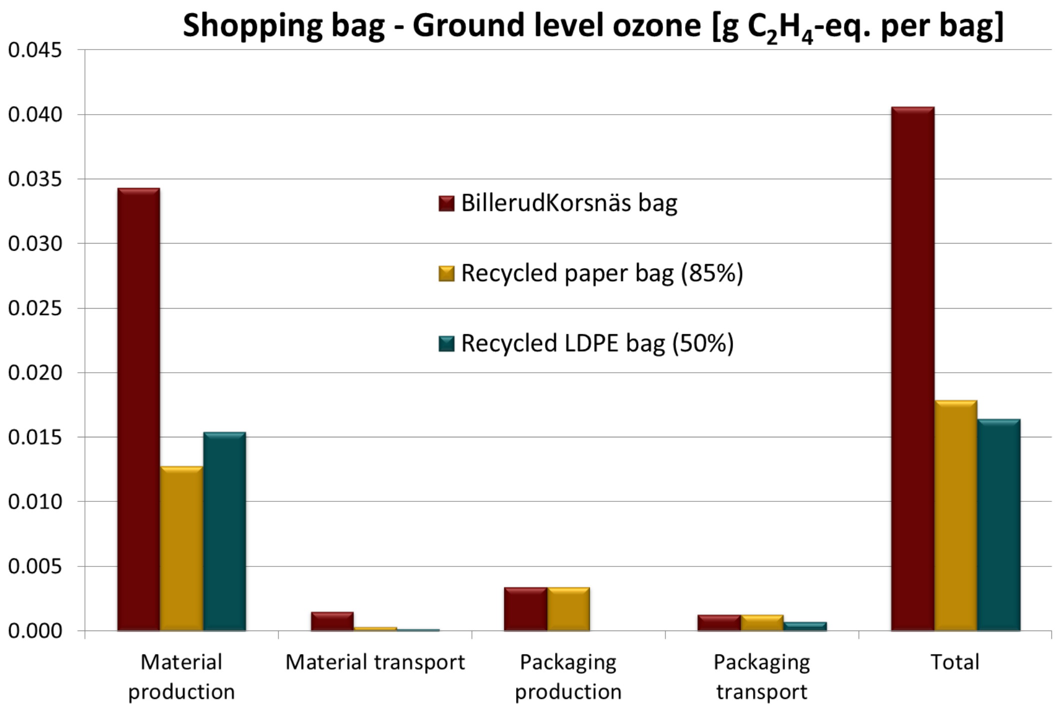

Figure 46. This shows the impact on ground level ozone for the shopping bags, from raw material production to final product at customer, without the renewable LDPE bag

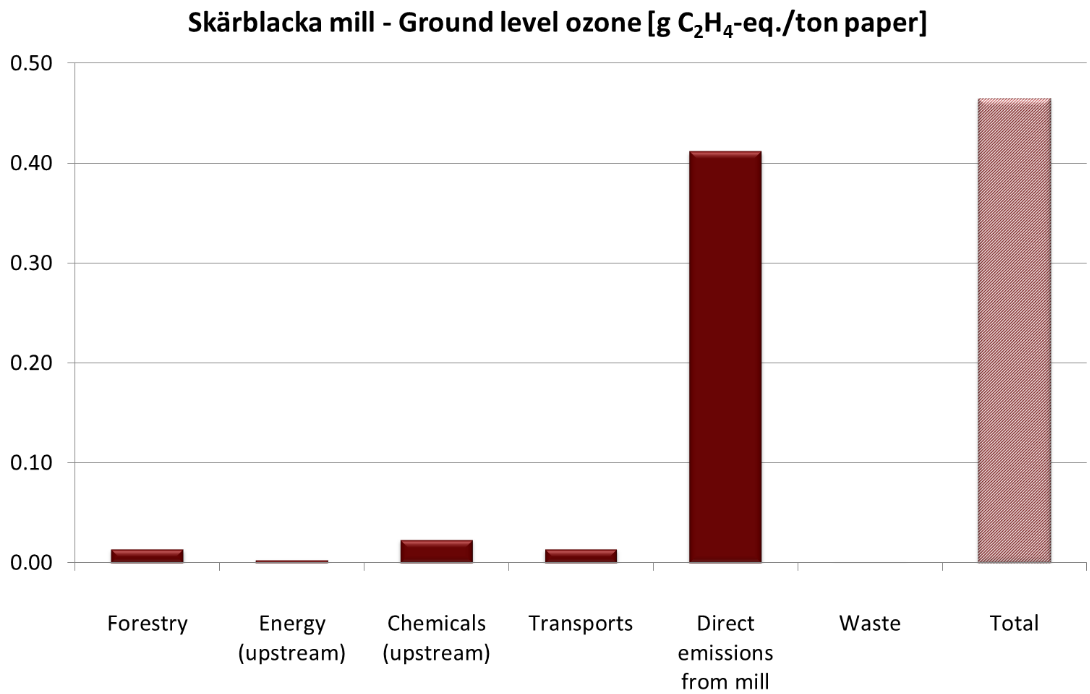

Figure 47. The impact on ground level ozone for the production of 1 tonne paper at Skärblacka mill

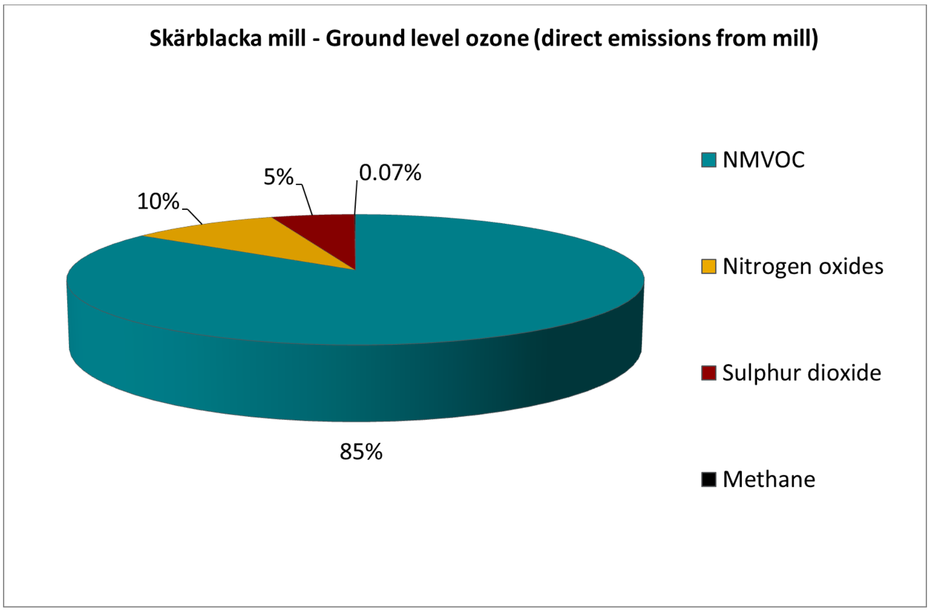

Figure 48. The distribution of the impact on ground level ozone from the direct emissions from Skärblacka mill

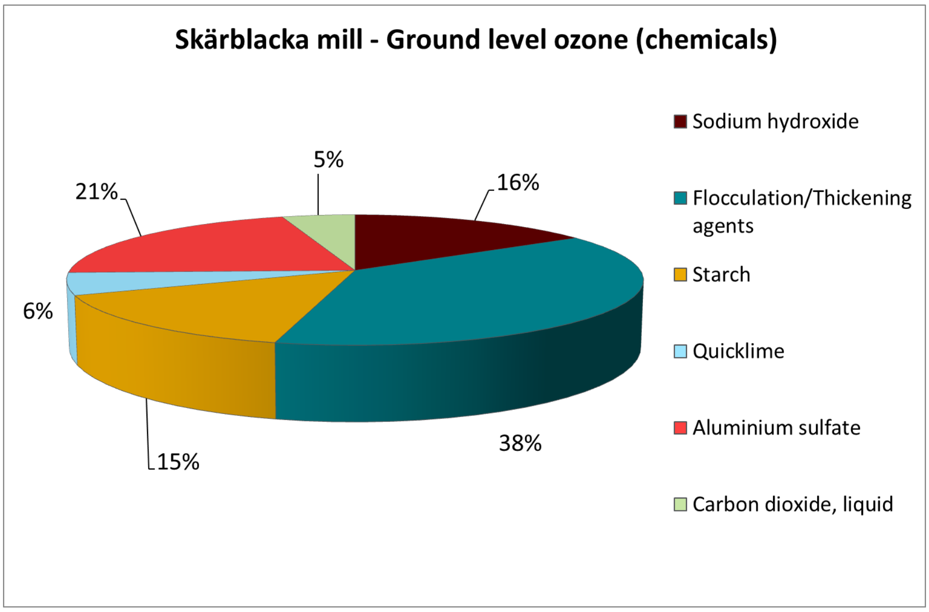

Figure 49. The distribution of the impact on ground level ozone from the chemicals used at Skärblacka mill

Primary energy demand

Primary energy is the energy contained in raw fuels received as input to a system. Primary energy has not been subjected to any conversion or transformation. Figure 50 shows the primary energy required for the shopping bags during their life cycle from raw material to a final product at the customer (cradle-to-customer).

The share of renewable energy totally used for the bags during their lifecycle is also in the figure (71%, 27%, 10% and 17% respectively). Renewable energy resources such as hydro, wind and solar energy, comes from electricity production. The BillerudKorsnäs bag actually require more primary energy per bag, however the largest part of this is biomass used in the paper manufacturing process. This comes from the utilisation of biomass as energy during paper production. All Kraft paper mills recover the lignin in the wood as black liquor in the black liquor boiler, which then can be used as energy internally in the mill. This energy could not been used elsewhere except at the mill in contrast to purchased fuels such as fuel oil or coal. For making unbleached Kraft paper, around 50 % of all the wood coming into the mill, is utilised as energy, the remaining 50 % ends up as fibres in the paper product.

The recycled paper bag also has some input of biomass which is originates from biomass used as energy in the production of the virgin material (15% content).

Uranium comes mainly from the electricity mix used during conversion (German mix) and the BillerudKorsnäs bag uses somewhat more uranium due to the high amount of nuclear power in the Swedish electricity mix, which is used at the mill. The uranium resource has been based on the released heat in the nuclear reactor. The relatively high amount of crude oil and natural gas for the recycled LDPE bag is mainly due to the virgin PE content of the bag, which is 50%. The recycled paper bag also required a great amount of natural gas in the recycling process.

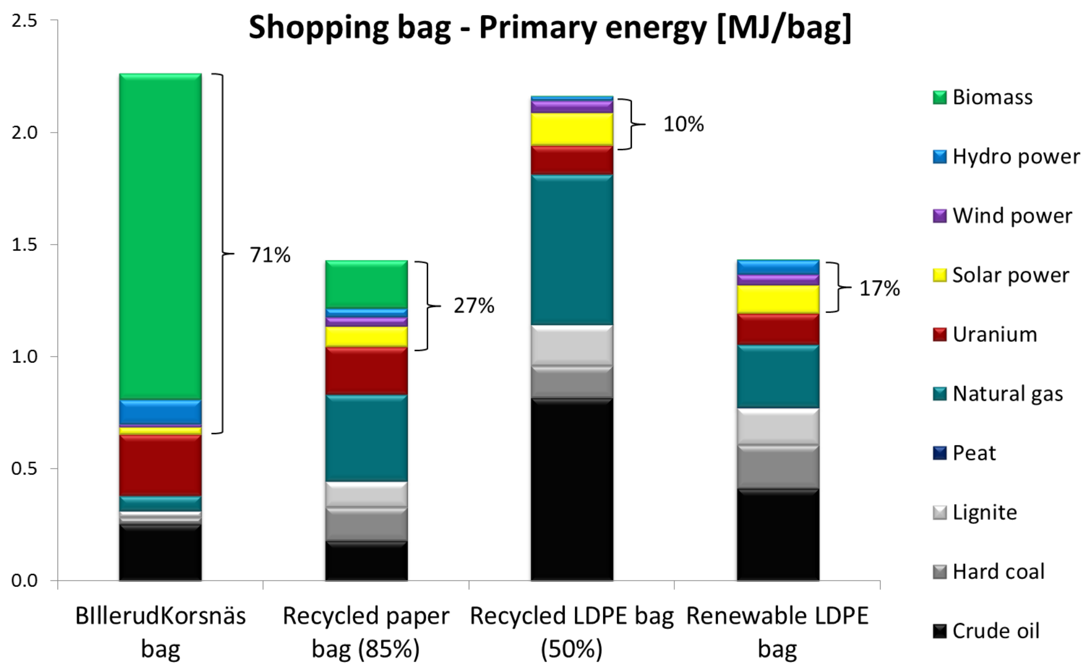

Figure 50. Primary energy demand, including all the upstream activities such as energy, transports, chemicals etc. required for the bags.

4.2.1 Comparison with benchmark data

Braskem is a large manufacturer that makes bio-based polyethylene from sugarcane ethanol and is located in Brazil. Braskem has performed an LCA (Braskem 2013) on their polyethylene and the results can be seen as a benchmark for bio-based polyethylene. Table 10 compares the different impacts based on the data used in this study with results from Braskem (Braskem 2013). Clearly, the data chosen in this study correspond relatively well with the Braskem results regarding acidification potential, eutrophication potential and ground level ozone formation potential. For the climate impact, the difference is substantial (1.76 compared to -2.15). However, here it is important to keep in mind that Braskem used a different methodology than what has been used in this study. Braskem has considered credits for "direct land-use change" as well as carbon removal from the atmosphere, and also substitution credit for co-produced electricity at the sugar cane mills. According to their report, the direct land use change is -1.1 kg CO_2 eq./kg PE. The carbon uptake from atmosphere, which is bound in the PE, can be calculated to -3.14 kg CO_2/kg PE. The credit from co-produced electricity is more difficult to know without knowing more about the actual data used, however even without considering that, the climate impact for the Braskem product *without* the known credits would be:

-2.15 + 3.14 + 1.1 = 2.09 kg CO_2/kg PE

This correspond relatively well with the data used in this study, which is 1.76 kg CO_2/kg PE.

Compared with Braskem, the data used in this study does not seem to be overestimated for climate, acidification, and eutrophication.

For ground level ozone however, the difference is relatively large; and since this high impact is due to one single emission (CO) in the database data (Ecoinvent), it should be treated with care.

Table 10. Comparison between Braskem and the data used in this study.

	Global warming potential [kg CO_2-eq./kg PE]	Acidification [kg SO_2-eq./kg PE]	Eutrophication [kg PO_4-eq./kg PE]	Ground level ozone [kg C_2H_4-eq./kg PE]
Data used in this study	1.76	0.018	0.0095	0.02
Braskem (Benchmark)	-2.15 (2.09)	0.038	0.018	0.0034

4.2.2 System expansion

Global warming potential

Figure 51 shows the global warming potential of the shopping bags when also the end-of-life treatment in the UK has been included, but in this figure no credits has been accounted for. Therefore, only the "burden", from the treatment processes; recycling, incineration, and landfill, as well as transports are taken into consideration.

For the paper bags, around 48 % of the impact from end-of-life is due to the recycling process, and this is mainly because of the electricity used in the process (UK mix). Landfill stands for 35 % while incineration only contributes with around 5 % and transports with 10 %.

For the recycled LDPE bag, the incineration process is dominating the end-of-life stage, where around 80 % of the impact from end-of-life is due to CO_2 emissions, which are released during incineration of the plastic. The recycling process stands for around 14 % of the total impact from end-of life, mainly because of the electricity usage. Landfill of plastic has a very small impact, only around 1 %, this is because it usually takes longer than 100 years for plastic material to decompose when put on landfill.

The renewable LDPE bag originates from renewable resources, the CO_2 released during incineration is not considered to be fossil, hence, the climate impact due to incineration is very small, and this is why the "End-of-life" in Figure 51 is much lower for the renewable LDPE bag than for the recycled LDPE bag, which originates from fossil sources.

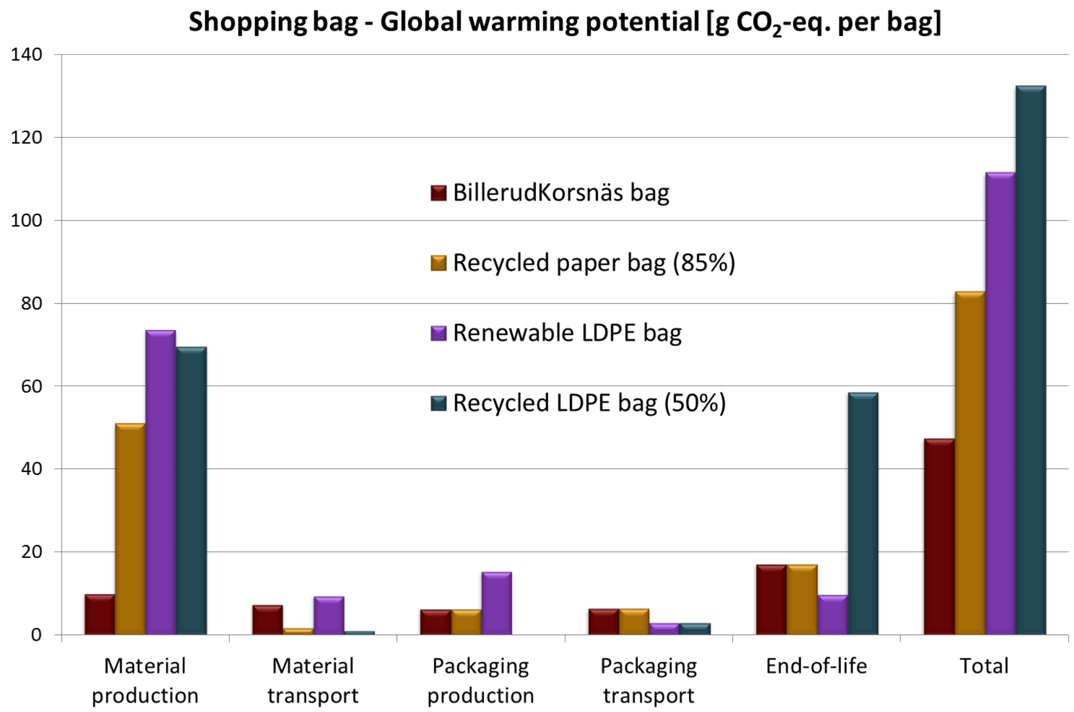

Figure 51. Global warming potential for the shopping bags, when also end-of-life has been included

Figure 52 shows the results when also avoided emissions have been accounted for. Avoided emissions means that when the bag is recycled, the materials is assumed to replace virgin material production, and the generated electricity and heat during incineration is assumed to replace European electricity and thermal energy from natural gas. The credits are always negative, since it is assumed that something with a high environmental impact can be avoided. The avoided emissions (credits) have been modelled based on the statistical data for waste management in the UK (see Table 9). In the "*Total (including credits)*" bar in Figure 52, these credits has been summarized to the total impact and since the credits have negative values, the total impacts are decreased compared to when they are not included.

Plastic has high energy content per kg material, higher than for paper. Therefore, when plastic is incinerated, a larger credit (due to generated electricity and steam) can be given per kg than for paper, hence, the avoided emissions from incineration is much more negative than for paper incineration. This is regardless if the plastic bag comes from recycled, virgin or renewable material, the energy content is still the same and therefore the credits for incineration are the same.

Avoided emissions due to electricity generation from landfill gas utilization have been accounted for the paper bags. These are, however, small compared to the other treatment processes. When plastic is put on landfill, the degradation process is much slower than for paper, hence, there can be no immediate utilization of landfill gas, and therefore no credit can be accounted for landfill of the plastic bags.

Including or not including end-of-life, has a relatively important effect on the total climate impact since it changes the outcome of which bag has the highest impact. The same is valid if the credits are included or not.

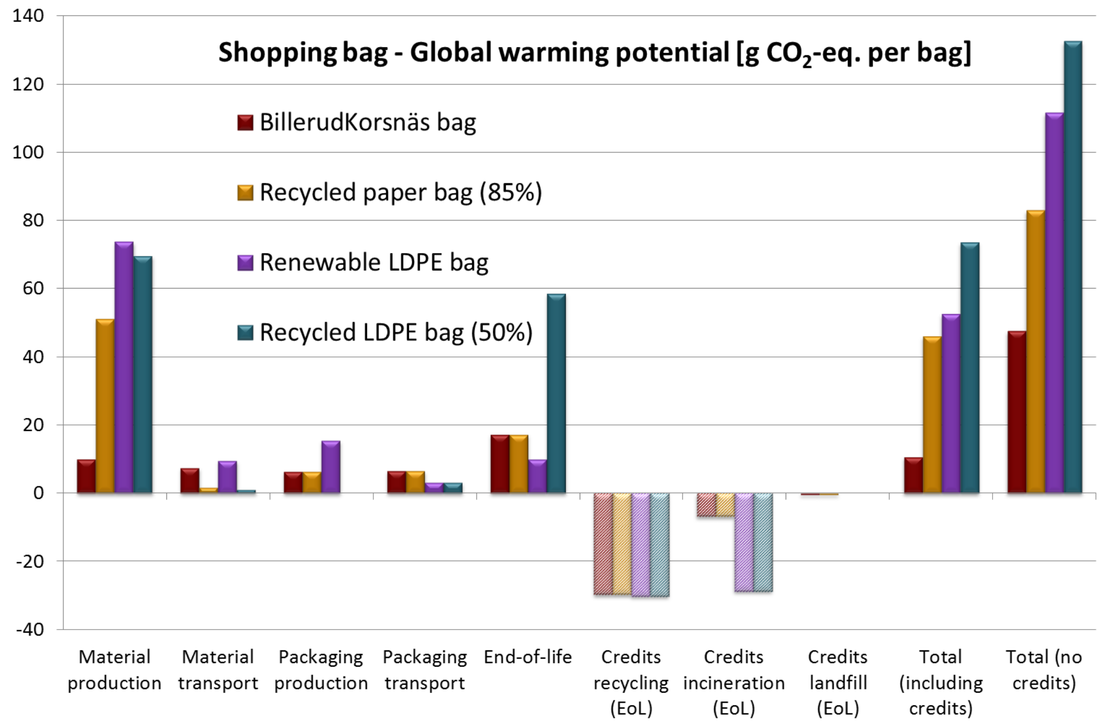

Figure 52. Global warming potential for the shopping bags, end-of-life as well as credits from avoided emissions from generated energy and virgin material production has been included

Acidification Potential

Figure 53 shows the impact on acidification potential. For the paper bags, around 65 % of the total end-of-life is due to the recycling process, and this is mainly because of the electricity used in the process (UK mix). Incineration accounts for around 14 %, landfill 5 % and transports 17 %.

For the plastic bags, the recycling process is dominating the end-of-life stage and stands for around 65 % of the total impact from end-of life; this is because of the electricity usage. The incineration process stands for around 18 % of the impact from end-of-life due to emissions of acidifying nitrogen and sulphuric compounds, which are released during incineration of the plastic bags. Landfill of plastic has a very small impact, only around 1 % of the total “end-of-life”.

In Figure 54, the avoided emissions are also accounted for. Including end-of-life, with or without credits, does not affect the total results for the bags relative each other.

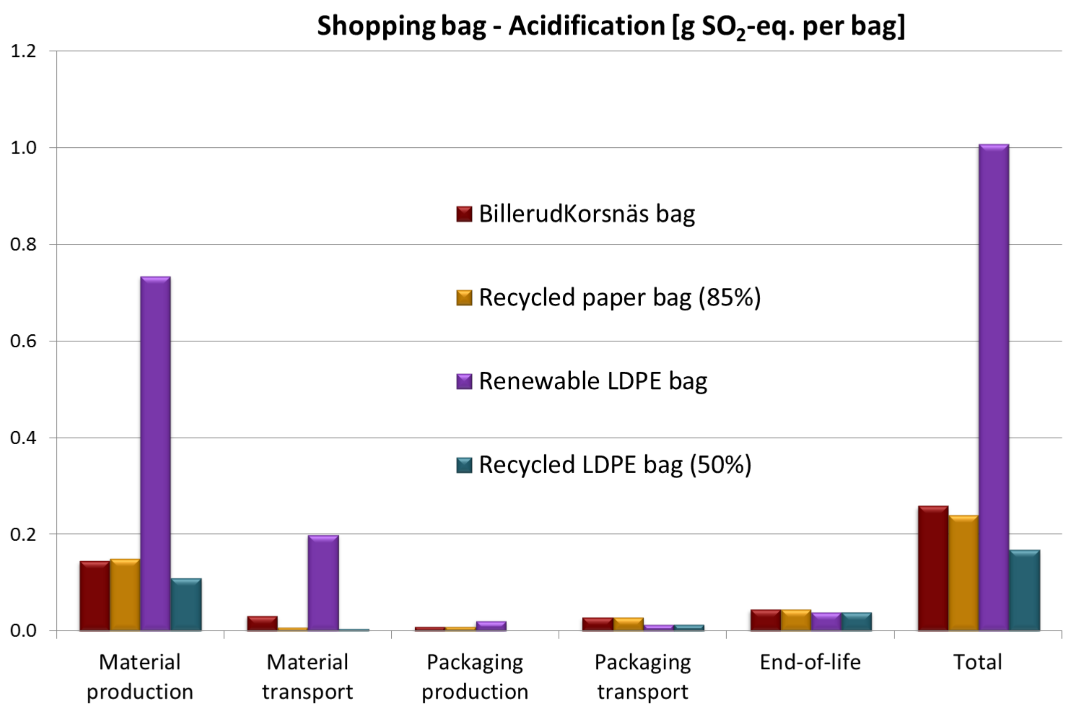

Figure 53. Acidification potential for the shopping bags, when also end-of-life has been included

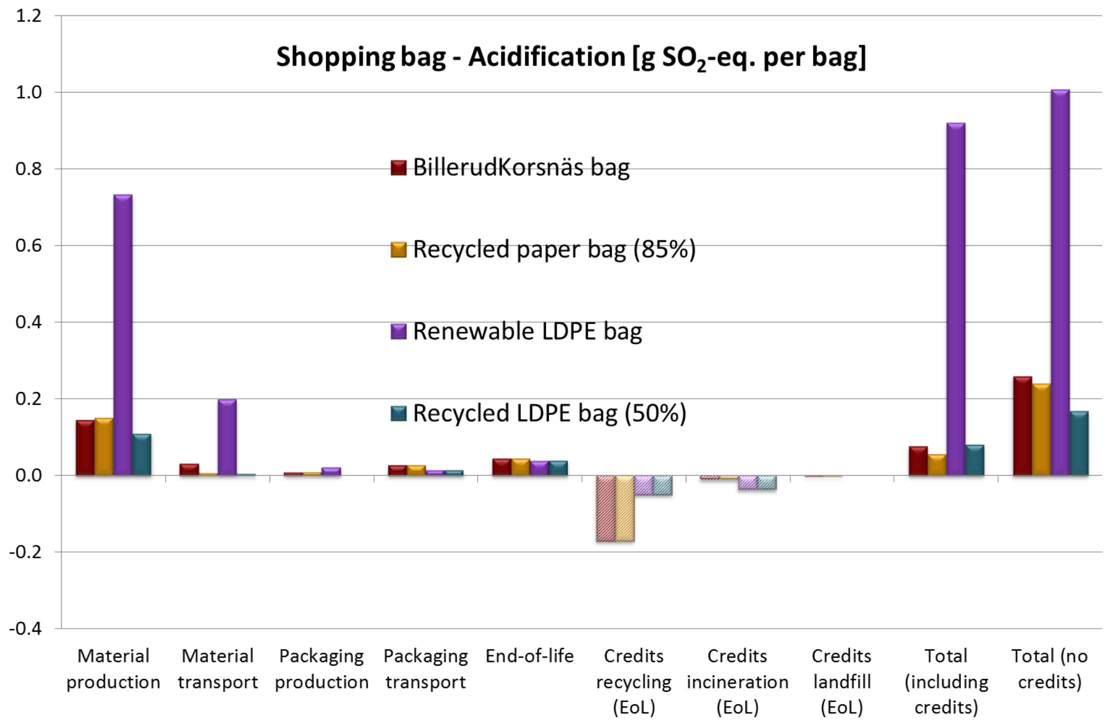

Figure 54. Acidification potential for the shopping bags, end-of-life as well as credits from avoided emissions from generated energy and virgin material production has been included

Eutrophication Potential

The impact on eutrophication when also including end-of-life can be seen in Figure 55. For the paper bags, around 57 % of the impact from end-of-life is due to the recycling process, and this is approximately equally due to emissions from the process (such as COD and nitrogen to water) as to the electricity used in the process (UK mix). Landfill contributes with 20 % of the total impact from end-of-life, while landfill and transports contribute with 9 % and 13 % respectively.

For the plastic bags, around 35 % of the impact from end-of-life is due to the recycling process, mainly because of the electricity used in the process. Landfill contributes with around 30 % of the total impact from end-of-life. Incineration of the plastic bag stands for around 20 % of the total impact from end-of-life.

In Figure 56, the avoided emissions have also been regarded. Including end-of-life, with or without credits, does not affect the total results for the bags relative each other.

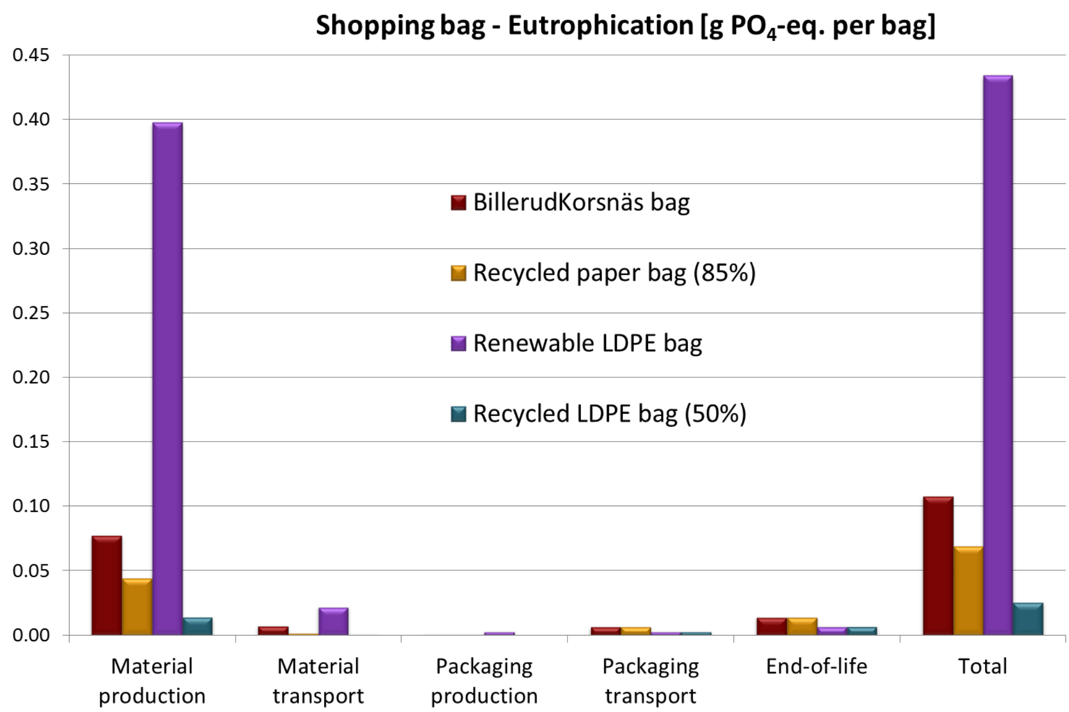

Figure 55. Eutrophication potential for the shopping bags, when also end-of-life has been included

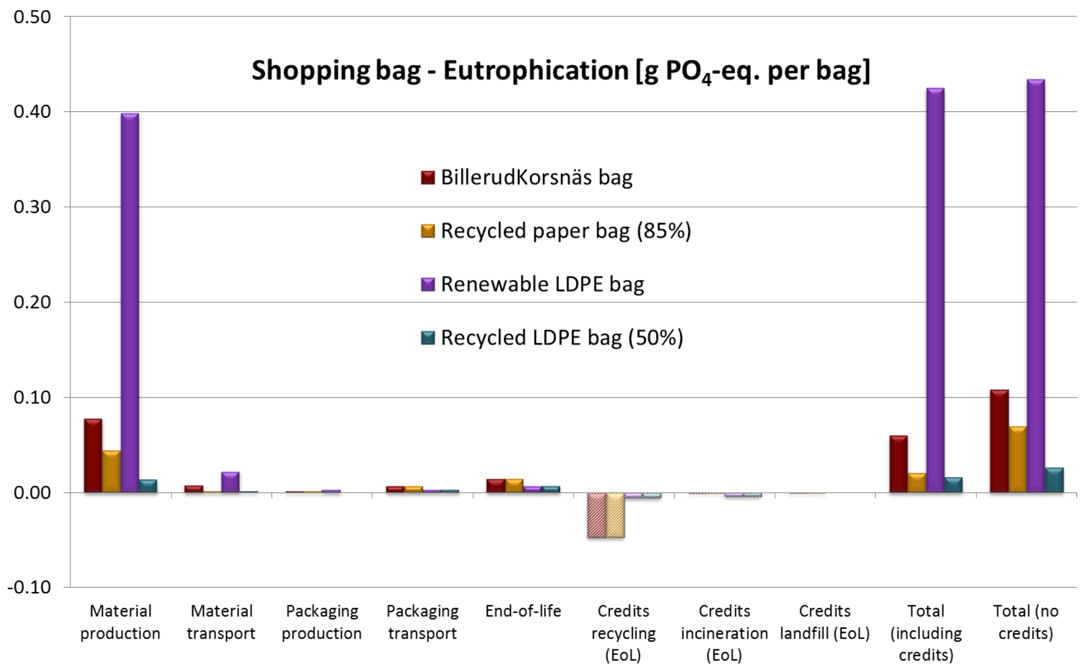

Figure 56. Eutrophication potential for the shopping bags, end-of-life as well as credits from avoided emissions from generated energy and virgin material production has been included

Ground level ozone formation potential

The impact on ground level ozone formation potential when also including end-of-life can be seen in Figure 57. Since the renewable LDPE bag is so dominating, making it difficult to see the impact from the other bags, these are shown separately in Figure 58 and Figure 60.

For the paper bags, around 35 % of the impact from end-of-life is due to the recycling process, and this is almost exclusively due to the electricity used in the process (UK mix). Landfill contributes with 48 % of the total impact from end-of-life, mainly because of methane emissions. Incineration stands for 9 % and transports for 8%.

For the plastic bags, around 60 % of the impact from end-of-life is due to the recycling process, mainly because of the electricity used in the process. Landfill contributes with around 11 % of the total impact from end-of-life, while incineration accounts for around 20 %.

In Figure 59 and Figure 60, the avoided emissions (credits) also have been included. There one can see there is an environmental benefit of recycling paper, since by doing so, resources and emissions for virgin material production, can be saved, and due to the relatively high environmental impact for virgin production, this is shown in Figure 60 as highly reduced and sometimes negative bars.

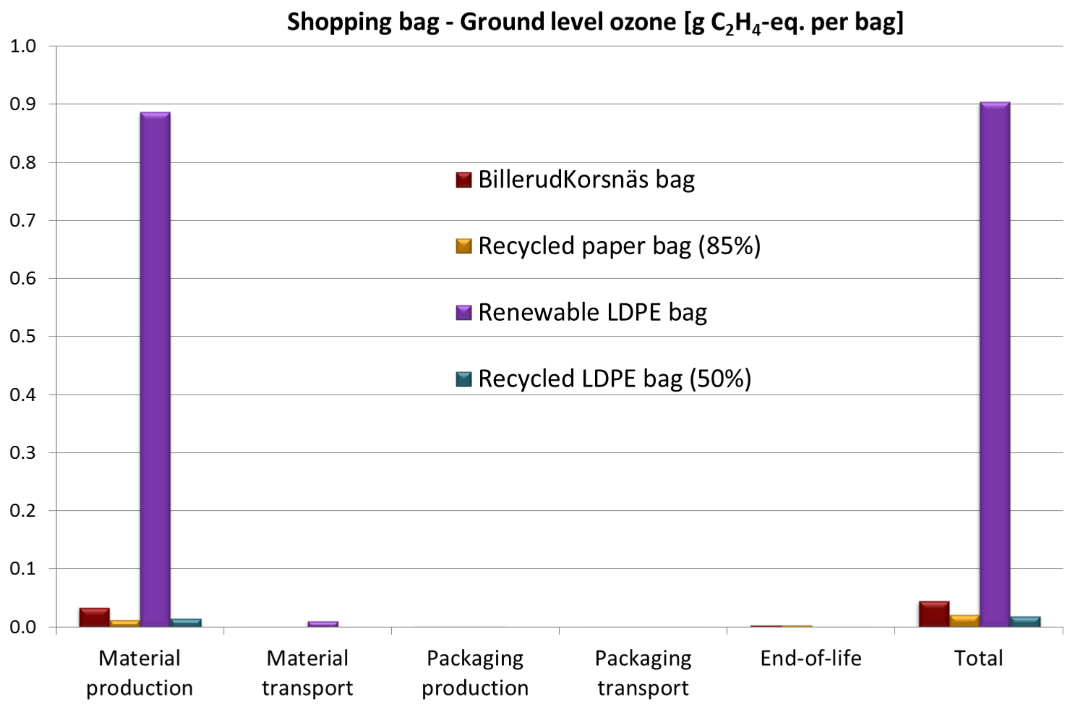

Figure 57. Impact on ground level ozone formation potential for the shopping bags when also end-of-life has been included

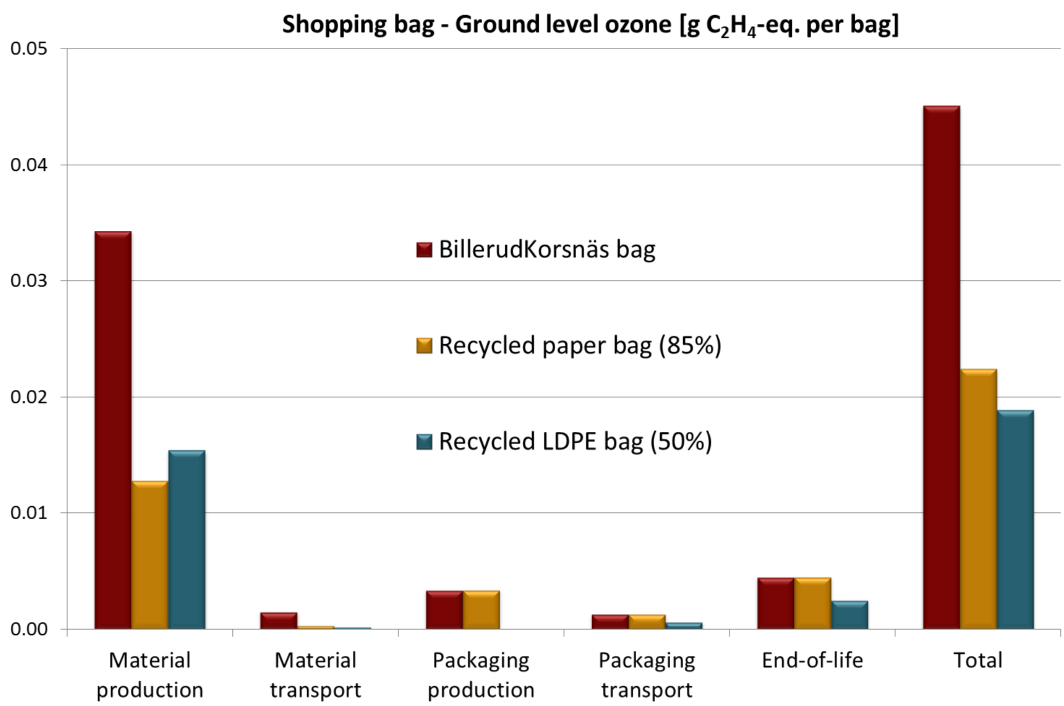

Figure 58. This shows the impact on ground level ozone formation potential for the shopping bags, including end-of-life, but without the renewable LDPE bag

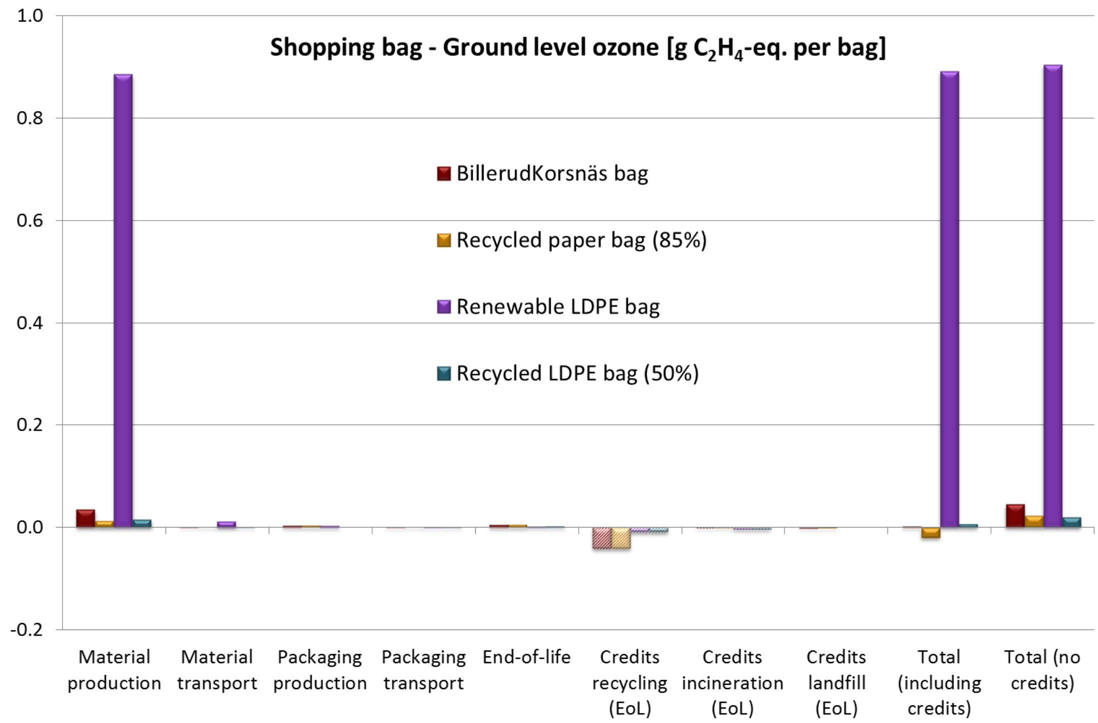

Figure 59. Impact on ground level ozone formation potential for the shopping bags, end-of-life as well as credits from avoided emissions from generated energy and virgin material production has been included

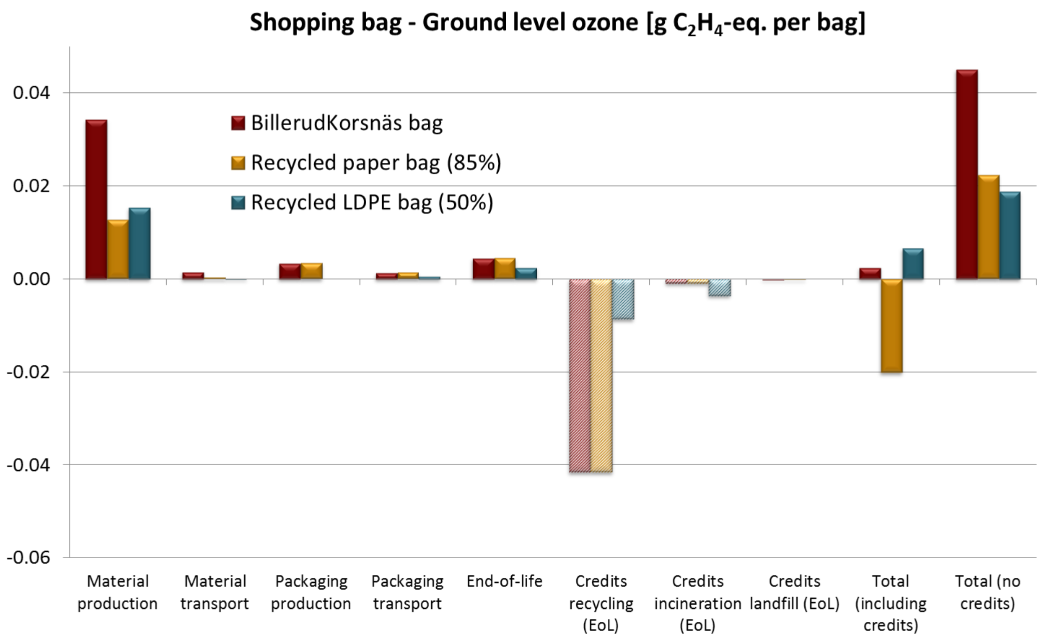

Figure 60. This shows the impact on ground level ozone formation potential for the shopping bags, including end-of-life and avoided emissions, but without the renewable LDPE bag

4.2.3 Sensitivity analyses

In Figure 61 to Figure 63, the results from different sensitivity analyses are shown for the shopping bags on regard to global warming potential. Figure 61 shows the results when the energy mix (for thermal energy) used for the paper machine for the recycled paper bag, was changed from the mix described in section 3.2.3, to 50 % natural gas and 50 % biomass. This is because although most mills use natural gas today, biomass is increasing according to (ACE 2016).

When changing the thermal energy mix, the total climate impact is decreased somewhat, although this effect is marginal, this is because the electricity mix used is of significance for the total impact from recycled paper bag.

In Figure 62 and Figure 63, the content of recycled material was set to 100 % for the paper bag and the plastic bag respectively. If the recycled paper bag were to consist of 100 % recycled fibres, it would not have a significant effect on the total climate impact, since the largest part (85 %) of the bag is recycled fibres anyway. For the recycled LDPE bag, the effect is somewhat larger. This is because the virgin content of the bag is relatively high (50 %) in the base case and virgin LDPE production has a great impact on the climate; therefore, the effect will be greater than for the recycled paper bag.

However, in each of the sensitivity analysis the BillerudKorsnäs bag has the lowest impact of all the bags.

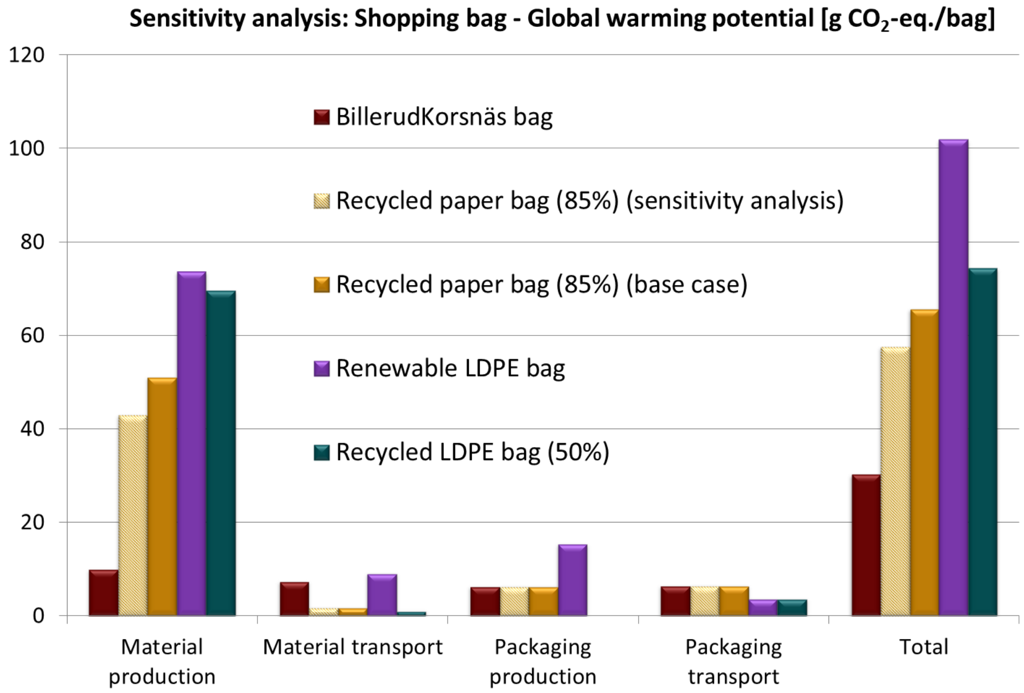

Figure 61. Results from sensitivity analysis: Thermal energy generated for the paper machine for making the recycled paper originates from 50 % natural gas and 50 % biomass

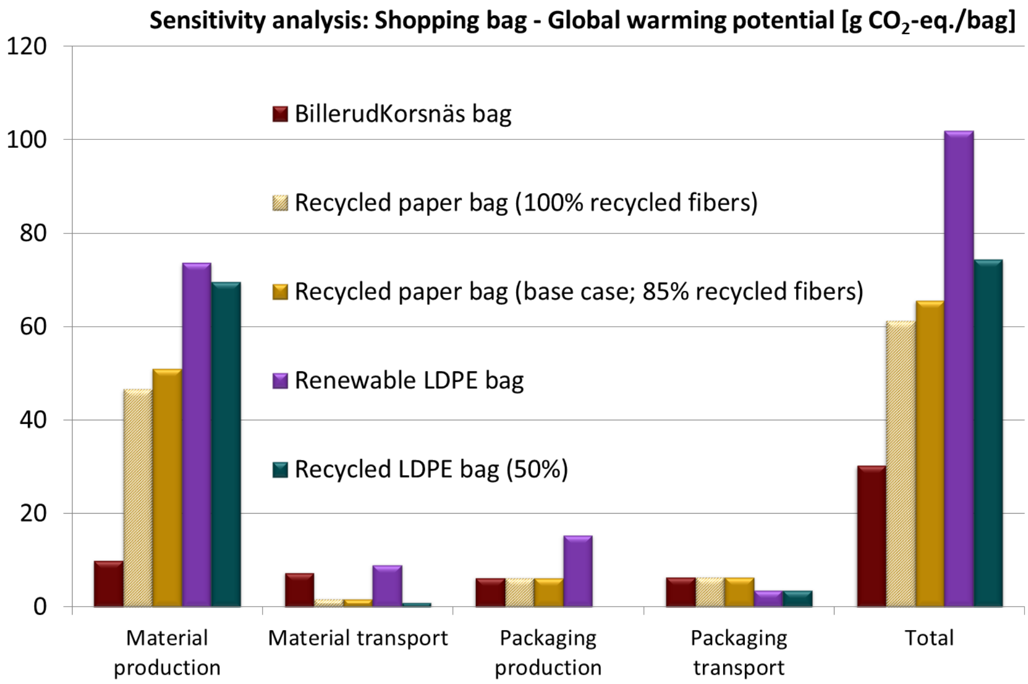

Figure 62. Results from sensitivity analysis: 100 % recycled fibres are used for the recycled paper bag

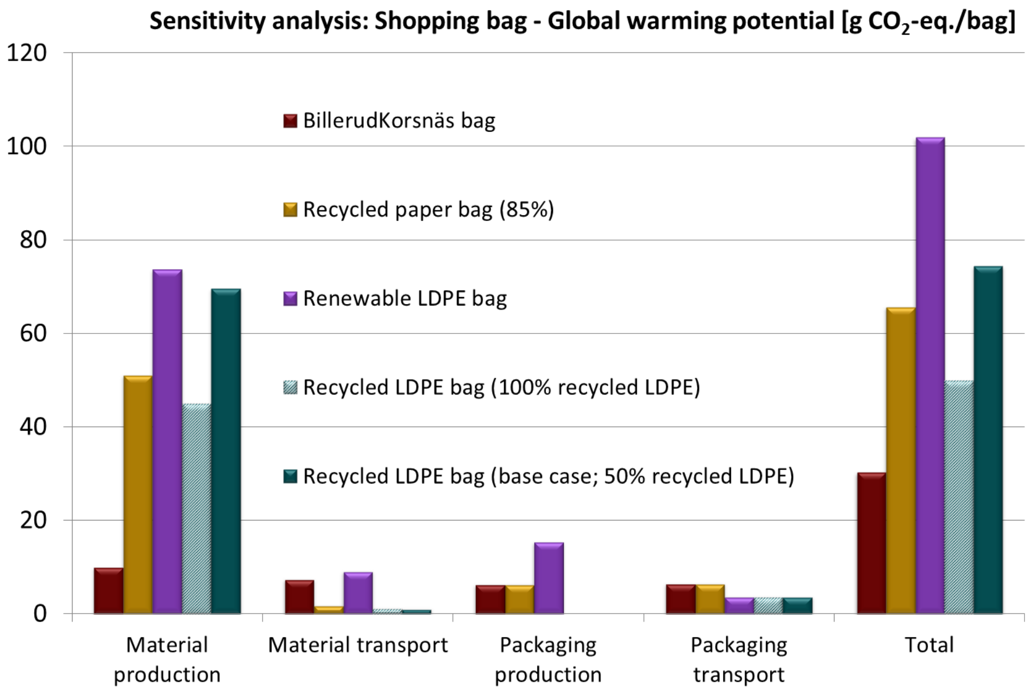

Figure 63. Results from the sensitivity analysis: 100 % recycled polyethylene is used for the recycled LDPE bag

4.2.4 Conclusions

For the base case, without including end-of-life and on regarding the climate impact (Figure 30), the BillerudKorsnäs bag has a remarkably lower impact compared to the other bags in the study. This is due to the relatively low impact during the material production at Skärblacka mill. In the base case, the recycled paper bag has the second lowest impact and the renewable LDPE bag has the highest impact.

The system expansion (end-of-life included), shows the same outcome, with the exception that the impact from the recycled LDPE bag increases and therefore the other alternatives seems to be more favourable. This is also true when avoided emissions also are accounted for.

Substituting the virgin content for recycled material in the sensitivity analysis, seemed to have a very small effect on the recycled paper bag, likewise when alternating the energy used for the paper machine. However, using 100% of recycled LDPE actually decreased the climate impact of the recycled plastic bag so that the total impact became lower than the recycled paper bag (with 85% recycled paper). Regardless, the BillerudKorsnäs bag had the best performance of the compared bags in the sensitivity analysis. It should also be mentioned that when the recycled content is changed in a bag, the quality and strength of the bag is also changed.

However, in the base case for acidification, eutrophication and ground level ozone formation (Figure 37, Figure 41 and Figure 45), the recycled LDPE bag shows the best performance. This is because of the higher impact from the material production at Skärblacka. Here, the direct emissions from the mill and to some extent the upstream production of the chemicals (especially flocculation/thickening agents and starch) are important parameters to address.

The system expansion (end-of-life included), shows the same outcome for acidification, eutrophication and ground level ozone formation, as for the base case. This is true when avoided emissions also are accounted for, except for ground level ozone, where the effect of including avoided emissions heavily reduces the impact for the paper bags and especially for the recycled paper bag.

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Appendix I – The results presented in tables

Table 11. Numeric values for global warming potential for the shopping bags.

Global warming potential [g CO_2-eq./bag]				
	BillerudKorsnäs bag	Recycled paper bag (85%)	Recycled LDPE bag (50%)	Renewable LDPE bag
Material production	10.00	51.10	69.65	73.70
Material transport	7.42	1.77	1.11	9.15
Packaging production	6.36	6.36	-	15.39
Packaging transport	6.48	6.48	3.68	3.68
Total	**30.26**	**65.70**	**74.43**	**101.92**

Table 12. Numeric values for global warming potential for the cement sacks.

Global warming potential [g CO_2-eq./sack]		
	D-sack	Generic cement sack
Material production	37.10	68.44
Material transport	2.53	1.79
Packaging production	61.05	75.75
Packaging transport	6.99	5.88
Total	**107.67**	**151.85**

Table 13. Numeric values for acidification potential for the shopping bags.

Acidification potential [g SO_2-eq./bag]				
	BillerudKorsnäs bag	Recycled paper bag (85%)	Recycled LDPE bag (50%)	Renewable LDPE bag
Material production	0.1450	0.1500	0.1091	0.7340
Material transport	0.0320	0.0076	0.0049	0.1980
Packaging production	0.0087	0.0087	-	0.0212
Packaging transport	0.0280	0.0280	0.0159	0.0159
Total	**0.214**	**0.194**	**0.130**	**0.969**

Table 14. Numeric values for acidification potential for the cement sacks.

Acidification potential [g SO_2-eq./sack]		
	D-sack	Generic cement sack
Material production	0.368	0.325
Material transport	0.011	0.008
Packaging production	0.087	0.168
Packaging transport	0.030	0.025
Total	**0.496**	**0.526**

Table 15. Numeric values for eutrophication potential for the shopping bags.

Eutrophication potential [g PO_4-eq./bag]				
	BillerudKorsnäs bag	Recycled paper bag (85%)	Recycled LDPE bag (50%)	Renewable LDPE bag
Material production	0.0775	0.0444	0.0141	0.3980
Material transport	0.0079	0.0019	0.0012	0.0219
Packaging production	0.0014	0.0014	-	0.0034
Packaging transport	0.0069	0.0069	0.0039	0.0039
Total	**0.0936**	**0.0545**	**0.0192**	**0.4272**

Table 16. Numeric values for eutrophication potential for the cement sacks.

Eutrophication potential [g PO_4-eq./sack]		
	D-sack	Generic cement sack
Material production	0.159	0.112
Material transport	0.003	0.002
Packaging production	0.014	0.050
Packaging transport	0.007	0.006
Total	**0.183**	**0.170**

Table 17. Numeric values for ground level ozone formation potential for the shopping bags.

Ground level ozone formation potential [g C_2H_4-eq./bag]				
	BillerudKorsnäs bag	Recycled paper bag (85%)	Recycled LDPE bag (50%)	Renewable LDPE bag
Material production	0.0343	0.0128	0.0154	0.886
Material transport	0.0015	0.0004	0.0002	0.0116
Packaging production	0.0034	0.0034	-	0.0033
Packaging transport	0.0013	0.0013	0.0007	0.0007
Total	**0.0406**	**0.0179**	**0.0164**	**0.9016**

Table 18. Numeric values for ground level ozone formation potential for the cement sacks.

Ground level ozone formation potential [g C_2H_4-eq./sack]		
	D-sack	Generic cement sack
Material production	0.060	0.033
Material transport	0.00058	0.00036
Packaging production	0.010	0.018
Packaging transport	0.0014	0.0012
Total	**0.072**	**0.052**

Table 19. Numeric values for the impacts per ton sack paper produced at Karlsborg mill (ton refers to metric ton)

Karlsborg mill				
	Global warming potential [kg CO_2-eq./ton paper]	Acidification potential [kg SO_2-eq./ ton paper]	Eutrophication potential [kg PO_4-eq./ ton paper]	Ground level ozone formation potential [kg C_2H_4-eq./ ton paper]
Forestry	31.09	0.092	0.022	0.014
Energy (upstream)	7.44	0.034	0.026	0.006
Chemicals (upstream)	233.33	1.56	0.574	0.153
Transports (forest/chemicals/fuels)	46.49	0.34	0.063	0.025
Direct emissions from mill	47.05	1.62	0.885	0.392
Waste	2.12	0.004	0.004	0.0007
Total	**367.52**	**3.64**	**1.57**	**0.590**

Table 20. Numeric values for the impacts per ton paper (for shopping bags) produced at Skärblacka mill (ton refers to metric ton)

Skärblacka mill				
	Global warming potential [kg CO_2-eq./ton paper]	Acidification potential [kg SO_2-eq./ ton paper]	Eutrophication potential [kg PO_4-eq./ ton paper]	Ground level ozone formation potential [kg C_2H_4-eq./ ton paper]
Forestry	29.54	0.087	0.021	0.013
Energy (upstream)	5.66	0.020	0.041	0.003
Chemicals (upstream)	54.89	0.286	0.350	0.023
Transports	30.10	0.159	0.037	0.014
Direct emissions from mill	19.21	1.424	0.601	0.412
Waste	0.96	0.002	0.002	0.0003
Total	**140.37**	**1.98**	**1.05**	**0.465**

Appendix II – Chemicals impact

Table 21. The impact per kg chemicals, used at Skärblacka mill.

Chemicals at Skärblacka mill	Climate [g CO_2-eq./kg]	Acidification [g SO_2-eq./kg]	Eutrophication [g PO_4-eq./kg]	Ground level ozone [g C_2H_4-eq./kg]
Aluminium sulphate	423	7.8	1.3	0.5
Carbon dioxide	582	1.2	0.3	0.2
Flocculation /Thickening agents	2710	11.5	36.5	1.2
Sodium hydroxide	1043	2.6	1.4	0.2
Starch	565	6.0	4.9	0.3
Quicklime	1006	1.4	0.3	0.3

Table 22. The impact per kg chemicals, used at Karlsborg mill.

Chemicals at Karlsborg mill	Climate [g CO_2-eq./kg]	Acidification [g SO_2-eq./kg]	Eutrophication [g PO_4-eq./kg]	Ground level ozone [g C_2H_4-eq./kg]
Hydrogen peroxide	848	0.8	0.1	0.1
Sizer	1880	14	16	4
Sodium chlorate	173	0.8	0.3	0.1
Sodium hydroxide	273	1.9	0.7	0.1
Starch	565	6.0	4.9	0.3
Sulphuric acid	59	7.9	0.2	0.4
Quicklime	1006	1.4	0.3	0.3

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