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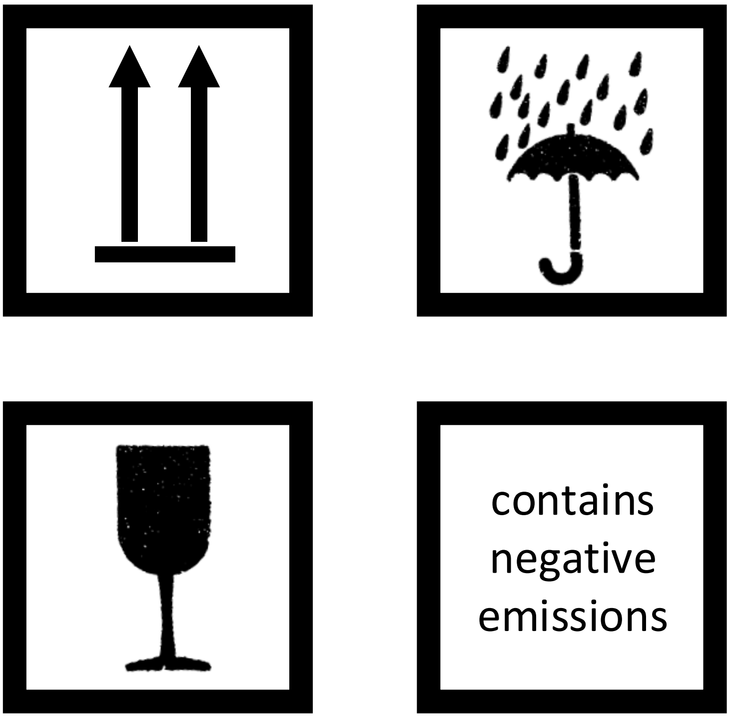

Perspectives on the value of BECCS

The Cost of Bio Energy Carbon Capture and Storage in the Pulp and Paper Supply Chain

Master’s thesis in Industrial Ecology

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Department of Space, Earth and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

To prevent a devastating global temperature increase the concentration of greenhouse gases (GHG) should not increase. However, the concentration of GHG in the atmosphere is already at a level, that most pathways to global temperature targets require negative-emission technologies (NET), which remove GHG from the atmosphere. One of these NETs is Bio energy carbon capture and storage (BECCS). In Sweden, 30% of the current fossil GHG emissions could be offset using this technology. Despite the need, currently, NET applications are not recognized as carbon mitigation for private developers. Thus, there is no value to a plant operator in applying BECCS.

This thesis argues therefore for a value of reduced carbon emission through BECCS in pulp making. It evaluates the cost increase and emission reduction of products down the supply chain until the end-user. Packaged drinks, a corrugated board box and a book were identified as representative paper products for the analysis. The changes of costs and carbon footprint through BECCS are then related to the price and carbon footprint of consumer products. It was found that the cost increase, resulting from implementation of BECCS in pulp and paper industry, would remain within the range of 0.1%- 0.2% for the investigated low value products. As the products' respective carbon footprint can be reduced substantially by attributing the captured carbon to the product (i.e. 3% -91%), the intangible value in low-carbon products increases, too.

The industry of investigation in this thesis is the Swedish pulp and paper industry, which constitutes Sweden's largest energy consuming and GHG emitting industry. The industry's energy supply is dominated by bioenergy and the GHG emissions consequently are predominantly of biogenic origin, making it a relevant industry for BECCS application.

The work concludes that the additional perspectives on the value of emission control helps to remove communication barriers that may have prevented the implementation of BECCS. With this supply chain perspective on BECCS, pulp producers (possibly in collaboration with supply chain partners) could have a reason to unlock investments and start mitigating climate change through pulp production, even without political incentives.

Key words:

BECCS costs, BECCS barrier, negative emission technology, incentive, accounting, pulp and paper industry, carbon neutral, supply chain, value chain, carbon footprint, Sweden

Abbreviations

ADt	Air Dried tonne
BECCS	Bio Energy Carbon dioxide Capturing and Storage
CCS	Carbon Capturing and Storage
CDR	Carbon dioxide removal
ECM	energy corrected milk
EU ETS	European Union Emission Trading Scheme
GHG	Green house gas
GTP	Global Temperature change Potential
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
NET	Negative Emission Technologies
PPI	Pulp and Paper Industry, pulp and paper industry
UNFCCC	United Nations Framework Convention on Climate Change

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1. Introduction

Currently almost all forms of human activity, may it be transport, services, real estate, consumables like food and household products, or materials, are associated with emissions of greenhouse gases (GHG). That state of the system and the increasing population constitutes a pathway to increasing environmental impact. To reduce the danger and effect of climate change, the United Nations Framework Convention on Climate Change secretariat (UNFCCC) aims to coordinate the global response to limit the global average temperature increase. In the Paris Agreement of 2015, it was agreed to hold the temperature increase below 2°C compared to the pre-industrial level and to try to limit it to a 1.5°C increase. (UNFCCC, 2015).

To stabilise the global climate and limit the temperature increase, net GHG must be reduced to zero. For this reason, the Intergovernmental Panel on Climate Change (IPCC) reviews, among other things, a large set of GHG emission scenarios and their associated temperature impact. Many scenarios that achieve climate stabilisation rely on Carbon Dioxide Removal (CDR), respectively Negative Emission Technologies (NETs), that enable the reduction of the GHG concentration in the atmosphere (IPCC, 2014, p. 136). Bio Energy Carbon dioxide Capturing and Storage (BECCS) is one of the NETs that are most commonly employed in the scenarios reviewed by the IPCC (IPCC, 2014, p. 52; van Vuuren *et al.*, 2018; Kemper, 2015). The rational of negative carbon dioxide (CO_2) emissions through BECCS is as follows: CO_2 from the atmosphere is absorbed by plants through photosynthesis and by that becoming biomass. Burning biomass and releasing the CO_2 back into the atmosphere is argued to be climate neutral. Following this argument, it can be argued that capturing and storing biogenic CO_2 is carbon negative, as CO_2 is removed from the atmosphere and not released again.

A report from the International Energy Agency from 2017 suggest that the Carbon Capturing and Storage (CCS) capacity - regardless of the source of CO_2, needs to increase tenfold by 2025 to be on track to meet the 2°C target (IEA, 2017b). With a proven capture rate of 9.3 $Mt\ CO_2$ in 2017 and the aim of capturing 400 $Mt\ CO_2$ in 2025, the actual capturing requires an even more substantial increase (IEA, 2017b). As of 2017 only one BECCS plant was installed worldwide, at an ethanol plant in the USA (IEA, 2017b). For Sweden, the immediate BECCS potential is estimated to be 16.7 $Mt\ CO_2$ yearly (Karlsson *et al.*, 2017).

In order to limit global temperature increase, the EU Climate Plan for 2030 targets to reduce the GHG emissions by at least 40% compared to 1990, in combination with associated goals regarding energy efficiency and a renewable energy share (EC, 2014). A strategy for 2050, as required by the Paris agreement, is expected in the beginning of 2020. The current strategic long-term vision, presented in November 2018, suggests the ambition for climate neutrality by 2050 (EC, 2018b). In this vision, BECCS is identified as one of the main opportunities to achieve negative emissions (EC, 2018a, p. 332). Looking at Sweden, the Climate Act which was ratified in 2018, sets goals for 2030 and 2040 on the path to net- zero emissions in 2045 and negative emissions thereafter. In 2045, GHG emissions from activities in Sweden are to be reduced by at least 85% compared to 1990. The remaining emissions can be offset with the carbon uptake by the eco cycle and credits through so called ‘climate projects’ abroad to reach net zero (Government Offices of Sweden, 2018b). Yet, today there are no political incentives for BECCS implementation, neither in the EU (Geden *et al.*, 2018) nor Sweden (Karlsson *et al.*, 2017). Further there are no indications of any political initiatives to introduce economic incentives for the capturing of biogenic CO_2 emissions in the near term (Geden *et al.*, 2019; Fridahl and Lehtveer, 2018). In addition are negative emissions provided by private developers not recognised in current GHG accounting schemes (Zakkour *et al.*, 2014). As a result, only one BECCS application is installed worldwide (IEA, 2017b) and it is questionable whether companies involved in manufacturing processes associated with emission of CO_2 of biogenic origin would integrate CCS in their plants by themselves.

In Sweden, 52 million tonnes CO_2 from fossil fuels and 32 million tonnes CO_2 from biofuels were emitted in 2017 (Naturvårdsverket, 2018c, 2018d, p. 26). Accounting for fossil and biogenic emissions, the Swedish pulp and paper industry (PPI) is responsible for 23 million tonnes of CO_2 (Hansson *et al.*, 2017), or 27% of the nation's CO_2 emissions, constituting the highest emitting industry. The PPI is powered almost exclusively by residual biomass from pulp making. The majority of the CO_2 is emitted from the recovery boiler as a point source, which makes it well fitted to apply BECCS.

CCS technologies are considered a mature technology, but the challenge is to find ways to unlock investments. So far, the few CCS in operation are applied to power plants and industries of different types (e.g. coal or natural gas power plants and steel or hydrogen production) (IEA, 2017a). In these, CCS is used to avoid emission taxes or most commonly to improve oil production in aging oil fields, so called enhanced oil recovery (IEA, UNIDO, 2011; IEA, 2017a). In the development of CCS, the cost effectiveness [costs/tonne CO_2 captured] and the capture rate [captured CO_2/ generated CO_2] are decisive elements for application or further development. In some cases, the costs are also presented connected to the price increase of primary products, like steel, cement or pulp.

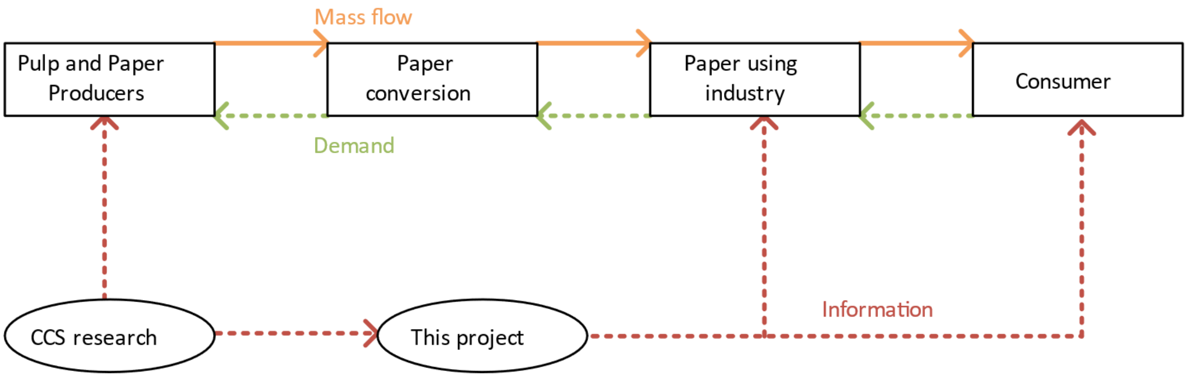

Figure 1 Position of this project in the CCS research, translating the information for consumers and the paper using industry.

This perspective on the cost of captured CO_2 is useful for development decisions for CCS technologies or in the development of cost-effective policy instruments. However, a narrow focus on the average abatement cost in primary production may say little about the effects on the final product. These primary products, like steel, cement or pulp, only have a value to society if transformed to a product with a function. It therefore makes sense to consider the effects of investments in BECCS on the final product (e.g. a beverage container) and not only on the primary product (e.g. pulp/paper). The aim of this thesis is to provide this more complete and relatable perspective, by setting the costs and emission reduction in relation to the supply chain. As the captured CO_2 emissions will not be rewarded by political schemes, these are assumed to be part of the products carbon footprint and able to be passed down the supply chain, parallelly to the costs. The analysis will be done by the selection of representative products, that will be identified as a first step. The basic idea of the project is presented in Figure 1: The results of CCS research, which are currently directed to Pulp and Paper Producers, are taken to other actors in the supply chain, by connecting the existing results to the costs and carbon footprint of final products.

The supply chain approach of connecting a cost increase in the production of primary products with consumer products was inspired by Rootzén and Johnsson (2016), and Skelton and Allwood (2013). The former investigated the impact of an increased steel price on a passenger car, due to a price on CO_2 emissions. They assert that the retail price increases 0.5% if a carbon price of 100 $€/\ tCO_2$ is assumed for the steel production. Skelton and Allwood (2013) investigated the changes of the expenditure structure of steel using sectors, assuming increasing steel costs due to a price on carbon emissions. They found that the share of steel expenditures in the costs is limited even in steel intensive sectors and that an increase of the steel cost would have little effect on the cost of final products.

2. Aim of the report

The aim of this thesis is to explore prospects for implementation of BECCS in the Swedish PPI by adding a new perspective on the investment costs. In this thesis the supply chain for pulp and paper, from primary production to final end use, is investigated to answer the following two research questions:

I. How much would the cost of final products increase, if due to the implementation of BECCS the cost of pulp production increases?
II. How would the carbon footprint of products change, if the used pulp reduces the embedded emissions?

3. Background

This section covers: (i) the current political and technical progress of BECCS and its ability to deliver negative emissions; (ii) the Swedish PPI, discussing its historical development and relevance in the economy regarding energy usage and GHG emissions; (iii) a description and discussion of the processes in the production of paper products, leading to; (iv) a discussion of the possible integration of BECCS.

3.1. Application of negative emission technologies

3.1.1. Political progress

Negative emission technologies are currently not incentivised by policy makers. Generally, the political ambitions to limit GHG emissions are directed towards fossil GHG emissions. Thus is CCS listed as a complementary policy in the 2030 climate and energy framework of the EU. It further suggests to “enable commercial deployment by the middle of the next decade”, yet only sets it explicitly in relation to fossil power generation (EU, 2014, 4.3). The EU Emission Trading Scheme (EU ETS), which is presumed to be the main instrument to reach the European targets (EC, 2014), includes fossil CCS since 2013 (Jönsson *et al.*, 2013). Consequently, are biogenic not covered by the EU ETS (EC, 2017b; Zakkour *et al.*, 2014). Nor is it covered by the Swedish carbon tax (Government Offices of Sweden, 2018a). In line with that, neither was BECCS ever seriously considered in the negotiations for the 2021-2030 trading period in the EU ETS (Scott and Geden, 2018).

Moreover, regulatory challenges remain with respect to transport and storage of CO_2, regardless of the source. For example, the international London Protocol prohibits the export of CO_2 for sub-seabed storage (Dixon *et al.*, 2014). Similarly, national or local law could have to be amended (Heffron *et al.*, 2018).

In an analysis of how the Swedish PPI historically was encouraged by policy to reduce the CO_2 emissions, Scordato *et al.* (2018) find that national laws were more effective than supranational ones, like the EU ETS. The reason found in the study was the more advanced knowledge about the local industry, but they still point out that the national laws were designed to meet EU directives. Gulbrandsen and Stenqvist (2013) see a risen awareness in the studied paper manufacturing companies through the EU ETS, which however is still not translated to the search for low carbon solutions. The reason for the ineffectiveness of the EU ETS was found in wrong benchmarks in the allowance allocation, which are derived from the energy consumption rather than emission intensity (Stenqvist and Åhman, 2016).

3.1.2. Technological progress

Emission scenarios aligned with the ‘well below 2°C’ target outlined in the Paris Agreement extensively employ negative emission technologies to neutralize hard to mitigate emissions or to include negative emissions in case of an emissions overshoot (Fuss *et al.*, 2018). The emission pathways investigated in the IPCC “Special Report – Global Warming of 1.5°C” all include this technology (Rogelj *et al.*, 2018), and attempts to design pathways to lessen the dependence on NETs can still not remove the need for these entirely (van Vuuren *et al.*, 2018).

Seven major technologies are identified, including: “Afforestation & reforestation”, “Bioenergy carbon capture and storage (BECCS)”, “Biochar”; “Ocean fertilisation”, “Soil carbon sequestration”, “Enhanced weathering” and “Direct air capture” (Minx *et al.*, 2018). BECCS is one of the most important methods for achieving negative emissions in a vast majority of studies (Fuss *et al.*, 2018). Two factors that could restrict the deployment of BECCS are often discussed. Firstly, the “global bioenergy potential”, which is concerned with how much land is dedicated for bioenergy production and potential conflicts with other land uses. Secondly, the “global storage potential”, which is assessed to be globally sufficient, yet regionally limitations might still exist (Fuss *et al.*, 2018).

BECCS, also referred to as Bio-CCS, is a sub field of the overall CCS technology, differentiating only in the CO_2 source. A recent comprehensive review by Bui *et al.* (2018) assessed the technical readiness level of key technologies related to CCS. Overall technical maturity was attested to the concept, since technologies for capturing transport and storage already reached commercial scale.

3.1.3. BECCS and its notions

The notion of negative emissions in case of capturing and storage of biogenic CO_2 comes from the assumption that emissions of biogenic feedstock are carbon neutral. National emission inventories use this way of arguing in their reports (IPCC, 2013, pp. 714–716; Haberl *et al.*, 2012), as well as policy instruments like the EU ETS in their design (EC, 2017b, 2018c, 38–39). Haberl *et al.* (2012) trace this accounting back to the Kyoto Protocol and the applied practices of relating the emissions of land use change and the energy system.

This assumption, however, is in its generality not undisputed, as it depends on the biomass source and scope of investigation. Haberl *et al.* (2012) present a wider scope than the plant level, emphasising the land use change emissions and the time lag between growth, energy conversion and regrowth. While for example the CO_2 emissions of using organic waste as source for energy could be accounted as neutral, the conversion of a forests to farmland for bioenergy crop cultivation is highly likely to result in an accounting error. This is why, the source of biomass and the conversion of the land are decisive factors for the assessment of carbon neutrality. Zanchi *et al.* (2012) also point out the importance of the biomass source and the considered time horizon for the analysis, stating that not all biomass is climate neutral. Given these arguments, there are also attempts to quantify the climate effects of biogenic GHG emissions, e.g. through adaptation of emission factors like the Global Warming and Temperate change Potential (GWP and GTP) for bioenergy (GWP_{bio}, GTP_{bio}) (IPCC, 2013, pp. 714–716).

Similarly, Fajardy and Mac Dowell (2017) investigates BECCS regarding its sustainability and resource efficiency to deliver negative emissions. They employed a water, carbon and energy footprints perspective and observed a high case dependency regarding the source of the biomass feedstock. The direct and indirect emissions from Land-use Change, production, pretreatment and transport of the biomass were found to be decisive for the outcome. Breakeven times to deliver carbon negative emissions, relating the released and the captured emissions, ranged from 1 year to 35 years. They however did not assess woody biomass.

For forest biomass, Berndes *et al.* (2016) point to a positive climate impact of bioenergy, despite referencing to the diversity of biomass sources and their respective impacts. While acknowledging the complexity of issue, following this generality, forest biomass is assumed carbon neutral in the analysis presented in this thesis. Moreover, all captured biogenic CO_2 emissions are assumed to be negative, as they originate from forest biomass. For an individual pulp producing company, attention should still be given to the biomass sourcing, so that Land-use Change emissions from sourcing of biomass are limited (Cintas, 2018).

3.2. The Pulp and Paper Industry (PPI)

3.2.1. Position in Sweden and the global trade

Pulp from Sweden has a global share of around 6% of production and export, while paper has a share of around 3% in production but more than 8% of export (KSLA, 2015). With a production share of approximately 26% of all produced pulp in 2017 in Europe, the Swedish Pulp and Paper Industry (PPI) constitutes the biggest pulp producer in Europe. Together, Sweden and Finland account for around 50% of the European virgin pulp production (CEPI, 2017). The export share in Sweden is at 85% for market pulp, respectively 90% for paper (Skogsindustrierna, 2019a). The export of pulp and paper products account for 7-8% of the Swedish export volume (SCB, 2019a).

Historically the PPI, together with the forest industry, has been an important industrial sector in Sweden (Järvinen *et al.*, 2012). In the first half of the 20th century Sweden was the world's largest exporter of pulp, finally being overtaken by Canada. In the second half of the century the industry refocused on paper production, producing newsprint and packaging material. The Finnish industry also moved to paper production, but, as opposed to Sweden, focused on printing and writing paper. In the early 2000s the paper production rose to over 12 million tonnes and decreased slightly to around 10 million tonnes since. The industry in Sweden and Finland both developed their product range successively from newsprint to packaging, to printing and writing and later to magazine papers, increasing the added value (Järvinen *et al.*, 2012).

In 2011 64% of the pulp and 60% of the national paper production were produced by the industry's largest firms, SCA, Södra, StoraEnso and Holmen. Originally being competitors they now have specialised into different market segments (Ottosson and Magnusson, 2013). Södra for example only produces sawn wood and market pulp, SCA has a good stand in hygienic products such as tissues (Ericsson *et al.*, 2011).

3.2.2. Energy usage and CO_2 emissions in the PPI

Looking at the global scale, the PPI plus printing accounted for around 7.5% of industrial energy consumption (IEA, 2017b, p. 43) and for 3% of the total direct industrial fossil CO_2 emissions in 2014 (IEA, 2017b, p. 39). Using these substantial amounts of energy for their production, the PPI is considered an energy intensive industry. The production of one tonne sulphate pulp form black liquor with the energy content of approximately 19 gigajoules (IEA, 2017a). With a total of 137 million tons of produced sulphate pulp globally, approximately 1.8 exajoules were combusted in the sulphate pulp process in 2016. This makes black liquor worldwide the fifth most important fuel after coal, oil, natural gas and gasoline (Kuparinen *et al.*, 2019). Figure 2 describes the distribution of pulp and paper mills in Europe, with the emission density through onsite emissions in the PPI. Individual mills emitting more than 0.1 $Mt\ CO_2/$ year are shown by coloured squares. The emission density is indicated by blue shading of the regions; the darker the colour, the higher the emissions. As can be seen the emission density is highest in areas with kraft pulp production. In Finland and Sweden, which both are home to several kraft pulp mills, the density is one of the highest.

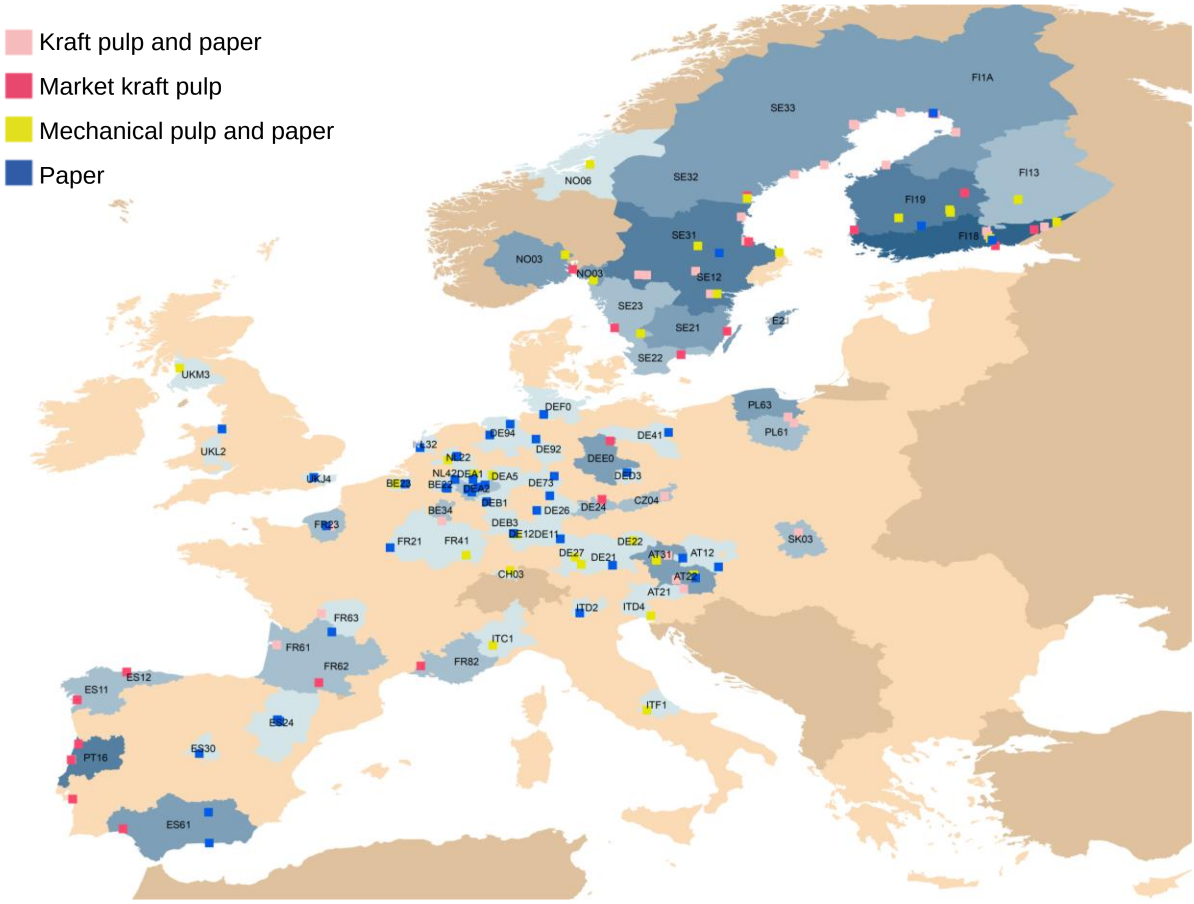

Figure 2 The geographical distribution of on-site CO_2 emissions from the European PPI. Adapted from (Jönsson et al., 2013)

In Sweden, manufacturing is the largest energy consuming sector, with a share of 35% of all consumed energy. The PPI is the largest industry in that sector, accounting for 18% of the energy use, see Figure 3. It is further responsible for 46% of the CO_2 emission originating from stationary point sources in Sweden, accounting for biogenic and fossil sources (Hansson *et al.*, 2017). In 2011 around two thirds of the PPIs energy source were from biomass (50TWh), 30% were electricity (23 TWh) and only 2.5 TWh came from fossil fuels, with an decreasing share of fossil fuels (Ottosson and Magnusson, 2013). The corresponding development of CO_2 emissions is represented in Figure 4 for the time between 2002 and 2017. Historically bigger changes in the energy source were undertaken in response to the first oil crisis in 1973, led by a national voluntary programme for energy intensive industries (Lawrence *et al.*, 2018). As a consequence, the fossil CO_2 emissions decreased from 8 million in 1973 to less than 1 million tonnes since in 2014 (Scordato *et al.*, 2018). This has resulted in the internationally lowest fossil carbon footprint per tonne of product and low application of fossil fuels (Scordato *et al.*, 2018).

Thollander and Ottosson (2008) identified an energy efficiency gap (i.e. an unrealised potential for further efficiency gains) in the Swedish PPI, but without further quantification. For the Swedish energy intensive industries in total, Backlund *et al.* (2012) estimated a potential energy efficiency improvement of 13% by investment in more efficient technologies and 20% by improved energy management practices. Since then the specific electricity consumption has remained relatively unchanged (Skogsindustrierna, 2018c). Reasons for the efficiency gap in the PPI were firstly found in technical factors and secondly other priorities, often market related and therefore probably caused by the way energy issues are organized within firms (Thollander and Ottosson, 2008).

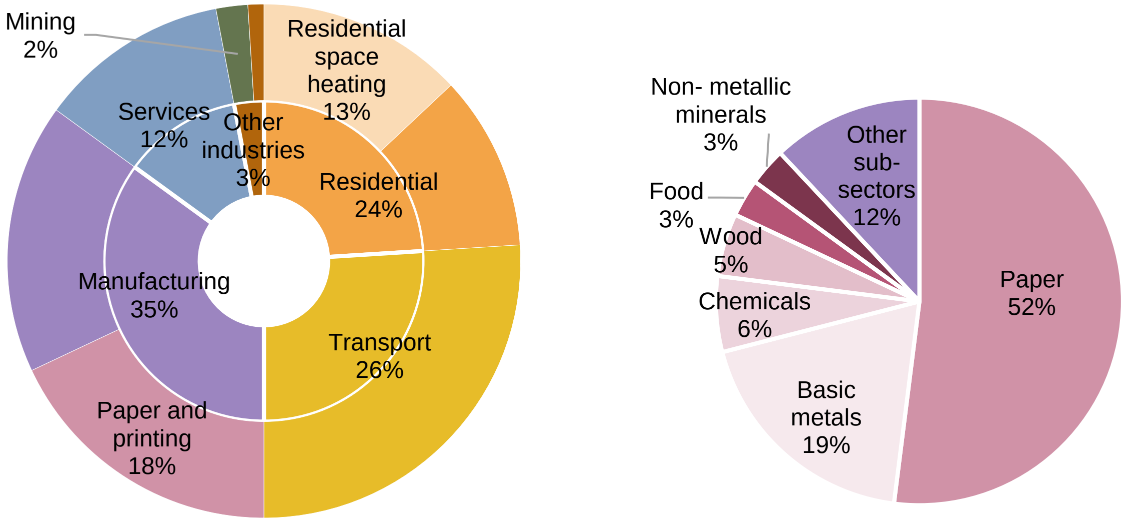

Figure 3 Largest energy end-uses by sector, Sweden, 2016. (left total, right manufacturing)[1] *adapted from (IEA, 2019)*

As depicted in Figure 10 (p. 24), there are three main CO_2 streams in a pulp plant: the recovery boiler, the biomass boiler and the lime kiln. If fossil fuels are used for the operation, it is usually limited to the lime kiln, yet in start-up and shut-down phases fossil fuels can be used in all three. For the global PPI Kuparinen *et al.* (2019) estimate the emissions from the recovery boiler to be 1600-2400 kg kg CO_2 per Air Dried tonne of pulp (ADt) from biogenic sources and only 10-20 CO_2/ ADt from fossil fuels. For the lime kiln, fossil emissions are estimated at 100-250 kg CO_2/ ADt. The application of the biomass boiler and, if necessary a fossil fuel boiler, depends on the steam requirements of the mill.

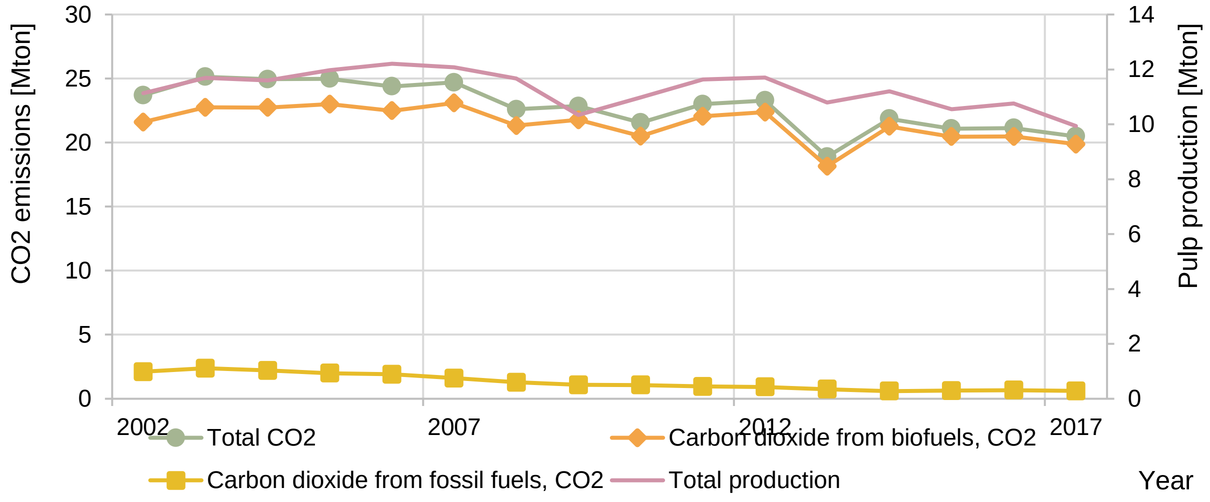

Figure 4 Direct CO_2 *emissions and production levels of the Swedish PPI as reported by the industries environmental database (no complete report, see Appendix A) (Skogsindustrierna, 2018a)*

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[1] Other industries includes agriculture, mining and construction; other sub-sectors includes all remaining manufacturing sub-sectors beyond the top-6

3.2.3. Processes in the Supply Chain

The pulp and paper industry is a diverse industry, Carlsson *et al.* (2009) divide the supply chain of the pulp and paper industry in the following 4 consecutive networks: The Procurement Network, which is supplying wood material; the Production Network, which is converting the wood logs into paper products; the Distribution Network, which convey the products to merchants, and finally the Sales Network, constituting the market. To understand different kinds of paper and then the application of CO_2 capturing in the pulp production, a focus will be laid on the Production Network. It again includes 4 consecutive steps: chip mills, converting logs into wood chips; pulp mills, converting the chips into pulp; paper mills, converting pulp into paper, and finally converting plants, using paper to manufacture paper products. The first three are considered as pulp and paper industry, conversion plants are not (Ericsson and Nilsson, 2018). The final paper products include e.g. cut-to-size paper, books, corrugated board boxes or liquid packaging cartons, including printing. The different steps towards paper production can vary and therefore enable the production of a wide range of different papers.

Wood

In Europe paper is almost entirely made from wood fibres (CEPI, 2017). A typical differentiation is between hardwood or broadleaves (birch, beech, oak) and softwood or evergreens (pine, spruce) (CEPI, 2019). In the European wood consumption softwood dominates with 71%, against 29% for hardwood (CEPI, 2019). With 80%, the Swedish forests have a higher share of softwood, see Figure 5. Table 1 summarizes the differences between these two categories. As the yield (tonnes of wood/tonne of pulp) or the wood density (t/m3) can change, a typical unit for the used wood for pulp production is m^3 wood/ADt (EC, 2015, p. 502).

Table 1 Wood types, adopted from (CEPI, 2019) and (Bajpai, 2018)

	Hardwood Trees	**Softwood Trees**
Type of tree	Oaks, beeches, poplars, birches and eucalyptus	Mainly pine and spruce
Usage	In Europe it is mostly birches (found in Sweden, Norway, the UK and Spain) and eucalyptus (found in Portugal, Spain and Norway) that are used for papermaking.	In Europe pine is found in the UK, Norway, Finland, France, Spain, Portugal and Greece. Spruce is found in the UK, Finland, Norway and Sweden.
Average length of fibres	1mm	3mm
Percentage of fibre in wood	90-95%	36-70%
Features	Achieving bulk, smoothness, opacity	Providing additional strength. Also suitable for writing and printing
Typical Products	Writing papers, printing papers, tissue papers	Shipping containers, grocery bags, corrugated boxes

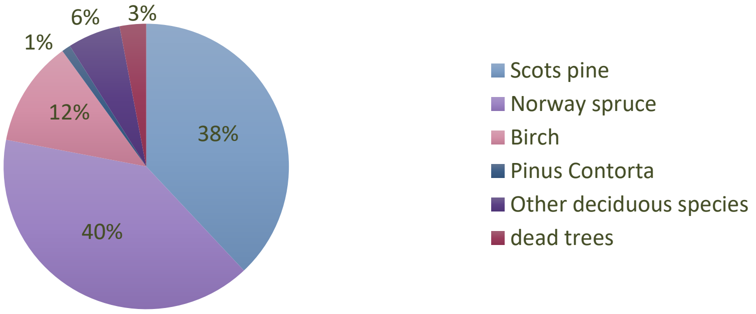

Figure 5 Standing volume, Sweden (2010-2014), adapted from (KSLA, 2015, p. 3)

Description pulping

The wooden raw material is transported to the pulp mill either as roundwood or in the form of wood chips and dust from sawmills. In Sweden the ratio is 80/20 (Skogsindustrierna, 2016).

Pulping can be done in different ways, with different product properties. Table 2 summarizes the most important pulping processes by relating these to the wood used, the product properties, typical products and the number of mills of each technology in Sweden. A typical differentiation in the processes is made between mechanical pulping, in which the fibres are separated by mechanical attrition and chemical pulping, whereby the fibres are resolved by boiling wood chips in a chemical solution and dissolving lignin. These technologies can also be mixed, that both, mechanical force and chemical reactions, release the fibre. These can be called semichemical or chemimechanical, depending on the dominating technology (Bajpai, 2018). Another way to produce pulp mass is by using recycled paper.

Mechanical pulping is an umbrella term for all processes that do not use chemicals besides water and steam to break down the wood. All the work is done by physical pressure, which requires large amounts of energy input, often electricity (Bajpai, 2015). The wood is transported as logs to the mill and shredded in small pieces. There are different technologies to do this, which correspondently result in different pulping results. Compared to chemical pulping the strength of mechanically produced pulp is lower. Therefore typical final products are ‘non-permanent’ paper goods, like newspaper or printing and writing paper (Bajpai, 2015; EC, 2015).

Chemical pulping can also be divided into different technologies. The most common way of chemical pulping is the so-called kraft pulping or sulphate pulping, which represents more than 70% of all produced pulp in Sweden 2017 and more than 95% of chemical pulp (Skogsindustrierna, 2018d). Sulphite pulping is more flexible regarding process control and producible products, but the pulp is weaker than Kraft pulp (Navard, 2013).

The pulp, both mechanical and chemical, can be bleached to improve the appearance in terms of brightness and cleanness. The bleaching technologies are quite diverse as well, regarding the chemicals used. A clear separation can however be drawn between the bleaching of mechanical and chemical pulp. The brightness of chemical pulp is enhanced by removing the remaining lignin, constituting the reason for a further reduction of the overall yield. Bleaching of mechanical pulp however aims at changing “chromophoric groups” in the lignin polymers, as the lignin is to full extend still in the pulp (EC, 2015, p. 496).

Recycled pulp is produced by breaking collected paper into small pieces to be able to remove the ink and a following separation of the ink from the fibres. The yield of recycled fibres lays, depending on paper and the process, between 70 and 90% (Fardim *et al.*, 2013).

Mechanical and Sulphate pulping require similar amounts of primary energy (in Sweden around 16 GJ/ t product (Stenqvist, 2015)), yet in mechanical pulping it comes from grid electricity, while sulphate pulping gets it from biomass incineration. The huge biomass-use makes sulphate pulping eligible for BECCS and the dominance in Sweden leads to focus on this technology.

Table 2 Summary of pulping processes, adapted from (Bajpai, 2018, p. 299), "Mills in Sweden" from (Skogsindustrierna, 2019b, 2018a)

Process	Chemicals	Species	Pulp Properties	Uses	Yield	Mills in Sweden
Mechanical pulping	None; grindstones for logs disc refiners for chips	Hardwoods such as poplar or light-colored softwoods such as spruce, balsam fir, hemlock, true firs	High opacity, softness, bulk; low strength and brightness	Newsprint, books, magazines	92% - 96%	5
Chemi-mechanical pulping	Chemithermomechanical pulp; mild action; $NaOH$ or $NaHSO_3$		Moderate strength		88% - 95%	6
Sulphate/ Kraft process, pH 13-14	$NaOH + Na_2S$ (15%-25% on wood); unlined digester, high recovery of pulping chemicals, sulfur odor	All woods	High strength, brown pulps unless bleached	Bag, wrapping. linerboard, bleached pulps for white papers	65% - 70% for brown papers; 47%—50% for bleachable pulp; 43%—48% after bleaching	22
Sulfite, acid, or bisulfite pH1.5—5	$H_2SO_3 + HSO_3^-$ with Ca^{2+}, Mg^{2+}, Na^+, or NH_4^+ base, Ca^{2+} traditional but outdated because no recovery process; lined digesters	Hardwoods such as poplar and birch and nonresinous softwoods; Douglas fir is unsuitable	Light brown pulp if unbleached, easily bleached to high brightness, weaker than kraft pulp but higher yield	Fine paper, tissue, glassine, strength reinforcement in newsprint	48%-51% for bleachable pulp; 46%-48% after bleaching	2
	Mg^{2+}base	Almost all species, spruce and true firs, preferred	Same as above but lighter colour and slightly stronger	Newsprint, fine papers. etc.	50%-51% for bleachable pulp;48% - 50% after bleaching	
Neutral sulphite semi-chemical pH 7—10	$Na_2SO_3 + Na_2CO_3$; about 50% of the chemical recovered as Na_2SO_4	Hardwoods (preferred): aspen, oak, alder, elm, birch; softwoods: Douglas fir sawdust, and chips	Good stiffness and moldability	Corrugating medium	70% - 80%	2

Sulphate/ Kraft pulping

The principal operation of a pulp mill is presented in Figure 10. As depicted, the main input for the Kraft pulping process is wood. These are chipped and then cooked in the so-called digester for a few hours. It contains a chemical solution of sodium hydroxide ($NaOH$) and sodium sulphide (Na_2S), called “white liquor”. During the boiling process the two ions hydroxide and hydrosulfide ion dissolve lignin in the wooden chips. The wood structure can break down into pulp, as lignin holds the fibres in the wood together. The raw pulp is then transferred to the pulp washing system. A screening and de-knotting step and another delignification further refines the pulp (Fardim *et al.*, 2013; EC, 2015; Bajpai, 2015). After preparation the pulp can be sent to bleaching. If the aim of pulping is not paper making, but the production of products like rayon, acetate, cellophane or food additives, hemicelluloses is removed additionally to lignin. The pulp is called ‘dissolving grade’ (Fardim *et al.*, 2013; Bajpai, 2015).

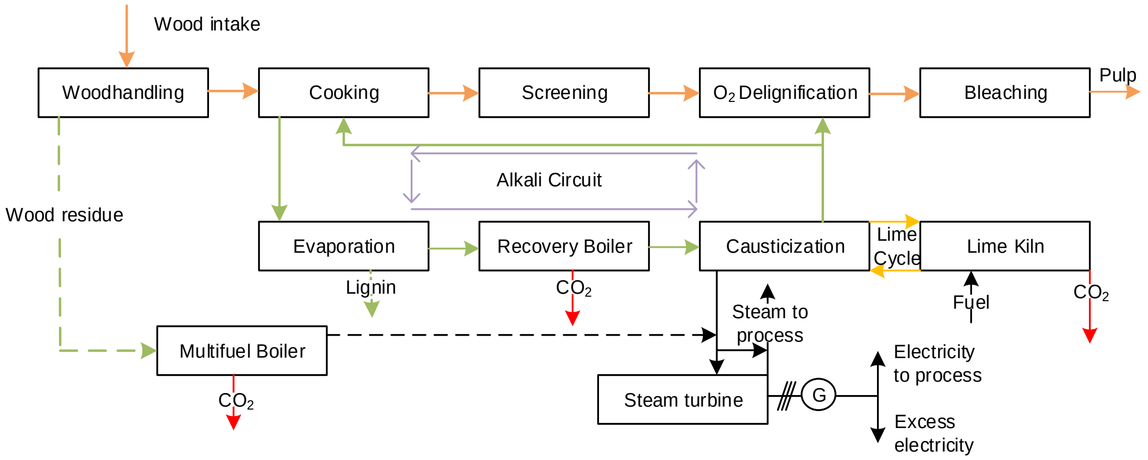

Figure 6 Kraft/ sulphate pulp mill operations and CO_2 streams, adapted from (Kuparinen et al., 2019)

The used cooking solution, then called “black liquor”, is washed off the pulp and recirculated into a recovery process. It runs parallel to the pulping process, to recover the cooking chemicals (compare the Alkali Circuit in Figure 6). In a first step, the dissolved solids content concentration in the solution is risen from 14-18% to 70-85% by evaporation. The concentrated black liquor is then sent to and burned in the recovery boiler, to recover the sodium and sulphur to be used again in the pulping. The incineration of the organic mass in the recovery boiler and the biomass boiler releases thereby enough energy to make the mill more than self-sufficient in electrical and heat energy (EC, 2015), so that excess electricity and heat can be sold. The recovered salts, sodium carbonate (Na_2CO_3) and sodium sulphide (Na_2S), flow out of the recovery boiler and dissolve in the process water, called “weak white liquor”, forming the solution called “green liquor”. After further clarification or filtration, the sodium carbonate is causticized to sodium hydroxide ($NaOH$) with lime (CaO). The two original compounds were recovered and can be used again for pulping. The used lime (calcium carbonate or CaO_3) is sent to a lime kiln and recovered to calcium oxide (CaO), see the Lime Cycle in Figure 6.

Because parts of the raw material are dissolved and incinerated for energy production, the overall pulping yield is lower in Kraft pulping, compared to mechanical pulping, which does not remove lignin from the pulp. The net production of pulp is measured at a moisture content of

10%, referred to Air Dried tonne (ADt). Paper products are measured at a moisture content level of 6% (EC, 2015, p. 840).

When the pulp is directly used for paper making, it is pumped to the paper mill. If the paper machine is not integrated in the pulp plant, it can be sold as Market Pulp, either as "wet lap" (about 50% water) or "dry lap" (15-20% water) (Bajpai, 2018, p. 180; EC, 2015, p. 34). In Sweden 21 of 31 pulp mills were directly connected to a paper mill, respectively 23 of 38 paper mills were integrated to a pulp mill (Skogsindustrierna, 2019b).

Paper manufacturing

Paper is a dried net formed of the pulp fibres. However, the term "paper" covers a wide range of different grades with different properties and qualities, which are influenced by the used raw material and the paper making process. Broadly classified, one can distinguish between paper (tissue, newsprint, bags, towels, napkins, stationery, etc.) and paperboard (linerboard, corrugating media, tubes, drums, milk cartons, recycled board, roofing felt, fiberboard, etc.) (Biermann, 1996). Thereby the properties to be accomplished decide about the pulp used and how it is treated. Most broadly, the paper properties are characterized by strength and printability (Brannval, 2009). The strength is highly influenced by the fibre used. Hardwood has shorter fibres and is therefore weaker but smoother, chemical pulp is more flexible and stronger, and respectively vice versa for softwood and mechanical pulp (Brannval, 2009). The properties to be achieved can be designed by the selection of the different raw materials and the subsequent processing. Table 3 describes some of the detail for the most common paper grades.

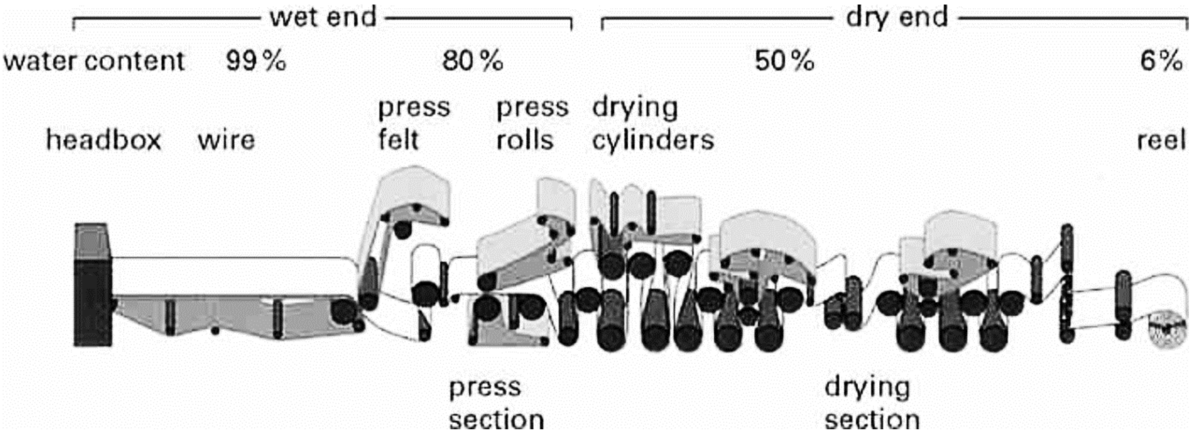

Figure 7 A simplified Fourdrinier paper machine (Brannval, 2009, p. 7)

Paper is commonly produced in Fourdrinier paper machines (EC, 2015, p. 661), in principle similar to the one depictured in Figure 7. The pulp suspension is fed in the headbox, the left side in Figure 7. Optionally in combination with fillers and chemicals. A woven cloth, the wire, takes the material evenly spread and forms the web of fibres, which is transported to a series of rolls and presses. The water is removed continuously, and the properties adjusted until the paper is rolled on the reel to be transported. (Brannval, 2009; Bajpai, 2015). If the paper net in the machine breaks, the material is re-pulped in the 'broke' system (EC, 2015, p. 665). Overall between 98-99% of the fed fibres end up in the end product (for liner it sometimes goes down to 95%) (EC, 2015, pp. 728–729). Fillers are added to adjust the material properties or replace (save) fibres. Examples of these are clay, lime, titanium dioxide or calcium carbonate (EC, 2015, p. 688). Not further discussed final processing steps include sizing, coating, calendaring or winding (Bajpai, 2015).

Table 3 Examples of major raw materials used for the manufacturing of different types of paper. Adopted from (EC, 2015, p. 683) plus data from (Skogsindustrierna, 2019b)

Paper grade		**Major raw materials used**	**Some product characteristics and product examples**	**Mills in Sweden**
Graphical paper	Newsprint	Few added chemicals; sometimes pigments added; very little colour; uses mechanical pulp or RCF	Narrow weight range: 40 - 52 g/m a) 100 - 70 % RCF-based + 0 - 30 % TMP b) mainly TMP + 0 - 50 % DIP	4
	Writing and printing	All grades of fibre, mainly bleached; fillers, sizes, colours, brighteners; may be coated; wide range of basis weights	Precise specification for user; specific weight from 30 g/m^2 to 50 - 60 g/m2 (LWC) up to 90 - 150 g/m^2	8
	Tissue	No added fillers; wet strength additives; uses chemical pulp and RCF in different mixtures	Light-weight product (1), e.g. handkerchiefs: 15 g/m^2 (for three sheets), napkins: 20 g/m (for two sheets)	7
	Speciality papers	Specific fibre processing; the pulp used can vary considerably in type and quality	This group covers a wide range of grades	5
Packaging material	Kraft wrapping	No added fillers; coloured; uses mainly unbleached kraft pulp	High strength product; 70 - 100 g/m2	8
	Kraftliner or Testliner	No added fillers; uses unbleached kraft pulp and RCF or RCF only	Heavier weight: 110 - 160 g/m Testliner: 90 - 100 ^{0}/0 RCF	6
	Board	Often different compositions in different plies; mostly multiply sheet; all fibre types including RCF	Higher basis weights: 175 g/m^2 + (up to 2 000 g/m^2)	8

(1) The sheet made on a tissue machine rarely exceeds 40 g/m3. The higher basis weights of tissue products are achieved by plying up in converting.

RCF = Recycled fibre(s) – TMP = Thermo mechanical pulp

Paper converting industry

In the paper conversion industry, paper and other raw materials like plastics are combined and further processed. There is a great variety of different paper products. Main groups are corrugated board and corrugated board packages, folding boxes, labels, books and brochures and products for household and hygiene (Wilken, 2013). The processes can vary in complexity and value added. A possible division can be drawn between printing, laminating, corrugating and saturating (Casey, 1961). In general the following processes can be identified in all paper conversions: Forming processes, of changing the shape; separating processes; joining processes of combining material; printing processes and transport processes, in which the location and amount of the material is changed (Wilken, 2013).

3.3. BECCS in the Pulp and paper industry

The application of CCS to the emission of market pulp mills and integrated pulp and paper mills is similarly possible as capturing in other industries. Garðarsdóttir (2017) investigated CCS in different industries and found similar costs for similarly sized emission sources. Besides the pulp and paper industry she investigated the steel industry, refining and petrochemical industries, cement plants and aluminium production. Investment costs of 100 to 200 M€ were found. To set this number in relation to other investments, the development of investments in the Swedish PPI since 1990 is depicted in Figure 8. The investments in recent years as depicted in the Figure, summing up to 12 Billion SEK, include singe investments in facilities and machines in a range between 400 to 800 M€ (Skogsindustrierna, 2019a).

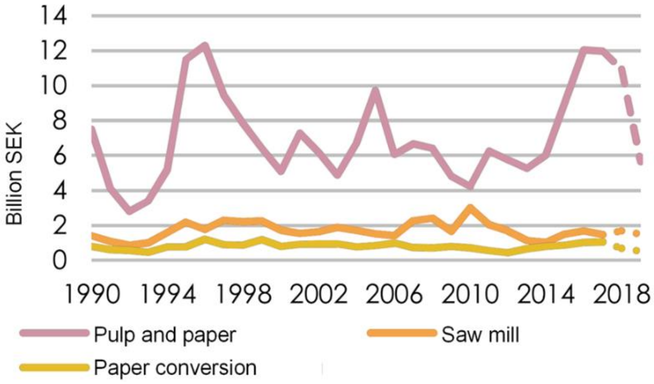

Figure 8 Historical development of investments in the Swedish Forrest industry (10 SEK is roughly 1€). Adopted from (Skogsindustrierna, 2019a)

The global potential for capturing CO_2 in sulphate pulp mills is estimated to be about 137 $Mt\ CO_2$/ year by capturing in sulphate pulp mills (Kuparinen *et al.*, 2019). In 2013 the two Swedish Pulp mills 'M-real Husum' and 'StoraEnso Nymölla' captured CO_2. However, the aim was the CO_2 utilisation in the production of PCC (precipitated calcium carbonate) and not storage (Jönsson *et al.*, 2013).

Table 4 gives an overview of early cost estimates of BECCS in the PPI collected from several identified studies. Table 5 presents more detailed costs estimates from two recent studies. Since pulp mills differentiate from each other in their technical design and consequently the energy balances (Stenqvist, 2015), so do the prerequisites for implementations of CCS. The assessments in this work is based on a range of costs and captured emissions. Important factors in the cost estimates are, whether transport and storage are included, and e.g., assumptions on the cost for electricity/ natural gas

Market pulp mills typically have enough energy/ steam available to power the CCS plant (for the cost of producing less electricity), while in integrated mills most of the excess heat/steam of pulping is already used, making it necessary to produce additional heat/steam, and thereby increasing fuel use (Möllersten, 2002; Hektor, 2008; Garðarsdóttir *et al.*, 2014; Onarheim *et al.*, 2017a; Anheden *et al.*, 2019).

Table 4 Summary of previous studies

Author	**Mill**	**Technology**	**total captured [$kt\ CO_2$/ year]**	**Cost [€**/$t\ CO_2$]**	**Storage included [€*/$t\ CO_2$]**	**Cost €/ ADt**	**captured emissions $t\ CO_2$/ADt**
Ekström et al. (1997) *	Market pulp	MEA	10.000-15.000 (PPI in Sweden)	32–36*** (= 30–34 USD/ $t\ CO_2$)	Not mentioned		
	Integrated	MEA		26–32*** (= 25–30 USD/ $t\ CO_2$)	Not mentioned		
Möllersten (2002) Marginal electricity from coal power plants	Market pulp	BLGCC with CO-shift	7.800 (PPI in Sweden)	85 *** (= 80 USD/ $t\ CO_2$)	Not mentioned		1.6
	Integrated	BLGCC with CO-shift			Not mentioned		2.2
Möllersten (2002) Marginal electricity from NGCC power plants	Market pulp	BLGCC with CO-shift	5.400 (PPI in Sweden)	106*** (= 100 USD/ $t\ CO_2$)	Not mentioned		
	Integrated	BLGCC with CO-shift			Not mentioned		
Hektor (2008)	Market pulp	MEA		25–53	Yes, onshore- 3.3		
	Market pulp	Chilled ammonia		22	Yes, onshore- 3.3		
	Integrated	MEA		20–65	Yes, onshore- 3.3		
	Integrated	Chilled ammonia		17–38	Yes, onshore- 3.3		
Hektor and Berntsson (2009)	Market pulp	MEA		29–51	Yes, onshore- 3.3		
	Integrated	MEA		20–66	Yes, onshore- 3.3		
Hedström (2014)	Market pulp	MEA	715	45 **** (=431 SEK/ $t\ CO_2$)	Not mentioned	607 SEK	1,39
	Market pulp	Selexol process	318	50 **** (=453 SEK/ $t\ CO_2$)	Not mentioned	272 SEK	0.60
	Market pulp	Rectisol process	393	10 **** (=88 SEK/ $t\ CO_2$)	Not mentioned	67 SEK	0.76 t

* Cited by Möllersten (2002), report could not be found
** as reported, not adjusted to inflation
*** converted to EUR with average 2002 exchange rate (0.9456 USD/EUR) (ECB, 2019)
**** converted to EUR with average 2014 exchange rate (9.1 SEK/EUR) (ECB, 2019)
BLGCC = black liquor integrated gasification with combined cycle
MEA = Monoethanolamine ¨

In the models developed by Garðarsdóttir (2017) the investment costs for large sources (cement plants, steel mills, recovery boiler in pulp mills) were found to be in the range of 10-20€/ $t\ CO_2$, while energy costs tend to be >20€/ $t\ CO_2$. The investment costs for smaller sources are higher, estimated to 35€/ $t\ CO_2$. In a related study for a recovery boiler in a pulp mill total costs of 61.80 [€/ $t\ CO_2$ captured] were found, capturing 681.8 [kt/year]. The operating costs constitute 67% of these costs. The investment cost account for the remaining 33% (Garðarsdóttir *et al.*, 2018). The specific investment costs [€/ $t\ CO_2$ captured] were found to decrease with increasing capacity (Garðarsdóttir *et al.*, 2018)

Table 4 presents a few studies that investigated CO_2 capturing technologies for pulp mills. Möllersten (2002) did one of the earliest studies, combining the entire industry scale together with the study of a single mill. In the calculations of Hektor (2008), the carbon avoidance costs was calculated for different capture technologies (MEA & chilled ammonia) with different economic scenarios for different CO_2 streams. The results range between 25-53€/ $t\ CO_2$ for a market pulp mill and for an integrated pulp and paper mill between 20-65€/ $t\ CO_2$ for capturing using the MEA technology. The cost in a market pulp mill, using chilled ammonia, is around 22€ and ranges for an integrated mill between 17-38 €/ $t\ CO_2$. He was not explicit about the total captured CO_2, nor the share of biogenic CO_2. Hektor and Berntsson (2009) calculated the emission costs of CO_2, but were not explicit about the total captured amount CO_2. For the costs estimates both the transportation costs and storage costs are included (3.3 EUR/ $t\ CO_2$). Hedström (2014) used three technology scenarios for the carbon capturing, including an economic analysis. All reported studies investigate northern softwood pulp mills, only one recent study could be identified that investigated a eucalyptus kraft mill in south America, which is in principle similar to the northern mills (Kuparinen *et al.*, 2019).

Table 5 gives an overview of the results from some of the more detailed studies investigating CCS in pulp mills producing *bleached softwood sulphate pulp*, either as standalone pulp mill or as integrated pulp and paper mill. These results have formed the basis for the further analysis presented in this work.

One of the more detailed recent studies was conducted by Onarheim *et al.* (2017b, 2017a). The technology of choice is amine-based post-combustion CCS. The first case is a standalone market pulp mill with a capacity of 800,000 ADt/ year. The second case is an integrated pulp and board mill, with a pulp production capacity of 740,000 ADt/year and folding boxboard production of 400,000 ADt/year. The study of both pulp mills includes 6 different capture scenarios for different flue gas sources, compare Figure 6 for the CO_2 sources.

The other detailed study was conducted by Anheden *et al.* (2019). The studied stand-alone bleached sulphate softwood market pulp mill has a capacity of 700,000 ADt/yr, while due to a 92% availability a 644,000ADt/yr production is assumed. In this study 8 different capture scenarios are investigated, for different CO_2 sources or technical setups.

The CCS plant of the two studies also have technical differences, regarding the split flow configuration (solvent extraction) and the absorber set up. Onarheim *et al.* (2017a) always used only one absorber, while in the study by Anheden *et al.* (2019) also a two absorber setting is investigated. This means that exhaust gases from two different emission sources are not treated by the same CCS plant. The pulp mills differ also with regards to the energy balance. In the pulp mill of Onarheim *et al.* the excess energy is 40% higher due to a higher flow of black liquor to the recovery boiler. This means more energy but also more CO_2 emissions. Further, 40% of the energy used in the lime kiln in the study by Onarheim *et al.* (2017a) are assumed to come from fossil fuels, while in Anheden *et al.* (2019) the lime kiln is powered by bark

The cost estimates in the two studies are based on different assumptions (e.g. plant lifetime) and methodologies. Onarheim *et al.* (2017b) calculates the levelized cost of pulp production, coming up with the final costs of pulp. From that the cost increase can be calculated comparing the new pulp price to the base case. The cost calculations in Anheden *et al.* (2019) are more straight forward, using the costs of the CO_2 capture plant which, in turn, is used to estimate the cost increase of pulp. Onarheim *et al.* (2017b) use different economic scenarios for the calculation. According to Anheden *et al.* (2019) the first scenario, in which no credits for captured CO_2 emissions are granted, should be used to make the results comparable.

Onarheim *et al.* (2017b) included transport and storage cost of 10€/ $t\,CO_2$, which were also added to the cost of the Anheden *et al.* (2019) study.

The two most central results for this thesis are the “captured biogenic emissions per ADt of pulp” and the “additional costs per ADt of pulp”. In this study, based on the review of Onarheim *et al.* (2017b) and Anheden *et al.* (2019) the following factors are assumed, combining stand-alone pulp mills and integrated pulp and paper mills.

- Approximately **1.6 kg** biogenic CO_2 can be captured per air dried tonne of produced pulp (captured emissions are evenly allocated to all produced pulp).
- The implementation of a BECCS plant in a pulp mill would increase the costs per air dried tonne of pulp by **110€ / 1143 SEK** (including transport and storage)
  If no allocation is done the cost for negative emissions will approximately account to **68€** per 1000kg captured biogenic CO_2.

The technical details can be found in Onarheim *et al.* (2017a) and Anheden *et al.* (2019).

Table 5 Results of the two studies (Onarheim et al., 2017a, 2017b; Anheden et al., 2019)

Capture Case	CO_2 Source	CO_2 emissions t/adt	Captured biogenic emissions t/adt	avoided emissions t/adt	captured emissions t/adt	captured of total emissions	Levelized cost [€/adt] of pulp (LCOP)	additional costs €/adt	Cost of avoided CO_2 (€/t)	Cost of negative CO_2 (€/t)
Pulp mill Onarheim et al., 2017										
Base case 1A		2.70	**-**			0%	523			
2A-1	REC	0.86	**1.85**	1.85	1.85	68%	643	**120**	65	**65**
2A-2	MFB	2.36	**0.34**	0.34	0.34	13%	554	**31**	92	**92**
2A-3	LK	2.46	**0.14**	0.25	0.25	9%	543	**20**	81	**144**
2A-4	REC + MFB	0.52	**2.19**	2.19	2.19	81%	659	**136**	62	**62**
2A-5	REC + LK	0.61	**1.99**	2.09	2.09	77%	652	**129**	62	**65**
2A-6MP	REC + MFB+ LK	0.27	**2.33**	2.43	2.43	90%	677	**154**	63	**66**
Integrated pulp and board mill Onarheim et al., 2017										
Base case 1B		2.92	**-**			0%	523			
2B-1CO2MP	REC	1.13	**2.00**	1.80	2.00	61%	671	**148**	82	**74**
2B-2	MFB	2.56	**0.37**	0.37	0.37	12%	556	**33**	90	**90**
2B-3	LK	2.66	**0.15**	0.27	0.27	9%	545	**22**	83	**147**
2B-4CO2MP	REC + MFB	0.87	**2.36**	2.05	2.36	70%	695	**172**	84	**73**
2B-5CO2MP	REC + LK	0.95	**2.15**	1.97	2.26	67%	687	**164**	83	**76**
2B-6CO2MP	REC + MFB+ LK	0.76	**2.51**	2.16	2.63	74%	714	**191**	89	**76**
Pulp mill Anheden et al. ,2019										
Base Case		2.29				0%				
1a	LK	2.01	**0.28**	0.28	0.28	12%		**19**	68	**68**
1c	REC	0.77	**1.53**	1.53	1.53	66%		**81**	53	**53**
1c_II	REC, reduced flue gas flow	0.89	**1.40**	1.39	1.40	61%		**80**	57	**57**
3a	REC	0.79	**1.50**	1.36	1.50	68%		**102**	68	**68**
4a	LK +REC	0.69	**1.60**	1.61	1.60	70%		**82**	51	**51**
4a-II	LK + REC, 2 absorbers	0.70	**1.60**	1.60	1.60	69%		**83**	52	**52**
4c	LK + REC	0.67	**1.62**	1.33	1.62	74%		**120**	74	**74**
4c-II	LK + REC, 2 absorbers	0.67	**1.62**	1.31	1.62	74%		**125**	77	**77**
REC – Recovery boiler | LK – Lime Killen | MFB – Multi-fuel boiler										
CO_2Stamp aligned to Onarheim with 10€/tonne CO_2 added for transport and storage										

4. Methodology

The aim of this study has been to describe the supply chain for pulp and paper and to investigate how price and embedded GHG emissions of final products would be influenced by investments in BECCS in the primary production of pulp and paper. The methodological approach was divided into two parts:

(1) Description of the production in the pulp and paper industry.
    a) Mapping the PPI supply chain
    b) Assessing the material flows
    c) Assessing the monetary value flows
(2) Case studies: Four representative products were chosen for further investigation to estimate the effects of investments in BECCS in the pulp and paper industry on final products.
    - Oat drink
    - Milk
    - Corrugated board packaging
    - Hardcover novel

4.1. Production in the Swedish pulp and paper industry

Of the different pulping processes, sulphate pulping is the most promising candidate for BECCS application. By analysing the production structure in the PPI, it was investigated which pulp and paper products are produced in Sweden. Relating these to the paper grades presented in section 3.2.3 it was then investigated how the products relate to sulphate pulp production.

This mapping of material and value flows in the Swedish PPI was done with production data and the specific value of the products, which were assumed to be equal to the export value, following the methodology of Joelsson and Athanassiadis (2015a).

The representation of the mass and value flows was done by Sankey diagrams. Attention was turned to the parallel representation of mass and economic flows, to enable management based on the data (Schmidt, 2008). An example is depicted in Figure 9. In this kind of graph the magnitudes and destinations of different flows are depicted by different sized arrows. The graphical representation was done with the software e!Sankey (ifu Hamburg GmbH, 2018).

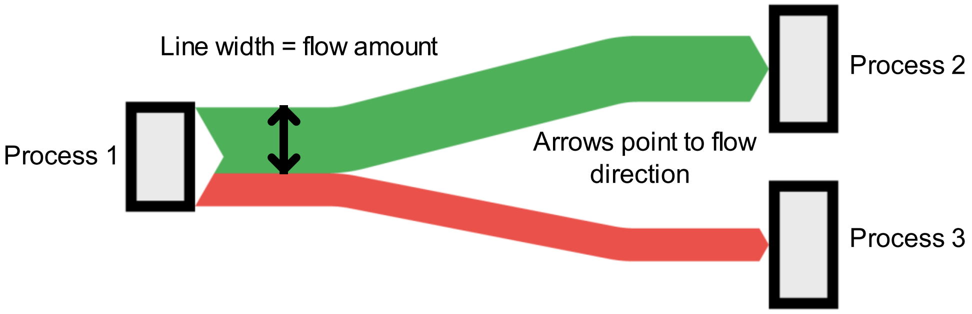

Figure 9 Principles of Sankey diagrams

4.2. Case studies

The mapping of material and value flows in the Swedish PPI, described in Section 4.1, was used as the foundation for the selection of representative products. These come from the product groups with the largest material and value flows, which use sulphate pulp. It is important to notice that it is not aimed to represent a specific product, produced in a specific plant, but to find a representative estimation for the group of products. Given the high export share of the products, it can also not be assumed that all products are produced entirely in Sweden. A corrugated board box may be produced in Poland, just using paper from the mill with BECCS.

The analysis of the case studies' supply chain was performed in the following three steps.

I. **Estimation in which steps the economic value of the products is created, including the role of paper in the final products, using recent market data.**

The price of the final product is set in relation to different processes and input materials in the creation of the product. Case- specific costs are indicated in the following sub sections. The cost factors that were assumed to be the same in all cases are transport costs and the share of wholesale and retail of the final price:

- Truck transport has been assigned a cost of 0.14 SEK per tonne- kilometre (Vierth *et al.*, 2008)
- Wholesale and retail are assumed to take a share of 5% and 20% of the price, respectively, roughly following an assessment by Willoughby and Gore (2018)
- In Sweden the tax for most products is 25%, for food is 12% and for books is 6% (skatteverket, 2019)
- For all conversion from SEK to EUR, the average exchange rate between 13 May 2018 and 14 May 2019 was used: 10.3864 SEK = 1 EUR (ECB, 2019)

II. **Analysis of the carbon footprint of the product through applicable Life Cycle Assessment (LCA) reports.**

The carbon footprint of a product, also known as embedded emissions of a product, is calculated by using a bottom up approach to look at the emissions of all processes associated to the production of the product (Wiedmann and Minx, 2007). For this purpose, the total emissions from these production processes are allocated to the production of a single product. This gives an estimate of the emissions e, associated to each process p, here denoted by e_p. The estimate of the total carbon footprint is then done by summing up the respective emissions of all processes over all life stages n, see equation (1). The boundaries of the technical system of production, which is to be covered by LCAs, are limited to a cradle-to-gate scope, i.e. the inclusion of all activities, from material extraction (the cradle) until the final product is manufactured and ready. The respective gate will be indicated in each case, ranging from the factory gate to retail. Inclusion of additional steps requires more assumptions about future conditions of transport and waste handling. As the inclusion of BECCS does not change the actual tangible product, these steps after "the gate" are not affected and will be excluded.

$$\sum_{p=1}^{n} e_p = \mathit{Carbon\ Footprint} \tag{1}$$

The climate impact discussed in this thesis will use the summarized CO_2- equivalent numbers ($CO_{2,e}$) of the included LCAs in accordance with their respective choice. In all cases it is calculated using the Global Warming Potential (GWP) with a time horizon of 100 years, as it is the currently most common choice.

The results of the analysis in I. and II. are aggregated in a graph illustrated in Figure 10. The composition of the carbon footprint of a single product is depicted in the left side of the graph. The respective value composition on the right.

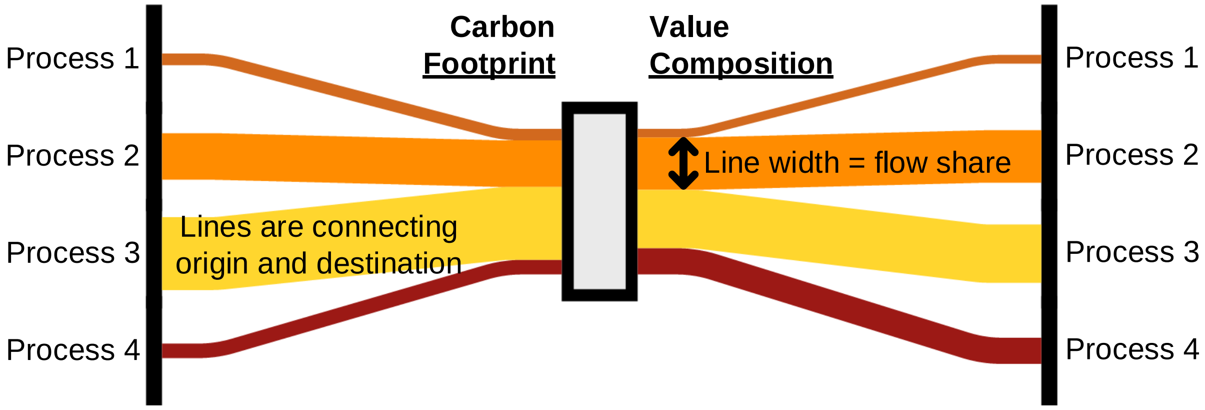

Figure 10 Example graph for the carbon footprint and value composition of a product.

III. Determining how much paper is used in the products, using LCAs.

By using the information about material use in the applied LCAs the amount of paper can be extracted. This enables an estimation of the impact of BECCS on the carbon footprint and the value of the product, as explained in the next section.

4.3. Calculation of the impact of BECCS

The methodological approach used in this work, i.e., comparing the carbon footprint of an improved product with a baseline product, can be related to the methodology of a “carbon handprint”, developed by Vatanen *et al.* (2018). The carbon handprint is defined as the reduction of the carbon footprint. As described in section 3.3, the integration of BECCS in a pulp mill would allow the capturing of biogenic CO_2, while pulp is produced. If these captured emissions are allocated equally to the produced pulp, negative emissions would be part of the embedded emissions, constituting the carbon handprint. Based on previous assessments by Onarheim *et al.* (2017b) and Anheden *et al.* (2019) (see Table 5) the cost increases and negative emissions associated with the integration of BECCS in a pulp mill are, are translated into the following two basic assumptions:

- The integration of BECCS in a pulp mill increases the cost, per air dried tonne of pulp, by **110€** (= 1143 SEK), and
- **1.6 tonne** of biogenic CO_2 can be captured per air dried tonne of pulp produced.

In conversion from pulp to paper these factors change slightly. Pulp is measured with 10% moisture content, while paper is measured with 6% moisture content. Furthermore 1-2% of the fed fibres are lost and do not end up in the paper. Assuming therefore that no negative emissions are allocated to the lost fibres, the following factors are used:

- The costs per air dried tonne of paper increases by **117€** (= 1212 SEK) when integrating BECCS, and
- **1.7 tonne** of biogenic CO_2 can be captured per air dried tonne of paper.

If no allocation is done, the cost for negative emissions will amount to **68€** per 1000kg captured biogenic CO_2.

For a product that use X gram of paper the increase of costs and decrease of embedded emissions was consequently calculated according to equation (2) and (3), respectively.

$$\begin{gathered} 0.00117 \left[\frac{EUR}{\text{g paper}}\right] * \text{X [g paper]} = \text{Z [EUR]} \\ 0.001212 \left[\frac{SEK}{\text{g paper}}\right] * \text{X [g paper]} = \text{Z [SEK]} \end{gathered} \tag{2}$$

$$1.7 \left[\frac{g\ captured\ CO_2}{\text{g paper}}\right] * \text{X [g paper]} = \text{Y [g } CO_2\text{]} \tag{3}$$

Figure 11 illustrates how the results of the Calculation of the impact of BECCS have been presented graphically, using the same case as presented in Figure 10. In the example the carbon footprint is built up along the supply chain (Process 1-4), with the total embedded emissions amounting to 50 emission units. If, by using BECCS, 10 emission units were captured, the carbon footprint would be reduced from 50 to 40. At the same time, the application of BECCS added 0.10 value units and increased to costs from 5.00 to 5.10. For this example, this makes a 20% embedded emissions reduction for a 2% price increase.

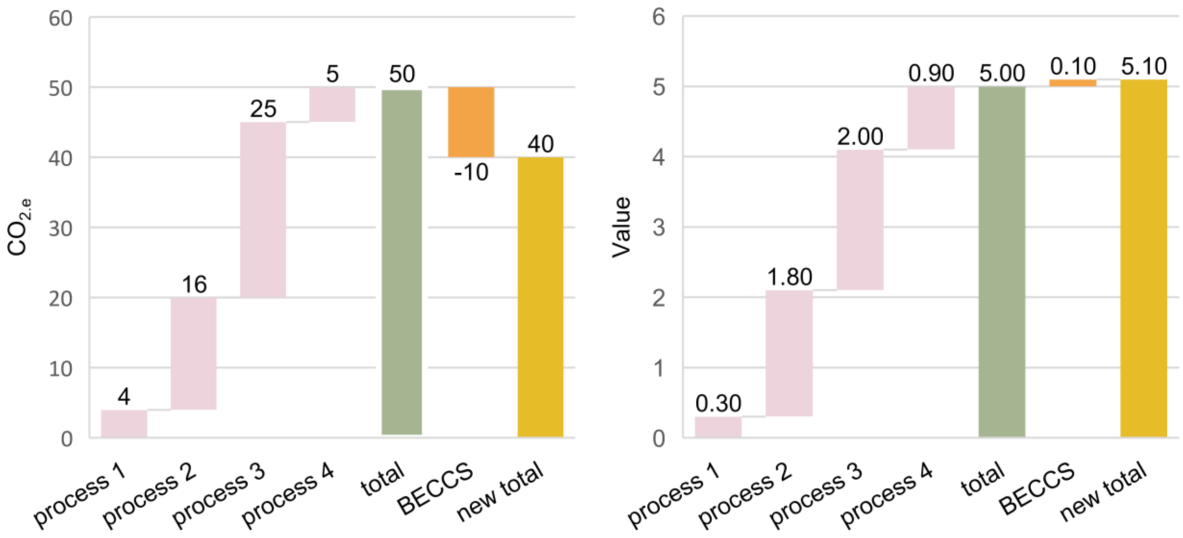

Figure 11 Example changes by the carbon handprint on embedded emissions (left) and the economic value (right)

4.4. Introduction to the case studies

The first two case studies discuss packaging with liquid packaging board, first for an oat drink (Section 4.4.1) then for milk (Section 4.4.2). After that corrugated board packaging is discussed (Section 4.4.3), and then finally a hardcover novel (Section 4.4.4).

4.4.1. Oat- drink

The following case uses calculations from a LCA, commissioned by Oatly and conducted by IVL (Florén *et al.*, 2013). Florén *et al.* (2013) investigated three different drinks, an “aseptic oat drink”, a “fresh oat drink” and semi skimmed milk. The functional unit is one litre of drink consumed at the consumers home. The scope is “cradle-to-grave” for the situation in 2012.

The study of Florén *et al.* (2013) and a LCA for Tetra Pak (Markwardt *et al.*, 2017) used data from the Ecoinvent database for the production of the so called liquid packaging board. This data was collected in four mills, which together represent 95% of the European capacity (ecoinvent, 2009), located in Sweden and Finland (Markwardt *et al.*, 2017, p. 64). In Sweden 3 paper mills produce liquid packaging board (Skogsindustrierna, 2019b). The board is assumed to be 100% kraft paper, furthermore no paper losses in the conversion to the drink container are assumed.

The climate impact (adopted to cradle to retail) of the oat drinks was estimated to be 0.309 kg $CO_{2,e}$ for the aseptic oat drink and 0.429 kg $CO_{2,e}$ for the fresh oat drink for 2012. In a more recent calculation by CarbonCloud the emissions for the oat drinks were updated. For 2017 they are 0.30 kg $CO_{2,e}$for the aseptic and 0.38 kg $CO_{2,e}$ for the fresh drink. Comparing the descriptions of both calculations, a switch from fossil to more bio- energy in the oatmill and oatbase production site can be observed (Oatly AB, 2019). Further, different assumptions or scopes could have changed the results.

In this study the situation in 2012 is used for packaging and the carbon footprint results. In the summary attention will also be given to the more recent data for packaging (Markwardt *et al.*, 2017). In the following the different cases will be described in more detail.

Aseptic oat drink

The basic raw materials to produce an aseptic oat drink are oats and other ingredients such as rapeseed oil which need to be farmed and processed. These are then combined to create the final product at the Oatly plant in the south-west of Sweden.

I. Estimation of value creation

In 2018, the costs for oats (Grynhavre Väst) in the west of Sweden ranged from a low of 127 SEK/100 kg in March 2018 to a high of 246 SEK/100 kg during October 2018. Since then it price has remained at the higher level and is currently, in the beginning of May 2019, at 245 SEK/100 kg (Jordbruksaktuellt, 2019). Approximately 0.13 kg of oats are used per litre of drink, of which the costs amount to 0.17- 0.32 SEK. Here the costs for oats after milling are assumed to be 1 SEK, incorporating the value added and that not all parts of the oats end up in the drink and therefore more oats could be needed. Other ingredients, like water, oil and minerals are assumed to cost 0.5 SEK

The costs of the packaging are dependent on the contract with TetraPak. TetraPaks business model have been described as “Bait and hook business model”, in which the initial investments like the packaging machine is cheap and further purchases like the packaging material are TetraPaks primary source of income (Andreason and Wind, 2015). Since no official statistics describing the packaging costs could be retrieved only statements on the raw material cost can be made. For high strength the liquid packaging board is made from chemical pulp, sometimes in combination with semi-chemical pulp (Kirwan, 2013, 13.2). The liquid packaging board can be classified as multiply paper and paperboard. Chemical pulp costs about 6800 SEK/t (CN tariff code 4703) and the paper about 7900 SEK/t (CN tariff code 4810 90). The packaging paper with plastic coating costs around 15,000 SEK (CN tariff code 4811 50). With 22.1g of paper in the packaging, the paper is approximately worth 0.17 SEK and the pulp 0.15 SEK. The liquid packaging carton costs around 0.40 SEK, including the plastic coating. The package with prints, cap and filling machine will cost more. Here, and in the similar cases, it is assumed to cost 1 SEK.

Transport costs are estimated to 0.1 SEK by using the summarized estimate of Ahlberg *et al.* (2017) of around 0.6 tonne-kilometre associated to the Oat drink.

In total the costs estimate amount to 2.6 SEK, before the processing at Oatly, retail and tax. The retail price is assumed to 18 SEK.

II. Carbon Footprint

A total of 309 g $CO_{2,e}$ is assessed (Florén *et al.*, 2013). Farming of the oats and other ingredients accounts for 30% of these emissions. These are characterised by energy usage and N_2O emissions from fertilisers. Milling of the oats stands for 2% caused by energy usage from electricity and fuel oil. The emissions in retail stand for around 0.1% and transport in all lifecycle steps accounts for 13%. The included transports are entirely truck transports. The package stands for 19% of the emissions. In a remake of the study by Florén *et al.*, Ahlberg *et al.* (2017) estimate the share of liquid packaging board to 37% of the embedded emissions of the packaging, while the polymers have a share of 42%, using the same ecoinvent data.

III. Material

The aseptic oat drink is packaged in a TetraPak - “Tetra Brik® Aseptic Edge 1000 ml” - produced in Sweden. The carton consists of 22.1 g liquid packaging board, 4.7 g polymers and 1.4 g aluminium. The cap consists of 3.36 g polymers. These numbers changes slightly to 21.6 g liquid packaging board, 5.0 g PE, 1.4 g aluminium and 3.0 g PE in the cap, in newer versions of the package (Markwardt *et al.*, 2017).

Fresh oat drink

The production of the fresh oat drink is fairly similar to the aseptic one, except for one big difference. While in the production of the aseptic drink all process happens in the Oatly plant in Sweden, the fresh drink is only partially produced there. The in Sweden produced oatbase is transported to the north of Germany. There, the oat drink is produced, using further ingredients, and packaged. The final product it transported back to Oatly in a refrigerated truck. From the Oatly warehouse the oat drinks are sold to wholesale and then to customers. In addition, the package is produced in Italy and not by TetraPak.

I. Estimation of value creation

The cost structure of the fresh oat drink is similar to the aseptic drink. The milled oats are assumed to cost 1 SEK, the package is assumed to cost 1 SEK. The wholesale is assumed to take 5% of the price and retail 20%. The transports play a bigger role in this product. Using the same factors as before plus additional 0.6 tonne- kilometre for the refrigerated transport from Germany and less than 0.1 tonne- kilometre for the transport of the package from Italy, double the transport costs are estimated. The processing plant in Germany is assumed to add 20% of the products value. The retail price is assumed to 19 SEK.

II. Carbon Footprint

Total emissions of 429 g $CO_{2,e}$ are identified (Florén *et al.*, 2013). The primary production is farming of the oats and other ingredients, which account for 22% of the emissions. The processing industry is identical to the aseptic drink with 2% share. The package stands for 10% of the emissions and is discussed later. The emissions in retail stand for around 0.3%, slightly increased due to the refrigeration. The additional transportation by truck to Germany and another carton source increase its share to 27%.

III. Material

The fresh oat drink is packaged in a carton produced in Italy. The carton consists of more cardboard (28.4 g) and less plastic, that is 3.5 g polymers and a cap of 2.65 g polymers.

4.4.2. Milk

I. Estimation of value creation

Looking on the economics of milk production, an important factor is the price the farmers get for the milk. In April 2019 this was 3.37 SEK/kg (Sedenius, 2019). The costs for producing milk is estimated to 5.40 SEK/kg milk by the Swedish milk farmer association (Styrelsen Sveriges Mjölkbönder, 2018), whereas this source also refers to a 2 SEK lower price than the costs. These are assumed to be covered by subsidies. With 0.6 tkm transport the respective costs are assumed to cost 0.1 SEK. The package is again assumed to cost 1 SEK. The rest of 7 SEK is assumed to go to the dairy, including transport.

II. Carbon footprint

For comparison of the oat drinks with milk, the LCA of Florén *et al.* (2013) used a report which describes the emissions for milk production in Sweden in the year 1990 and 2005 (Cederberg *et al.*, 2009). They see an overall decreasing carbon intensity during that period. An allocation between milk and beef of 85% to 15% based on physical properties result in emissions of 1.02 $CO_{2,e}$ per kg energy corrected milk (ECM). Other studies come to similar emissions, despite having different system boundaries, allocation or GHG prediction models. For example Henriksson (2014) estimated average emissions to 1.16 kg $CO_{2,e}$ per kg ECM, but without allocation to by- products. Allocating similarly 85% of this to milk, result in emissions of 0.99 kg $CO_{2,e}$ per kg ECM. A LCA for milk production in Sweden by Arla resulted in emissions of 0.97 kg $CO_{2,e}$ and 1.16 kg per kg ECM, depending on the methodology (Dalgaard *et al.*, 2016). Here the data of Florén *et al.* (2013) is used.

The carbon footprint of milk until the retail gate is 1258 g $CO_{2,e}$. The primary production, that is the feed production, represents 30% of these emissions. They come mainly from N_2O from the soil and the production of fertiliser and GHG emissions due to fossil fuel use. The milk production on the farm stands for 55% of the emissions, which almost entirely come from methane emissions from cows. The product production in dairies stand for another 8%, which were estimated from the 2011 environmental report of the dairy company Arla. The package is responsible for 3% of the emissions. Retail for only 0.02% and transports for 4%.

III. Material

Data for TetraPak - “Tetra Rex 1000 ml” - is used. In the model by Florén *et al.* (2013) it has 25.5 g cardboard and 4.5 g polymers plus additionally 3 g polymers for the cap, even though more recent data indicate less material-use, with 23.1 g cardboard and in total 6.17 g polymers.

4.4.3. Corrugated board box

Corrugated board refers to a composite board of different paper. In between layers of paper/ liner lays a medium (called fluting), which is corrugated and glued to the outside layers.

I. Estimation of value creation

At Ikea Sweden a set of two moving boxes costs 20 SEK (16 SEK excluding taxes) (IKEA, 2019a). In Germany the same set costs the customer 2.99€ or 31.1 SEK (IKEA, 2019b).

For unbleached Kraftliner the cost estimate is around 4,300 SEK/tonne (CN code 4804 11). Semi chemical fluting paper costs around 5900 SEK/ tonne (CN code 4805 11). Testliner and fluting costs around 5200 SEK/tonne (CN code 4805 24, 4805 25 and 4805 11). Finally, “Cartons, boxes and cases, of corrugated paper or paperboard” cost around 18,100 SEK/tonne (CN code 481910).

With the respective mass share of the different products, paper costs around 8.5 SEK. Ikea is assumed to be retail, adding value of 3 SEK, and the conversion of the paper to the corrugated board box with printing is assumed to take the final share of 3.5 SEK.

II. Carbon Footprint

The used LCA information is produced from the European Federation of Corrugated Board Manufacturers (FEFCO), based on their LCA database (FEFCO, 2019). The used LCA database also includes Swedish paper mills, for fluting (recycled and virgin) and liner (Kraftliner and Testliner), as well as for the corrugated board production (FEFCO, 2018). It is aimed to be a generic database for all forms of corrugated board, reporting the data on a ‘per tonne of product’ basis. The data is on cradle- to- grave basis, therefore the end- of- life and avoided emissions were removed in the following calculations. Taking fossil emissions and land use change emissions together, a total of 841 $kg\ CO_{2,e}$ per tonne of product were assessed. Other conversion steps like printing were not included.

For the moving boxes this leads to a carbon footprint of 1.57kg.

III. Material

The production of one tonne corrugated board takes, according to the European model, 1.147 tonne of paper on average (FEFCO, 2018, p. 16). Of that 9.5% (204kg) is virgin Kraftliner, which is produced with sulphate pulping. Other fibre inputs than virgin sulphate pulp is not part of the BECCS discussion.

The box of the case study weights 1.87 kg (IKEA, 2019b).

4.4.4. Hardcover novel

The next studied product is a hardcover book/ novel, building upon the LCA data of Pihkola *et al.* (2010). The book assessed in the LCA is produced and sold in Finland. The scope of the study is cradle to retailer, including wood harvesting, chemical and other raw material production, pulp and paper making, printing and transport.

I. Estimation of value creation

The price of books vary, depending on the content, publisher and probably society. Wirtz (2019, p. 106) estimated the cost distribution for entertainment books for the German market as depicted on the left in Figure 12. However, the nature of the rough estimate becomes obvious as the same author estimated these values differently in a former version of his book (Wirtz, 2006, p. 75), see the right in Figure 12. The retail costs include wholesale and retail, which take a fairly equal share. First copy costs cover the content production, marketing and administration, which are toward each other in the same magnitude. Production costs include the physical production (2/3) and distribution (1/3). Levine (2011) estimates the production costs even lower, to 3.50 USD for a 25 USD hardcover book

The 300-page hardcover novel is assumed to be sold for a customer price of 300 SEK. The production costs are around 65 SEK, of which around 40 SEK are the physical material costs. Printing paper costs around 7700 SEK/ tonne, or 3.9 SEK/ 500 g (CN tariff code 4810 10). Other process costs are e.g. labour, binding and other materials costs.

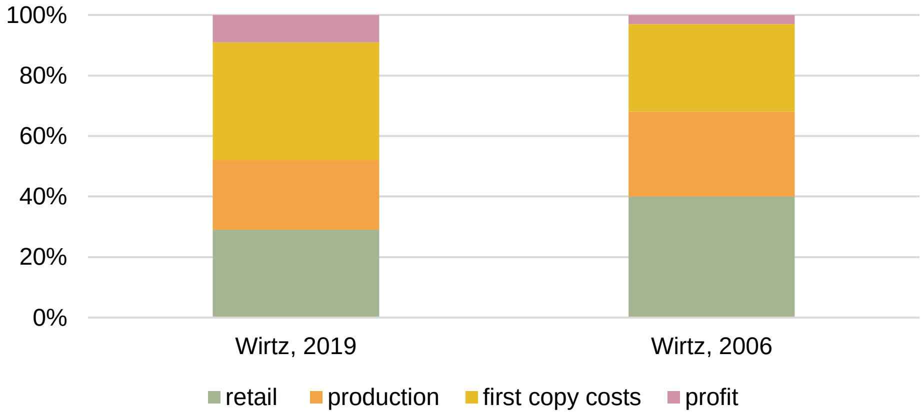

Figure 12 Cost structure book (Wirtz, 2006, 2019)

II. Carbon Footprint

No study could be identified in which the environmental impact of content production was assessed, therefore the analysis here is focused on the material production. It probably does not influence the results strongly, because the emissions can be distributed to all copies.

Printing is so far not discussed as a life cycle step. The technology used is called ‘Sheetfed offset printing’. The data for the step was collected from four book printers in Finland. Of the six described printing processes it is has the highest specific energy consumption per tonne and the highest paper consumption. In this study a rate of 1.28 kg paper/kg product was used. Other technologies like ‘Cold web offset’ or ‘High speed inkjet’ printing have an energy consumption rang around half the chosen technology. However, the ink consumption of this technology is at least half less than any other. The printing ink is described with ecoinvent data. The GHG emissions in printing originate from electricity usage.

The cradle- to- retailer carbon footprint of this book was calculated to 1.16 $kg\ CO_{2,e}$. Because the book was printed in Finland, the climate impact from purchased electricity is higher than it would be in Sweden. As Sweden has a more than 4 times smaller carbon intensity than Finland, a recalculation of only the printing step yields a carbon footprint of 0.77 $kg\ CO_{2,e}$ (Carbon intensity data of the medium voltage grid by Moro and Lonza (2018) were used).

III. Material

The book has 300 pages, which means 150 sheets in the format 205 mm x 135 mm and weights 500g. The paper used is described in Table 6, whereas no statement about the different mass shares was done in the LCA report, therefore an assumption about the mass share was done based on the described weight (gsm = grams per metre square).

Table 6 Paper in the studied book

			assumption mass share	mass kraft paper kg	Negative emissions
Cover:	1300 gsm board	100% defibred pulp from board and unbleached paper	15%	0	0
	150 gsm coated fine paper	11% pine kraft pulp, 34% birch kraft pulp, 50% pigments, 5%, binders	2%	4.5	7.2
Inner sheets:	90 gsm uncoated fine paper	21% pine kraft pulp, 50% birch kraft pulp, 25% fillers,4% binders	79%	281	449
End papers:	150 gsm uncoated fine paper	21% pine kraft pulp, 50% birch kraft pulp, 25% fillers,4% binders	2%	7.1	11..36
Jacket:	150 gsm coated fine paper, water varnish		2%		

5. Production in the Swedish pulp and paper industry

In 2017, 4.3 million tonnes of market pulp and 10.3 million tonnes of paper were produced. Figure 13 gives an overview about the different mass flows. 57% of the market pulp was produced in the five largest of the 18 market pulp mills (Skogsindustrierna, 2018d). The situation is similar for paper, in which 54% of the capacity is covered by the 14 largest of 38 mills (Skogsindustrierna, 2018d). Most of the produced paper products are exported as paper without the conversion to final products. The translation of the mass flows to value flows is presented in Figure 14.

The left part of the figures presents the different produced pulps. Sulphate pulp, the pulp discussed in the BECCS application, thereby takes the largest share. A large part of “bleached sulphate softwood pulp” goes to export as market pulp. “Other sulphate pulp” includes all other sulphate pulps that are not bleached and from softwood. “Mechanical and semi- chemical pulp” and “Sulphite pulp” are not discussed for BECCS application.

Pulp is either sold as market pulp or used in the paper production. The lower right part of the figures describes the paper production, which can typically be split in the following four larger product groups. Packaging material is the paper grade of which most is produced, and which presents the largest value flow. It is subdivided into kraft wrapping paper, kraftliner, testliner, fluting and paperboard for packaging. As apparent in Table 3 (p.16) is kraft wrapping paper dominated by unbleached kraft pulp. Kraftliner, testliner, fluting is either produced from kraft pulp or recycling material. Paperboard could be produced from all pulp grades. Graphical paper is the second most produced paper grade in Sweden, constituting also the second largest value flow. It includes newsprint, mechanical printing paper and woodfree printing paper. Woodfree paper refers to paper made from chemical pulp in which the lignin is removed, the other subgroups are dominated by mechanical or recycling pulp, see Table 3. Tissue paper is the third most produced grade. While it has a lower share in the production volume, the higher specific value increases its importance regarding the value flow. It uses chemical pulp and recycling paper in different relations, depending on the product (Table 3). Other paper is the group with the lowest importance and is not discussed further.

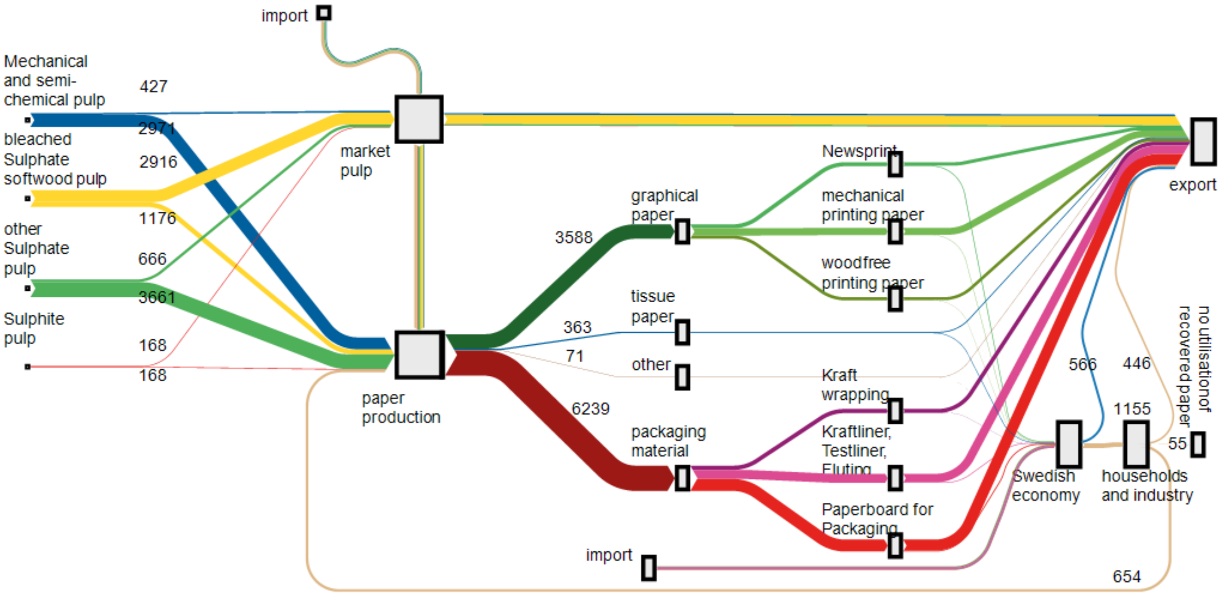

Figure 13 Mass flows in the pulp and paper production in Sweden 2017 in kt, see appendix for sources

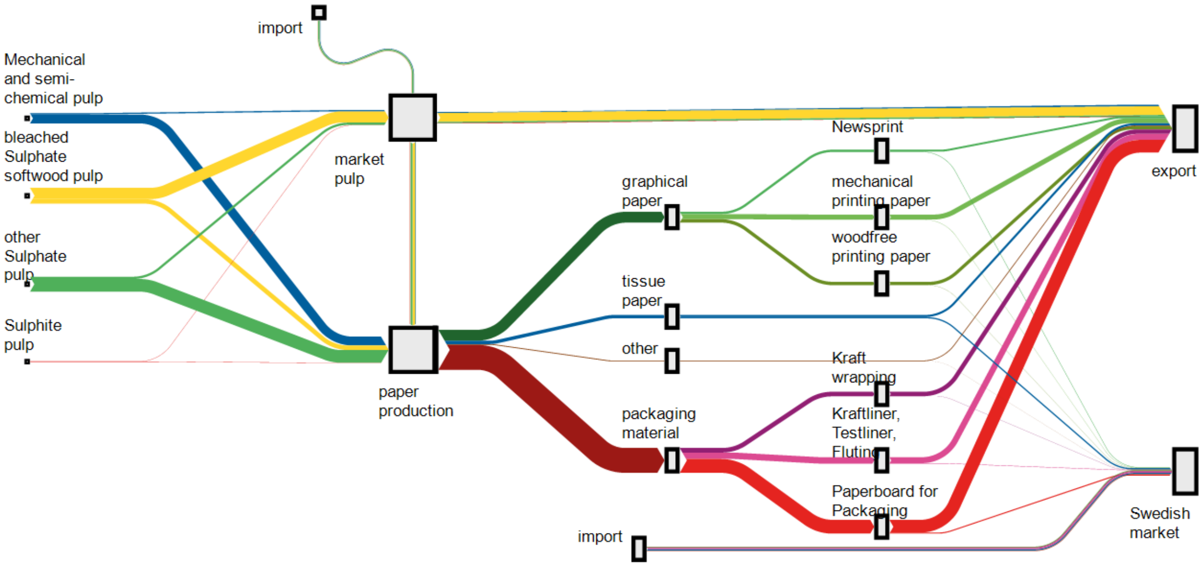

Figure 14 Economic flows in the pulp and paper production in Sweden 2017 in tSEK, see appendix for sources

6. Case study results

This section presents the results for the products that were introduced in chapter 4.4. In the cases the carbon footprint and value distribution are depicted in the first figure. The second figure presents the changes of carbon footprint and value if BECCS is applied.

6.1. Oat drink and milk

6.1.1. Aseptic oat drink

Using equation (3) and the packaging data provided, 37.6 g of captured $CO_{2,e}$ can be allocated to this product. This is a reduction of 12% of the embedded emissions.

Following equation (2), changing the pulp costs 0.03 SEK more, respectively 0.15% of the retail price of 18 SEK.

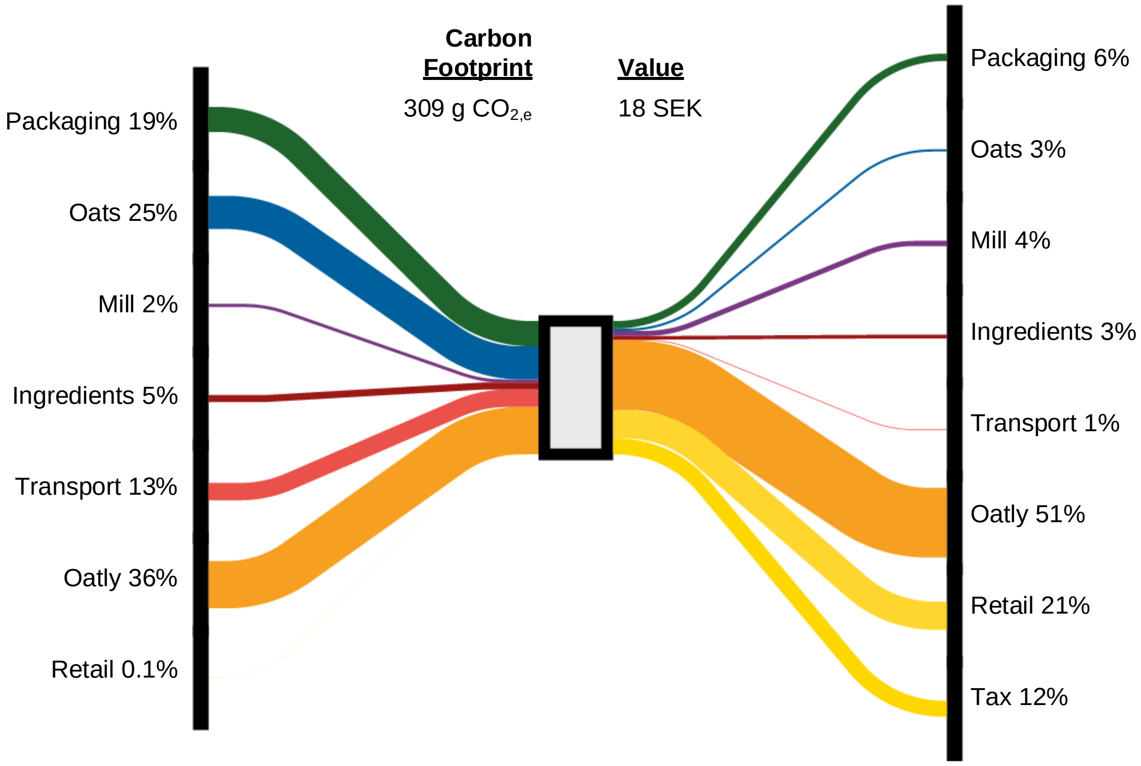

Figure 15 Current carbon footprint and value distribution for aseptic oat drink

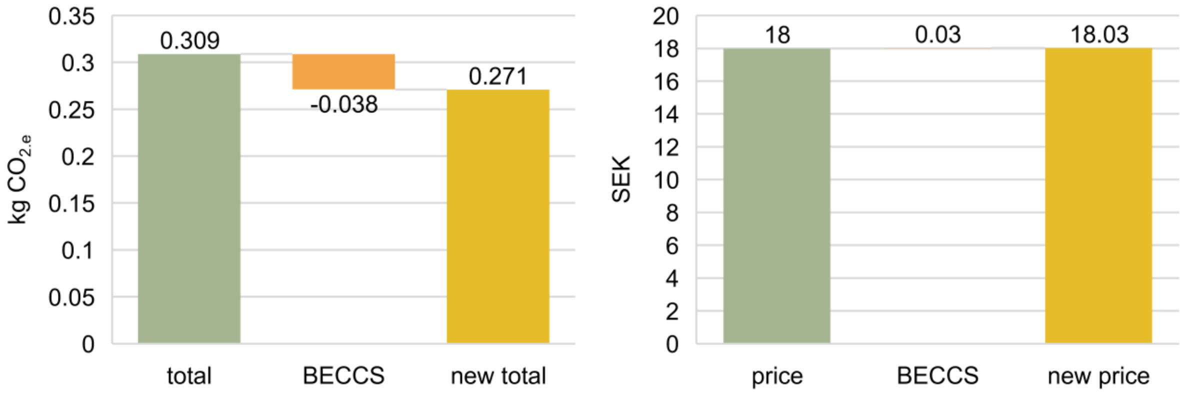

Figure 16 Carbon handprint changes for aseptic oat drink, carbon footprint left, cost right

6.1.2. Fresh oat drink

Using equation (2) and the packaging data provided, 48.3 g of captured CO_2 can be allocated to this product. This would be a reduction of 11% of the embedded emissions. Given that more material is used than in the former case, this would outweigh the production of the packaging (excluding the transport from Italy).

Following equation (3), the cost of the product increases by 0.17%, or 0.04 SEK compared to the retail price of 19 SEK.

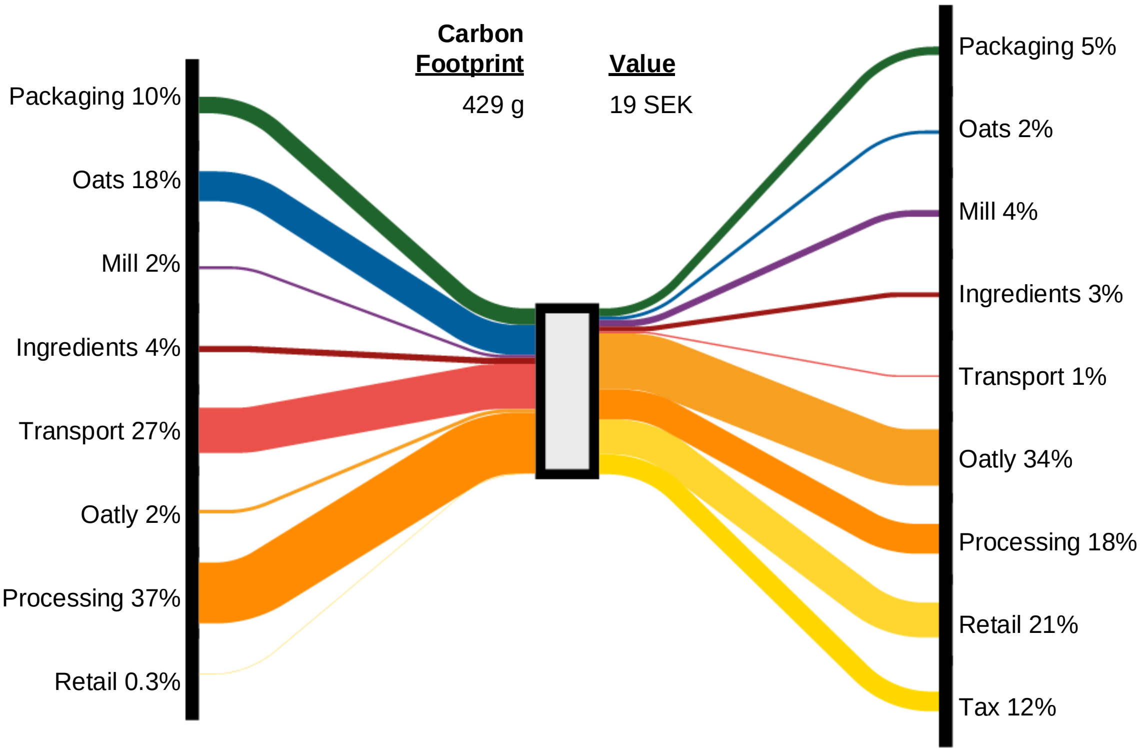

Figure 17 Current carbon footprint and value distribution for fresh oat drink

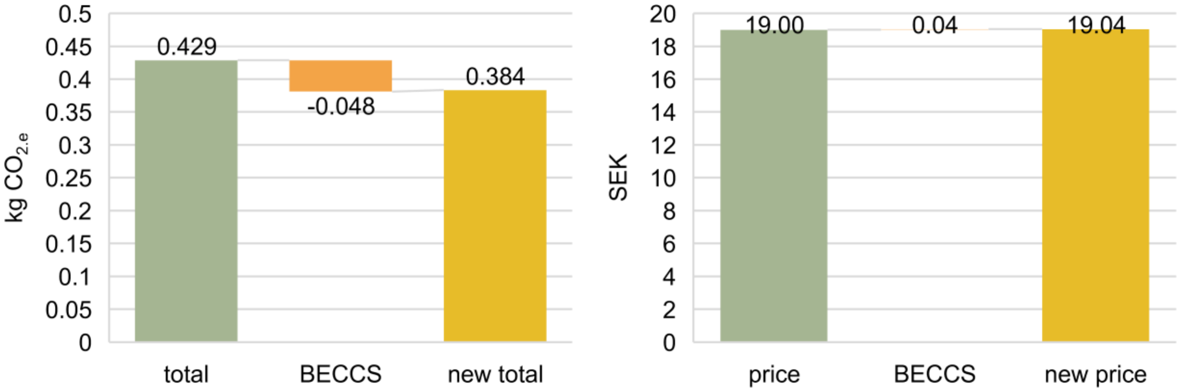

Figure 18 Carbon handprint changes for fresh oat drink, carbon footprint left, cost right

6.1.3. Semi skimmed milk

Conducting the calculations for this product with equation (2) one can allocate 43.4 g of captured CO_2 emissions to the milk carton. Given the high total emissions of the product, the BECCS reduction results in a 3% emissions decrease.

Increasing the costs of the pulp leads to an increase of 0.03 SEK, an increase of 0.28% compared to an 11 SEK retail price (equation (3)).

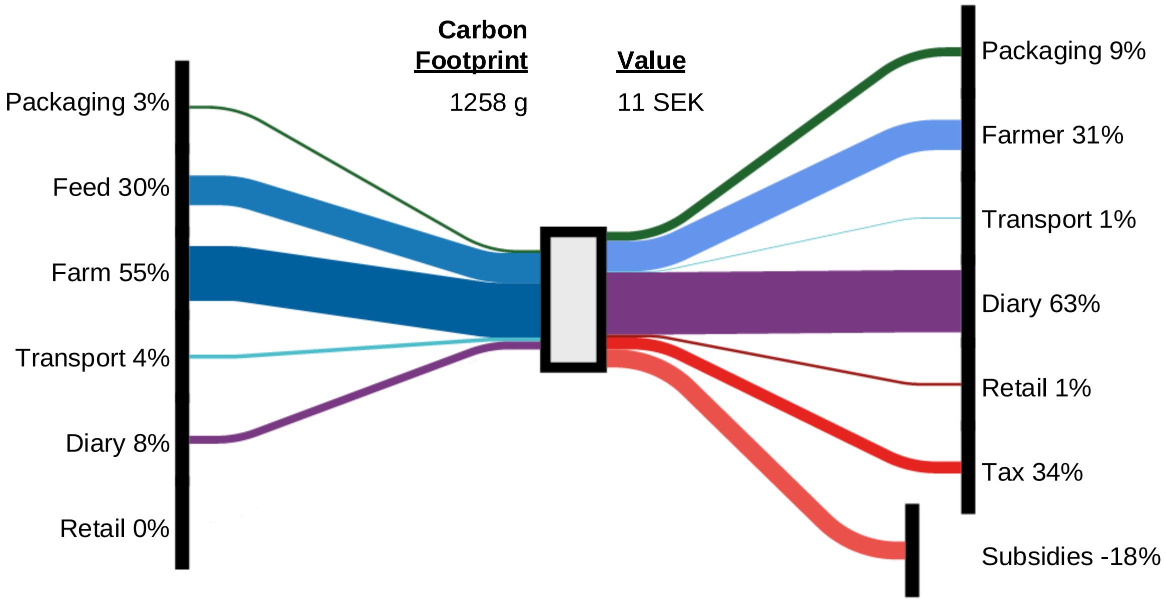

Figure 19 Current carbon footprint and value distribution for milk

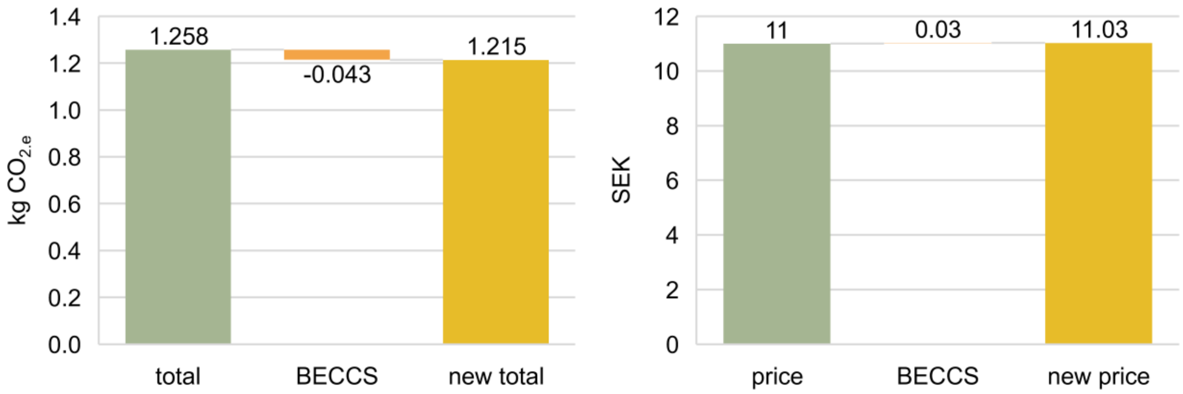

Figure 20 Carbon handprint changes for milk, carbon footprint left, cost right

6.2. Corrugated board box

With the emission factor of 841 kg $CO_{2,e}$/ tonne corrugated board, the emissions are at a level of 1.57 kg $CO_{2,e}$ for theses boxes. A reduction of 0.35 CO_2, respectively 22% of the embedded emissions, is possible, capturing 185 kg CO_2 per tonne corrugated board (equation (2)). No captured CO_2 is allocated to the 147 kg of waste- paper.

Using equation (3), the corrugated box costs 0.25 SEK more. That is an increase of 1.25% of the customer price. In Germany the same set costs the customer 2.99€ (31.1 SEK), the increase of 0.25 SEK constitutes a 0.80% price increase.

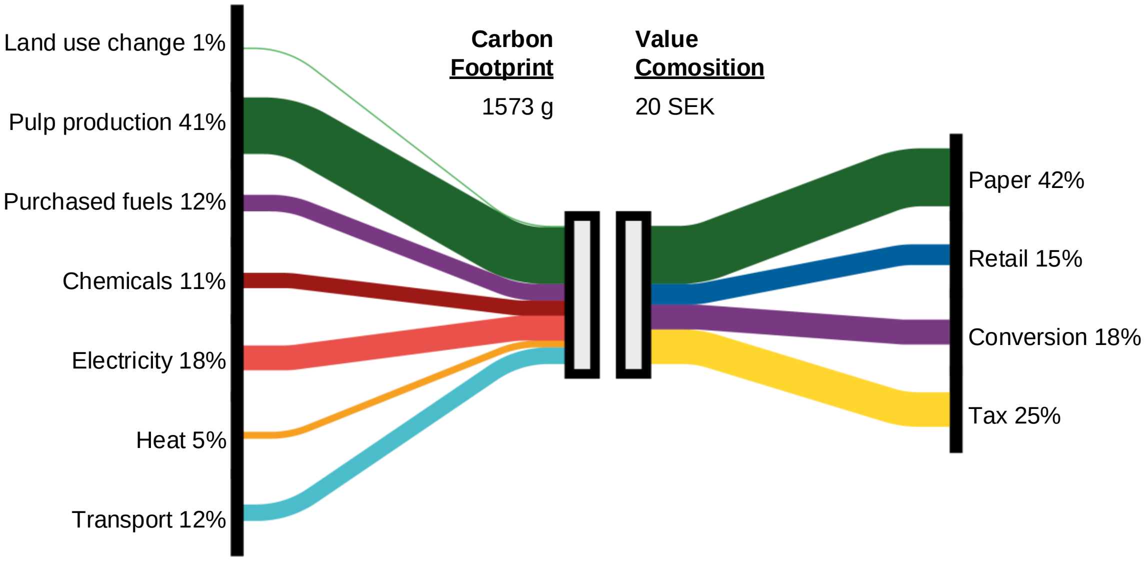

Figure 21 Current carbon footprint and value distribution for a moving box

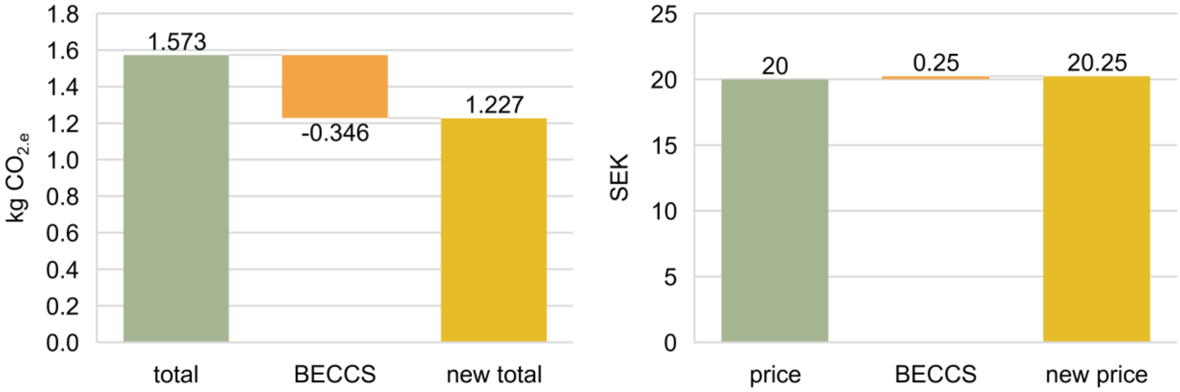

Figure 22 Carbon handprint changes for a moving box, carbon footprint left, cost right

6.3. Hardcover novel

Using the assumptions of the mass share of different parts of the book, about 320g of 500g are made of virgin kraft pulp, whereas only about 100g are softwood/ pine pulp and 220g are hardwood/ birch pulp. If both kinds of pulp come from pulp mills with BECCS, an emission reduction of 544 g is possible (equation(2)). That is a reduction of 47% for Finland and 71% for Sweden. If in Sweden only the softwood is from such pulp mills, the emissions would be reduced by 22%, respectively 49% for hardwood pulp.

In case the kraft paper source is changed and more expensive material is used, the final price would increase by 0.39 SEK (equation (3)). That is 0.13% of the retail price. If only softwood is replaced the final price would increase by 0.04% and respectively 0.09% for hardwood.

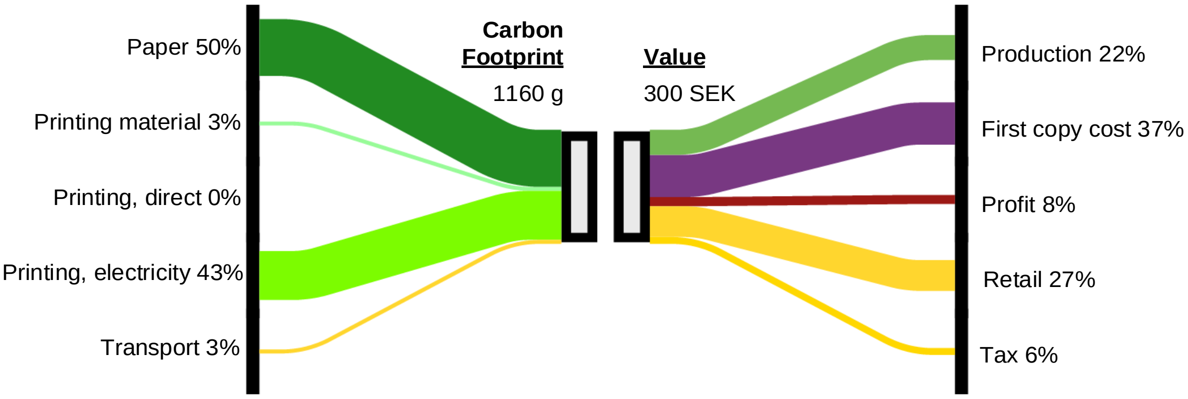

Figure 23 Current carbon footprint and value distribution for a novel (production in Finland)

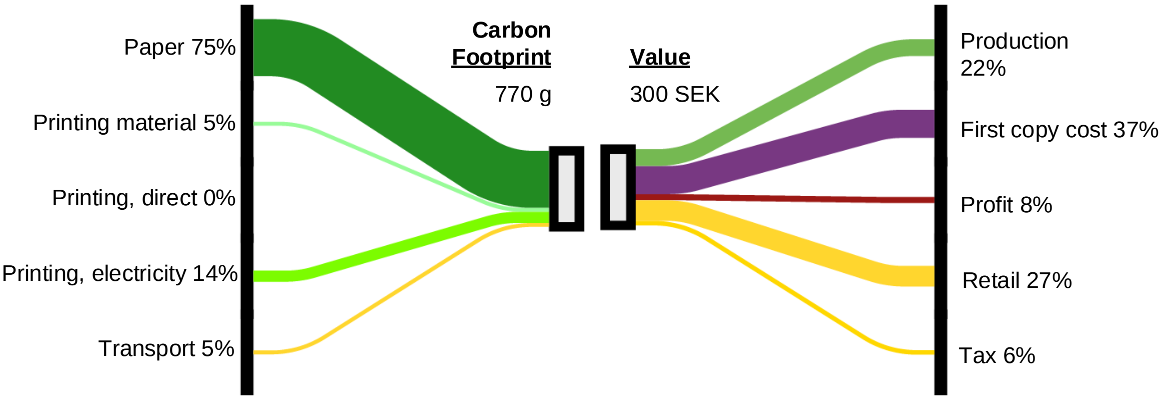

Figure 24 Current carbon footprint and value distribution for a novel (production in Sweden)

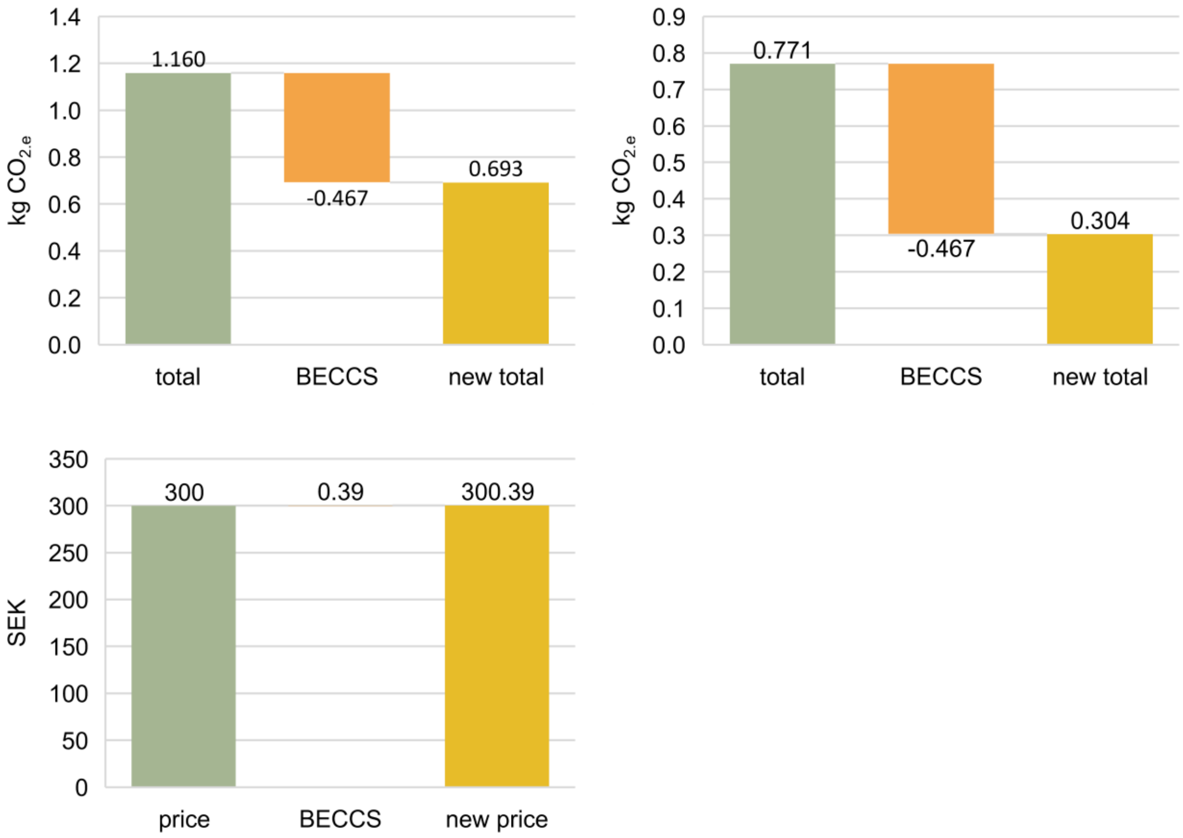

Figure 25 Carbon handprint changes, carbon footprint top (printing in Finland left, in Sweden right), cost bottom

6.4. Summary of results and sensitivity analysis

The results of this chapter are summarized in Table 7. In addition, for comparison, a number of additional cases not covered in the Methods and Results section have been included. The products that were discussed in more detail are indicated by the ✓- Symbol in front of the name. The variation is done with updated carbon footprint information, or assumptions on the degree of sulphate pulp usage.

If the negative emissions are not equally allocated to all produced pulp, the negative emissions have costs of 68€ per tonne CO_2. If these negative emissions compensate the cradle- to- gate emissions, i.e. the carbon footprint, the cost would increase as presented in the two most right columns.

The robustness of the results was tested by varying the two base assumption about BECCS in pulp and paper production from section 4.3. These are that the costs per air dried tonne of paper increases by 117€ when integrating BECCS, and that 1.7 kg of biogenic CO_2 can be captured per air dried kg of paper. For the sensitivity analysis all cases in Table 7 were recalculated with capture costs of 234€ and 58.50€ per tonne of paper and with the capture rate factors 1.5 and 1.9 kg CO_2/ kg paper. The boxplots in Figure 26 present the range of the results and the sensitivity to a variation of the used factors. The solid box thereby represents 50% of the result values around the average and the thin lines include the other quartiles further from the average. The cross represents the mean and the dots represent outliers. The capturing factor per produced pulp and the cost increase factor show robustness against changes, which allows to assume reliability of the results.

Table 7 Summary of the results with further variation of input factors. All data are reported per functional unit (i.e. per litre of drink; per set of moving box; per book)

Product	Price		Carbon foot-print	Kraft pulp usage	Potential emission reduction		Price increase		Price increase if carbon zero	
	SEK	EUR	g $CO_{2,e}$	g	g		EUR		EUR	
√Aseptic oat drink, 2012	18	1.73	309	22.1	37.6	12%	0.003	0.15%	0.21	12.12%
√Aseptic oat drink, 2017	18	1.73	300	21.6	36.7	12%	0.003	0.15%	0.20	11.77%
√Fresh oat drink, 2012	19	1.83	429	28.4	48.3	11%	0.003	0.18%	0.29	15.95%
√Fresh oat drink, 2017	19	1.83	380	28.4	48.3	13%	0.003	0.18%	0.26	14.13%
√Milk	11	1.06	1258	25.5	43.4	3%	0.003	0.28%	0.86	80.77%
√Moving box, Sweden	20	1.93	1570	203.8	346.4	22%	0.024	1.24%	1.07	55.44%
√Moving box, Germany	31.1	2.99	1570	203.8	346.4	22%	0.024	0.80%	1.07	35.71%
√Novel, Finland	300	28.88	1160	320	544.0	47%	0.037	0.13%	0.79	2.73%
√Novel, Sweden	300	28.88	770	320	544.0	71%	0.037	0.13%	0.52	1.81%
√Novel, Sweden softwood	300	28.88	770	100	170.0	22%	0.012	0.04%	0.52	1.81%
√Novel, Sweden, hardwood	300	28.88	770	220	374.0	49%	0.026	0.09%	0.52	1.81%
√Novel, Finland, incl. maculature 29%	300	28.88	1160	412.8	701.8	60%	0.048	0.17%	0.79	2.73%
√Novel, Sweden, incl. maculature 29%	300	28.88	770	412.8	701.8	91%	0.048	0.17%	0.52	1.81%
√Novel, Sweden softwood, incl. maculature 29%	300	28.88	770	129	219.3	28%	0.015	0.05%	0.52	1.81%
√Novel, Sweden, hardwood, incl. maculature 29%	300	28.88	770	283.8	482.5	63%	0.033	0.11%	0.52	1.81%

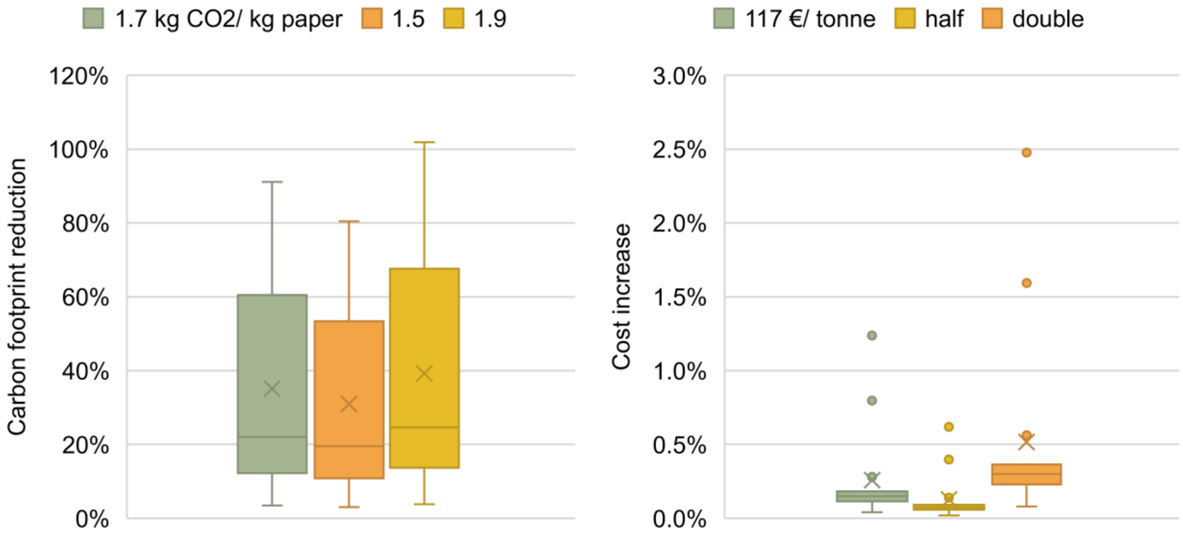

Figure 26 Sensitivity of the results changing the factor of captured emissions per tonne paper (left) and for changing the costs (right).

7. Discussion

7.1. New perspective on BECCS in the PPI

The results show that installing and running a BECCS plant in a pulp mill influences the cost of the final products marginally, while reducing the carbon footprint of the final products substantially through the associated negative emissions from BECCS. All studied products show a cost increase of less than 1.5% compared to the retail price - the highest increase is for a moving box, consisting entirely of paper. Yet, if the corrugated board was not purchased as a moving box, but as packaging for products like electrical appliances or furniture, the cost increase of 0.02 € for the moving box would be negligibly small. The cost increase of the other products is in the range of 0.1 - 0.2%. It should be noted that the limited increase is remarkable given that the analysed products are low-value products.

The current focus in the academic literature involved with CCS research tend to analyse the costs in a 'per tonne CO_2' or 'per tonne primary product' perspective. However, these perspectives have limited relevance for stakeholders outside the CCS research community, policy making and primary product producers.

A widening of perspectives, including final products in the discussion, as suggested in this thesis, allows to include more stakeholders. These could range from customers to the industry that uses paper, and furthermore also the general public and policy makers that could then reconsider the position towards the topic. The hope is that this thesis allows a process of re-evaluating how much the new technology would increase the costs for companies and costumers and at the same time increase the value, by reducing the climate impact. This could open the possibility to unlock investments in BECCS for business reasons, regardless of political incentives.

Given the timeframe and the intended generality of the study, the magnitude of the results is more important than the exact figures. It was shown that the economic value of paper in final product is low, compared to the costumer price. This allows to use more expensive climate friendly paper, without considerably affecting the costs for final products. Thereby the physical properties of the pulp, or subsequently the paper are not changed, while at the same time BECCS made the paper climate friendly. For the analysed and other not analysed products, the results are sensitive to a number of factors: a divergent design, alternative material composition, production facilities and transportation distances. The costs are further influenced by contracts between the supply chain partners. Nevertheless, the trend was found to be consistent over all studied products.

The results are in line with the two studies from which the methodology of comparing costs of primary production with final products is derived (Rootzén and Johnsson, 2016; Skelton and Allwood, 2013). The difference is that in this study everyday- products are analysed, making it more relevant to frequent purchasing decisions, compared to cars, construction, machinery or electronic equipment. Still, the magnitude of the carbon handprint compared to the cost increase is somewhat surprising.

7.2. BECCS in the PPI put into context

The technology applied in this analysis exists and is ready to be applied. However, for pulp mill operators the process of installing a CCS plant is not that straight forward. Complications include the identification of applicable storage sites, the installation of the transport infrastructure and legal amendments to be allowed to store the CO_2 (Heffron *et al.*, 2018). If the infrastructure and legal barriers are not eliminated, this discussion would not be useful. On the other hand, the process it driven by fossil CCS, which is already discussed on high political level and already included in the most important GHG accounting schemes (Zakkour *et al.*, 2014), for example the EU ETS (compare paragraph 3.1.1). Social or public acceptance of CCS, especially regarding CO_2 storage was identified as another barrier for the application, which currently seems to be lacking (Fridahl and Lehtveer, 2018). However, the following low prioritization from the political sphere is still seen as the main barrier (Fridahl and Lehtveer, 2018), which also constituted the starting point for this work, due to missing political incentives.

If BECCS is then included in paper production and used as carbon handprint argument, as argued (section 4.3), the practical implementation needs to be managed. It needs to be made sure that the carbon handprint is calculated in the right way to avoid fraud. As with LCA calculations, where the results depend on the chosen scope and assumptions, the effect could be assessed differently. Part of that argument is also the possibility that a policy scheme that reward negative emissions is introduced at the same time. If the negative emissions would be rewarded through that policy, these should not be seen as part of the product anymore to avoid double accounting. For the assessment here, this is not important, because these policies do not exist but should be considered in case of its implementation. Then it would depend on the plant owners decision, on how much negative emissions would be rewarded through the scheme and how much would be attributed to products.

7.3. Possible application

The increased intangible value of customer products by decreasing the climate impact can be a reason for companies to pursue a development of climate friendly technology and unlock investments in BECCS.

The economic value of management based on carbon footprints and communication of these on products has the potential to be huge (Buxel *et al.*, 2015). Several industries try to estimate and communicate carbon footprint reductions for a wider range of products (Vatanen *et al.*, 2018). For food products various voluntary carbon-labelling schemes are in use all over the world, also in attempts to argue for the value of packaging (Muthu, 2016). This kind of environmental communication and marketing is an own field with its own rules, e.g. to avoid greenwashing. One example is the ISO 14063 2010 standard on environmental communication, which requests: transparency, appropriateness, credibility, responsiveness and clarity (Vatanen *et al.*, 2018). Yet, it is a lot of work, that lead attempts of doing so to fail before, drawing attention to the need of balancing precision and usefulness (Avlonas and Nassos, 2014, pp. 217–226). The barriers of this management are important for planning the implementation, but do not change the conclusion that were drawn in this work.

McKinnon (2010) argues that decarbonisation potentials could also be reached without a product level accounting. For that, expansions of the above analysis from product level to company level can easily be done, using general information about the mass of used paper. Similarly, not only the product is affected, as carbon labelling is primarily seen as a tool to improve the public environmental image of the involved companies (Upham and Bleda, 2009). Consequentially, carbon labelling is not foremost directed to customers, but also to other parties in the supply chain, as stated in the following (Upham and Bleda, 2009, p. 22):

> “In terms of GHG emissions reduction, the main benefits of carbon labelling are likely to be incurred not via communication of emissions values to consumers, but upstream via manufacturers looking for additional ways to reduce emissions. This point is quite widely accepted as applying to eco-labelling in general.”

Even though the impact on the cost is assessed to be marginal, the cost increase needs to be borne from the customer. These need to coincide with an increase of the products value, which has different dimensions. On top of the economic value the products value also includes e.g. functional, emotional, symbolic and environmental value (Väätänen, 2017). The Swedish population was surveyed recently on climate issues, including questions on the purchasing behaviour. The results indicate that 70% of Swedes would pay up to 5% more for a company’s product if they knew the company is working on its emissions performance (Naturvårdsverket, 2018b).

Overall it is important to note that the first application could rather be directed to niche markets in which the willingness to pay a little more is higher. In the most recent Eurobarometer, the respondents who have no or only seldomly struggles to pay bills, more often than other groups state that responsibility to tackle climate change lies upon them as individuals rather than on the authorities (EC, 2017a, p. 29). This could also be a hint that they could also be willing to pay more.

In fact, a carbon neutral office paper is already being offered by the pulp and paper producer Stora Enso, showing that there could be a market for such a product. In this case, the carbon neutrality notion is achieved through the purchase of carbon emissions reduction certificates in three carbon offsetting programs (storaenso, 2019a).

7.4. Possible misunderstandings

It is argued that BECCS could reduce the carbon footprint of products. This can be seen as an argument to produce or use more material, which, however, still has an environmental impact. Furthermore, even if the biogenic emissions are neutral, is it still more beneficial not to emit in the first place than to capture. Consequently, energy efficiency or carbon capturing are not enough, but also less material production and different product designs should be part of the discussion (Allwood *et al.*, 2011; Allwood *et al.*, 2017). An obvious example is to recycle paper, rather than producing virgin pulp. Further, if more biomass would be used for the capturing process, the embedded energy in the products increases and the economy wide availability of this energy for other sectors decreases. These effects do not change the result of the thesis and are therefore not assessed or discussed here. Nevertheless, awareness should be drawn to it.

Moreover, the inclusion of social aspects next to environmental and economic aspects should be part of the discussion on sustainability. As an example, in the case of milk packaging, it has been pointed out that milk farmers perceive the price paid by dairies as too low to survive (Styrelsen Sveriges Mjölkbönder, 2018). Similarly, discussions about other weak actors in products supply chain may relativize the priority of changing the production of the packaging if a price increase of the product is accepted.

7.5. Limitations

The following three points are important to understand the implications of the new perspective:

The calculations compare the price of products with the cost of materials. These stand in relation to each other, but pricing is not necessarily directly dependent on the costs. The pricing of companies is a separate field of management and includes internal calculations and tactics of business development (Simon and Fassnacht, 2018). Following that, this thesis cannot give implications regarding pricing.

The consideration of environmental impacts of pulping and subsequent processes was limited to the climate impact, i.e., other externalities were not assessed. Such impacts could include, e.g., effects on the ecosystem quality or human health, resource stress regarding biomass supply, or reactions on the energy system. These impacts are important to consider, but part of the overall discussions on BECCS application (IPCC, 2014, p. 21) and not changed through this thesis.

In this thesis biogenic emissions from woody biomass are assumed to be neutral. Given the possible bioenergy accounting error this may not always be the case. Nevertheless, if the captured emissions were not negative, CCS would still reduce the carbon footprint to the same amount and therefore does not change the insights generated by the new perspective.

7.6. Ideas for further research

This thesis develops a new perspective on the value of BECCS for end-product consumers. The application of this perspective is, however, not limited to BECCS in pulp production. Therefore, the scope could be extended to other industries with BECCS or CCS possibilities, exemplary biochemicals production (Scarlat *et al.*, 2015).

Moreover, some aspects were left out. In a subsequent study it would be interesting to study the impacts on business practice, these include:

- Pricing of climate positive products in all stages of the supply chain and cost pass through patterns
- The interactions within the industry (Swedish PPI) and the subsequent industry supply chain to identify barriers and driving forces
- How other emission reduction possibilities, like electrification or use of bioenergy, are perceived by the companies and if other more easy- to- mitigate potentials are already used
- The interaction of customers and businesses in the introduction of the new concept, of *products with negative emissions*
- Finally, it would also be interesting to study the interaction between single companies and the political sphere, as the companies may depend on the policy makers regarding support in legal adjustments and infrastructure development

In addition to the companies and their pricing management it would be interesting to investigate the financial burden of households, if the price of more commodities would be increased due to BECCS or CCS application, or climate positive technologies in general.

Another aspect worth exploring is the impact of applying BECCS in the PPI at a larger scale:

- How would the biomass demand change if all paper would be produced with BECCS?
- How would the regional energy production change, if pulp mills would not deliver heat or electricity?
- How much could the carbon footprint of companies or regions change, e.g. if companies switch completely to paper with negative emissions?

Another aspect is the implications of selling negative emissions as part of a product, here the following questions could be interesting:

- How do these negative emissions fit into (voluntary) offset programs, such as the EU ETS, Certified Emission Reduction units in the Clean Development Mechanism, or private offset programs like the “Verified Carbon Standard” and what are the reasons for missing integration (Zakkour *et al.*, 2014)?
- How negative emissions through BECCS can be combined with the idea that carbon is also stored in biomass products like paper (e.g. in the standard PAS 2050 (BSi, 2008))?

8. Conclusion

This thesis sets the costs and negative emission of BECCS application in the production of pulp in relation to consumer products. As a first step the currently present supply chain of representative consumer products was analysed. By that, the different processes were assed regarding their share in the economic value and the carbon footprint. Based on this, the corresponding cost increase and carbon footprint reduction due to BECCS application was assessed. It was found that the carbon footprint of consumer products can be reduced substantially (i.e. 3%- 91%), while the cost increase is marginally small (i.e. 0.1%- 1.2%). The results show that the cost increase of pulp production can be related to a carbon footprint reduction, an improvement of the products intangible value.

To conclude: The benefits of climate change mitigation through BECCS are only mentioned implicitly without further quantification. However, being aware of the urgency of the topic, the implementation of mitigation technology cannot wait. By providing new perspectives on the costs related to the integration of BECCS in the pulp and paper industry, this thesis can hopefully contribute to overcome some of the communication barriers related to BECCS. By showing that BECCS influences the costs of consumer products only minimally while potentially adding value to the product through a carbon footprint reduction – this work suggests that BECCS is not as disadvantageous as it could be perceived, even in absence of political incentives. This leaves less reason to not start mitigating climate change in pulp production.

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Appendix

A. Sankey Sweden pulp and paper production

Steps to the Sankey diagram of the economy from left to right. Observe that the mass for pulp and paper was inserted with their respective moisture content, 10% for pulp, 6% for paper.

1. Production of different pulp grades (Skogsindustrierna, 2018d)
2. Separation of other chemical pulp with other sulphate pulp with production data of (Skogsindustrierna, 2018a) and the fact that there is only one sulphite mill in Sweden (Skogsindustrierna, 2019b). Assuming that 50% of the produced sulphite pulp is sold as market pulp or used for paper production respectively. The sulphite mill is called “Nymölla mill” by Stora Enso and has a capacity of 340 kt pulp and 485 kt paper yearly (storaenso, 2019b). Dissolving grade paper is not part of the discussion. There is only one mill that produces dissolving grade. It is called “Domsjö Fabriker” and no paper is produced there.
3. Import and export (SCB, 2019b)
4. Paper production of different grades (Skogsindustrierna, 2018d)
5. Export share of paper production (Skogsindustrierna, 2018d)
6. Recycling rate (Naturvårdsverket, 2018a)
7. Export paper for recycling (SCB, 2019b)
8. Utilisation of paper for recycling (Skogsindustrierna, 2018c)
9. Paper in exports [total paper in economy minus recycled paper] no landfill (Naturvårdsverket, 2018a), no stock assumed (Skogsindustrierna, 2018c)
10. Consumption (Skogsindustrierna, 2018b)

The self-reported data that is reported by the industry, is attested to be accurate (Stenqvist, 2015).

A clear decomposition of Sulphate pulp and other chamical pulp in (Skogsindustrierna, 2018d) was not possible, due to a uncomplete documentation in the database of the PPI federation (Skogsindustrierna, 2018a). Some factories like “Stora Enso, Skoghalls Bruk” (pulp capacity 645,000 ADt) are not reported. The share of “other chemical pulp” could therefore also include unbleached sulphate pulp or hardwood sulphate pulp, as exemplary for “Stora Enso, Skoghalls Bruk” that produced around 193,000 ADt of unbleached sulphate pulp for internal use in 2017 (storaenso, 2018), here it is however categorised as “other chemical pulp”. In Sweden however only two chemical pulp mills do not use sulphate pulping (Skogsindustrierna, 2019b). One is a bio- refinery, which only produces dissolving grade market pulp, which is not included. The flow is therefore dominated by sulphate pulp.

To calculate the value flows the specific value of the different grades were calculated with the export data, see Table 10 in Appendix B. These values are fairly similar over the last years, besides for the ”other” grade, as depicted in the figure below. The specific values of 2017 were used (see Table 8 and Table 9) and multiplied with the mass data of all flows. In this calculation the methodology of Joelsson and Athanassiadis (2015b) is followed, acknowledging that internal flows in companies or even integrated pulp and paper mills do usually not have the same price than on the open market. The use of specific export values is backed by the similar prices on the Swedish and the export market, see Figure 28. Due to the above-mentioned composition of “other chemical pulp” were the flows multiplied with the “other sulphate pulp” multiplicator, besides 340 kt sulphite pulp that go to paper production.

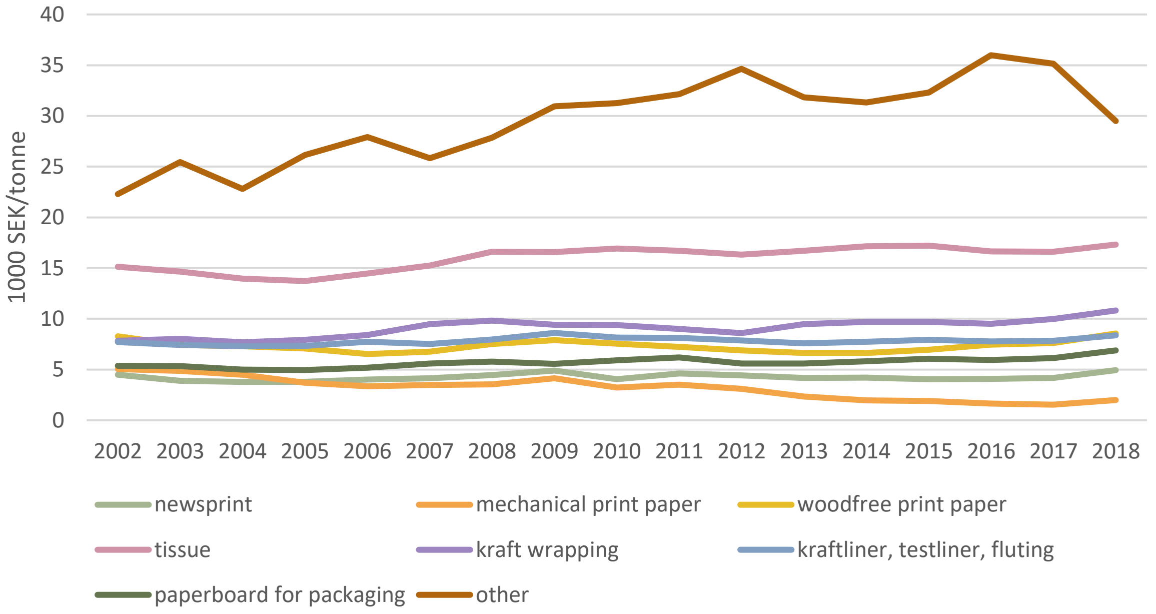


Figure 27 Specific value of paper grades over time (SCB, 2019b)

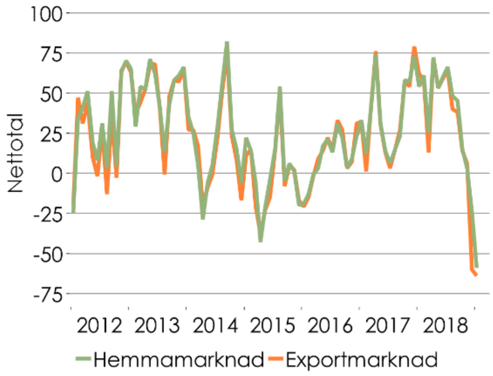
Table 8 Key values for the reported paper grade classes

Paper grade	Secific value [SEK/tonne]	Total production, t SEK	Total production, tonne
Newsprint	4,163	3,187,965	765,747
mechanical print paper	5,108	10,575,379	2,070,201
woodfree print paper	7,609	5,673,455	745,648
graphical paper	**5,427**	**19,436,799**	**3,581,596**

tissue	**16,611**	**4,846,140**	**291,745**
Kraft wrapping	7,866	9,521,048	1,210,397
Kraftliner, Testliner, Fluting	5,098	11,364,870	2,229,315
paperboard for packaging	8,305	24,229,336	2,917,428
packaging material	**7,097**	**45,115,254**	**6,357,140**
other	**21,133**	**2,018,866**	**95,533**

Table 9 Key values for the reported pulp grade classes

Pulp grade	**Specific value [SEK/tonne]**	**Total export, tSEK**	**Total export, tonne**
mechanical and semi- mechanical pulp	5,315	2,254,601	424,188
bleached sulphate softwood pulp	6,829	16,904,136	2,475,182
other sulphate pulp	6,153	2,588,786	420,713
sulphite pulp	3,252	86,969	26,740
recycling paper	1,343	601,014	447,366

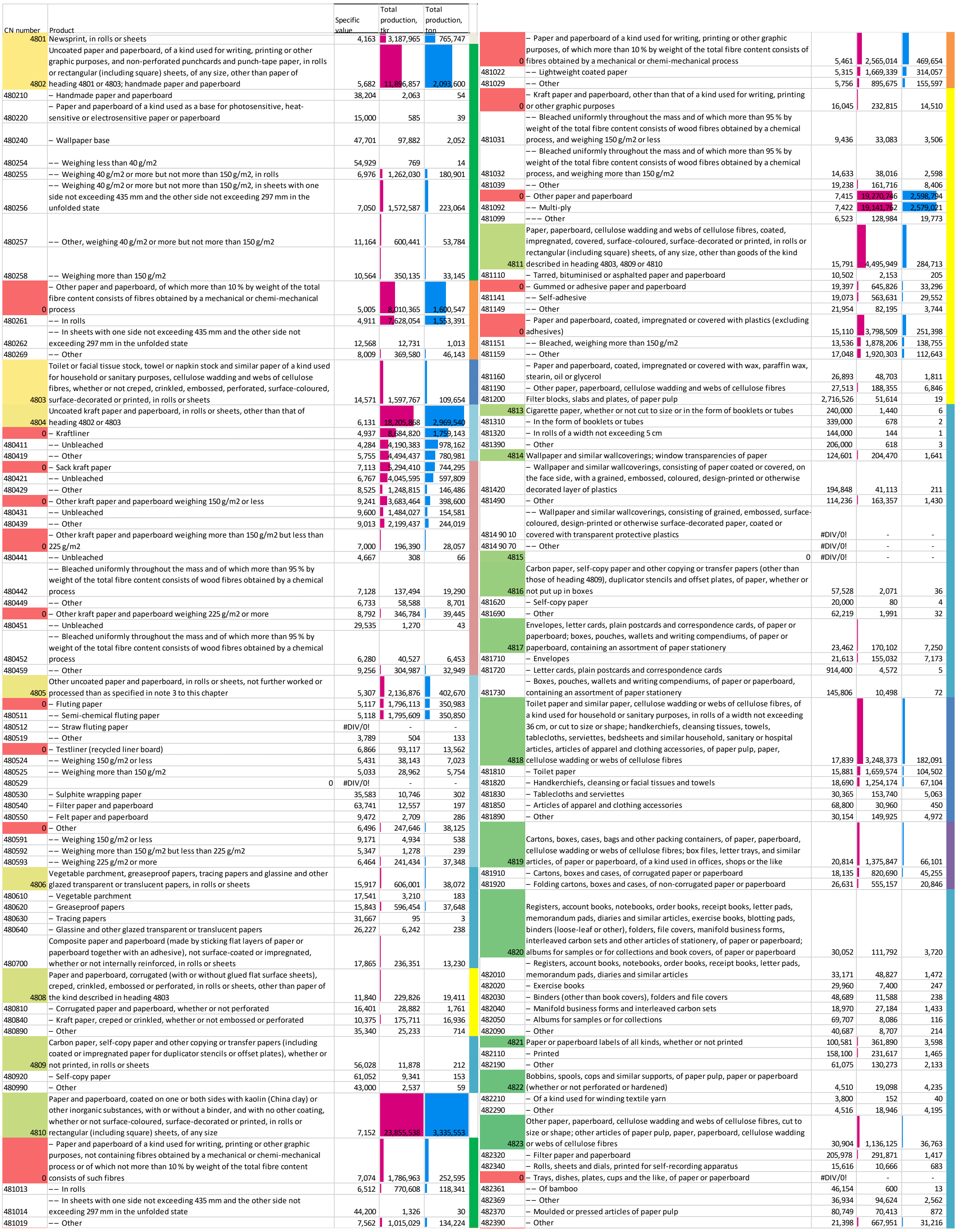


Källor: Konjunkturinstitutet, Macrobond

Figure 28 Comparison of prices on the Swedish and the export market (Skogsindustrierna, 2019a, p. 12)

B. Value of paper products

Table 10 Economic value of different paper products (SEK/tonne) with their respective export volume in mass and SEK in 2017 (CN code). Source (SCB, 2019b)



CN number	Product	Specific value	Total production, tkr	Total production, ton
4801	Newsprint, in rolls or sheets	4,163	3,187,965	765,747
4802	Uncoated paper and paperboard, of a kind used for writing, printing or other graphic purposes, and non-perforated punchcards and punch-tape paper, in rolls or rectangular (including square) sheets, of any size, other than paper of heading 4801 or 4803; handmade paper and paperboard	5,682	11,896,857	2,093,600
480210	– Handmade paper and paperboard	38,204	2,063	54
480220	– Paper and paperboard of a kind used as a base for photosensitive, heat-sensitive or electrosensitive paper or paperboard	15,000	585	39
480240	– Wallpaper base	47,701	97,882	2,052
480254	–– Weighing less than 40 g/m2	54,929	769	14
480255	–– Weighing 40 g/m2 or more but not more than 150 g/m2, in rolls	6,976	1,262,030	180,901
480256	–– Weighing 40 g/m2 or more but not more than 150 g/m2, in sheets with one side not exceeding 435 mm and the other side not exceeding 297 mm in the unfolded state	7,050	1,572,587	223,064
480257	–– Other, weighing 40 g/m2 or more but not more than 150 g/m2	11,164	600,441	53,784
480258	–– Weighing more than 150 g/m2	10,564	350,135	33,145
0	– Other paper and paperboard, of which more than 10 % by weight of the total fibre content consists of fibres obtained by a mechanical or chemi-mechanical process	5,005	8,010,365	1,600,547
480261	–– In rolls	4,911	7,628,054	1,553,391
480262	–– In sheets with one side not exceeding 435 mm and the other side not exceeding 297 mm in the unfolded state	12,568	12,731	1,013
480269	–– Other	8,009	369,580	46,143
4803	Toilet or facial tissue stock, towel or napkin stock and similar paper of a kind used for household or sanitary purposes, cellulose wadding and webs of cellulose fibres, whether or not creped, crinkled, embossed, perforated, surface-coloured, surface-decorated or printed, in rolls or sheets	14,571	1,597,767	109,654
4804	Uncoated kraft paper and paperboard, in rolls or sheets, other than that of heading 4802 or 4803	6,131	18,205,868	2,969,540
0	– Kraftliner	4,937	8,684,820	1,759,143
480411	–– Unbleached	4,284	4,190,383	978,162
480419	–– Other	5,755	4,494,437	780,981
0	– Sack kraft paper	7,113	5,294,410	744,295
480421	–– Unbleached	6,767	4,045,595	597,809
480429	–– Other	8,525	1,248,815	146,486
0	– Other kraft paper and paperboard weighing 150 g/m2 or less	9,241	3,683,464	398,600
480431	–– Unbleached	9,600	1,484,027	154,581
480439	–– Other	9,013	2,199,437	244,019
0	– Other kraft paper and paperboard weighing more than 150 g/m2 but less than 225 g/m2	7,000	196,390	28,057
480441	–– Unbleached	4,667	308	66
480442	–– Bleached uniformly throughout the mass and of which more than 95 % by weight of the total fibre content consists of wood fibres obtained by a chemical process	7,128	137,494	19,290
480449	–– Other	6,733	58,588	8,701
0	– Other kraft paper and paperboard weighing 225 g/m2 or more	8,792	346,784	39,445
480451	–– Unbleached	29,535	1,270	43
480452	–– Bleached uniformly throughout the mass and of which more than 95 % by weight of the total fibre content consists of wood fibres obtained by a chemical process	6,280	40,527	6,453
480459	–– Other	9,256	304,987	32,949
4805	Other uncoated paper and paperboard, in rolls or sheets, not further worked or processed than as specified in note 3 to this chapter	5,307	2,136,876	402,670
0	– Fluting paper	5,117	1,796,113	350,983
480511	–– Semi-chemical fluting paper	5,118	1,795,609	350,850
480512	–– Straw fluting paper	#DIV/0!	-	-
480519	–– Other	3,789	504	133
0	– Testliner (recycled liner board)	6,866	93,117	13,562
480524	–– Weighing 150 g/m2 or less	5,431	38,143	7,023
480525	–– Weighing more than 150 g/m2	5,033	28,962	5,754
480529	0	#DIV/0!	-	-
480530	– Sulphite wrapping paper	35,583	10,746	302
480540	– Filter paper and paperboard	63,741	12,557	197
480550	– Felt paper and paperboard	9,472	2,709	286
0	– Other	6,496	247,646	38,125
480591	–– Weighing 150 g/m2 or less	9,171	4,934	538
480592	–– Weighing more than 150 g/m2 but less than 225 g/m2	5,347	1,278	239
480593	–– Weighing 225 g/m2 or more	6,464	241,434	37,348
4806	Vegetable parchment, greaseproof papers, tracing papers and glassine and other glazed transparent or translucent papers, in rolls or sheets	15,917	606,001	38,072
480610	– Vegetable parchment	17,541	3,210	183
480620	– Greaseproof papers	15,843	596,454	37,648
480630	– Tracing papers	31,667	95	3
480640	– Glassine and other glazed transparent or translucent papers	26,227	6,242	238
480700	Composite paper and paperboard (made by sticking flat layers of paper or paperboard together with an adhesive), not surface-coated or impregnated, whether or not internally reinforced, in rolls or sheets	17,865	236,351	13,230
4808	Paper and paperboard, corrugated (with or without glued flat surface sheets), creped, crinkled, embossed or perforated, in rolls or sheets, other than paper of the kind described in heading 4803	11,840	229,826	19,411
480810	– Corrugated paper and paperboard, whether or not perforated	16,401	28,882	1,761
480840	– Kraft paper, creped or crinkled, whether or not embossed or perforated	10,375	175,711	16,936
480890	– Other	35,340	25,233	714
4809	Carbon paper, self-copy paper and other copying or transfer papers (including coated or impregnated paper for duplicator stencils or offset plates), whether or not printed, in rolls or sheets	56,028	11,878	212
480920	– Self-copy paper	61,052	9,341	153
480990	– Other	43,000	2,537	59
4810	Paper and paperboard, coated on one or both sides with kaolin (China clay) or other inorganic substances, with or without a binder, and with no other coating, whether or not surface-coloured, surface-decorated or printed, in rolls or rectangular (including square) sheets, of any size	7,152	23,855,538	3,335,553
0	– Paper and paperboard of a kind used for writing, printing or other graphic purposes, not containing fibres obtained by a mechanical or chemi-mechanical process or of which not more than 10 % by weight of the total fibre content consists of such fibres	7,074	1,786,963	252,595
481013	–– In rolls	6,512	770,608	118,341
481014	–– In sheets with one side not exceeding 435 mm and the other side not exceeding 297 mm in the unfolded state	44,200	1,326	30
481019	–– Other	7,562	1,015,029	134,224
0	– Paper and paperboard of a kind used for writing, printing or other graphic purposes, of which more than 10 % by weight of the total fibre content consists of fibres obtained by a mechanical or chemi-mechanical process	5,461	2,565,014	469,654
481022	–– Lightweight coated paper	5,315	1,669,339	314,057
481029	–– Other	5,756	895,675	155,597
0	– Kraft paper and paperboard, other than that of a kind used for writing, printing or other graphic purposes	16,045	232,815	14,510
481031	–– Bleached uniformly throughout the mass and of which more than 95 % by weight of the total fibre content consists of wood fibres obtained by a chemical process, and weighing 150 g/m2 or less	9,436	33,083	3,506
481032	–– Bleached uniformly throughout the mass and of which more than 95 % by weight of the total fibre content consists of wood fibres obtained by a chemical process, and weighing more than 150 g/m2	14,633	38,016	2,598
481039	–– Other	19,238	161,716	8,406
0	– Other paper and paperboard	7,415	19,270,746	2,598,794
481092	–– Multi-ply	7,422	19,141,762	2,579,021
481099	––– Other	6,523	128,984	19,773
4811	Paper, paperboard, cellulose wadding and webs of cellulose fibres, coated, impregnated, covered, surface-coloured, surface-decorated or printed, in rolls or rectangular (including square) sheets, of any size, other than goods of the kind described in heading 4803, 4809 or 4810	15,791	4,495,949	284,713
481110	– Tarred, bituminised or asphalted paper and paperboard	10,502	2,153	205
0	– Gummed or adhesive paper and paperboard	19,397	645,826	33,296
481141	–– Self-adhesive	19,073	563,631	29,552
481149	–– Other	21,954	82,195	3,744
0	– Paper and paperboard, coated, impregnated or covered with plastics (excluding adhesives)	15,110	3,798,509	251,398
481151	–– Bleached, weighing more than 150 g/m2	13,536	1,878,206	138,755
481159	–– Other	17,048	1,920,303	112,643
481160	– Paper and paperboard, coated, impregnated or covered with wax, paraffin wax, stearin, oil or glycerol	26,893	48,703	1,811
481190	– Other paper, paperboard, cellulose wadding and webs of cellulose fibres	27,513	188,355	6,846
481200	Filter blocks, slabs and plates, of paper pulp	2,716,526	51,614	19
4813	Cigarette paper, whether or not cut to size or in the form of booklets or tubes	240,000	1,440	6
481310	– In the form of booklets or tubes	339,000	678	2
481320	– In rolls of a width not exceeding 5 cm	144,000	144	1
481390	– Other	206,000	618	3
4814	Wallpaper and similar wallcoverings; window transparencies of paper	124,601	204,470	1,641
481420	– Wallpaper and similar wallcoverings, consisting of paper coated or covered, on the face side, with a grained, embossed, coloured, design-printed or otherwise decorated layer of plastics	194,848	41,113	211
481490	– Other	114,236	163,357	1,430
4814 90 10	–– Wallpaper and similar wallcoverings, consisting of grained, embossed, surface-coloured, design-printed or otherwise surface-decorated paper, coated or covered with transparent protective plastics	#DIV/0!	-	-
4814 90 70	–– Other	#DIV/0!	-	-
4815	0	#DIV/0!	-	-
4816	Carbon paper, self-copy paper and other copying or transfer papers (other than those of heading 4809), duplicator stencils and offset plates, of paper, whether or not put up in boxes	57,528	2,071	36
481620	– Self-copy paper	20,000	80	4
481690	– Other	62,219	1,991	32
4817	Envelopes, letter cards, plain postcards and correspondence cards, of paper or paperboard; boxes, pouches, wallets and writing compendiums, of paper or paperboard, containing an assortment of paper stationery	23,462	170,102	7,250
481710	– Envelopes	21,613	155,032	7,173
481720	– Letter cards, plain postcards and correspondence cards	914,400	4,572	5
481730	– Boxes, pouches, wallets and writing compendiums, of paper or paperboard, containing an assortment of paper stationery	145,806	10,498	72
4818	Toilet paper and similar paper, cellulose wadding or webs of cellulose fibres, of a kind used for household or sanitary purposes, in rolls of a width not exceeding 36 cm, or cut to size or shape; handkerchiefs, cleansing tissues, towels, tablecloths, serviettes, bedsheets and similar household, sanitary or hospital articles, articles of apparel and clothing accessories, of paper pulp, paper, cellulose wadding or webs of cellulose fibres	17,839	3,248,373	182,091
481810	– Toilet paper	15,881	1,659,574	104,502
481820	– Handkerchiefs, cleansing or facial tissues and towels	18,690	1,254,174	67,104
481830	– Tablecloths and serviettes	30,365	153,740	5,063
481850	– Articles of apparel and clothing accessories	68,800	30,960	450
481890	– Other	30,154	149,925	4,972
4819	Cartons, boxes, cases, bags and other packing containers, of paper, paperboard, cellulose wadding or webs of cellulose fibres; box files, letter trays, and similar articles, of paper or paperboard, of a kind used in offices, shops or the like	20,814	1,375,847	66,101
481910	– Cartons, boxes and cases, of corrugated paper or paperboard	18,135	820,690	45,255
481920	– Folding cartons, boxes and cases, of non-corrugated paper or paperboard	26,631	555,157	20,846
4820	Registers, account books, notebooks, order books, receipt books, letter pads, memorandum pads, diaries and similar articles, exercise books, blotting pads, binders (loose-leaf or other), folders, file covers, manifold business forms, interleaved carbon sets and other articles of stationery, of paper or paperboard; albums for samples or for collections and book covers, of paper or paperboard	30,052	111,792	3,720
482010	– Registers, account books, notebooks, order books, receipt books, letter pads, memorandum pads, diaries and similar articles	33,171	48,827	1,472
482020	– Exercise books	29,960	7,400	247
482030	– Binders (other than book covers), folders and file covers	48,689	11,588	238
482040	– Manifold business forms and interleaved carbon sets	18,970	27,184	1,433
482050	– Albums for samples or for collections	69,707	8,086	116
482090	– Other	40,687	8,707	214
4821	Paper or paperboard labels of all kinds, whether or not printed	100,581	361,890	3,598
482110	– Printed	158,100	231,617	1,465
482190	– Other	61,075	130,273	2,133
4822	Bobbins, spools, cops and similar supports, of paper pulp, paper or paperboard (whether or not perforated or hardened)	4,510	19,098	4,235
482210	– Of a kind used for winding textile yarn	3,800	152	40
482290	– Other	4,516	18,946	4,195
4823	Other paper, paperboard, cellulose wadding and webs of cellulose fibres, cut to size or shape; other articles of paper pulp, paper, paperboard, cellulose wadding or webs of cellulose fibres	30,904	1,136,125	36,763
482320	– Filter paper and paperboard	205,978	291,871	1,417
482340	– Rolls, sheets and dials, printed for self-recording apparatus	15,616	10,666	683
0	– Trays, dishes, plates, cups and the like, of paper or paperboard	#DIV/0!	-	-
482361	–– Of bamboo	46,154	600	13
482369	–– Other	36,934	94,624	2,562
482370	– Moulded or pressed articles of paper pulp	80,749	70,413	872
482390	– Other	21,398	667,951	31,216